LGP (LIGHT GUIDE PLATE) PATTERN DESIGN BY USING LIGHT TOOLS FOR BACK LIGHT UNITS OF TFT LCD TVS

A Thesis

by

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LGP (LIGHT GUIDE PLATE) PATTERN DESIGN BY USING LIGHT TOOLS FOR BACK LIGHT UNITS OF TFT LCD TVS

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I dedicate this thesis to my husband who has always been there for me through thick and thin.

ABSTRACT

The light guide plates and their pattern play a critical role on the brightness and the uniformity of the back light unit hence the liquid display panel. If the brightness and the uniformity can be brought to a level that will allow the unit to incorporate fewer or cheaper optical structure, the resulting panel becomes more competitive in terms of cost and process . Therefore, the scope of this study is to design a dot pattern that will increase the uniformity and the brightness of the back light unit to a level that will allow discarding more expensive films such as reflective polarizers.

To achieve this purpose an LGP pattern was designed by using an optical simulation tool (Light Tools), the resulting plate was produced and the results with the real measurements were compared against simulation. The results showed significant improvement over existing LGPs.

The system studied in this work incorporated a 39" panel with 52 LED placed at the short edge of the back light unit. The uniformity target was 75% (VESA standard value) from 1/6 of the active area and the brightness target was 300 nits. Optical stack was aimed to be DBEF free and the power classification target was A+. The size, optical stack, power consumption and the location of the LEDs are, any and all of them, the challenges that make this study unique.

The initial parameters resulted in a distribution of 61% uniformity, but this trial served as a starting point to compare the dot's optical parameters with the real world results leading to optimum parameterization. After which, the design results were much closer to production results. The final design achieved the minimal targeted

specifications of 300 nits (338 nits) and 75% (76.63%) uniformity.

Simulating the light guide plate's dot pattern and testing many pattern distributions saved both time and money compared to producing all of them.

ÖZETÇE

Işık kılavuzu plakalar ve desenleri arka ışık üniteleri ve dolayısıyla likit kristal panellerin parlaklıkları ve eş dağılımları üzerinde oldukça etken bir rol oynamaktadır. Parlaklık ve eş dağılım daha az veya daha ucuz bir optik yapı kullanımına izin verecek seviyeye getirilebilirse ortaya çıkacak olan panel sadece maliyet değil, üretim süreci açısından da daha rekabetçi bir pozisyona sahip olacaktır. Bu çalışmanın kapsamı, yansıtıcı polarizerler gibi daha pahalı filmlerden kurtulmak hedefine ulaşmak için, parlaklık ve dağılımı iyileştirecek bir ışık kılavuzu nokta desen dağılımı tasarlamaktır.

Bu hedefi yakalamak için nokta deseni tasarlarken Light Tools optik simülasyon yazılımı kullanılacak ve simülasyon sonuçları üretim sonuçları ile karşılaştırılacaktır. Bu karşılaştırma sonucunda noktaların ve arka ışık ünitesinin optik modelleri iyileştirilecektir.

Çalışma kapsamında kullanılan arka ışık ünitesi 39” bir likit kristal panele ait, 52 adet LED içeren yandan (kısa kenar boyunca) aydınlatmalı bir ünitedir. Ünitenin LED'leri kısa kenar üzerine yerleştirilmiştir. Eş dağılım hedefi %75 (VESA standardı gereği), parlaklık hedefi ise 300 nittir. Aynı zamanda kullanımı hedeflenen optik yapıda DBEF filmi olmamalı ve güç tüketim sınıfı ise A+ olmalıdır. Boyut, LED sayısı ve yerleşimi, güç tüketimi ve optik yapının her biri başlı başına birer çalışma konusu olabilirler.

İlk parametreler ile alınan baskının ve üzerinde yapılan ölçümlerin sonucunda panelin eş dağılımı %61 çıkmıştır. Bu deneme sayesinde gerçek dünya ölçüm sonuçları ile

simülasyon sonuçları karşılaştırılmış ve nokta deseninin optik parametreleri optimize edilmiştir. Bundan sonra yapılan denemeler ve alınan baskıların sonuçları ile yapılan simülasyonların çıktılarının oldukça yakın olduğu görülmüştür. Final tasarım hedefleri tutturmuş ve %76.63'luk bir eş dağılım ve 338 nitlik merkez parlaklığa ulaşmıştır.

Nokta dağılımını deneme yanılma yöntemi yerine simülasyon ile finalize ederek gerek maddi olarak gerekse zaman açısından büyük bir avantaj sağlanmıştır.

ACKNOWLEDGEMENTS

First of all, I wish to state my gratitude to my advisor Assoc. Prof. Dr. Göksenin Yaralıoğlu for his support, guidance and indulgence during my thesis studies. I am sincerely grateful for his thorough reading of this thesis and for his helpful comments.

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This thesis would not have been possible without their support; I would like to thank VESTEL Electronics Inc. and VESTEL Optical Systems Design Group for providing me the necessary equipment and softwares to conduct my studies. I thank all members of Optical System Design Group for being my colleagues and for their comments. Also, for the assistance, I am grateful to DS Electron Inc. and their design team.

I extend my special thanks to my parents and my sister for being my lifelong friends and believing in me throughout my life. Their generous and unselfish love always warms the cockles of my heart.

Last, and most importantly, thanks to my husband for being everything to me.

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CHAPTER I

INTRODUCTION

1.1 Motivation

The television is an indispensable part of the daily life of modern human since the 1950's. First as a mean of communication much like the radio even with amateur television operators, it is now an essential part of our life for communication, entertainment and even, with the new flat panel displays and this bezel technology, home decoration.

TFT-LCD TV's (Thin Film Transistor - Liquid Crystal Display) are quickly growing and overcoming in numbers the existing CRT TV's (Cathode Ray Tube TV's). More and more each day the number of companies producing CRT TV's diminishes. The thin structure, long life, higher resolution and more modern appearance of the LCD TV's make them the number one choice over the CRT's. Along with lower energy consumption and better resolution; the massive investment in liquid crystal glass manufacturing in Asia, namely in Korea and Taiwan and to a lesser extend Japan, caused the LCD TV's to triumph over the plasma TV's.

The liquid crystals are not self emitting molecules. Therefore, an external light source is necessary for the operation of these displays. With the progress in LEDs, the light source utilized for this purpose is becoming more and more LEDs rather than fluorescent lamps (CCFL, EEFL). The LEDs offer better control over the intensity, less energy consumption and thinner design possibilities.

Apart from its electronics, an LDC TV is comprised of two main parts: a back light unit (light source) and the liquid crystal cell (valve). Back light provides a uniform flat lighting from backside of the liquid crystal cell, is the second most expensive component, and it greatly affects the optical and visual quality of the LCD TVs. Depending on the position of the light source back light units may be separated into two categories: edge type and direct type. Due to the cost efficiency, thinner structure and the design variety the trend is on the edge type BLU LCD TVs.

A typical edge-type LED based BLU includes a light source, a light guide plate (LGP) and several optical films that modify the light. The most important element of an LED based back light unit (BLU) is, after LED's of course, the light guide plate (LGP). The light-scattering dots or pattern on the LGP scatter the reflected light rays traveling within the LGP such that the light rays are emitted from the LGP's top surface as a surface light source. Thus, the design of the LGP's pattern plays a crucial role for a BLU in achieving maximum performance (high brightness and uniformity) with lowest cost possible.

1.2 Scope of this Thesis

Within this thesis the main target is to explain the steps in which an LGP pattern for a TFT-LCD TV is created and tested. In that purpose, first of all the history and then the concepts used will be studied so that the reader familiarizes with them, third step will be the literature review, namely other studies conducted in the field. Only after this familiarization is done, the design steps will be illustrated. The result of these steps will be compared to the produced unit and finally the results will be discussed.

CHAPTER II

BRIEF HISTORY

2.1 Television

The television has been on the market since towards the end 1920's. It is a means for mass communication (although single direction) same as radio but to a wider extend. The availability of the video cassettes, DVD's and similar media made the television far more indispensable than the radio. Even today with the progress in digital streaming and internet TV channels along with connected TV (television sets that are able to connect to the internet) the penetration of television is increasing.

2.2 CRTs

This is the first type of television to be built. It operates by accelerating a beam of electrons toward phosphor coated glass. The phosphor coating is excited by the incoming electrons and the collision with them, emitting light to release this energy and relax. First TV's were black and white with a single kind of phosphor that would emit a white light. In the late 50's, beginning of 60's the color television was introduced to market. Of course with the lack of proper color broadcast the penetration took a couple of decades. The principle of the color television was the same as the BW TV; the electrons were accelerated and send on the phosphor that this time had three components: Red, Green and Blue. These are the primary colors that the human eye can sense. Yellow may be created by mixing red and green and violet via red and blue. But these primary colors may not be replicated by the mixture of others.

The idea behind the color television is to hit the proper colors with the proper ratio to create (mimic) the desired color. To obtain yellow, red and green must be hit, to obtain brown, again red and yellow but this time with far less intensity and even with higher red than green, etc... The same principle is inherited by the following technologies, PDP, LCD, OLED...

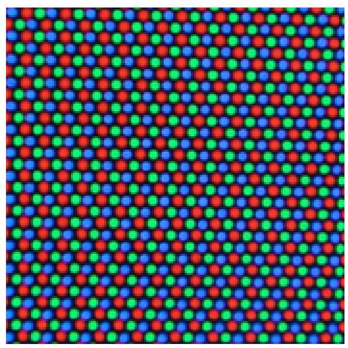


Figure 1: Magnified view of CRT Phosphor [1]

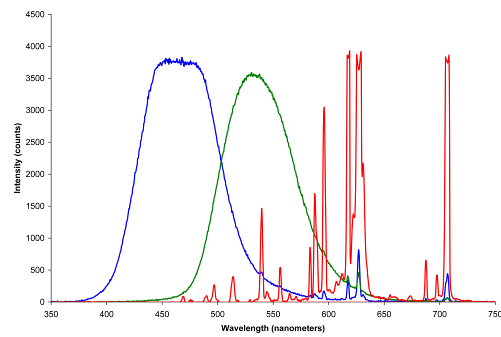


Figure 2: Spectra of phosphors in a common CRT [1]

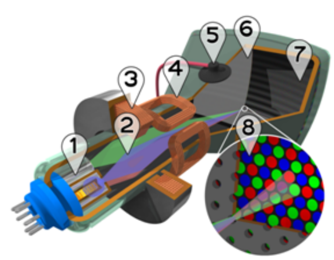


Figure 3: Cutaway rendering of a color CRT [1]

1. Three Electron guns (for RGB phosphor dots)
2. Electron beams
3. Focusing coils
4. Deflection coils
5. Anode connection

5. Mask for separating beams for RGB part of displayed image
6. Phosphor layer with RGB zones
7. Close-up of the phosphor-coated inner side of the screen

2.3 PDP

Plasma display panels utilize the same principle as the CRT TV's: the glass is coated with phosphor which emits light when excited. The manner in which the phosphor is excited is very different though.

In a PDP, behind the front glasses there are small chambers in which exist the gas that will turn into plasma and the phosphor to be excited. By applying high frequency onto this gas in the chamber, plasma is created and it emits UV. This UV, similar to the mechanism in the fluorescent lamps, excites the phosphor coating and the light is thus created.

Contrary to popular belief, plasma televisions do not go down to absolute zero, absolute black. In order to have a fast response (smaller response time) the plasma is kept in a dimmed state. It is a compromise between the response time and black performance.

2.4 LCD TVs

LCD TVs operate by modifying the polarization of the light as it passes through the liquid crystal layer sandwiched between two quartz glasses that do not alter the polarization of the light and two polarizers. First of these polarizer polarizes the incident light from the back light unit (BLU) to be modified by the LC layers and the second, (closer to viewer) that is also called analyzer, filters the light exiting the glasses.

These two polarizers are always perpendicular to each other and if the LC layers do not modify the light, they would filter everything and the pixel would be dark (black) (Figure 5); if the LC layers change the polarization of the light by pi/2 then the pixel would be bright (white) (Figure 6).

Figure 4: The working Principle of the Top Polarizer (Analyzer) [2]

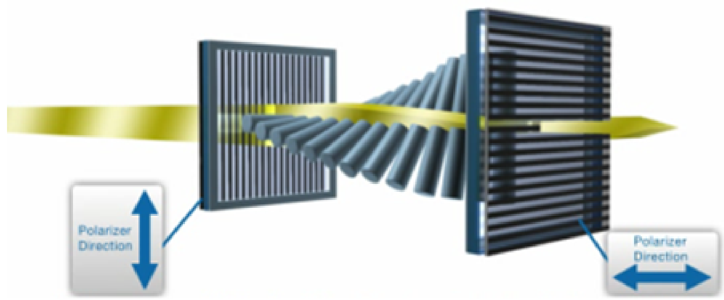


Figure 5: Voltage = 0; Light Polarization Modified; Pixel White [2]

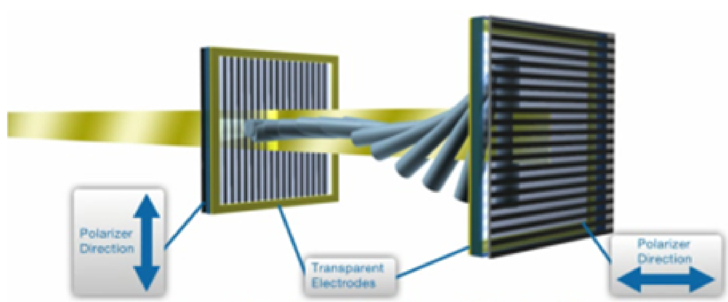


Figure 6: Voltage > 0; Light Polarization Unmodified; Pixel Black [2]

As they operate as a light valve and aren't self emitting, they require a light source that is bright enough, to compensate for the losses, and uniform, so that the TV is pleasant to the viewer.

Figure 7 is a general structure of an LCD TV i.e., the back light unit that provides the light and the liquid crystal cell that filters it. An LCD panel is composed of a back light unit, as shown here, which itself is composed of light source and optical sheets, a liquid crystal cell (glass) and possible top layers to modify the light according to use cases. It might be coated by AR/AG films, i.e., anti reflect / anti glare films preventing visual discomfort or privacy films preventing others from seeing the screen.

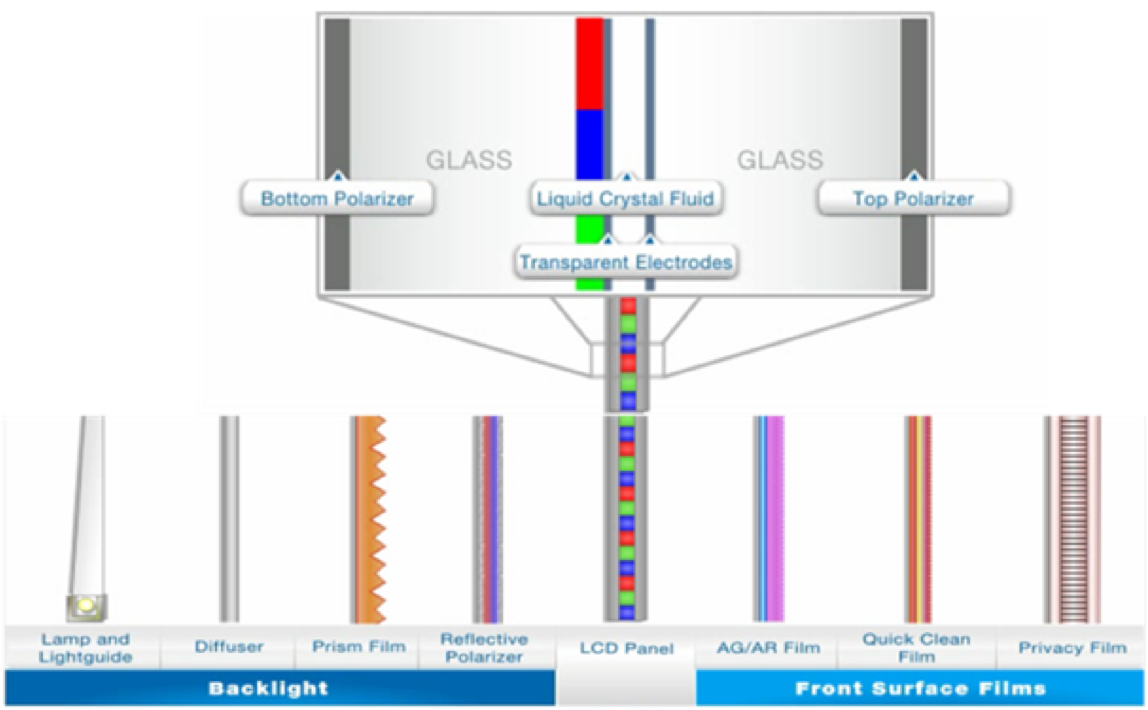


Figure 7: General Structure of an LCD TV [2]

As a new technology, in order to facilitate the penetration rate, the first samples' brightness levels were much higher. 2006's 17" LCD TVs were in the range of 700 nits. As the penetration rate increased and user felt comfortable with using LCDs instead of CRTs the brightness levels dropped along with the price. To decrease the cost of the panel the amount of light sources, optical films are decreased and cheaper components were used.

As of 2013, for TVs of 39” the brightness trend is in the range of 300-350 nits [3].

2.4.1 Liquid Crystal Cells

Liquid Crystals were discovered by Austrian scientist Friedrich Reinitzer in 1888 studying cholesterol derivatives. These derivatives have two melting points. Below the lowest melting point they are in solid state same as any other material. Between the two melting points they exhibit both solid and liquid properties e.g., they have crystalline -like structure yet they are also fluid. Their molecules are more structured that they would be in liquid form and have longer range order. Above the upper melting point they exhibit liquid properties as any other liquid.

The liquid crystal phase is a mesophase, i.e., a mid-way between the liquid and the solid states (phases). LC phase is thermodynamically stable. The three dimensional crystal lattice of the solids doesn’t exist in this phase but the order is higher than liquid phase. The temperature range generally is in between the solid and liquid ranges. Physical properties of a liquid crystal phase are anisotropic, unlike that of the liquid phase, which is isotropic.

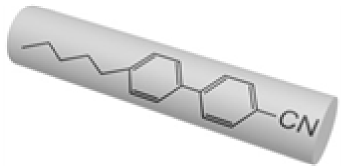


Figure 8: Rod-Like Liquid Crystal Molecule [4]

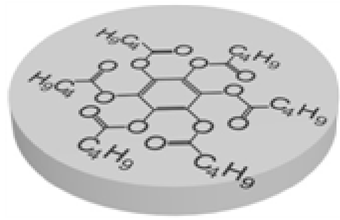


Figure 9: Disc-Like Liquid Crystal Molecule [4]

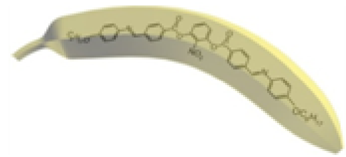


Figure 10: Banana Shaped Molecule [4]

Liquid crystal materials used in display applications generally have a rod-like shape with strong dipoles (opposing charges on the extremities) causing them to align to each other under favorable conditions (temperature higher than solid state to allow them to move freely [rotational freedom] but lower than liquid state not to disrupt the inter molecular interaction [translational order]). Indeed the tendency to point to a common axis is one of the distinguishing characteristics of liquid crystals. This axis is called the director.

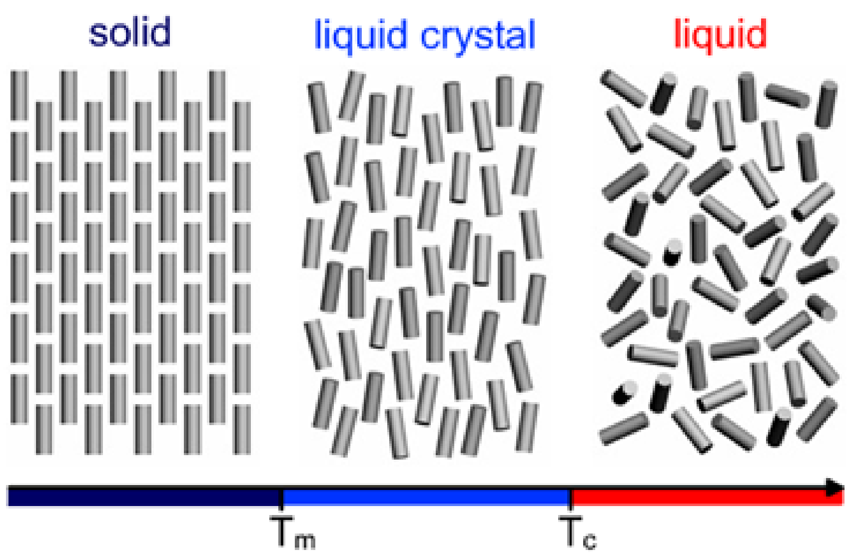


Figure 11: Different Phases of Liquid Crystal Material [5]

To be used in LCDs the liquid crystal materials must have certain properties to ensure long lifetime, easier control and stability:

- These materials must be chemically stable and should not degenerate due to light and/or heat. Otherwise, the amount of light coming from the back light unit and/or the heat generated by the light source, whether it is LEDs or CCFLs, would cause these molecules to change, deteriorate or degenerate. Because the transmittance of the liquid crystal cells is in the range of 4% to 7%, for a TV of 300 nits, a back light unit of 4000-7500 nits is required. This value is roughly equal to indirect sun light on a clear sky (7000-10000 nits) [8] .

- The birefringence is an optical property of the material. It means that the material affects the two polarizations differently. It is an important parameter for LC materials as it needs to modify the polarized light incident as a function of the current on each pixel.

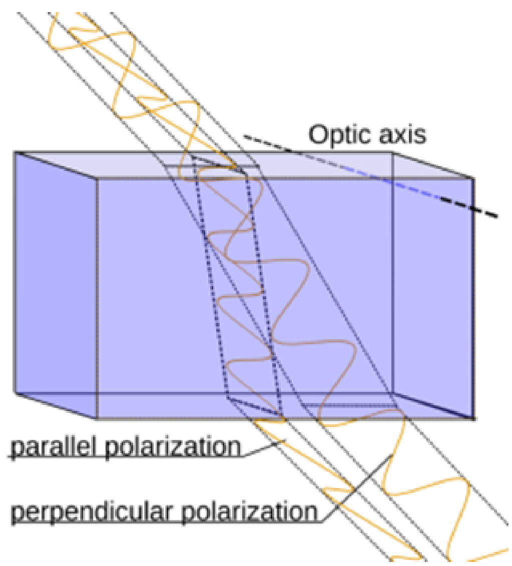


Figure 12: Modification of Different Polarized Light in a Birefringent Crystal [6]

Figure 13: Calcite Crystal and Its Birefringence [6]

- The viscosity of these materials needs to be low to be able to respond quickly to the electric field applied. This value directly influences an LC cell's response time.
- The dielectric anisotropy is also a factor affecting the response time. Higher this value is, faster and stronger the response of the molecules to the electrical field applied.

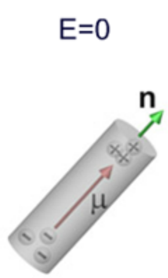


Figure 14: LC Molecule under E Field = 0 [2]

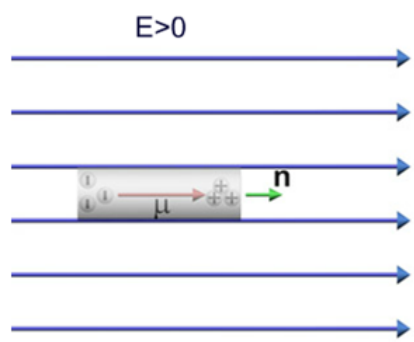


Figure 15: LC Molecule under E Field [2]

- The resistivity of the material needs to be high to prevent the leakage current between the two electrodes.
- The nematic phase of the LC material should be large enough to accommodate for the working range, generally $-40\,^{\circ}\mathrm{C} < T_N < 90\,^{\circ}\mathrm{C}$

2.4.1.1 *Polarization*

Polarization of an electromagnetic wave is the direction in which its electric field component oscillates. The polarization may be:

- Linear
- Circular
- Elliptical

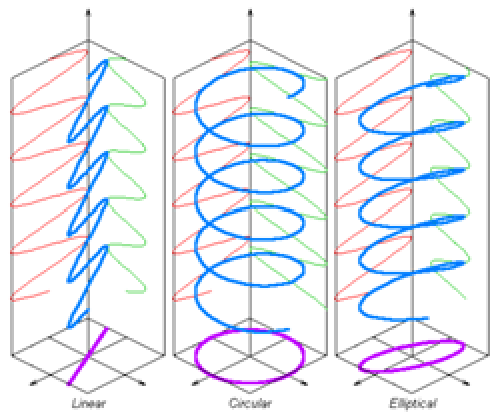


Figure 16: Different Types of Polarizations [7]

Polarization is a key concept in the LCD TVs. As the unpolarized light from the back light unit passes through the first layer of the liquid crystal cell (a polarizer) it adopts a linear polarization. As the light progresses within the LC medium, its polarization changes with respect to the electrical field applied to the material. The last layer the light has to go through is another polarizer (also caller analyzer). This polarizer is always perpendicular to the first one to prevent the Moiré effect (explained in the pattern design section). If there is no change in the polarization of the light, the two polarizers which are positioned perpendicularly, will absorb all the light and the display will be dark.

2.4.1.2 Polarizer

A polarizer is the device that filters out one of the two perpendicular polarizations of the incoming light and lets the polarization that matches with the polarizer pass. The filtering may be absorptive or reflective. Generally the polarizers on the LC cell glasses are absorptive polarizers as they are easier and cheaper to produce. The reflective polarizers are used as optical films to improve the transmittance of the cells. Figure 17 is the principle of an absorptive polarizer. As the name suggests, it absorbs the undesired polarization. More will be explained about reflective polarizers in the optical films section.

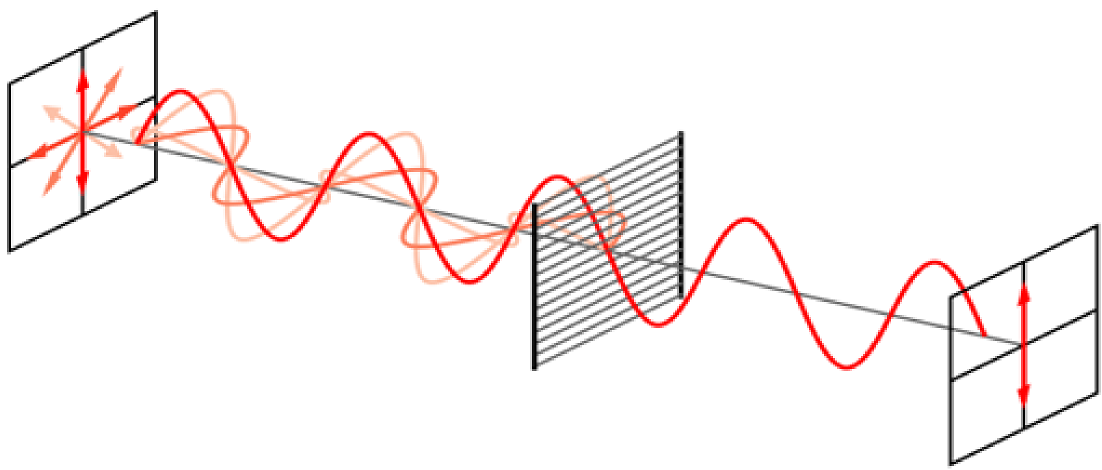


Figure 17: Absorptive Polarizer [7]

2.4.1.3 Transflective Cells

In addition to conventional transmissive cells, there are transflective cells that are less frequently used. These cells ensure the visibility of the screen even in day light conditions. The idea is to reflect the incident light towards the viewer in addition to the light coming from the back light unit thus increasing the visibility of the screen in daylight or any other bright light conditions [8].

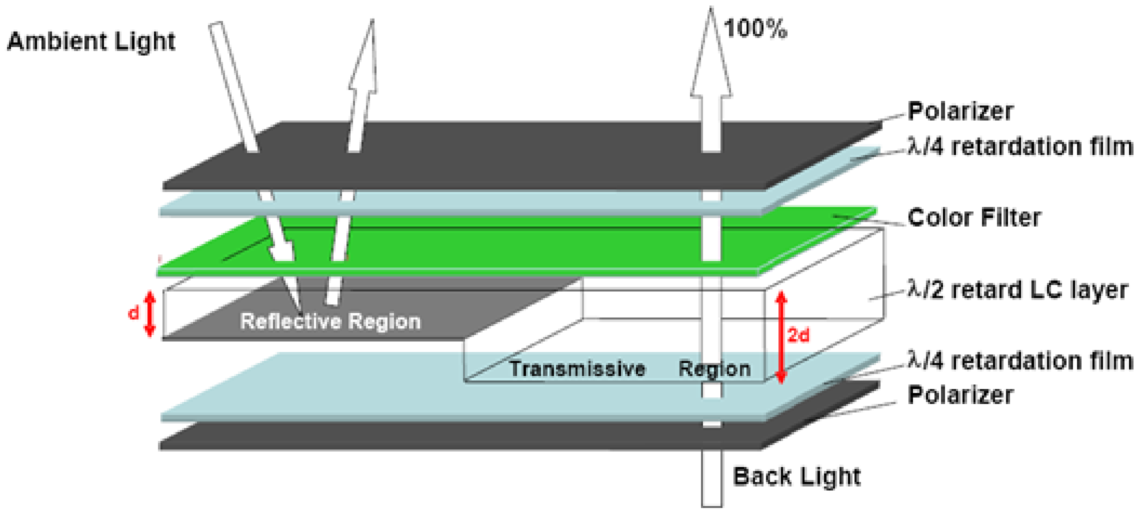


Figure 18: Transflective Cell Structure [2]

Figure 19: Transflective Cell Using Laptops [2]

2.4.2 Back Light Unit

The back light unit is the light source intended to be used for the liquid crystal display. As the liquid crystals are not self emitting, they require a light source to display an image. To be able to supply the brightness of 300-400nits of the liquid crystal displays, the back light unit must have a brightness of 5000 10000 nits as the transmittance of the cells is in the range of 4% to 7%.

There are two types of back light unit according to the light source utilized:

1. CCFL/EEFL based back light unit

2. LED based back light unit

CCFL/EEFL based back light unit are the first generations and use fluorescent lamps. The drive current for these lamps is in the range of 7 to 8mAand the drive voltage is in range of 2KV to 3KV. The DC voltage of 24 V from the power card is inverted into AC voltage of 2000V and applied to the lamps. Care must be taken to design these inverters and these lamps are very prone to leakage currents. If the heights of two lamps i.e., their distance from the backcover, aren't the same, their brightness will be different.

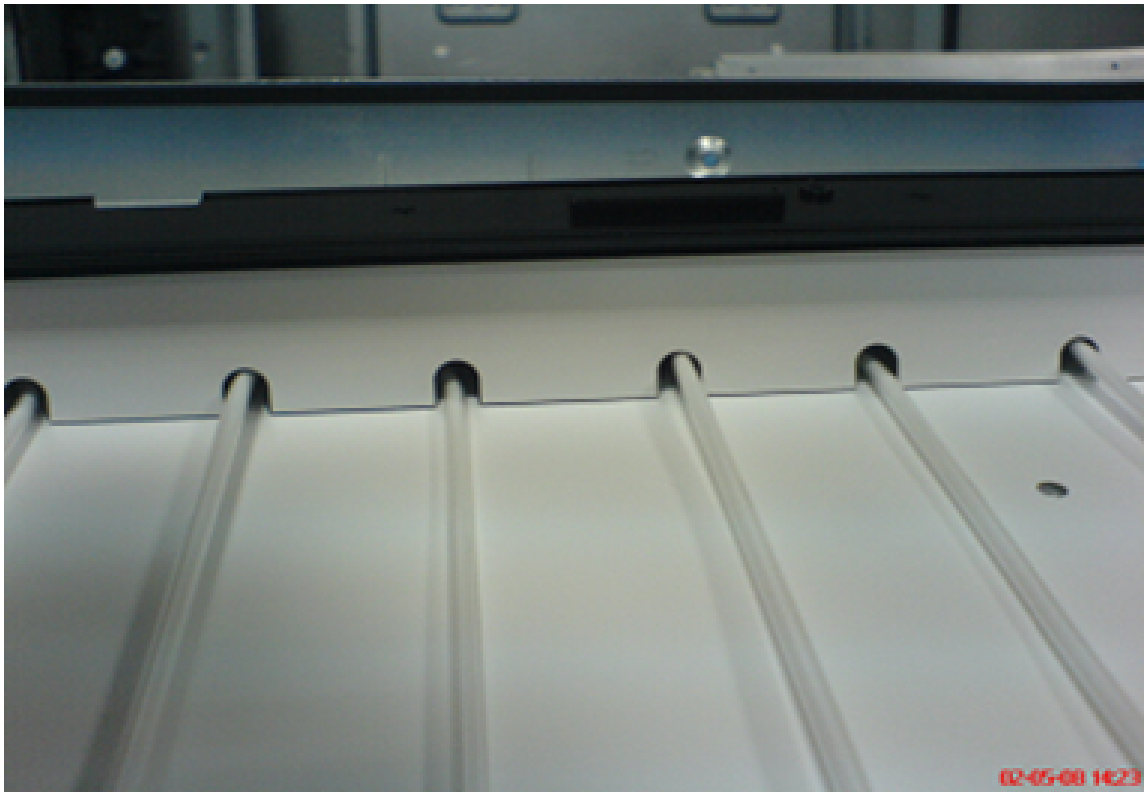


Figure 20: CCLF Based back light Unit [2]

The LEDs are easier to drive. LEDs must be driven with a constant current. The most important advantage of LEDs is that their brightness can be adjusted (dimmed) without any drawback or artifacts. They also provide the possibility of local dimming of the back light unit.

Depending on the light source placement in the BLU, a back light unit may either be:

1. Direct Lit
2. Edge Lit

In direct lit back lights the light source, whether it be FL or LED, is placed directly behind the LC cells. These units require a diffuser plate to diffuse the light from the light sources. Usually, diffuser sheets and other optical sheets don't have the diffusing strength to create a uniform lighting. Direct type back light units are capable of local dimming. In the case of FL's the local dimming can only be 1D, and is also called scanning. In the case of the LEDs, as they form a mesh of sources, the dimming may be 2D (2D local dimming). Furthermore, if RGB LEDs are used rather than white LEDs, 3D dimming i.e., color dimming is possible. Color dimming is creating a lower resolution of the image on the back light unit by controlling the RGB components of the LEDs (Figure 21 shows the lower resolution image of the picture on the back light unit). Thus, when the screen is showing red hue, the red component of the LEDs will be lit and the blue and green will be off. Since only one of the three components is lit, the power consumption will be about $^1/_3$ of the total consumption.Also by putting off the unnecessary components the light leakage will be averted and the color saturation will be much better.

Figure 21: 3D Dimming Demo [2]

Figure 22 shows the general structure of an Edge lit LED based LCD TV and the Figure 23 is a photo of the optical films along with their explanation.

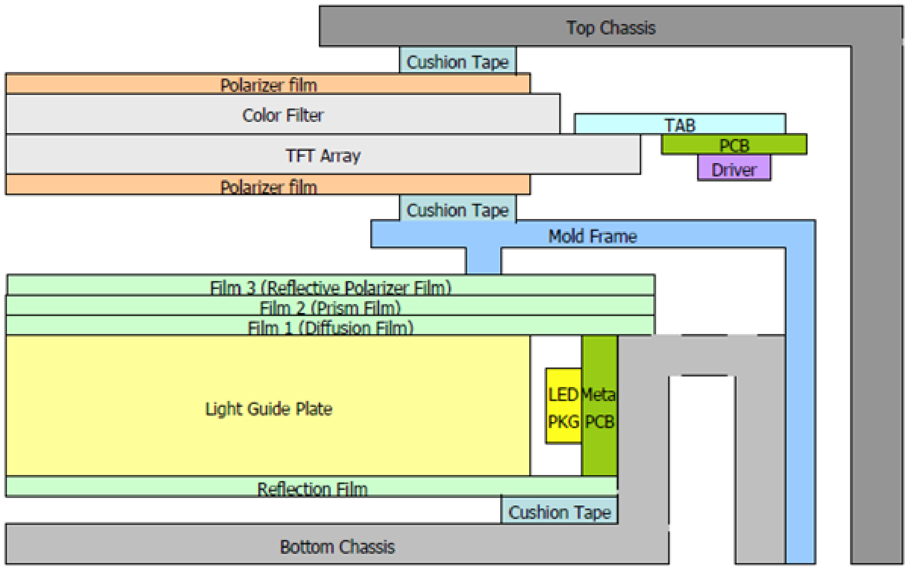


Figure 22: General Structure of an LCD Panel [2]

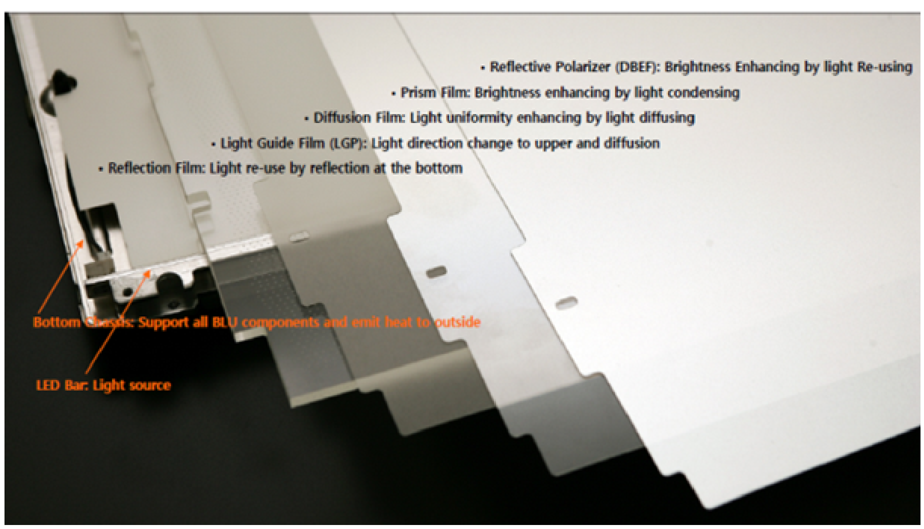


Figure 23: Optical Films Explained [2]

Figure 24: back light Unit Manufacturing Process [9]

Production of LCD panels is a labor intensive and delicate process and requires a clean room environment. The films that were explained above may be attached to each other and the other components because of static electricity. Staticly charged films are prone to particle contamination therefore, the whole production process must be performed in a clean room environment. Figure 24 shows a production facility and summarizes the production steps.

2.4.2.1 Light Sources

CCFL

Cold Cathode technology was developed over seventy years ago and was the first commercially available form of fluorescent lighting. CCFL are widely used in LCD TV back lights and laptops. They are also used in customized lighting designs for decorations to some extent.

Cold cathode fluorescent lamps operate on the same principle as regular fluorescent tubes i.e., it uses electricity to excite mercury vapor. The excited mercury atoms produce short-wave ultraviolet light that then causes the phosphor covering the glass enclosure to fluoresce, producing visible light.

The term Cold Cathode refers to the fact that the cathode is not independently heated, but instead operates at a much higher voltage to cause excitement of mercury vapor. So CCFL's do not use thermionic emission that regular fluorescents use.

The removal of the requirement to heat the tube allows Cold Cathode to turn on instantly. Furthermore, no heat requirement provides virtually unlimited switching (1million on/off cycles) without degradation of the lamps. Without the need for precise electrode temperature the Cold Cathode lamp can be operated at any desired brightness up to their maximum rating [10].

The CCFLs are cheaper than LEDs yet the LEDs have a higher market share as the power consumption achieved by LEDs is much lower and energy classes such as A, A^{+} even A^{++} are possible. The LED back light units, especially edge types, are much thinner than CCFL based ones. The dimming capabilities of an LED back light are far superior to FL based ones. Since the plasma in the fluorescent lamps must be maintained, dimming under 20% causes visible flicker. The LEDs are dimmable to any value between 0% and 100%.

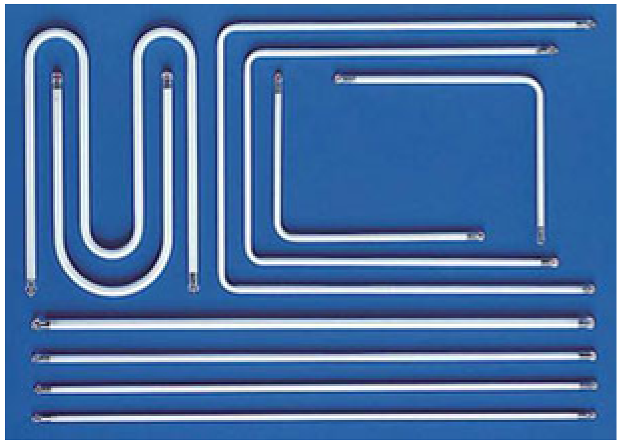


Figure 25: CCFL Types [2]

EEFL

The EEFL (External Electrode Fluorescent Lamp) differs from other fluorescent lamps with their electrodes mounted outside of the Lamp. External electrodes power the electric field in the lamp, creating plasma inside the lamp. Because of external electrodes, EEFLs do not generate heat at the electrodes and this enhances the life-time and the illumination stability incredibly while improving brightness efficiency. Because of the external electrodes, the lamps act as capacitors thus more than one EEFL connected in parallel can be driven with a single inverter.

LED

Electroluminescence

Electroluminescence is the phenomenon of obtaining light by applying electrical field onto a material. Contrary to creation of light via blackbody emission, e.g., incandescent lamps, electroluminescence converts electrical energy directly into radiated energy (light) without intermediate steps and heat generation. There are two mechanisms. First mechanism is to excite the material by high frequency electric field without actual electron flow through the material. The high frequency field turns the material into plasma causing it to lose electrons which will later recombine and give their energy as radiation. The second mechanism is the result of electron injection into semiconductor material (diode) that has been forward biased. Forward biasing of a diode of specific materials such as gallium and arsenide produces, holes and electrons [11] in the conduction band. These electrons and holes combine in the depletion zone and the energy thus lost by the electron is emitted as radiation. Depending on the band gap, the frequency of the emitted radiation is determined. The equation linking the frequency to the gap energy is as follows:

$$E = h.\nu$$

"h" is the Planck constant of 6.626 x 10^{-34} $Kg.m^2/s$

"ν" is the frequency of the emitted radiation (s^{-1})

The energy for electroluminescence is often expressed in eV, i.e., electron volt. 1eV is equal to the energy required to move one electron over a potential difference of 1 volt. 1 eV is equal to 1.602 x 10^{-19} joules. Thus for the green light of 550nm, the frequency of the light is 5.45 x 10^{14} Hz and the energy for this emission would be 2.25 eV (3.611 10^{-19} J). Given the visible spectrum stretches from 380nm to 780nm, the energy gap range for visible light emission is between 1.5895 eV and 3.2627 eV.

LED Basics

LED stands for Light Emitting Diode. It is comprised of several layers of semiconductor material superposed to create quantum wells and an injection mechanism to create and extract the photons.

An LED is a circuit element that emits light when forward biased. The emission of the LED is in a narrow spectrum, almost monochromatic, un-polarized and incoherent. The frequency of the light emitted depends on the energy gap of the semiconductor material. The material used to create the LED may vary depending on the desired emission, e.g., for the IR region of the spectrum AlGaAs, for the visible region, AlGaInP, GaPor GaN and for the UV region, AlGaN.

LED has a wide span of applications such as commercial and residential lighting, torches, highbay lighting and back lighting [12].

To create white light two approaches can be utilized. The first approach is a less efficient one that is mostly used for research purposes. This method uses dichromatic, trichromatic or tetrachromatic systems i.e., combining the emission of 2, 3 or 4 different colors. For the generated light perceived as white all the cone cells of human eye must be stimulated. To achieve this, red, green and blue or blue and yellow or other combinations may be utilized. With a control over the intensity of each channel, (color) this system may have a wide range of colors. This is a rather expensive and inefficient method used mainly for research as the color consistency may be achieved by controlling the intensities of each channel (each color component). As the intensity of LEDs deteriorate at different rate for different colors, to maintain color consistency the intensity of the colors that are not failing may be dimmed. The efficacy of the green LEDs is unfortunately very low even though the green is the color to which the eye is the most sensitive. This phenomenon is called the green gap. The materials emitting red or blue are very efficient but to have a bandgap suitable for green light these materials need to be modified (quantum wells etc...). These modifications are responsible for the green light's lower than expected efficacy.

Figure 26: RGGB LED System [2]

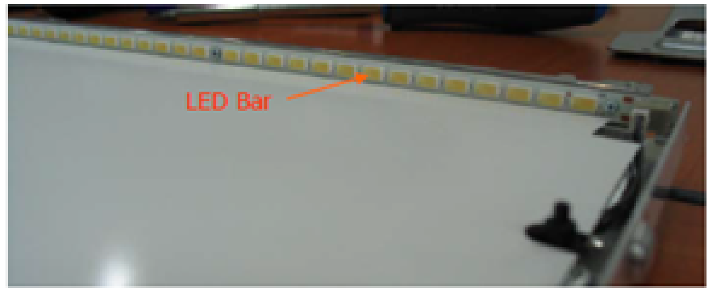


Figure 27: LED Bar in a Back Light Unit [9]

The efficiency is usually used where one type of energy is converted into another type. However in lighting a new term, the efficacy must be utilized. This is the ratio of the energy input to the LED to the luminous flux output of the LED. Since luminous flux is the radiant flux convolved with the response curve of the human eye, the same amount of radiant energy yield different amount of luminous energy, e.g., the green light @ 555 nm has a conversion factor of 673 lm/W where UV or IR light of 1 W yield zero luminous flux as they are beyond the range of the visible spectrum.

The second method of creating white light is to down convert the emission of the blue LED chip using yellow phosphor. The light emitting properties of phosphorous is very well known since it has been in use for CCFLs, CFLs and CRTs. There is also profound amount of know-how in the manufacturing and application of this material in the light emitting systems.

When an atom is excited by an external energy source, electrons rise to a higher energy state. Both in ground state and the excited state the energy that the electron is allowed to possess is more than one due to different quantum states values. This plurality is due to the atom's and/or crystal's structure. With the confinement of the atom in the crystal the degenerated states are separated to different energy levels. These energy levels are smaller compared to the energy gap. When the electron is excited with energy larger than the gap energy, the excess energy is relaxed as heat

(10^{-12} s). The electron thus relaxed to the stable energy level of the exited state is than further relaxed by emissive dispersion of energy and falls back to the lower energy level (10^{-8} s) (Figure 28 and Figure 29) [13, 16, 17]. Since the emission of the chip will be converted in the phosphor and each conversion causes losses, the phosphor should have less energy than the emission that excites it: Stoke's shift.

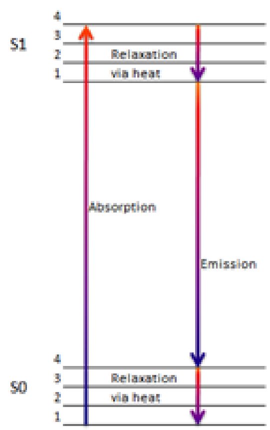


Figure 28: Stokes' Shift Model [13]

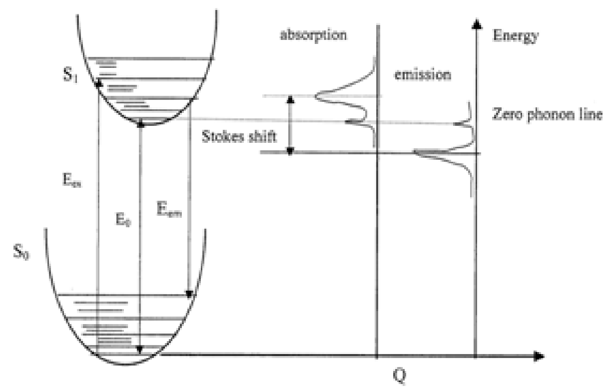


Figure 29: Stokes' Shift Energy Band Gap Model with Degeneration [13]

The first idea is to use UV LEDs excite white phosphor. But as the gap between the exciting emission's energy and the excited material's energy increases, the energy lost to conversion also increases. Therefore, the energy of the exciting photon and the phosphor should be closer. To achieve this logical solution is to use blue emission with yellow phosphor. This way the green and red sensing cones of the human eye (medium and long wavelength sensitive) are stimulated via the yellow phosphor and the short wavelength sensitive cone (blue) is stimulated by the blue emission of the chip. This method is the widest used method in sectors such as illumination, automotive, back lighting, commercial, industrial and residential lighting.

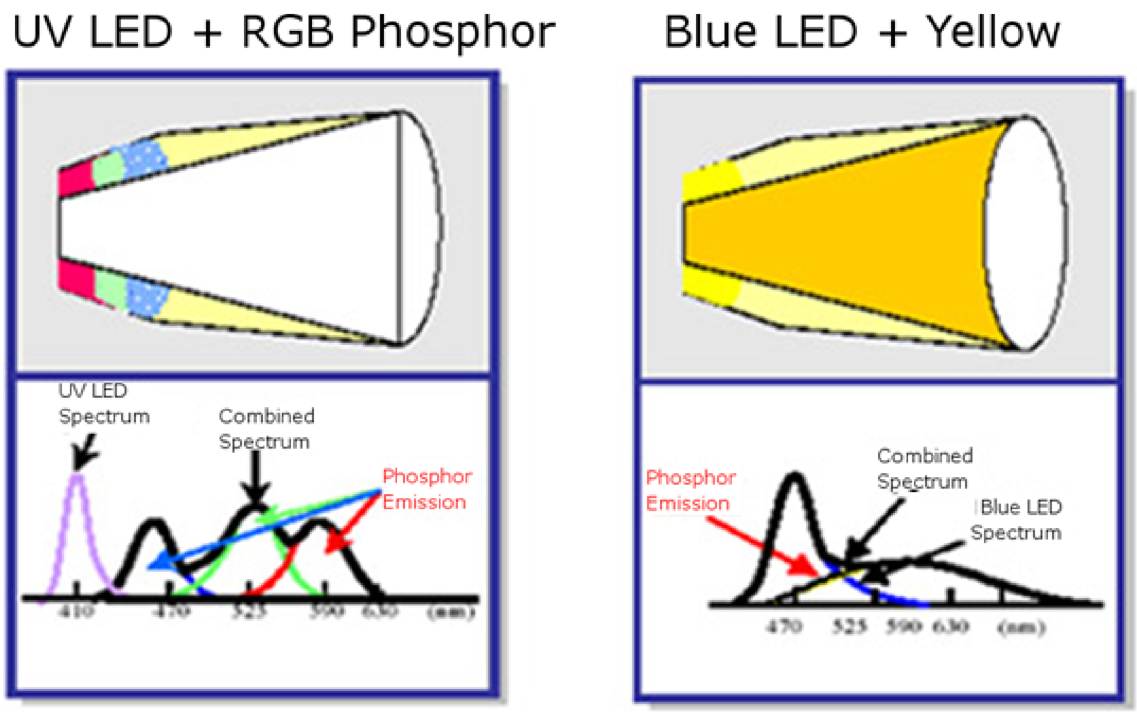


Figure 30: High Frequency Emitter & Phosphor [2]

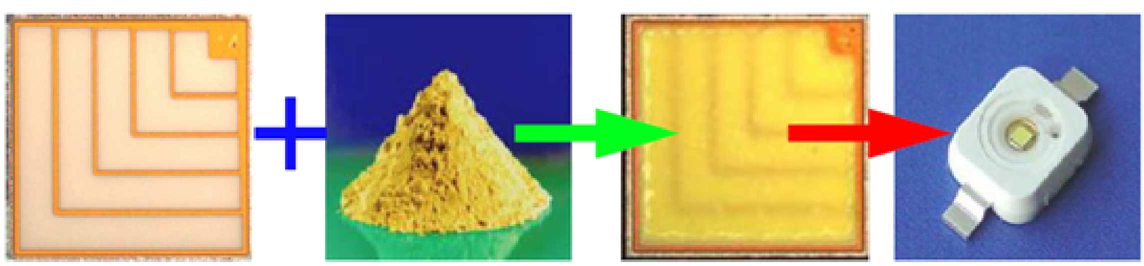


Figure 31: OSRAM Package [2]

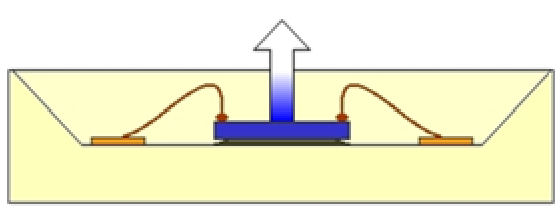


Figure 32: Emission from Chip and Phosphor [14]

Different solid state architectures were developed to increase the efficiency of the LEDs. Contrary to general definition, a contemporary LED isn't just a P-N junction. It has many other layers such as electron transport layer, hole transport layer, electron and hole injection layers, barrier layers, etc... In addition to these layers to move the electron - hole pair faster, more efficiently and in greater numbers, quantum wells were incorporated in the designs.

A quantum well is an energy depression region where the electrons and the holes are confined. Confining the particles in a predefined area of the crystal increases the chance of recombination and reduces the gap energy. However, producing quantum wells is not easy. In production, extra care should be taken in the epitaxial growth of this layer to prevent contamination. Contamination results in increased absorption of photons. There may be more than one of these quantum wells to increase the chance of confining the elements together. Normally an electron (or hole) shouldn't be able to cross over to the next quantum well. But the tunneling effect allows electrons to go from one well to another. This structure is called multiple quantum wells, MQW (Figure 33). MQW may be optimized in terms of wall smoothness by changing material composition. The smoothness of the walls is controlled by controlling the flow of gases in the reaction chamber (Figure 34 - 35).

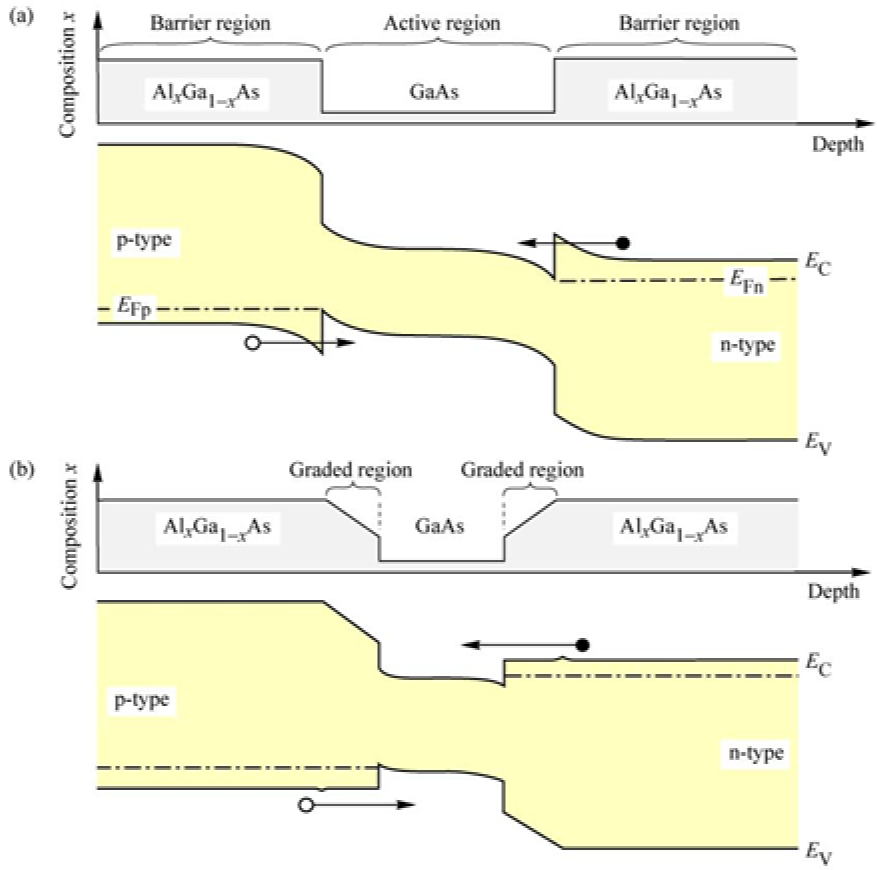


Figure 33: Quantum Well Structure [18]

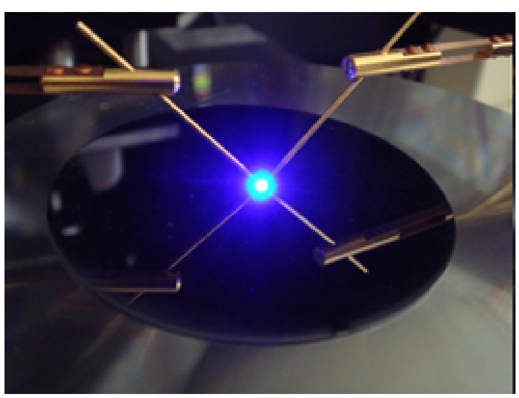


Figure 34: LED Test on a Wafer of Blue LEDs [14]

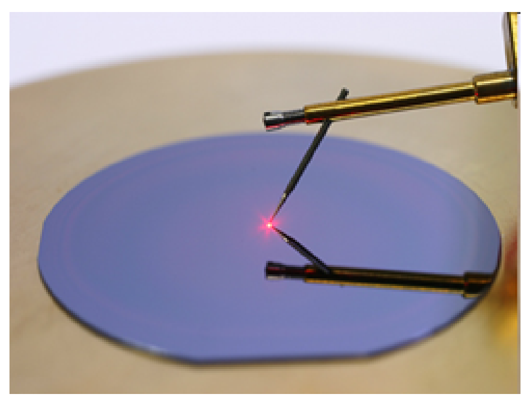


Figure 35: LED Test on a Wafer of Red LEDs [14]

Epitaxy

Epitaxy means growing layers of crystalline structure on a substrate with a crystalline structure that may or may not have the same composition as the layer. The new layers thus grown will have the same crystalline orientation as the substrate. The word comes from two Greek words, epi- prefix meaning over upon, as in epidermis, top layer of the skin and taxis meaning order, arrangement as in taxonomy which is science of arranging or classifying.

If the materials that are growing are the same as the substrate material, this process is called homoepitaxy and in case the grown layer is different, this process is called heteroepitaxy [19].

The epitaxial growth is conducted in pressure and temperature controlled chambers called reactors. The air inside the reactor is replaced by suitable gases. The pressure inside the reactor is adjusted by a series of vacuum pumps. First the primary pumps that adjust the pressure to 10^{-4} 10^{-6} bar then the secondary pumps create high vacuum of around 10^{-12} Bar. Low pressure levels are required to reduce the chances of contamination. Various gases are introduced into the reactor to produce different semiconductor junctions required to build LEDs or MOS FETs.

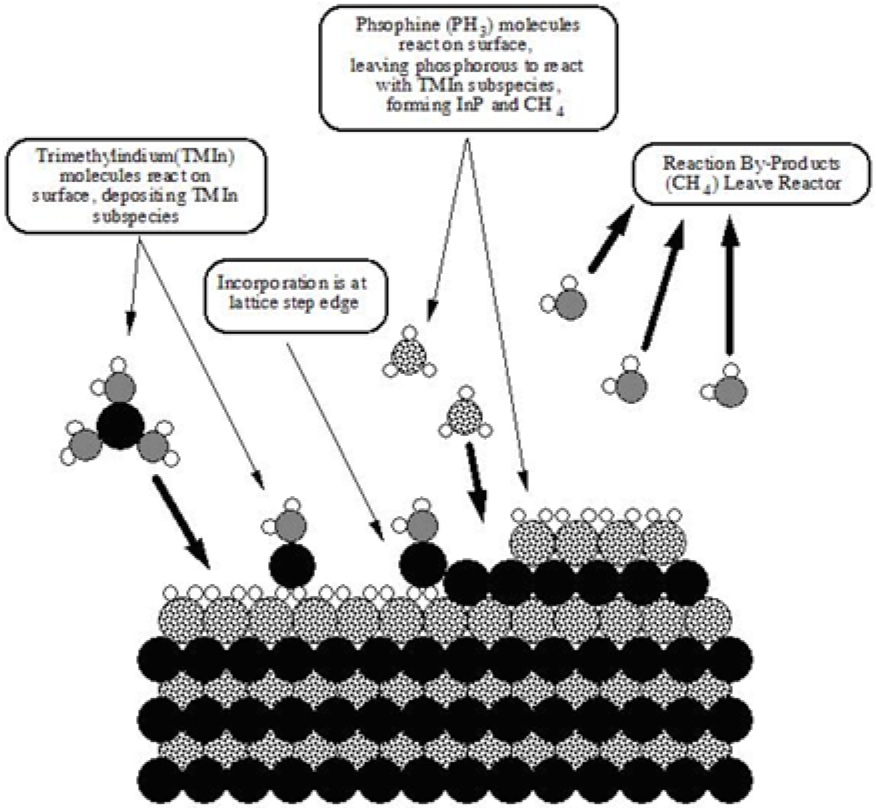


Figure 36: Metal-Organic Chemical Vapor Deposition [15]

String

A string is a serial branch of LEDs that is parallel to other branches in a circuit.

LEDs exhibit I - V characteristics as same as PN junctions diodes. A small change in the voltage results in a big change in the current. Figure 37 shows "I - V" graph of a Cree XP-G R4 LED @ 85C created with the data from their website [20]. 0.08 V deviation, a rise of voltage from 2.66 to 2.74, results in doubling the current from 100 mA to 200 mA. Therefore, LEDs may not and should not be driven using constant voltage circuits but rather the current control must be applied for reliable and long lasting systems.

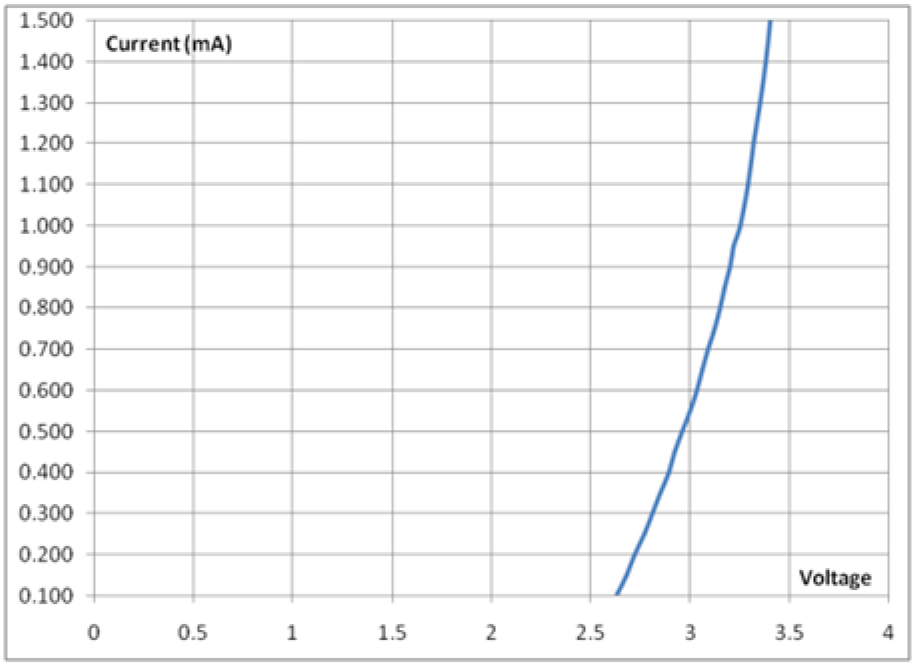


Figure 37: LED V - I Graph [20]

If the LEDs are not driven with constant current (CC), the deviations in the device voltage will affect the heat of the LED, the luminous output, the energy consumption and the efficacy. Higher the current more light is emitted. But also more heat is generated. As the heat starts to be generated the temperature of the crystal will increase and the density of the phonons in the system will increase, causing electron phonon collisions and non-radiative relaxations of electrons. This generates even more heat and due to photon phonon collisions, light is absorbed in the device structure (internal absorption). Both these mechanisms decrease the yield of the system and increase the energy consumption without increasing the light output. The graphs below show the power dissipation as a function of current. Since the voltage difference is minimal over a large range of voltages, the power and the current are almost linear. But, because of the mechanism described above, the luminous flux and current aren't linear. That is why, the efficacy of the system decreases as the current increases. Figure 38 (power) and 39 (flux and efficiency) were generated for the same LED whose IV curve was shown in Figure 37 at 85 °C.

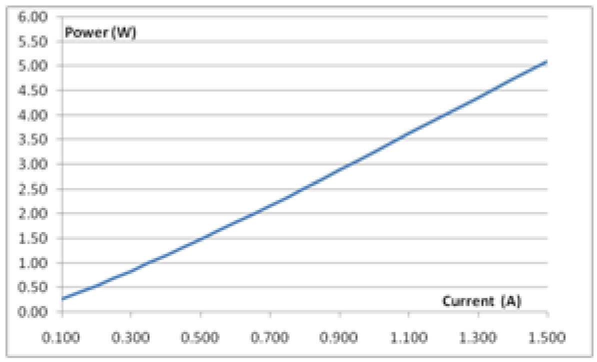


Figure 38: LED Power vs Current Graph [20]

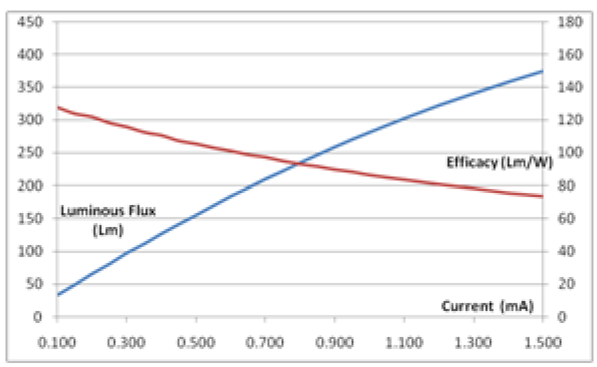


Figure 39: Flux and Efficiency vs Current [20]

Similarly, even when the current is kept at a constant rate, the increase in temperature will result in decreased flux output and efficacy almost linearly. (Figure 40)

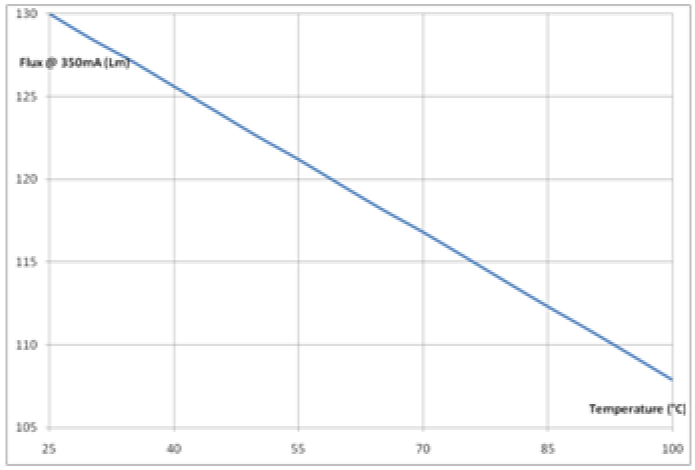


Figure 40: Flux Change versus Temperature [20]

Therefore, the cooling of the LED systems has a crucial role in the design. A well designed system that remains cooler is much more efficient, reliable and long lasting than a poorly designed system that heats up to higher temperatures. [21]

MCPCB

Conventional PCBs are inadequate to dissipate the heat generated by the LEDs. The most conventional prepreg materials such as FR-2 (phenolic cotton paper), FR-4 (woven glass and epoxy) or CEM-1 (cotton paper and epoxy)[22] do not satisfy the thermal conductivity requirement for high power LED applications. Systems built with prepreg materials cannot maintain the required thermal performance to help assure the lowest possible operating temperatures and brightest light output for high-intensity LEDs [23]. Instead metal core PCB (MCPCB) or standard FR-4 with high via densities are commonly used circuit board material in conjunction with Power LEDs.

The thermal conductivity of the FR-4 material is around 0.3 W/m.K through plane [24]. This value may be increased if thermal vias are used. Thus the power of the LED may be transported through the top plane of the FR-4 through the vias and the metal filling inside. Below is an example [25].

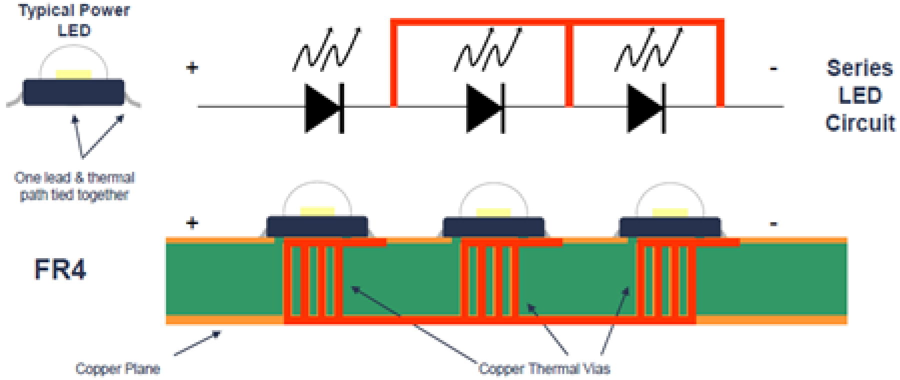


Figure 41: Via Holes for LEDs That Do Not Have Floating Pads for Thermal Management [20]

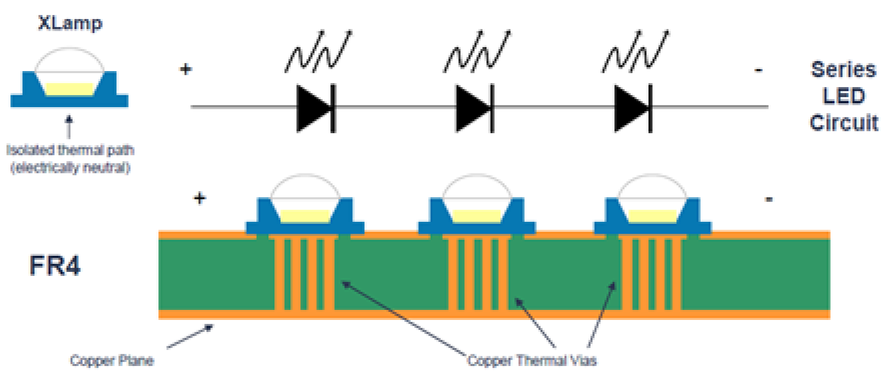


Figure 42: Via Holes for LEDs That Have Floating Pads for Thermal Management[20]

A better yet more expensive solution is to use MCPCB, i.e., metal core printed circuit board. These PCB may have aluminum or copper metal cores. The thermal conductivity of the Al is about 200W/m.K and that of copper is about 400 W/m.K. Due to the price of copper, MCPCB's are generally made of Al. The thermal stack is as follows: Copper traces (400W/mK), the dielectric (3 W/mK) [26] and aluminum (200W/mK). The bottle neck in this stack is the dielectric. This dielectic should be as thin as possible to provide as little thermal insulation yet it should not be too thin to fail electrical insulation.

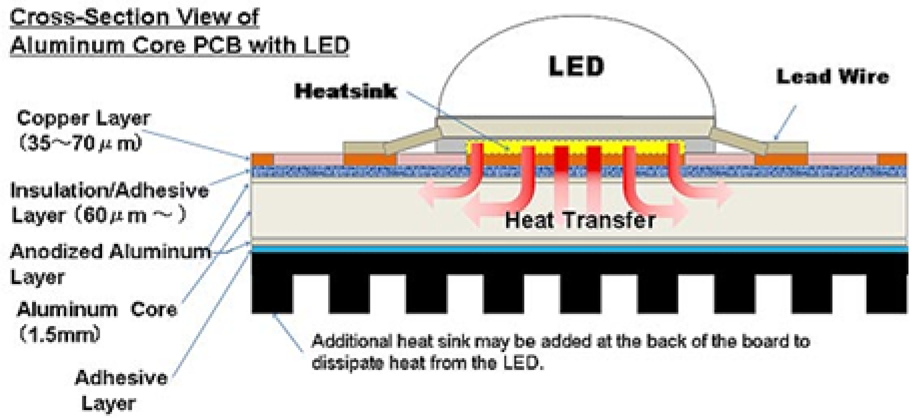


Figure 43: MCPCB [27]

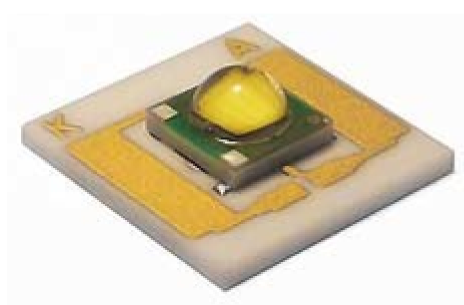
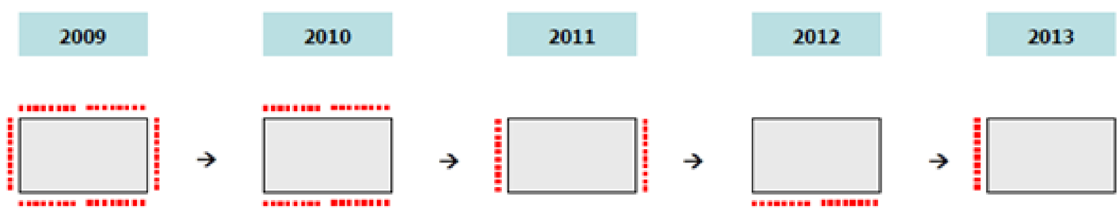


Figure 44: Ceramic PCB [28]

To overcome this bottle neck, ceramic PCB's may be utilized. These PCBs harness the electrical insulation of the ceramics together with thermal conduction. The drawback is that the thermal conduction of the ceramic material is not as high as the metals and the ceramic substrate is very fragile. Therefore, ceramic PCBs are not widely used in back lighting applications.

In general, the trend is to decrease the number of LED to reduce the cost of the system and the cost of operation. With the progress on the luminous flux obtained from one LED, it is possible to achieve this. Initial LED based back light units have had all 4 edges full of LEDs. As of 2013, the trend is to have only one edge lit by LEDs, with one or two LED bars.



	Q2'09	Q2'10	Q2'11 (f)	Q2'12 (f)	Q2'13 (f)
LED PKG #	432	288	144	144	82
LED Types	Middle power	Middle power	Middle power	Middle power	Middle power
LED Bar Location	4 sides	2 sides	1 side	1 side	1 side
LED Bar Location 2	Up/Down/Left/Right	Up/Down	Down	Down	Left
LED Bar #	6	4	2	2	1
LED Bar Cost Down		LED Bar # Reduction	LED Bar # Reduction	LED Price Reduction	LED Bar # Reduction

Figure 45: LED Reduction Forecast for 40" LED LCD TV back light Unit [9]

Beam Angle

Beam angle is the angle where the intensity of the rays falls to 50% of the maximum intensity value (Figures 46 - 48). This is a method of measuring how wide the beam of the LED is. This method is also used for the MR16 lamps. For the lighting systems that have the same amount of flux, smaller beam angle results in higher intensity and similarly for the same intensity, the system with lower beam angle will have lower flux.

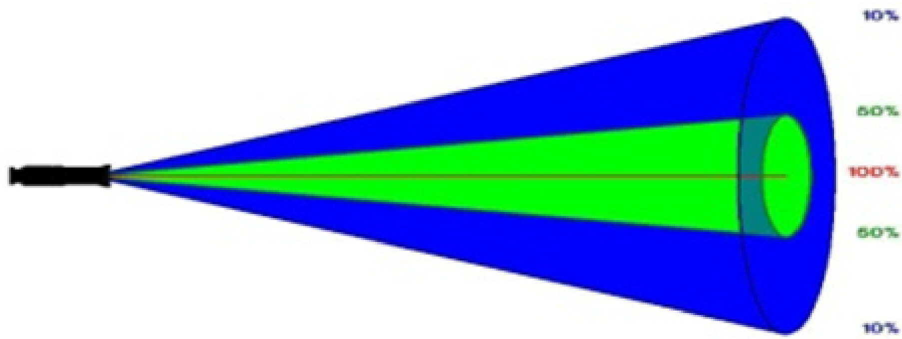


Figure 46: Beam Angle and Field Angle [20]

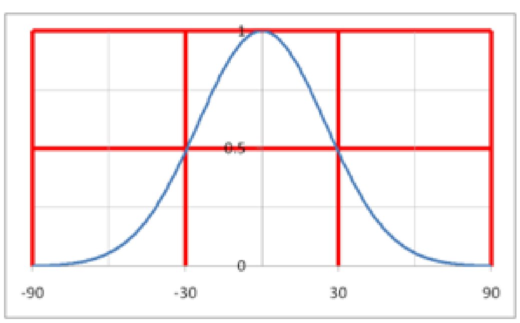


Figure 47: Intensity Distribution of a System with Beam Angle of 30° in Cartesian Coordinates [20]

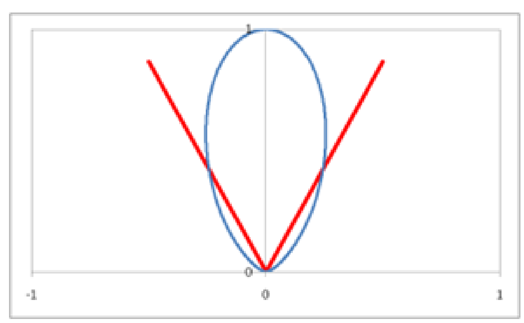


Figure 48: Intensity Distribution of a System with Beam Angle of 30° in Polar Coordinates [20]

2.4.2.2 Optical Films

Prism Sheet (BEF)

Brightness Enhancement Film (BEF) is also referred as prism sheet or lens film. It is a micro replicated prism structure film in the LCD back light module that enhances the luminance of the back light module and thereby the LCD module.

The prism sheet disperses light in horizontal and vertical directions. It refracts and collects light diffused from the diffuser sheet. This results in improved luminance. [29]

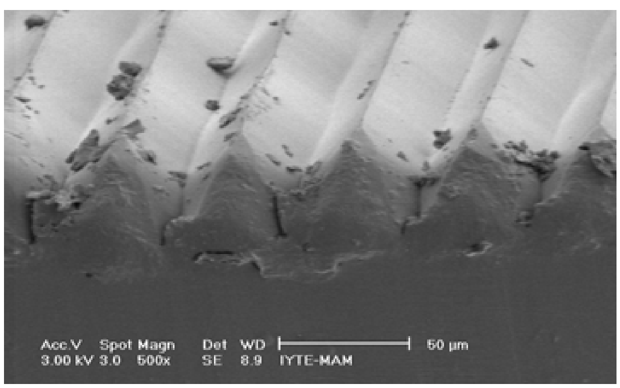


Figure 49: SEM Image of a Prism Film [2]

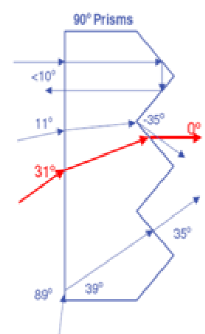


Figure 50: Working Principle of a Prism Film [2]

Reflective Polarizer (DBEF)

Dual Brightness Enhancement Film (DBEF) is a 3M proprietary technology. 3M has a strong IP, technical and manufacturing position in DBEF, but several panel makers are starting to seek alternative solutions to replace the DBEF film, especially by using diffusers to replace DBEF in their 32-40" LCD TV panels. A certain fraction of 32", 37" and 40" LCD TV panels are expected to be shipped without DBEF starting from 2013

DBEF market is rapidly growing for 1080p segment, which requires DBEF to meet the brightness requirement due to the low transmittance of the higher resolution. One challenge for the TV manufacturers is to achieve higher brightness while keeping the prices low. This is the main reason which drives the DBEF cost down. [29]

This film recycles the polarization that would otherwise be filtered at the cell and reflects it back towards the back light unit. As the back reflected light passes through the optical layers, e.g., diffuser sheets, the polarization is altered. Then the light reflects from the back reflector and passes through the optical structure once more. Thus the light with improper polarization behaves as if it was coming from a light source, unpolarized and incoherent. Since none of the optical films are 100% transmissive, the boost in the amount of light is around 40%.

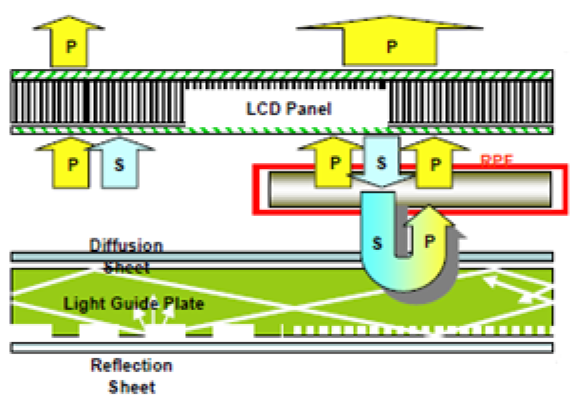


Figure 51: Mechanism of a Reflective Polarizer [30]

When the light is incident on a transparent dielectric, the reflection ratio of the two polarizations is different from each other. At an angle called Brewster angle, one of the polarizations is completely transmitted and the other is reflected.

The refractive index of a material may be changed by inducing stress upon it. The layers of the reflective polarizers have different indices resulting from the internal stress induced to them during production. The figures below show the layer structure of a reflective polarizer and the principle which it is based upon. The layers' refractive indices are 1.64 and 1.88.

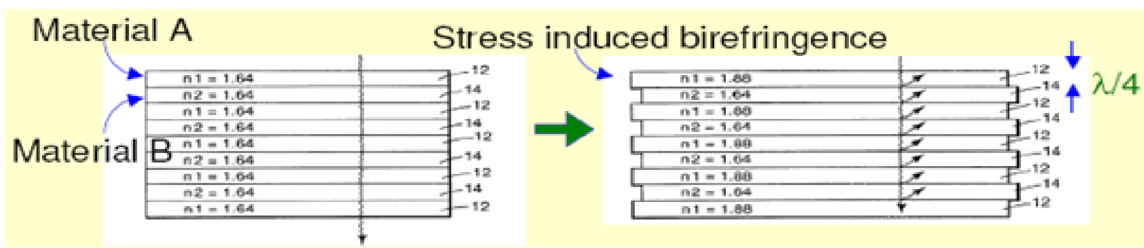


Figure 52: Layers of a Reflective Polarizer [30]

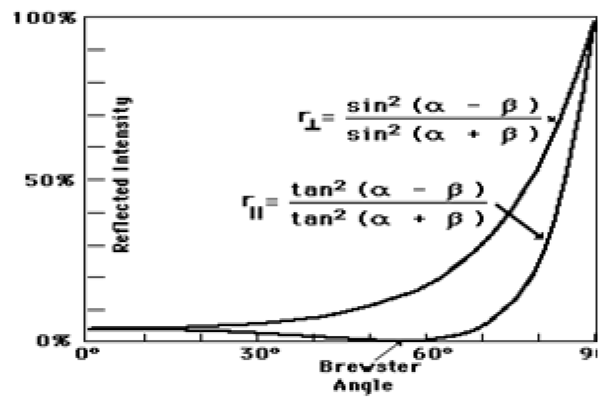


Figure 53: Separation of the Two Polarizations [30]

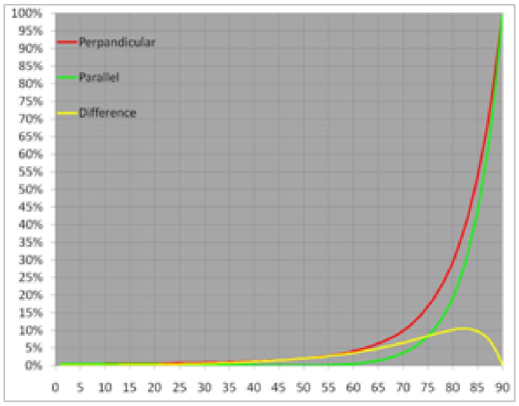


Figure 54: Polarizations in a Medium of 1.64 and 1.88 [2]

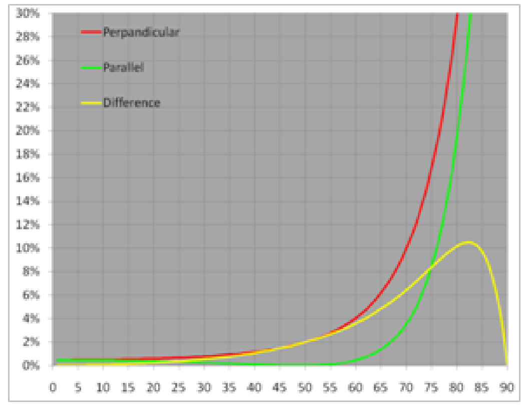


Figure 55: Polarizations in a Medium of 1.64 and 1.88 [2]

Diffuser Sheet

Diffuser sheets are used to diffuse the light coming from the LGP. They are one of the basic elements of the back light unit. Diffuser films are PET (polyester) or PC (polycarbonate) based.

In order to decrease the cost of the optical structure, the conventional DBEF + BEF + Microlens structure is being revised. This structure is the one with the highest possible cost and optical performance both luminance and uniformity wise. With the emergence of the lower brightness panels this structure may be replaced with 3 diffuser sheets structure. [29]

There are two types of diffuser sheets (DS); one that has volumic diffusion and the other has surface diffusion. The surface diffusing type is easier to produce therefore, the most commonly found one. Micro glass beads are deposited on the PET substrate film. If these beads' size and position becomes uniform then the diffuser sheet becomes a micro lens film.

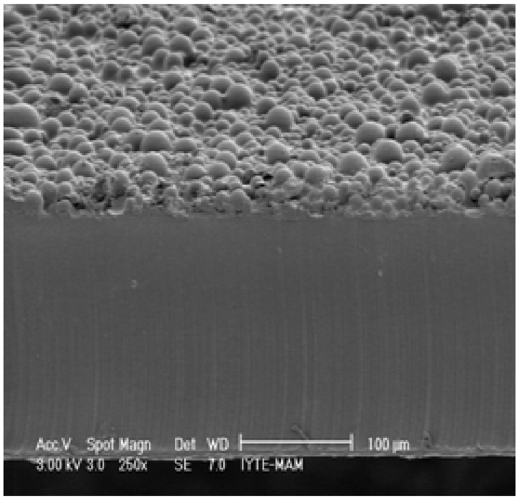


Figure 56: SEM Image of a DS [2]

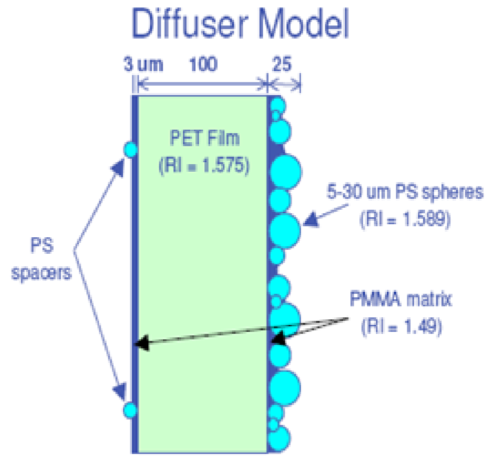


Figure 57: Diffuser Film Model [2]

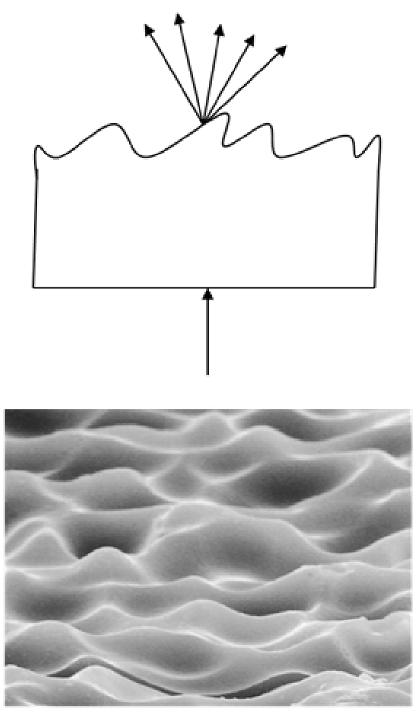


Figure 58: Surface Diffusion [2]

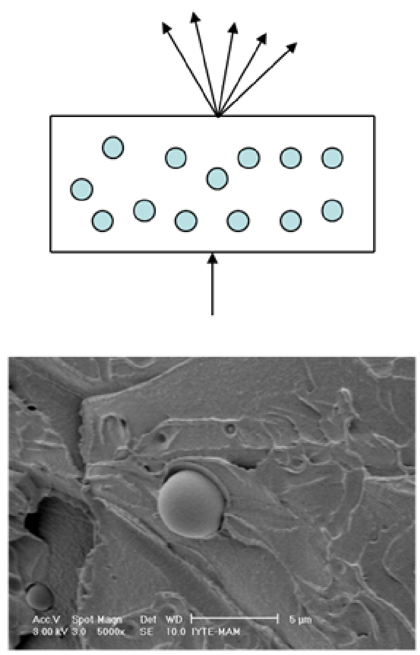


Figure 59: Volume Diffusion [2]

Micro Lens Sheet

Much like the diffuser sheets, Microlens sheets are also utilized for diffusion purposes. The difference between a microlens film(MLF) and a diffuser sheet is the size and position of the glass beads deposited on the PET substrate. In a diffuser sheet the position and size of these beads are random where in a microlens film they are regularly patterned with the same size. Thus a microlens has a lower diffusing strength but higher collimation somewhat similar to a prism film [31, 32].

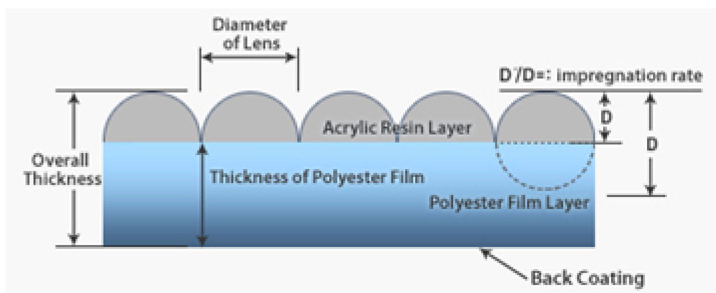


Figure 60: Structure of micro Lens Film [2]

Reflector Sheet

Reflector films are another basic element of the back light unit. A back light unit typically requires at least one reflector. The function of the reflector film is to reflect and recycle the light from the side of the light guide plate of the back light. The raw material of the reflector film is PET (Polyethylene Terephthalate) [29].

There are three kind of structure for reflectors. It may either be clear PET material infused with silver particles for reflection, micro porous PET structure or multi layer optical sheets (similar to reflective polarizers). The reflection rate of the silver infused clear PET is about 96%. The micro-porous PET has a range of reflection rate from 98% to 92%. The multilayered optical films also have about 98% reflectance but they are an obsolete technology as the production cost is higher than others.

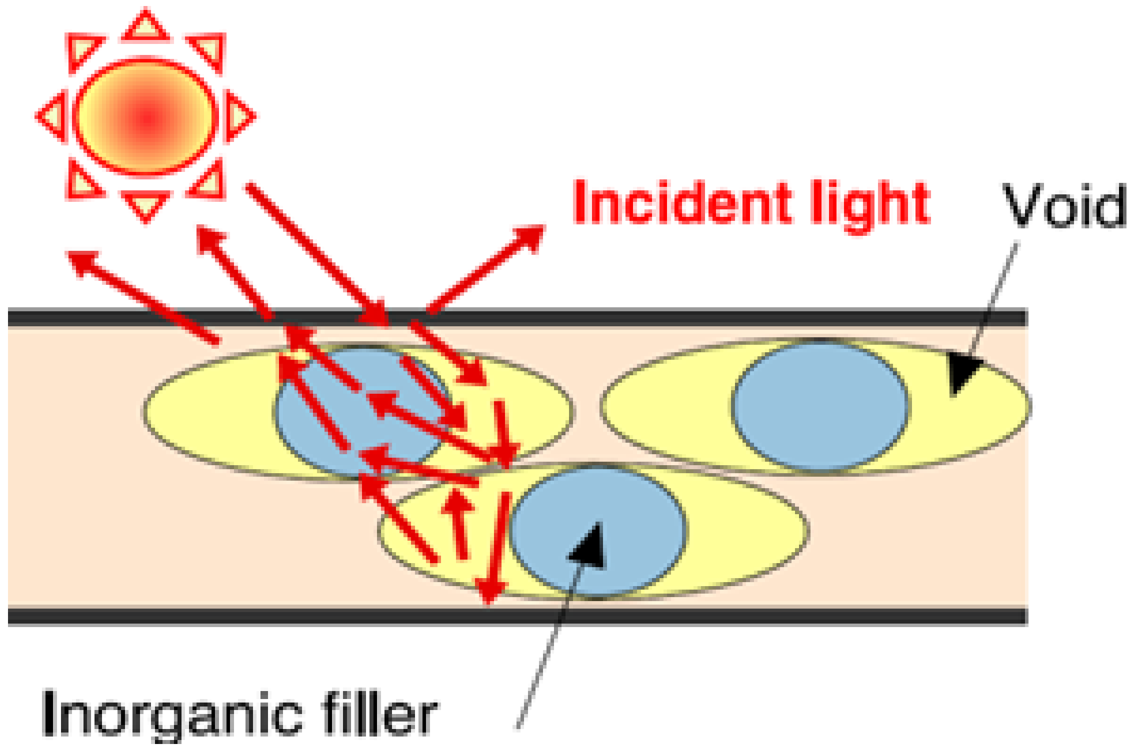


Figure 61: Reflector Sheet Model [2]

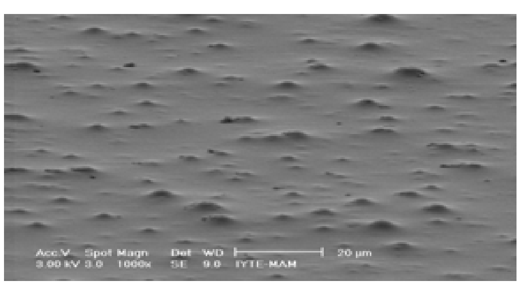


Figure 62: SEM Image of the Surface of a Reflector [2]

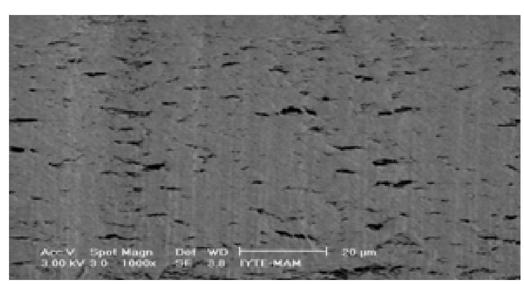


Figure 63: SEM Image of the Cross Section of a Reflector [2]

2.4.2.3 LGP

An LGP (Light Guide Plate) is conventionally a thick (between 1.5-4mm) acrylic sheet with engraved (imprinting), embossed (printing) or etched (laser printing) pattern of dots on the top or more frequently on the bottom face of the plate to direct the light incident to the surface towards the front of the display unit.

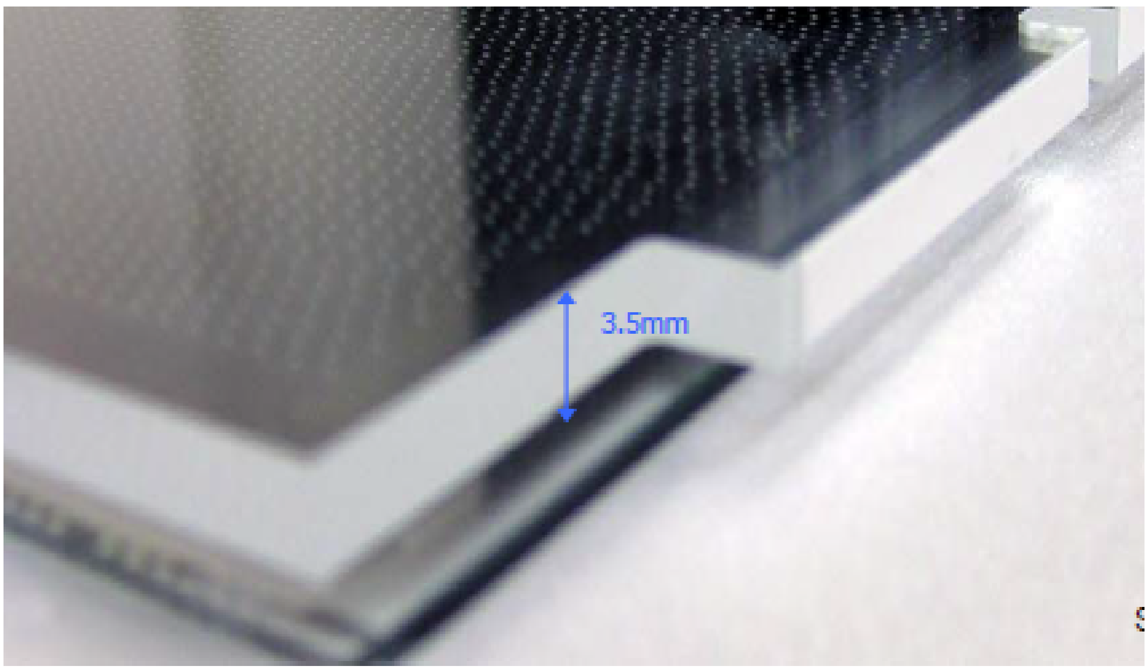


Figure 64: Light Guide Plate of 3.5mm Thickness [2]

Although the conventional material for an LGP is acrylic i.e., PMMA [Poly (Methyl Methacrylate)] other raw materials such as polycarbonate (PC) or polystyrene (PS) or a blend of those may also be used. In some cases diffusing material may be added to the blend to extract light instead of patterning. These minute particles are scattered throughout the panel and reflect light in all directions when combined with a light source. But this method is very inefficient and may not be used for large size displays.

PMMA is extremely transparent, highly weather resistant, and lasts longer than 30 years on average. On the bottom of the plate a matrix of lines can be etched, called V-Cutting, dots can be printed, a combination of both, or particulates are added into the plate itself. The purpose of all methods is to direct light out the front. [33]

PMMA can be bulk polymerized from MMA [34]. It may either be batch based or continuous cast. In batch polymerization (batch cast) the MMA is polymerized in polymerization cells. The pattern may be applied during the batch polymerization or raw LGP plates may be created via this process. These raw plates will be used for patterning using a different method. This process may be used to create "mother plates", giant plates that will be cut to size desired or smaller plates build to size. Since this process involves the production of molds and is slower than other processes, the cost is high and the yield is low.

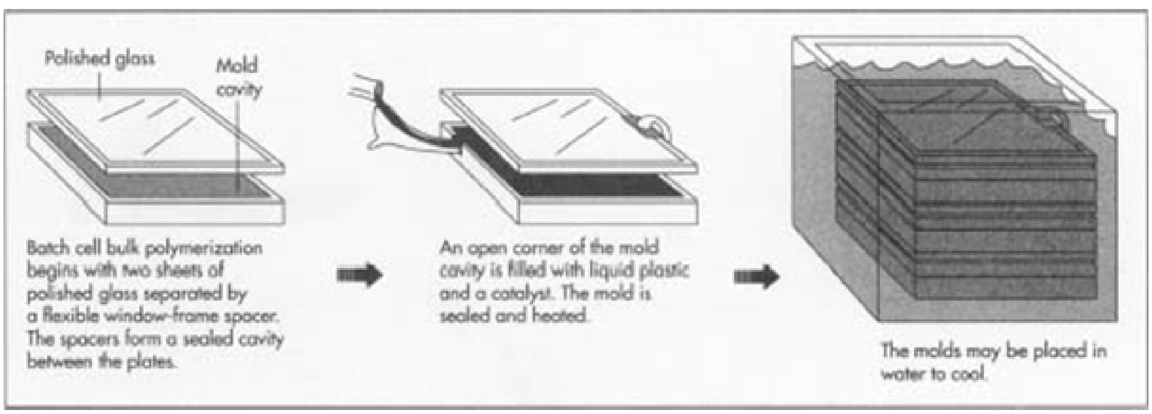


Figure 65: Batch Casting Steps [35]

In continuous batch casting, the monomer is fed into a pipe of desired shape, e.g., rectangular, and the polymerization occurs during the voyage of the material inside this tube. This process is similar to extrusion process where the input material and the output materials are the same. 2D printing is not possible in this method as the material goes through a defined shape. 1D printing, such as grooves and bumps with linear symmetry is possible. It is similarly used to create specific width shapes that will be cut to size or again to extrude mother plates.

The LGP plates, especially raw plates, may be produced via two methods described above. Also, as the result of these processes, the PMMA may be formed as long thin rods and cut into pieces forming the pellets that will be used for extrusion.

The extrusion process is very similar to the continuous casting. The material (pellets) is fed to a screw-like system where it is heated, melted and injected to a nozzle which feeds the extrusion mold. [36]

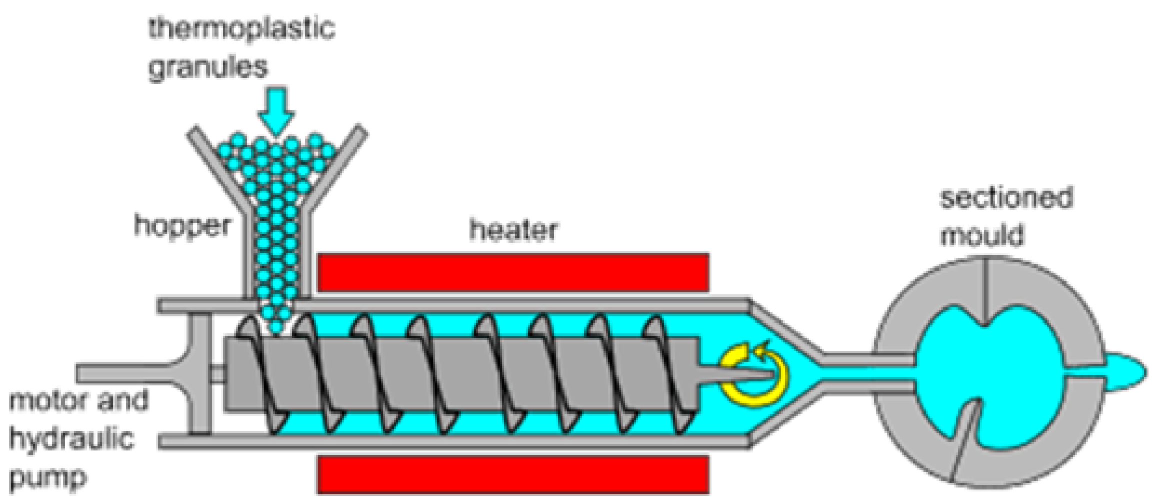


Figure 66: Thermoplastic Injection Molding [37]

Most commonly the production of the raw material for LGP is a big sheet of extruded PMMA that is called the mother plate. This mother plate is then cut into smaller pieces as needed and the pattern is applied to its surface. The edges are then polished to allow light to enter without hindrance.

The principle is to extract the light incident to the surface of the material by diffusing/scattering it via the pattern dots. A matrix of fine dots is printed onto the LGP using diffusive ink. These dots help scatter the light emitted from the light source. [38]

There are 3 approaches for the distribution and size of the dots in the pattern:

1. The position of the dots are predefined, the size vary to achieve the amount of extraction. An analogy would be the crystal lattice where the position of the atoms is fixed with the size of the atoms changing, bigger atoms (dots) for more extraction.

2. The size of the dots is fixed but the density changes. More dots means more extraction.

3. Both the size and the density are variable. This method is seldom used as it involves more variables to solve and more degrees of freedom.

Dots closer to the light source are smaller/scarcer in order o extract little amount and have more progress in the LGP towards the far corners. As the distance from the light source (LEDs) increases, the diameter of the dots (or the density) also increases. For a system that utilizes the first method, as the dot size increases the ratio of the area of the dot to the unit cell of the dots (the area that each dot has to itself, the area that it does not share with its neighbors) increases. Thus if the light incoming to the surface is considered to be uniform for such a small area, this ratio of dot - unit cell areas define the ratio of the light extracted.

Patterning

There are different methods of patterning with their advantages and drawbacks.

Dot Printing

This operation, also called ink printing, is the most flexible and cheap method but not the most efficient one as the brightness of this method is lower than the others.

A mask with the pattern is created similar to a sieve. This mask is superposed on the bare LGP and the ink is applied to the top via a squeegee, pushing the ink from the holes on to the PMMA. The system is then left to dry by curing via UV or IR radiation depending on the raw material of the ink. This mask is also called as a "silk".

The silk has to be replaced every 10.000 LGP. The takt time is very short (30 sec for a 46" TV).

Imprinting

The bare LGP is covered by a liquid precursor to PMMA and the imprinting mold is pressed on the system. The precursor polymerizes on the bare LGP with the shape imposed by the mold. To facilitate the drying process curing may be applied to the precursor. The curing may be done via heat, UV or IR radiation. This method requires the preparation of a mold with care and great precision.

V Cutting (Grooving)

V cutting is also called grooving. The LGP is cut horizontally (or vertically) by a blade. This technology has a very high takt time (300 sec for a 46" TV). The brightness obtained by this technology is higher than ink printing. The pattern variety is limited to lines and/or grids of lines.

Etching

Laser Etching

Laser etching is especially useful for prototyping. This technology doesn't require a pre-built template thus offers flexibility.

This method, although good for small numbers, isn't viable for larger numbers as the takt time is very long (300 sec for a 46" TV). Since the PMMA evaporates completely under heat without burning, this method is very clean.

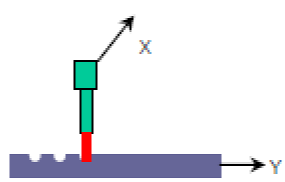


Figure 67: Laser Etching [9]

Mold Casting

Mold casting is changing (polymerizing) the precursor, MMA, into PMMA in a cast mould. It can either be done batches or continuously.

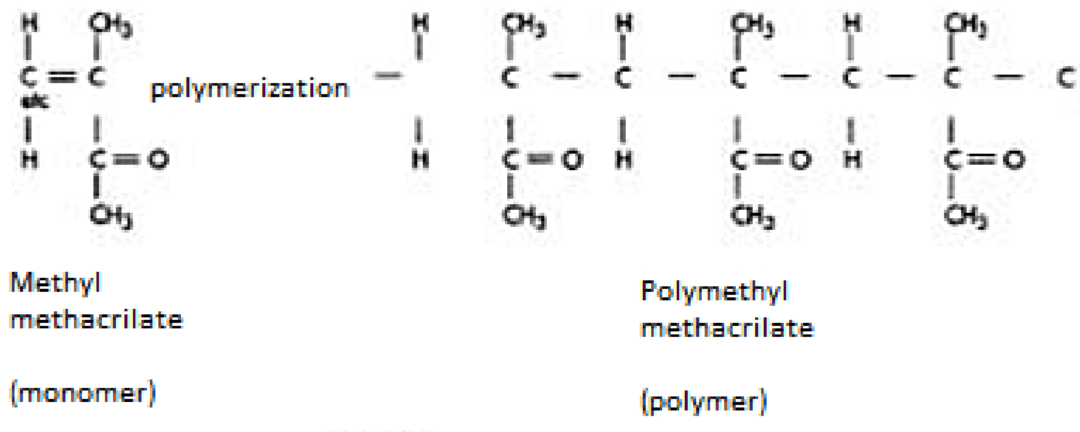


Figure 68: PMMA & MMA Molecular Structures [9]

Batch Casting

The mold used to create the PMMA sheets are highly polished glass molds, separated by a flexible plastic frame. This frame seals the two piece mold and because of its flexibility the cavity may shrink or enlarge during the process not only due to heat changes but also the volumic changes due to polymerization of the precursor inside. In other applications, metal plates may be utilized instead of glass. This way many plates may be stacked and clamped together by springs. This way the top of one plate would become the bottom of the other and more plates may be produced at once. The metal plates used in this method must be highly polished.

The cavity inside is filled by a premeasured amount of liquid MMA monomers to which catalyst of proper ratio is added. In some cases MMA prepolymer (material that has undergone polymerization but not finished its process) may also be added to the mixture. After filling the cavity the system is heated to initiate the polymerization of the MMA into PMMA during which process substantial amount of heat will be generated. Therefore, after the process is initiated the system may be immersed in a pool to quench the excess heat or fan blower may be utilized to cool off the mold. To ensure that the cure time is precisely followed and that there is no bubbles formed, the temperature cycles and these cycles are closely monitored by computers. It may take about 10-12 hours for thin sheets whereas the thick ones may require days.

After the curing time is achieved, the molds are opened and cleaned for next batch. The PMMA sheets may be used as is or may be annealed by heat (150C) to remove residual internal stresses that could cause the LGP to curve or bend under the heat of the LEDs.

The LGP thus created may have a pattern on its face that has been engraved to the mold. So far it has been used for small size application such as mobile phones and hand held devices [34].

Continuous Casting

The continuous casting process is similar to batch casting. The precursor is fed into the mold on one side and on the other side of the mold, PMMA is extracted. To be able to do this, the thickness of the plates must be thinner and the mold itself longer, giving enough time to the precursor to polymerize as it travels along the mold. Regions of different temperatures exist along the mold to cure the material inside and annealing of the material is done at the end of the mold. With this method, a predefined pattern may be engraved on the LGP but only in the direction of the mold, not a 2D pattern.

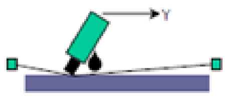
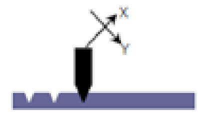
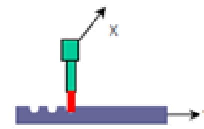
	Ink Printing	Molding (Stamping)	V-cutting	Laser Engraving
Principle	Patterned Mask → Ink Squeezing 	Molding by mold with pattern inside 	V-shape Grooving (# type patterning) 	Pattern engraving by laser beam by computer aided design 
Pattern type	Dot type, emboss	Dot type, emboss (prismatic)	V type, Line type/ Grid type, intaglio	Bar type, intaglio
Applications	MNT LGP NB LGP TV LGP	NB LGP S/M LGP (ex. Mobile phone)	MNT LGP (little portion)	TV LGP

Figure 69: Patterning Methods Overview [9]

	Ink Printing	Molding (Stamping)	V-cutting	Laser Engraving
Brightness	100% (basis)	100%	~103%	105%~
TAC Time (TV 46")	~30 sec	~200 sec	~300 sec	~300 sec
Pros	• High productivity (Fast TACT and inexpensive equipment) • General technology	• Less loss of material	• Higher brightness	• Higher brightness • Shorter development period • Non-contact technology (anti static technology) • More precise patterning
Cons	• Use of Mask and replacement • Yield rate (Not uniform quality due to labor-centered technology) • Low brightness • Noxious process (including CL)	• High cost for mold • Longer development period (mold manufacturing) • More expensive equipment • Large-size LGP technology is not proven	• Low productivity • Only line patterning possible	• Low productivity

Figure 70: Patterning Methods Pros & Cons [9]

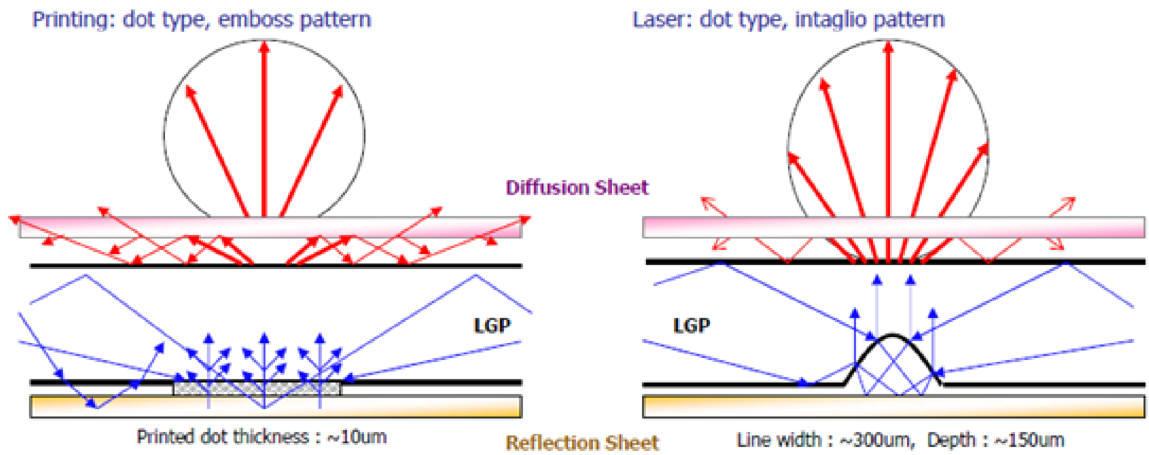


Figure 71: Difference between Dot Printing and Laser Etching [9]

2.5 Photometry, Radiometry and Units

Radiometry is the measure of electromagnetic radiation including the visible range. It plays a critical role in many sciences such as astronomy. This is the pure measurement of energy regardless of the photons interaction with the eye. The units are energy and power units.

Photometry on the other hand deals with the photons interaction with the eye. Therefore, the measurement range is far limited.

2.5.1 Intensity

The SI luminous intensity unit is the "Candela". This unit signifies the power emitted by a light source in a particular direction (solid angle [steradian, sr]) and is weighted by the luminosity function (Figure 72), i.e., the eye's response to the different wavelength.

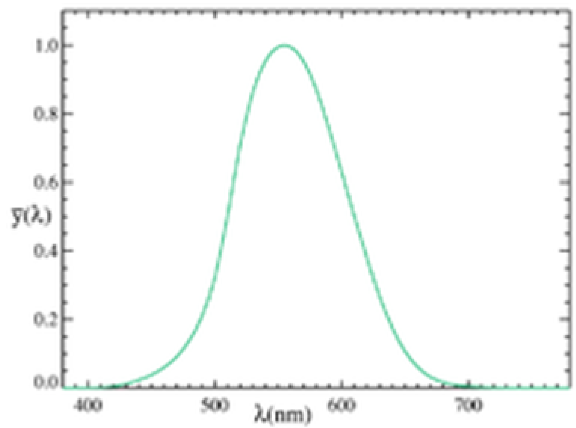


Figure 72: Photopic Luminosity Function [39]

The word candela means candle in Latin and the emission of a common candle is roughly 1 candela. Even if the emission is obstructed by an obstacle, the emission towards the unobstructed direction is still 1 candela.

The radiant intensity is similarly the amount of power per solid angle. The unit is watts per steradian (W/sr).

The luminosity function has its peak of 683lm/W at 555nm (green) [40].

2.5.2 Flux

The radiant flux of a source is the total energy radiated towards the entire space in all the wavelengths of the EM spectrum. The unit of flux is watts.

In photometry the flux is the same energy weighted by the luminosity function. The unit is called "Lumen" and it is an SI derived unit from Candela. 1 Lumen is the luminous energy emitted by a source of 1 Candela in a region of the space with a solid angle of 1 steradian i.e., the total flux of a source of 1 candela intensity is 4 lm (Figure 73).

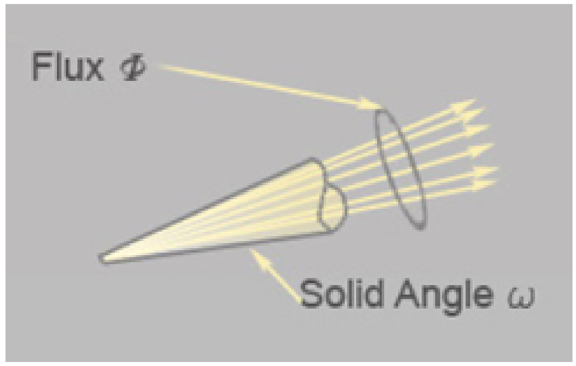


Figure 73: Flux Explained [41]

2.5.3 Illuminance / Luminous Emittance

This is the amount of light incident on a surface or emitted by a surface per unit area (Figure 74). The unit is Lux (lx) and is defined as 1 lumen per 1 square meter. In accordance to the law of Reverse Square, if a surface of 1 $m^2$is illuminated by 1 lx and is moved to twice the distance from the source the illuminance value drops to .25 lx and if the surface is moved to twice the distance, to receive the same amount of lumens its area should be doubled.

Similarly, when a surface is emitting light, such as an LCD TV or the reflection from a surface, the amount of light from unit area is called lux. This reflection (for ease of calculation is considered uniform) multiplied by the area yields the total flux emitted.

Whether it is incident light or emission, illuminance / emittance doesn't take into account the angle in which the light is incoming / outgoing.

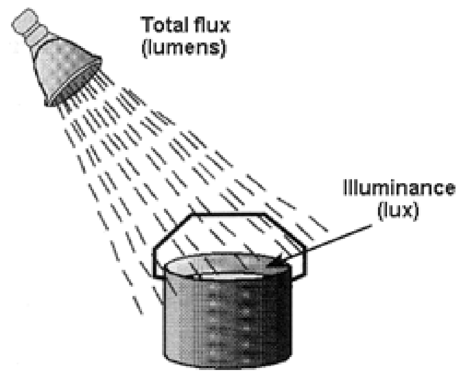


Figure 74: Analogy between Light and Water [41]

2.5.4 Luminance

Luminance is the amount of light emitted from a unit area into a specific direction of space. It is the lumen per square meter per solid angle and the SI unit is cd/m^2. A non SI unit that is more frequently used in the information display community is "nits" [42].

CHAPTER III

LGP DESIGN

3.1 Problem Definition

The target in an LGP design is to achieve required central brightness level and uniformity while keeping the number of LEDs as small as possible. To achieve better uniformity, more optical films may be used or tighter LED distribution may be chosen. These solutions will result in increased cost. Also high number of films will require higher light input because light will be absorbed in these films. This will increase the energy consumption by the LEDs.

The purpose of the new pattern that will be designed in this study is to get rid of the expensive reflective polarizer. In addition, the optical stack cost and the LED cost will also be minimized. The optical requirements are 300 nits at the center and 75% uniformity without any visual defects.

3.2 Previous Work

The literature on LGP design is limited due to the nature of the work. Usually, TV companies do not publish their LGP patterns and research on the subject. Below, a few published articles will be reviewed.

Jeong, Lee, Yoon and Choi [43] used a process called serration to increase the uniformity of the light distribution in the LGP and "Progressive Quadratic Response Surface Modeling" to optimize the dot distribution in a 2.2 inch edge-lit type back light.

Serration is the process of adding prisms to the LGP's edge that is in front of the LEDs. It is similar to the serrated edge of a blade. It acts as a prism film and doubles the number of light sources thus increasing the uniformity.

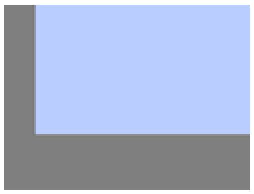


Figure 75: LGP with no Serration

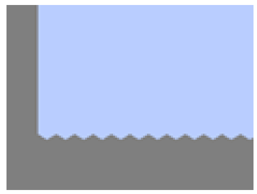


Figure 76: 120° Serration

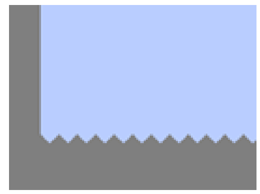


Figure 77: 90° Serration

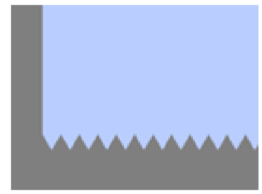


Figure 78: 60° Serration

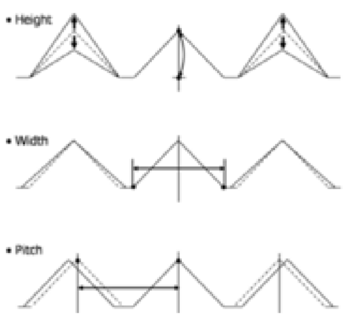


Figure 79: LGP Serration Parameters [43]

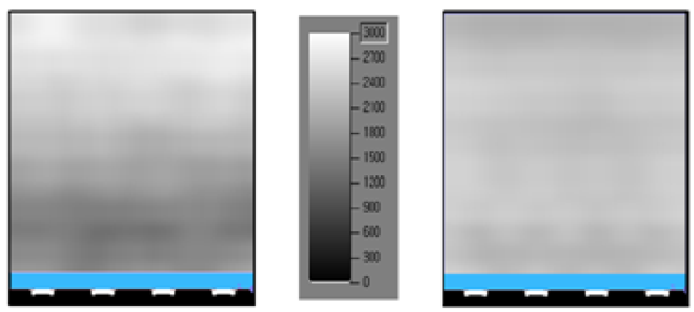


Figure 80: Results Before and After the Study [43]

As a result, the uniformity is increased from 38% to 82% and the illuminance is increased from 2241 lux to 2299 lux thus improving both brightness and uniformity together.

Since the human eye detects the intensity and not the illuminance, the customary unit used to define the light output of a display is the nits or cd/m2. As the spatial distribution of light will be uniform all over the display, Jeong, Lee, Yoon and Choi used the illuminance instead of intensity. Regardless of the unit used, the uniformity will be the same and so will the improvement ratio.

Young Chul KIM, Tae-Sik OH, Yong Min LEE [44] used receivers (optical detectors) at different distances in the LGP to measure the intensity of the light travelling in the PMMA block and the amount of light reflected from the face of the reflector below the LGP.

To model dot densities that will match these measurements, pattern density functions are introduced.

$$\text{Pattern Density}=[\text{P}.\text{e}^{(-y/60)}+\text{Q}.\text{e}^{(y/25)}.\text{R}]$$

P indicates the distance between the dots closer to the LEDs and Q, the distance between dots further away. The coefficient R is the general factor. These density functions are optimized for better uniformity and higher brightness.

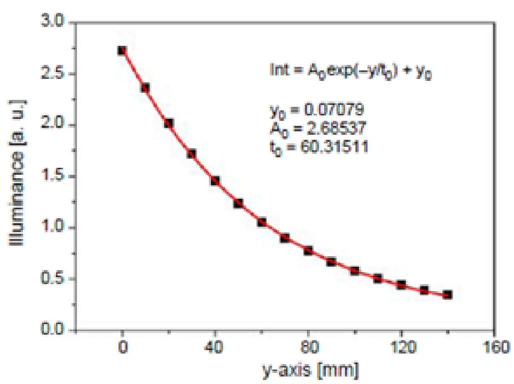


Figure 81: LEDs' Intensity vs. Distance [44]

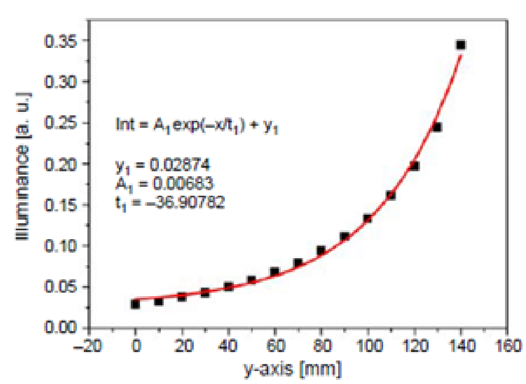


Figure 82: Reflector's Contribution vs. Distance [44]

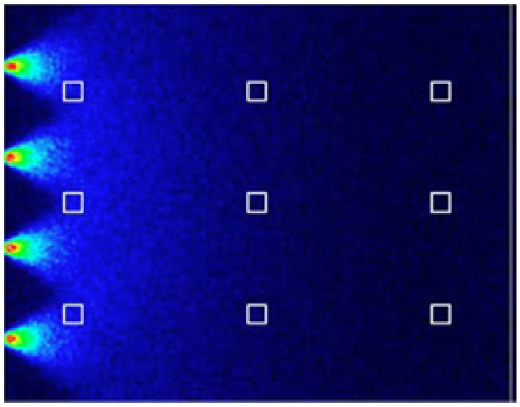


Figure 83: Equidistant Pattern with 9 Measurement Points [44]

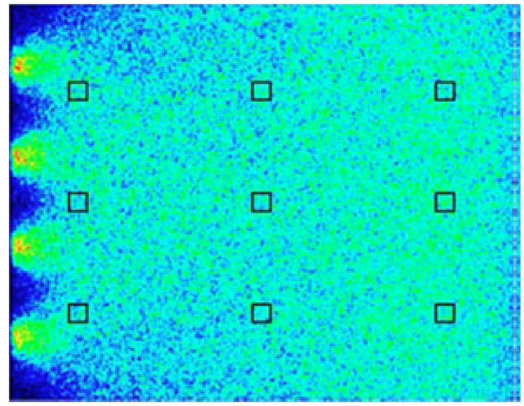


Figure 84: Optimized Pattern by the Pattern Density Function [44]

The uniformity is increased from 25% to 90.82%. The brightness improved only by a little from 751 lx to 781.6 lx (4% increases).

Jee-Gong Chang and Yu-Bin Fang [45] used regional approach. They divided the LGP into multiple regions and assign the same radius of dots into each region. Using an iterative approach, they modified the dot radius in each region and calculated the luminance until obtaining uniform distribution. Thus instead of calculating each and every dots, they transform the problem into computationally manageable state. They took simple Lambertian reflection as dots' optical model. The size of the dots in each region will differ to obtain uniform overall image.

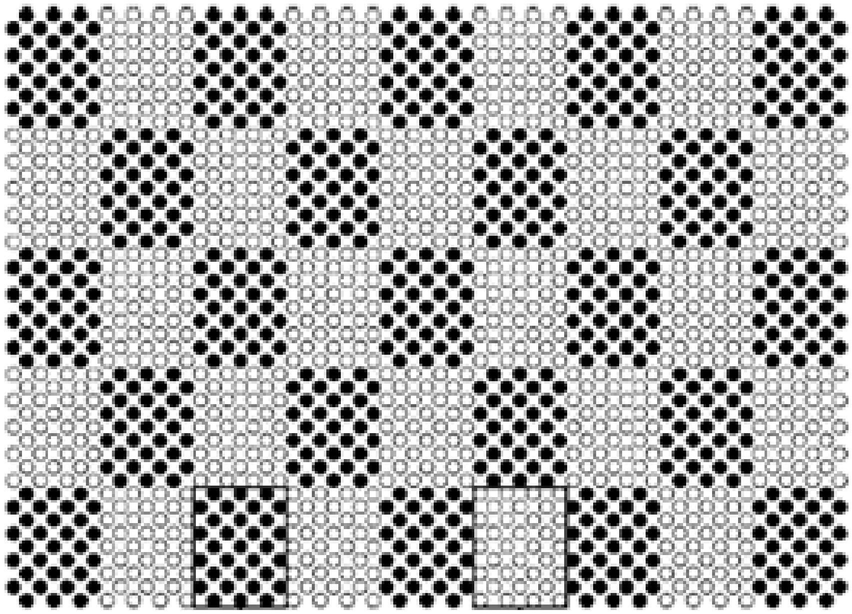


Figure 85: 45 Regions ofthe LGP, Template 1 & 2 Having Different Number of Dots [45]

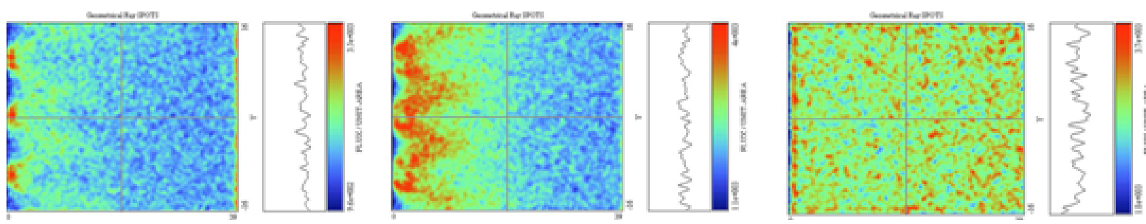


Figure 86: 2^{nd}, 3^{rd} and 36^{th} iterations [45]

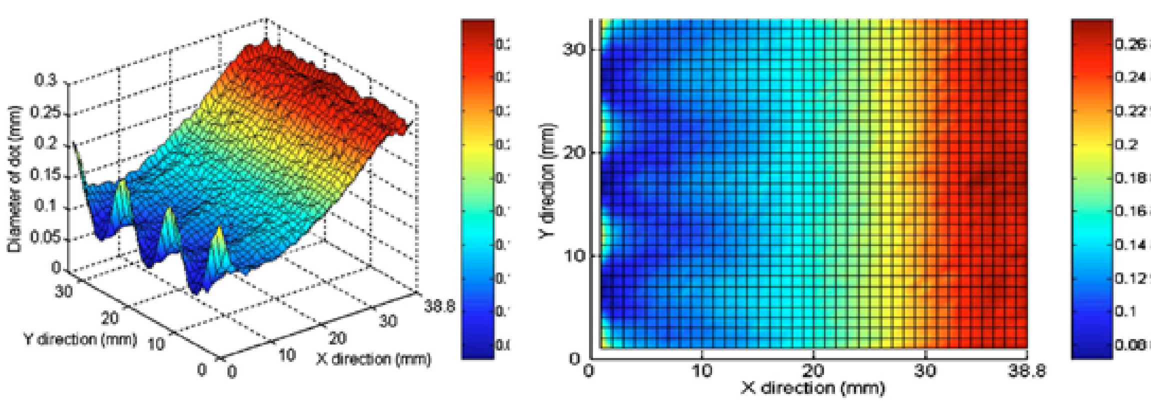


Figure 87: Resulting Dot Distribution [45]

3.3 Optical Components of the System

The optical components used in this work are as follows:

Supplier	Part Number (P/N)	Type	Thickness
Shinwha	SD 743	Diffuser Sheet	275μm
Shinwha	PTM 358-V	Vertical Prism Film	275μm
Shinwha	PTM 358-H	Horizontal Prism Film	275μm

Table 1: Optical Sheets Used in this Study

Supplier	P/N	Type	Thickness
DS Electron	Custom Design	LGP	3 mm

Table 2: LGP Used in this Study

PMMA raw material, 3mm thick, patterned to request, standard LGP.

Supplier	P/N	Type	Dimensions	Flux	LED Pitch
LGIT	7020	LED	7mm x 2mm x .9mm	67.3 Lm @ 100mA @ 25C	9.12 mm

Table 3: LED's Used in this Study

The string voltage of the system is 36V and the total consumption of the system is less than 40W (A^+ energy consumption). The LED bars are located only on the one of the short edges of the panel. This makes the design more challenging.

3.4 Design Flowchart

The flowchart of the design steps followed in this thesis is as below:

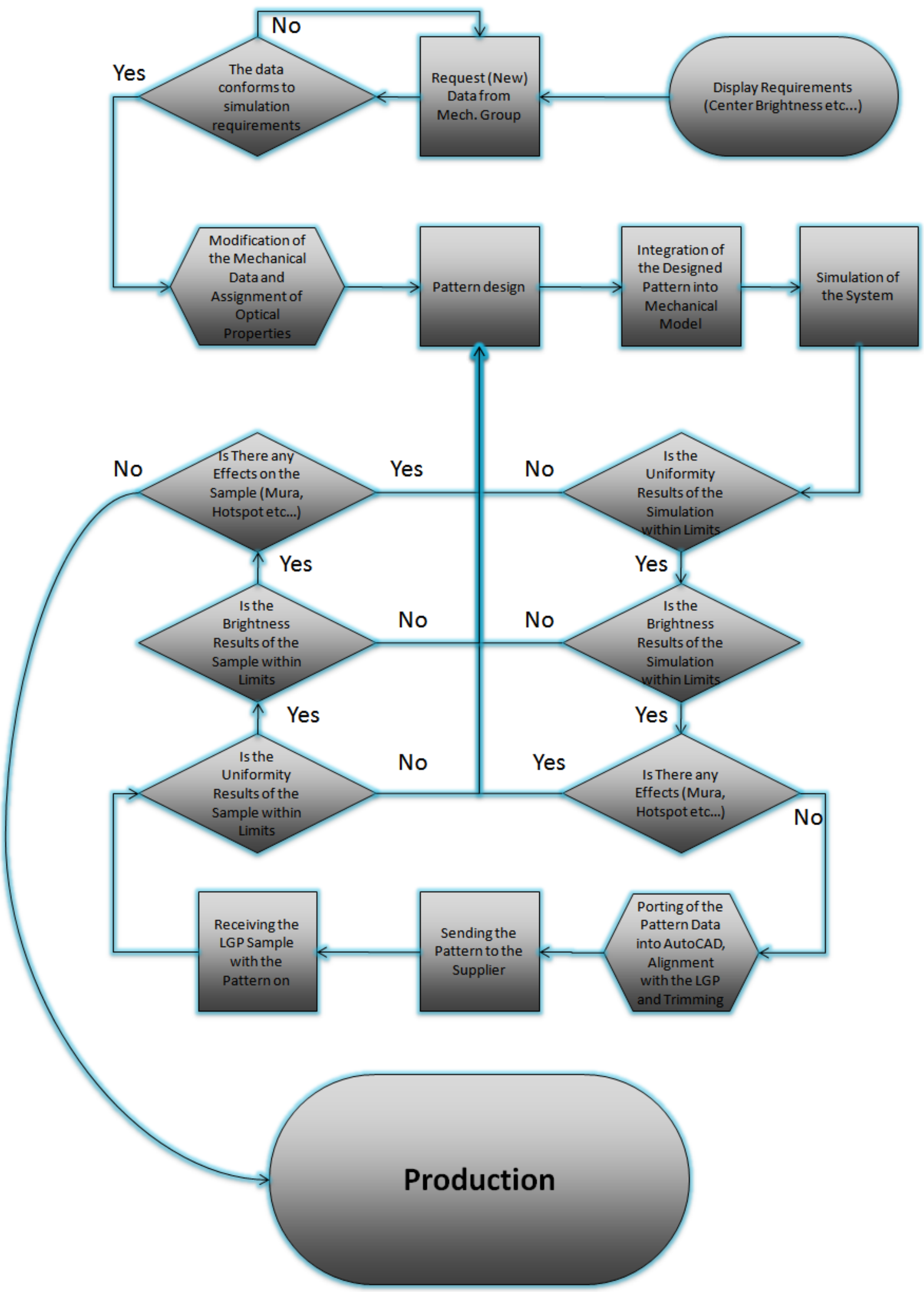


Figure 88: Design Flowchart

3.5 Display Requirements

The first is to decide and agree on the display's requirements such as:

- Center brightness : This is the brightness value in nits (cd/m2) of the central point of the display.
- Uniformity : The uniformity value is the lowest luminance value measured divided by the highest one:

$$Unif = \frac{L_{Min}}{L_{Max}} x100$$

To meet higher uniformity requirement one has to increase the light on the corners (especially the far side ones) and sides or decrease center brightness. If the number of light sources is already fixed than it is better to target the minimum acceptable uniformity value to have the highest possible brightness. As for most of the contents on the TV, the important context is in the middle where people most often stare at, the center brightness is very important (more important than sides and corners). Therefore, a uniformity value of 100% is not required. As an industry standard (VESA), 75% uniformity or, in some cases, 1.3 non uniformity ($1 : 1.3- > 77\%$) is accepted. To be on the safe side a target of 80% can be used.

Also the uniformity of a panel depends heavily on the pattern created. The brightness may be increased by changing the LEDs with higher brightness ones to increase but the uniformity is almost only affected by the pattern. The optical sheets' effect is more local than global thus they may shift the uniformity by a few percent.

The uniformity of a panel is measured from 9 points on the active area. The distance of these points from the upper / lower edge of the active are is equal to 1/10 of the height of the active area and similarly the distance from the right / left edges is equal to 1/10 of the width of the active area. Except for the 5th one, that resides at the middle of the active area. With the penetration of the LCD TVs and their becoming of a commodity, these points approached the center and the uniformity begun to be measured from 1/6 of the active area instead of 1/10. Some manufacturers took this one step further and used 1/4 of the display area. The value is always 75% uniformity but of course 75% from 1/10 is far more uniform than 75% from 1/4 .

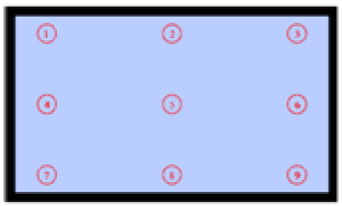


Figure 89: Uniformity Measurement Points from 1/10

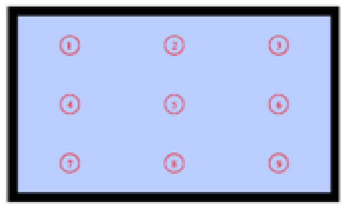


Figure 90: Uniformity Measurement Points from 1/6

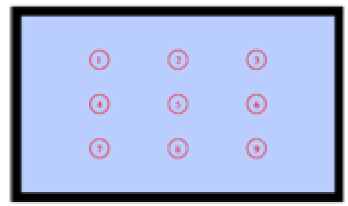


Figure 91: Uniformity Measurement Points from 1/4

The middle point is where the center brightness measurement is taken from. It is usually the brightest point. The darkest point would be the far side (from the LEDs) corner.

The central brightness value for 39" TV's are in the range of 300-350 nits. The LGP designed in this study is for a new generation LED TV and it is intended to eliminate the use of reflective polarizer. The brightness target (300 nits) chosen in this study is in conjunction with the trend of decreasing the brightness.

The number of LEDs, their driving current and the flux of each LED are chosen according to brightness and uniformity criteria. For this design, 52 LEDs driven at 110mA will be used with a flux of 67 lm each. More LED's driven at lower current values could have been used to obtain the same flux levels at a lower power consumption, but this would cause the cost to be higher. Similarly less LED's with higher current would result in less cost, but more energy consumption.

While designing the light source, i.e., deciding the number and the pitch, the electrical requirements should also be kept in mind. A string of LED is the total of LEDs that are attached serially e.g., for a system of 52 LEDs, there may be 4 strings with 13 LEDs in each string. The distance between the last LED of a string and the first LED of the other should be the same as the distances between the LEDs within the string. Otherwise bigger gap between the strings will cause Mura effect and/or will need special patterning which may be distinguishable by the viewer.

Also, the pitch of the LEDs must be chosen in a way that it is an integer multiple of pitch of the pattern dots, i.e., for each LEDs, there must be same number of dots. Otherwise, the dots will not be in the same position for each LEDs and the light extraction will have different ratios. At a point where the light is at its strongest (closest to the LEDs), this will cause hotspot problems. The dot pitch should have a value between 1.3 and 1.6 mm according to the supplier (their production limit). For example, for an LED pitch of 7.8mm either 1.3 or 1.56 mm pitch may be used (6 dots per LED or 5 dots per LED). To have better control over the light extraction it is better to have as much points as possible. Thus, to go with 1.3mm dot pitch is the better choice.

3.6 Mechanical Data Review

In the simulations throughout this study off the shelf optical simulation tools were used. These were Lighttools and DS Design Tool. To be able to simulate the optical properties of an optical stack and transfer the design quickly to the production team, the simulations were performed on the actual optical stacks whose mechanical drawings were available from the various groups at the company. Throughout this thesis a process flow were also developed to transfer the new stack designs to production. In this section, details of the changes that need to be performed on the existing mechanical data to be able to feed the data to the optical simulation tools will be covered.

The key design parameters are relayed to the mechanical group for 3D design. They also design the optical films and the LGP in accordance with the requirements such as the active region of the cell, the expansion coefficient of the PMMA etc... along with the LED bars, heat sinks and LED placements according to the optical team's specs and requirements.

This data is checked by the optical team for conformity. If it does not conform with the requirements of the simulation tools, new data is requested. Within this data, the position of the LEDs, optical films, LGP and LED Bars should be accurate. LEDs should be separable from the LED Bars so that the optical properties can be assigned separately. The most common problem is to have the LEDs and LED Bars as one entity (LEDs extruded from LED Bar) and the distance between LGP and reflector to be zero. These are easy to solve problems. This can be fixed with 3D design software such as AutoCAD or Rhino. The bar and the LEDs are created as rectangular prisms and their properties assigned.

As for the optical films, diffusers are used to diffuse the light to have a better, more uniform picture. They turn the dots into bright regions. They have little effect on the overall uniformity. Prism films are used to direct the light toward the viewer thus increasing the luminance but not the uniformity. Therefore, the optical films have little or no effect and thus may be ignored in the design of the LGP pattern. Any fine tuning will have to be empirical since the computational power required to solve the system with full optical sheets and components is too high.

To summarize, the reflector is moved away from the LGP, the optical films are deleted along with any mechanical components that does not have an optical impact (such as the back cover). To be able to start the design and to create the pattern, following data must be at hand:

- 2D drawings of the system. The requirements for this drawing are:
  - The LEDs and LGP must be aligned
  - Optical sheets must exist
    - In later stages, when the pattern is being edited, the optical films will be necessary to crop the pattern
  - Active area should be defined.
    - Active area is the area from which the light may be extracted
- 3D drawings of the system
  - All optical components must be included
    - LGP
    - Optical films
    - LEDs, LED Bars and connectors
      - LEDs and LED Bars should be separately defined

        - LED Bar and the heat sink should be separate entities
      - Reflector Sheet
        - There must be 0.01 mm distance between the reflector and the LGP.
      - Reflector strips under the middle frame (the plastic frame that holds the optical sheets down and provides base for the cell)
      - Pieces like sponge, Mylar etc... if any
      - Back cover
    - Any other parts that would have optical impact on the system.
      - These parts should be correctly aligned
      - They should be separate entities
    - The back cover, which will not be included in the simulation but will only hold information on the alignment and possible holes, should be a separate entity as well that can be deleted while running the simulation.

After due examination, any inconsistencies, inappropriate parts etc... should be modified.

3.6.1 Insertion of Space between LGP and Reflector

This distance can be introduced by opening the file with any CAD program and moving the reflector (e.g., with move command) 0.01mm away from the LGP. It can also be done by opening the properties of the reflector in LT (Light Tools) and changing the appropriate position (most commonly y-axis) by 0.01.

This distance may be bigger or smaller within the limits of reason. The height of the pattern dots should be kept in mind while setting this distance (0.007mm). Otherwise the pattern will be immersed in the reflector and the simulation will fail as the optical properties of the pattern will be overwritten by the optical properties of the reflector (95% Lambertian reflector with 5% absorption).

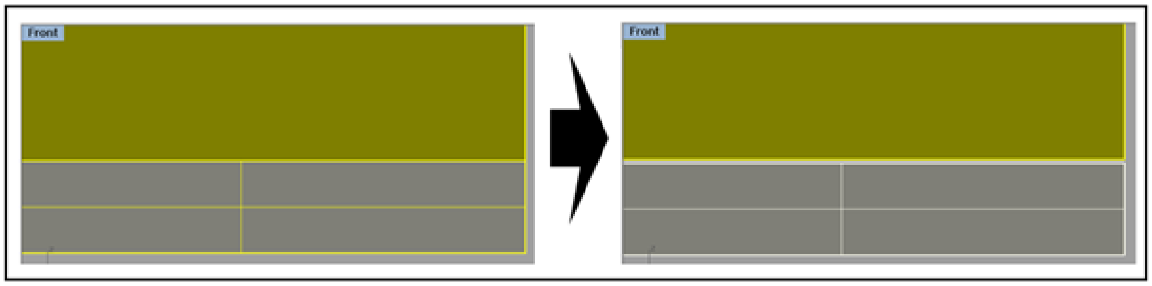


Figure 92: Introducing Distance between Reflector and LGP

3.6.2 Definitions of LEDs

To be able to define the sources, the LEDs and the LED bars must be separable. Otherwise the whole entity will be taken as a single source and the emission will be from each and every faces. Therefore, during the design of the LED bars and LEDs, LED shall be defined as objects, not extruded features of the LED bars. If this is the case, they will have to be recreated whether it is in the design tool or the 3D CAD software.

3.7 Pattern Design

As discussed before, the amount of the light to be extracted is proportional to the dot size. Therefore, the size of the dots must increase as the distance from the source increases. At the sides of the LGP that do not have any light sources, in order to prevent the light loss, a reflector tape is used. This reflector reflects the light back inside the LGP. Usually the reflector is a Lambertian or at best a Gaussian reflector and it does not reflect the light like a specular reflector (mirror-like) but it rather diffuses. Therefore, at the edges of the LGP the amount of light incident to the patterned surface increases compared to close proximity of the edges

The dots must not be aligned with the cell's pixels. The pixels are arranged in a rectangular pattern therefore, the dots must be arranged in a pattern with a dot angle different than 90°or 45°. This value is generally 60° for large sizes($\geq$ 32") and 30° for small sizes($\leq$ 28").Otherwise the dot placement will create an artifact called Moiré. Moiré is the phenomenon observed when two regular patterns are superposed at small angles (figures 93, 94 and 95).

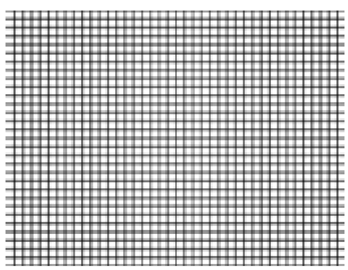


Figure 93: Rectangular Patterns Superposed @ 0°

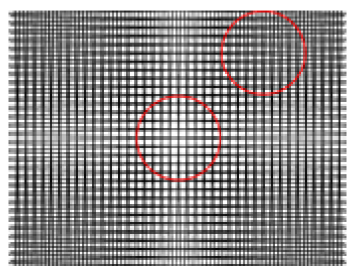


Figure 94: Rectangular Patterns Superposed @ 1°

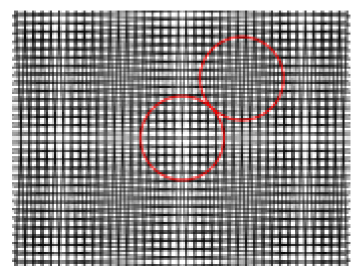


Figure 95: Rectangular Patterns Superposed @ 2°

To create this pattern, the software provided by DS Electron was used (the details about the use of this software and its GUI may be seen in the appendix).

3.7.1 Dot Properties and Shape

3.7.1.1 Ink

The material used to create the pattern's dots is called "ink" by the supplier. It is a mixture of solvent, SiO_2 and TiO_2. The solvent provide a medium in which micro beads are suspended. When the solvent dries out and the beads are left behind, they are stuck to the surface of the LGP. The mixture of TiO_2 and SiO_2 act as both a pigment that reflects and diffuses light and as a scattering medium.

This "ink" is thinned with a solvent and the thinning ratio plays an important role in light extraction properties. Thinner the ink is, lesser the light extraction but also the light absorption. As a convention, for large size displays (> 32") the ratio of the solvent in the ink is around 60%. Therefore, in this study we will start with this ratio as well.

TiO_2

Titanium dioxide is used as a white pigment. It can be used as food coloring (even used in medicine). Its refractive index is 2.614 [46]. It is also called as "perfect white" or "whitest white". Opacity of the material may be controlled by changing its particle size [47].

SiO_2

SiO2, silica, is the main material in glass production. Silica fused with Na_2CO_3 (soda) and CaO (lime) forms the soda-lime glass [48]. Pure silica can be crystalline (quartz) or amorphous. It has a refractive index around 1.54 [49]. The use of glass beads suspended in a medium is a technique used in BLU optical films. For instance the diffuser plates used in the CCFL/EEFL based LCD TV's have the structure of glass beads suspended in PET substrate. With proper size control, these beads may scatter and reflect the light as desired.

3.7.1.2 Shape

The thickness of the dot will not affect the optical behavior of the system too much therefore, the approach that the scattering / reflection / absorption happen on the surface will be sufficient. After the solvent vaporizes, the remainder will be the pigments and the beads.

A liquid drop on a flat surface has a specific shape depending on the surface tension of this liquid and its adhesion to the surface. This shape may be modeled as a very shallow cylinder. To some extent, as long as the thickness of the dot isn't very big, this model will work within expectations and simplifies the problem.

Figure 96: Dot Model

Although there are many dot shapes available such as the ones below, for more symmetrical arrangements and better control circular dots are used in this study.

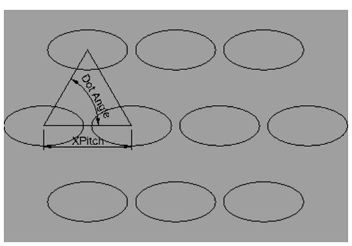


Figure 97: 2:1 Dot Ratio

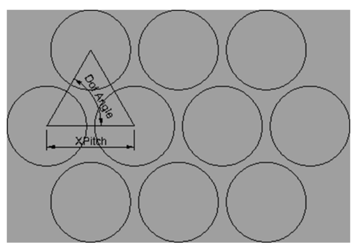


Figure 98: 1:1 Dot Ratio

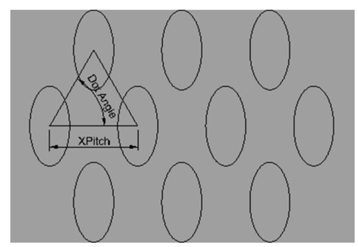


Figure 99: 1:2 Dot Ratio

3.7.2 Pattern Construction

The dot size from one edge to the other edge does not change linearly. To the first order, the amount of light per unit area of the surface may be considered uniform because of the internal reflections. Therefore, the light extracted from the beginning to the end at constant intensity requires the dots to grow towards the end quadratically.

A quadratic curve with the very end decreasing in size, because of the reflection from the edge reflector is a good way to start design. Of course, in theory this gives us an entirely uniform display. The minimum uniformity requirement for flat display panels is 75%. Therefore, a uniformity level of 80% may be targeted to have better luminance level at the center of the panel. So this quadratic curve may be multiplied with a Gaussian to give us the starting point.

The multiplication of the Gaussian with the quadratic is the approximation of a perfect world. In reality, as the light goes further away from the source it is extracted. Therefore, a linear factor would make sense.

The resulting curve, along with the others (all normalized to 100%) is as below.

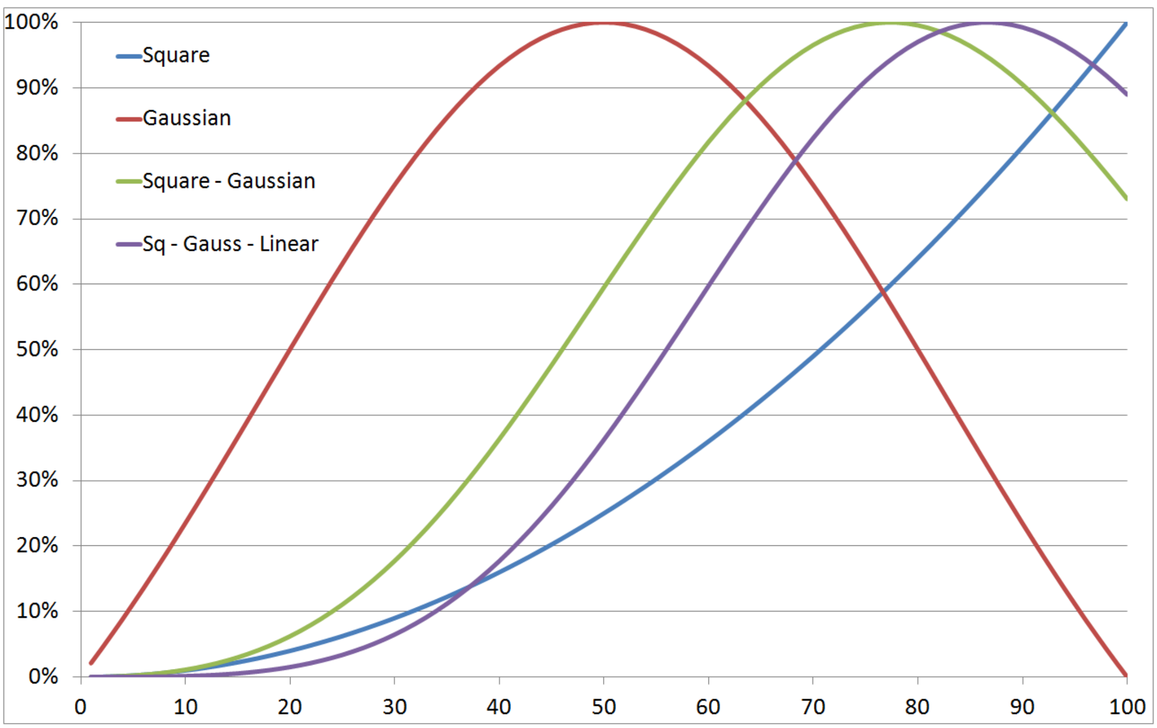


Figure 100: Calculation Curves

The purple curve is used for the initial selection of the dot size along the distance between the two sides of the LCD panel. After the corresponding dot size pattern is created, the data is simulated and fine tuning is conducted.

3.7.3 Pattern Integration into Model

The pattern, thus created, has to be integrated into the model. The dots are usually on the bottom side of the LGP (bottom side is the one closer to the back cover and the reflector). To do this the bottom surface is selected and a new pattern zone is created. The data about the pattern is ported into the simulation software. The detailed step about this process will be explained in the appendix. The most important thing is the alignment of the pattern with the LGP. Care must be taken to make sure that the pattern is not rotated with respect to the LGP by 90° or 180°. Also the middle of the LGP and the pattern must overlap.

CHAPTER IV

SIMULATION PARAMETERS OF THE SYSTEM

To simulate the system and optimize the pattern designed, Lighttools (LT) optical simulation software was used. This software is the most commonly used simulation software among panel designers especially in Taiwan, China and Korea. Also some of the optical film suppliers create their product libraries in LT to facilitate the design of the panel makers. OPTIS/SPEOS is another optical simulation tool that is widely used but in this study LT was used for its powerful user interface.

4.1 LGP

Correct modeling of the LGP is the crucial part of simulating the back light unit. This is the biggest and most important part of the optical system. It acts as a mechanical support and an optical element at the same time.

As in most cases, the LGP used in this study is composed purely of PMMA. Since the PMMA is considered to be pure and there will be no volume dispersion / diffusion, the transmittance of the material will be used as 100% and the optical property will be set as "Smooth Optical". From the "Advanced Properties" tab "Fresnel Loss" should be checked to make sure that the interface interactions are accounted for. The PMMA's optical properties are independent of the wavelength [50].

The material is set as PMMA from the readily available materials. If the material is not set to PMMA or other material is set, the refractive index should be entered manually or the refractive index of the selected material should be checked. Otherwise the results may be wrong.

If there are reflectors glued to the sides of the LGP, these faces will be selected and the reflection coefficient of these faces will be 95%. This is because a typical reflection coefficient of the selected material is around 95%.

For the reflector at the back of the LGP, care must be taken to make sure that the reflector and the pattern does not superpose. Since the height of the pattern is measured as $7\mu m$, a distance of $10\mu m$ would be enough.

The rest will be subject to Snell law for reflection and/or transmission. PMMA has a refractive index of 1.4914 and a critical angle of 42.1065°.

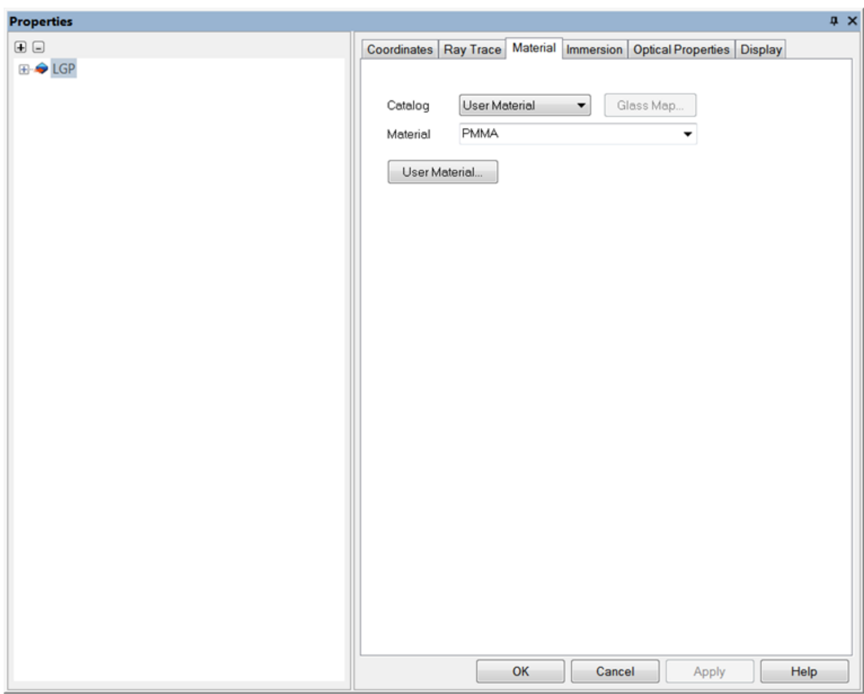


Figure 101: Material Assignment to the LGP

4.2 Pattern

To assign properties to the pattern the basic concepts of the reflection mechanism must be known.

4.2.1 Reflection

One can define 3 different types of reflection for the light reflecting from a surface:

1. Specular
2. Gaussian
3. Lambertian

These types are explained below.

4.2.1.1 Specular Reflection

This is the mirror-like reflection of the light from the surface of materials. The surface should be flat, smooth and without rugosity as is a mirror or water at rest.

Figure 102: Specular Reflection Model [51]

Figure 103: Specular Reflection from the Surface of Still Water [51]

4.2.1.2 Gaussian Reflection

This is between specular and Lambertian reflection. The average of the reflected / scattered beams has the same angle as the incident ray. The general traits of the image are perceivable but the image is fuzzy from Gaussian fanning.

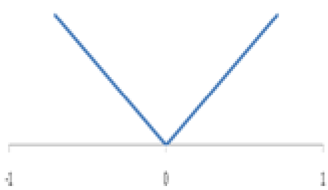


Figure 104: Specular Reflection

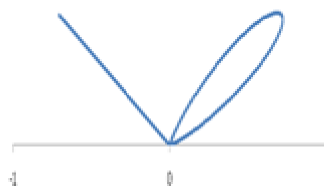


Figure 105: Gaussian Reflection

Figure 106: Gaussian Reflection of Firefox Logo [51]

4.2.1.3 Lambertian Reflection

When a surface is a Lambertian reflector then the reflected light is headed towards half space regardless of the incident ray's angle. Most of the surfaces met in the daily life such as fabric or not polished wood are Lambertian surfaces.

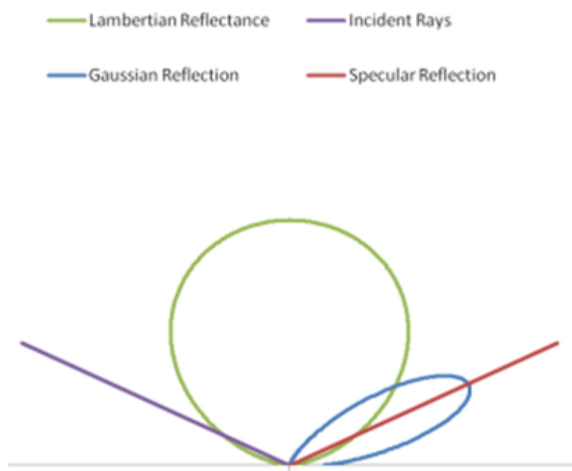


Figure 107: Specular, Gaussian and Lambertian Reflections

4.2.2 Pattern Properties

The pattern is considered to be Lambertian. Some optical simulation software take into account all three mechanisms. Lighttools however does not have a specular component. Instead Gaussian and specular components are combined together as "Near Specular". Lambertian is called "Diffuse". Below are the parameter screen for complete scattering model and the model used by the Lighttools.

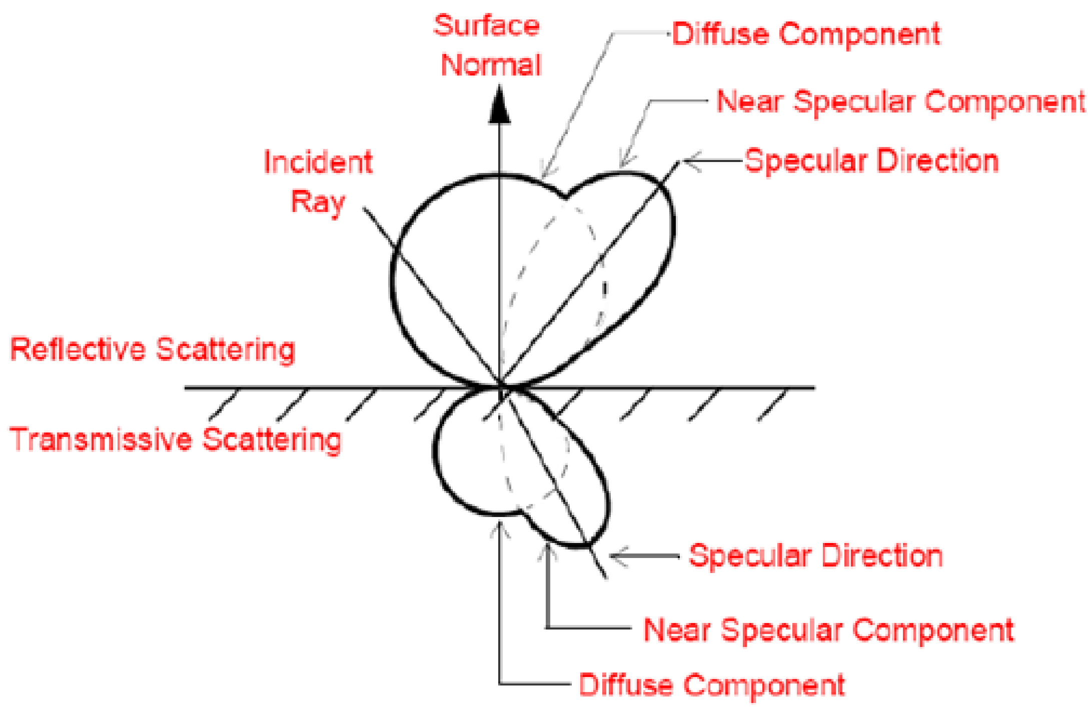


Figure 108: Complete Scattering Model of Light Tools

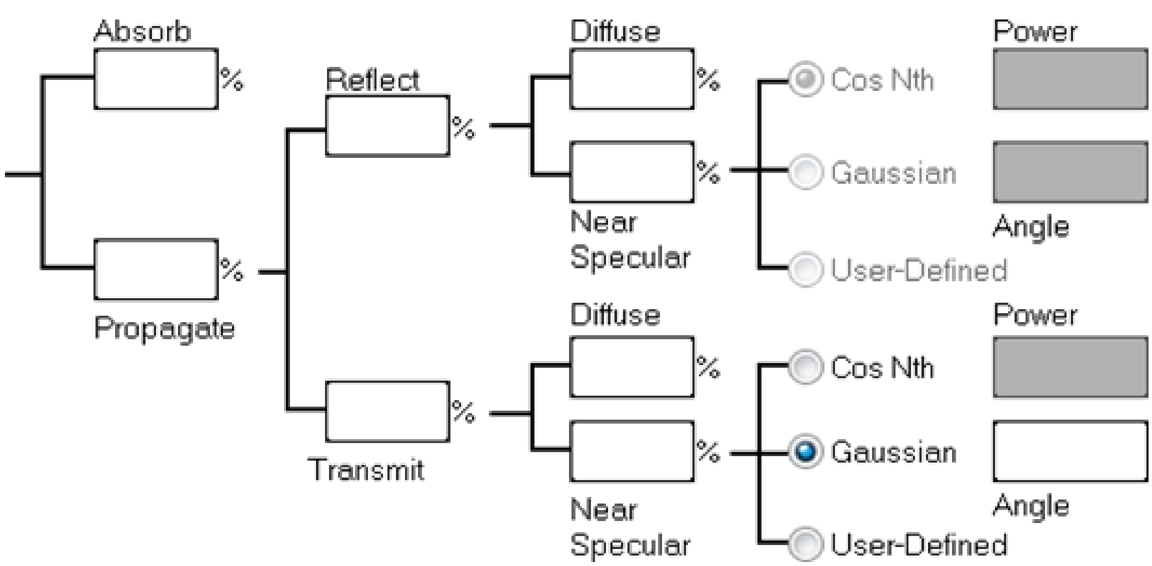


Figure 109: Complete Scattering Parameter Screens

There are studies where the dots are simply taken as Lambertian reflectors [52]. However this is not an accurate approximation. Since the dots consist of 40% ink with 60% thinner, the design should reflect this ratio and not be modeled by 100% scattering.

Since the nothing is perfectly reflective, a loss of 5% is anticipated. Therefore, $\boldsymbol{Absorb = 5\%}$ was specified in the software.

That leaves 95% to propagate. It is possible that the light reflected back and scattered forward are of the same ratio. At least it is a convention for this work. Since the ratio of the ink to solvent is 40% - 60%, a total scattering of 40% is a good point to start. Since the convention is that this 40% is equally divided both ways, the value for $\boldsymbol{Reflect\ is\ 20\%}$ and **100%** of that value will be $\boldsymbol{Diffuse}$. That leaves $\boldsymbol{80\%\ for\ Transmit}$. Of that **25%** will be $\boldsymbol{Diffuse}$ summing up to 20% of the total light. The rest, **75%** is $\boldsymbol{Near\ Specular}$ with $\boldsymbol{Gaussian}$ component selected and a value of **0.01**. This is very close to specular.

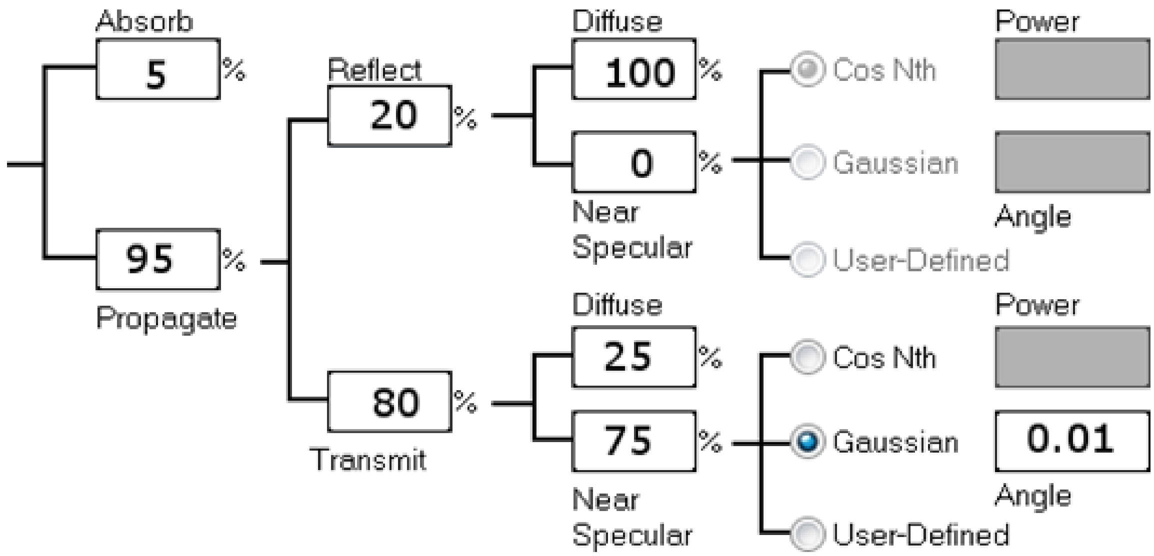


Figure 110: Complete Scattering Parameter Screens

With this model the light incident on a dot will have 5% of its intensity absorbed, 20% of the remaining 95% reflected diffusely, i.e., towards the inside of the LGP and the optical films, 20% transmitted diffusely, i.e., towards the reflector sheet on the back of the LGP which will be reflected back and finally, 60% is transmitted specularly. This transmit doesn't exclusively mean transmit, it means the control of this 60% (actually 57% taking into account the 5% absorption) is left to the simulator. The software will check the incident angle and decide on the fate of the beam. The mechanism for light propagation in the LGP is TIR (total internal reflection) and the refractive index of the PMMA play a crucial role in the calculations of TIR. If the angle is too wide, the incident ray will reflect from the surface. If not, the ray will pass into air and toward the reflector. This probability is calculated according to the Snell law. The refractive index of the PMMA is 1.4914 [53] thus the critical angle on interface to air is 42.106°.

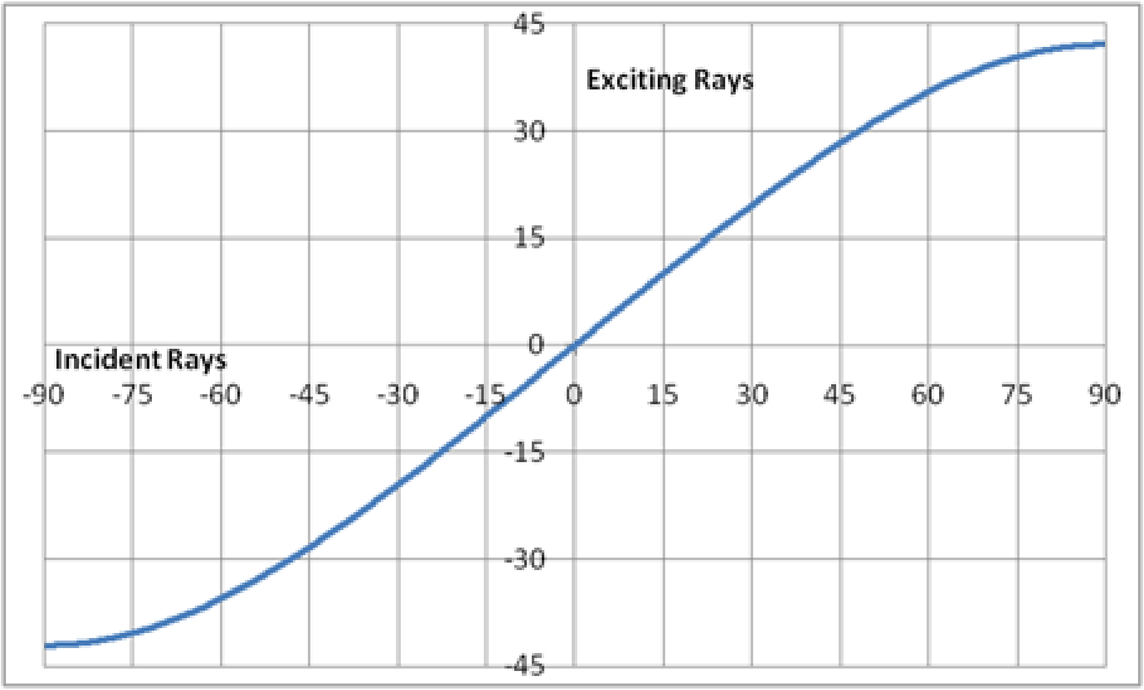


Figure 111: Snell's Law on PMMA - Air Interface

The pattern will be simulated as a shallow cylinder as discussed in the section 3.5.1.2. In Lighttools if the pattern is set as cylinder the software treats it as a half barrel on its side. Therefore, the pattern shape should not be set as cylinder but cone with a taper of 1. Taper is the ratio of the bottom surface to the top one. A cone of taper 1 is a cylinder on its round face. The height of the cone is set as 0.007 mm.

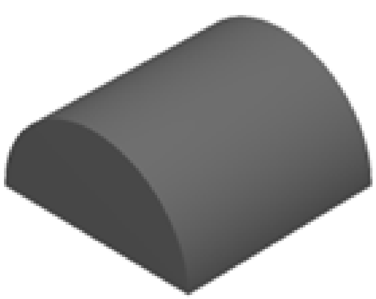


Figure 112: Cylinder Model of Light Tools

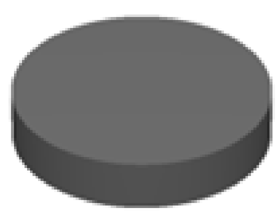


Figure 113: Cone (with Taper =1) Model of Light Tools

The parameters set initially may not be as accurate as expected. To make sure that they are and if not to find out the real parameters a produced panel with a known pattern must be measured and compared to the simulation results.

4.3 Reflector

For the reflector a simple scattering model would be enough. This means that the reflector is modeled as a Lambertian reflector without any specular or Gaussian component.

Since the reflectance of commercially available reflector sheets range from 96% to 98%, the reflectance of the sheet may be set as 95% taking into account the distance between the reflector and the LGP and the losses in between.

4.4 LEDs

Proper modeling the LEDs is as crucial as modeling the LGP . The standard LED intended for back light unit applications has a beam angle of 60° and a spatial light distribution as below.

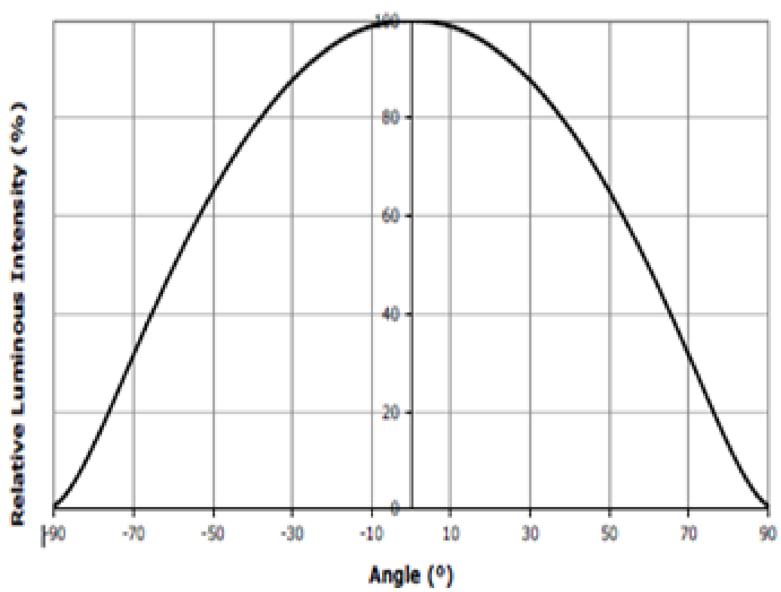


Figure 114: LGIT LED Spatial Distribution [14]

If the LEDs are not separate entities in the design, they should be made so as explained previously. Afterwards, the LEDs will be highlighted and assigned properties. They are set as surface emitters (surface source). After assigning this to the LEDs, the faces that will not emit should be set off. Thus making sure that the only emission will be from the face looking up towards the LGP. Also this emission should be set to go into the aim region of ±90° and not the whole space. Therefore, the angles are chosen as 0 and 90. If this is not set, since the surface cannot emit behind, only a portion of the flux is utilized.

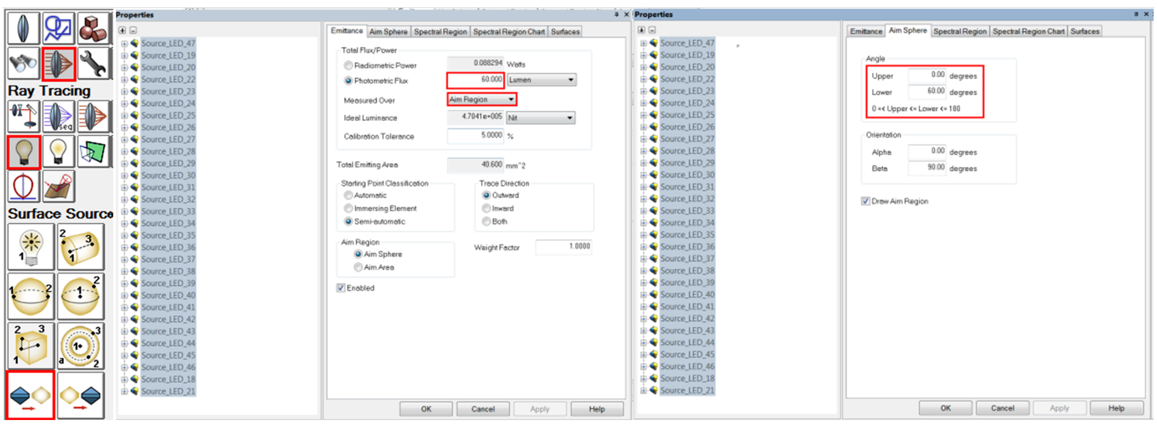


Figure 115: LED Parameterization Steps

4.5 LED Bars

The LED Bars produced for lighting applications are generally covered with a white mask to increase the reflectance of the PCB. The reflectance of these PCBs is measured to be 85%. Although this mask is shiny (specular and/or Gaussian components), since the area is very small and the probability of the light to hit this surface is minimal, it can be modeled as having simple scattering.

4.6 Others

Other components that do not have direct impact on the optical design and/or are auxiliary such as the aluminum bracket that is used for sinking heat may have properties fit for their use e.g., "mechanical absorber".

4.7 Receiver

To have complete simulation, the necessary components are the light source(s), the optical components and the receiver.

In Lighttools, receivers may be added to any surface e.g., the upper face of the LGP. In order to have flexibility and prevent any probable problems, it is better to create a "dummy plane" and assign the receiver to this dummy plane.

The plane must have the same height and width as face of the LGP. The position of this dummy plane must be a little higher (in Z Axis [or in some cases Y Axis]) so that there is no conflict and only the exiting rays are measured. 1 to 5mm distance is adequate. In the case of this study, the top surface of the LGP is at 3.55mm, therefore, the plane may be placed at 5mm.

After assigning a receiver to the plane, the properties of the receiver must be entered. This receiver is a forward simulation receiver. The measurement parameter will be "spatial luminance" as this is what is being measured from a panel when placed in a measurement setup.

The "spatial Lum Meter" is to be set as closely as possible to the real measurement devices. The measurement setup measures the devices from 500mm which is an industry standard in information display sector. The aperture value is the field of view of the measurement device. Larger aperture values correspond to measurement over a larger area. Normally this value is 1° as an industry standard therefore, the aperture of the meter may be set to 1° also. Since having a diffuser and having a greater field angle have similar results, instead of simulating the diffusers, the field angle is set to 30°.

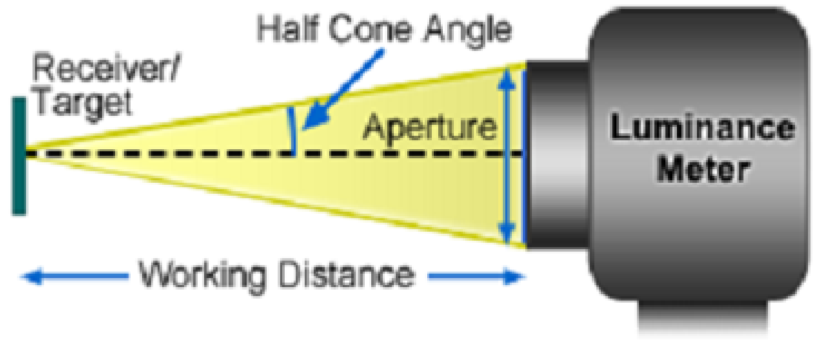


Figure 116: Aperture Angle of the Luminance Meter

The number of rays is a critical parameter in the simulation. If there are too many rays then the simulation will take too long (1-2 days), if there aren't enough then the simulation will not be accurate enough. At the beginning of the simulation, to check that the model is correctly constructed and working as it should, ray numbers such as 100.000-200.000 may be utilized. If the results are consistent, the ray number will be increased. As a good compromise between the accuracy and time 1M rays are used in this work.

The mesh of the receiver defines the points from where the measurements are taken. Normally in the real measurements 19 by 29 measurement points are used (551 points). These 551 points were created as a result of studies conducted on CCFL based back light units. That is the reason of having more point vertically even though the distance is smaller. The same values are taken for bins. Bins are the independent regions of the receiver. If the number of bins is increased the ray number should also be increased to keep the same amount of rays per bins but the results will be closer to reality

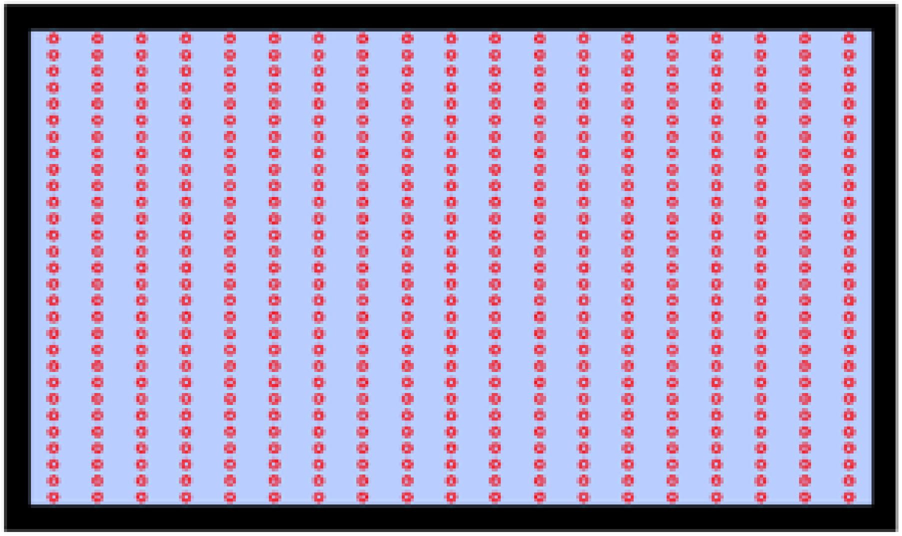


Figure 117: "551 Points Measurement" Measurement Points

CHAPTER V

SIMULATION STUDIES

5.1 First Step

The first pattern is designed according to the curve calculated.

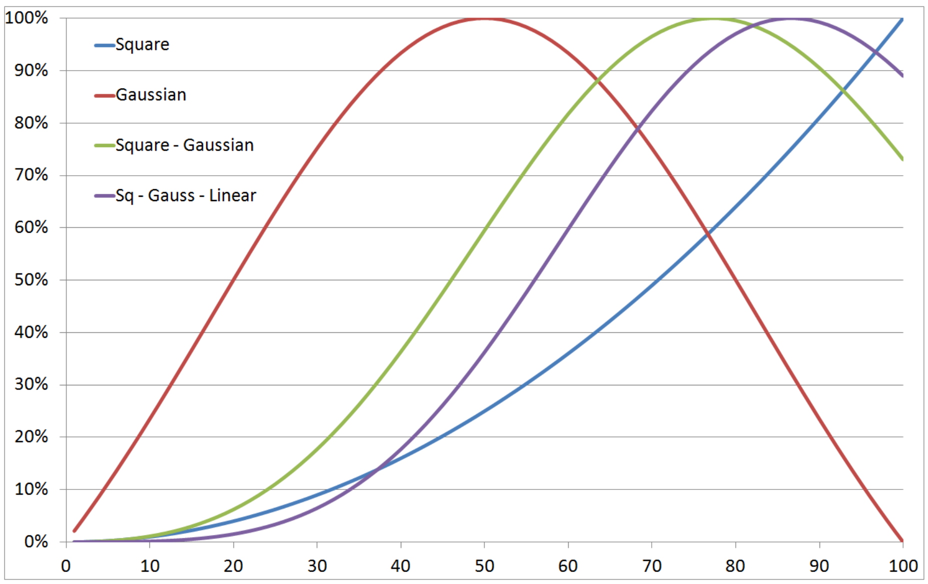


Figure 118: Calculation Curves

There are 423765 dots in this design. The positions of these dots do not change. Their size however is manipulated to extract the necessary amount of light. The minimum dot size is 0.3 mm. This value is the production limit of the supplier.

The pitch of the dots (X Pitch) is 1.52 mm corresponding to the $^1/_6$ of the LED pitch. Therefore, there will be 6 dots in front of each LED.

The maximum diameter of the dots is set as 1.4 mm. The maximum possible size the dots may have is calculated as $\frac{(XPitch)}{(2xCos(DotAngle))}$. The dot Angle is taken as 60°.

Therefore, the maximum possible dot size is equal to dot pitch. To prevent the dots from overlapping, it is better to set the maximum diameter as at least 0.1mm smaller than this value (1.52). As the result, to keep the calculations simple, the maximum diameter is chosen as 1.4 mm.

The dimensions of the active area of a 39” TV are 863.38 mm x 485.65mm. The back light units’ light emitting area should be larger than the active area of the LC cell and the LGP size is even bigger than the back light unit’s emission area. The pattern area of the LGP is 863.53 mm x 489.44 mm. These values are automatically calculated by the design tool. The dimensions of the LGP itself are 865 mm x 491 mm.

The parameters used to design the pattern are as follows:

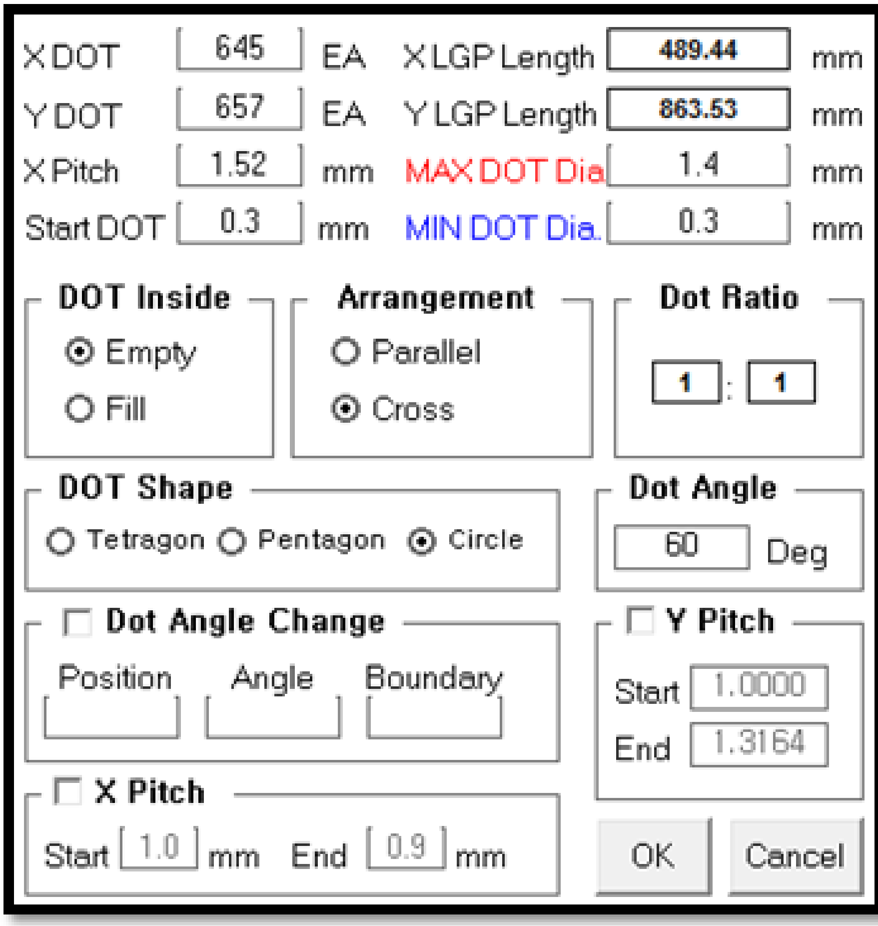


Figure 119: Dot Design Start Values

The first dot distribution was chosen as closely as possible to the curve calculated. The results are shown in the figure 120. The curve to the right is the cross section of the dot size distribution. An orange area means the dots in this region are of the biggest possible size and where there is black area the size of the dots is zero. Although the min seems to be zero, the software doesn't allow the dot size go below the preset "min dot dia" value. The minimum possible size is shown with purple. The horizontal and vertical value slices may also be examined to ensure the correct distribution is reached.

The vertical distribution plays the critical role on the management of the light. But the horizontal distribution should also be carefully designed to accommodate for the boundaries where the light density is not as high as the middle.

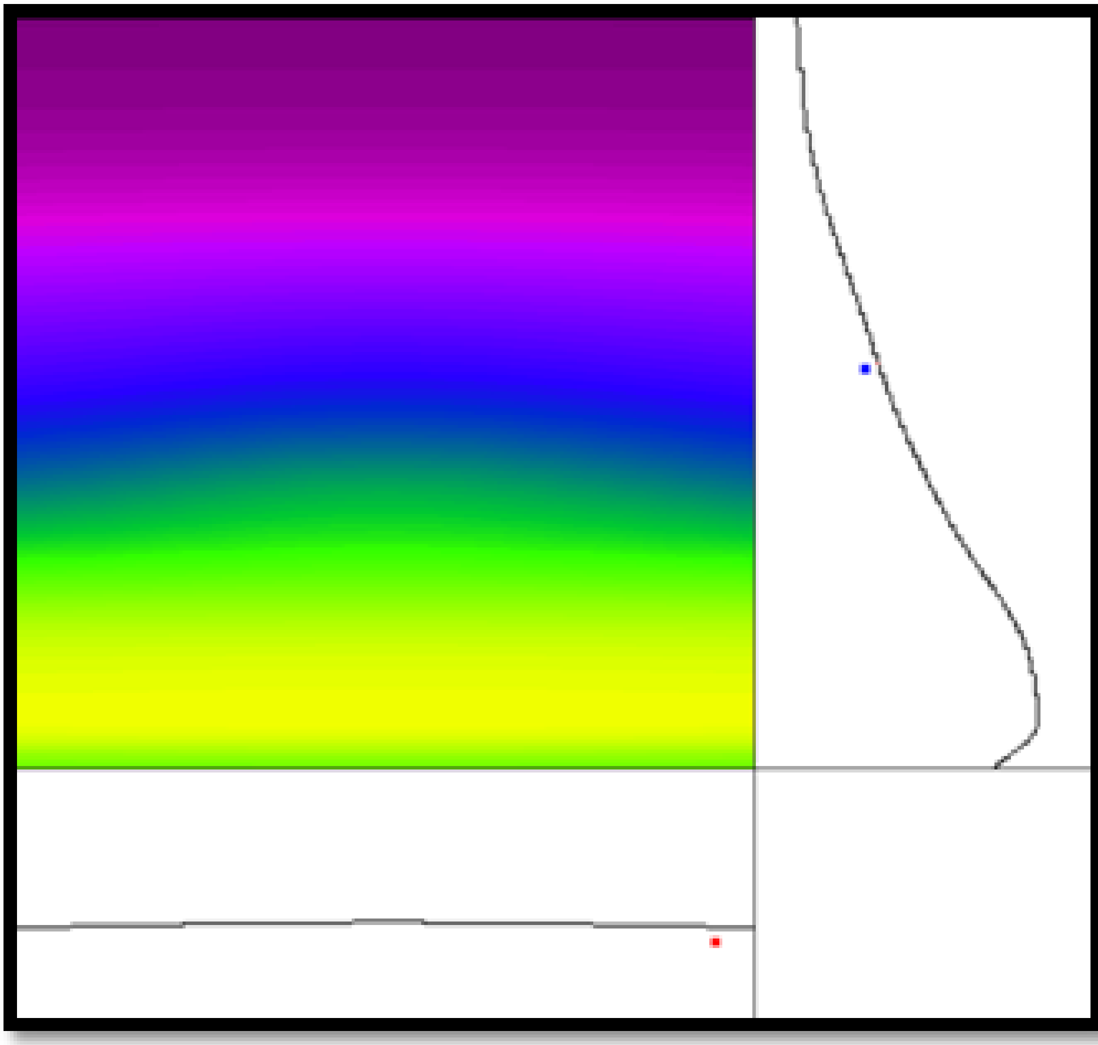
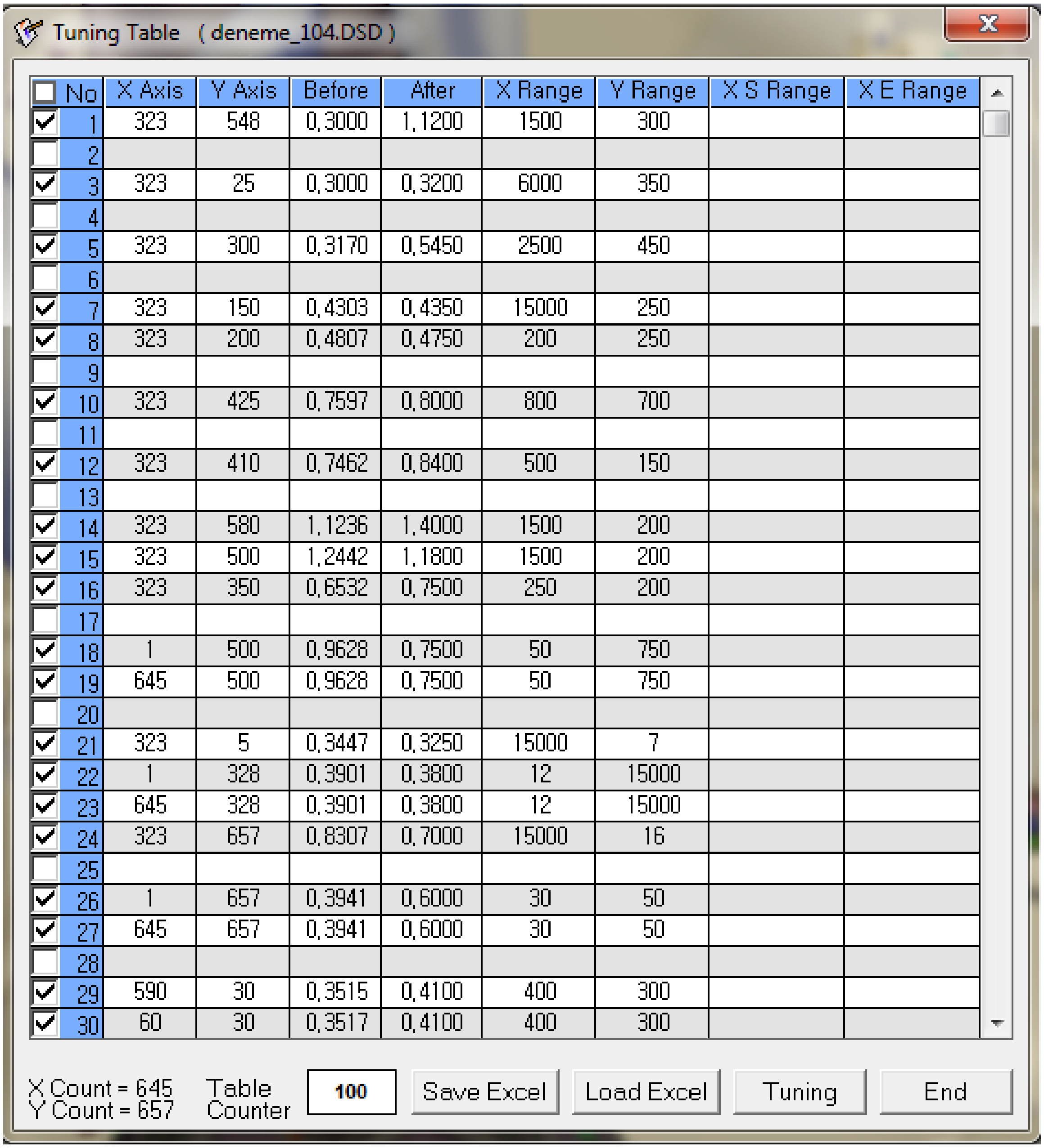


Figure 120: Distribution of the Dots and Horizontal and Vertical Cross Sections with the LEDs on top

To obtain this distribution, the table below (figure 121) was created and was fed to the software. Here, in this table the position and the size of the dots were entered along with the range of this modification. The software uses a Gaussian distribution.

A point placed in the middle of the panel with the biggest value possible will create a Gaussian distribution with the vertical and horizontal reach defined by the "X Range" and "Y Range" parameters. There is not only one way to obtain the desired distribution. This is a trial error process. With experience, the time to obtain desired outputs decreases.



No	X Axis	Y Axis	Before	After	X Range	Y Range	X S Range	X E Range
1	323	548	0,3000	1,1200	1500	300		
2								
3	323	25	0,3000	0,3200	6000	350		
4								
5	323	300	0,3170	0,5450	2500	450		
6								
7	323	150	0,4303	0,4350	15000	250		
8	323	200	0,4807	0,4750	200	250		
9								
10	323	425	0,7597	0,8000	800	700		
11								
12	323	410	0,7462	0,8400	500	150		
13								
14	323	580	1,1236	1,4000	1500	200		
15	323	500	1,2442	1,1800	1500	200		
16	323	350	0,6532	0,7500	250	200		
17								
18	1	500	0,9628	0,7500	50	750		
19	645	500	0,9628	0,7500	50	750		
20								
21	323	5	0,3447	0,3250	15000	7		
22	1	328	0,3901	0,3800	12	15000		
23	645	328	0,3901	0,3800	12	15000		
24	323	657	0,8307	0,7000	15000	16		
25								
26	1	657	0,3941	0,6000	30	50		
27	645	657	0,3941	0,6000	30	50		
28								
29	590	30	0,3515	0,4100	400	300		
30	60	30	0,3517	0,4100	400	300		

Figure 121: 1^{st} Step's Tuning Table

The Lighttools simulation result of this pattern with 1M rays is as follows:

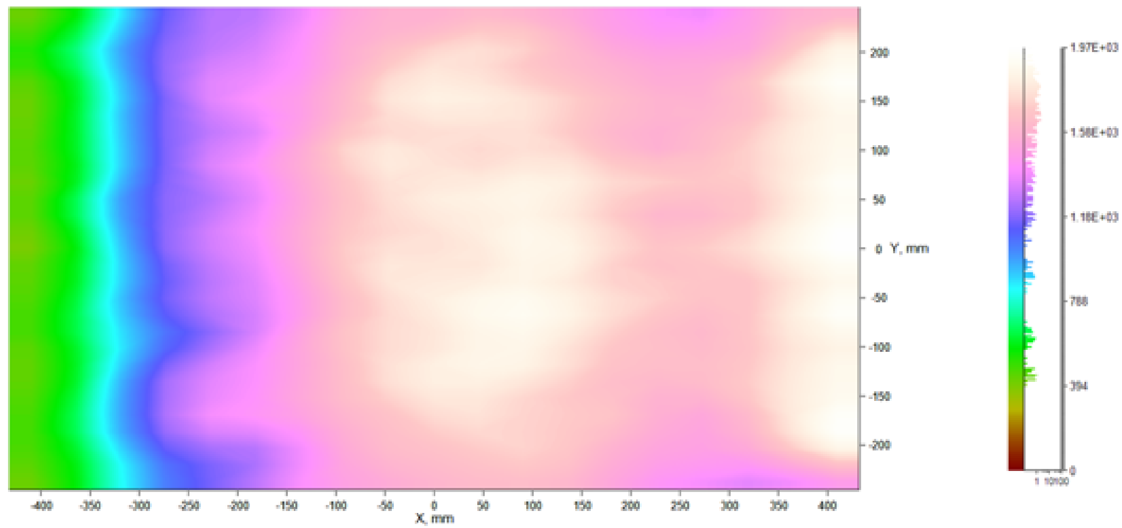


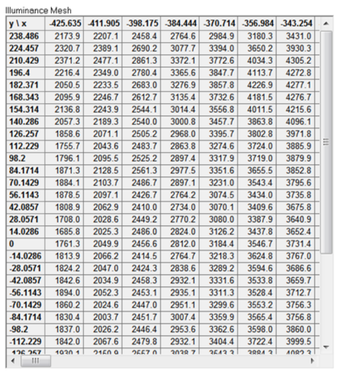
Figure 122: 1^{st} Step's Simulation Result

The result of this simulation showed that the far side of the LGP wasn't very well designed. Regardless, this design was sent to the supplier and the resulting panel was measured. Not only the far side wasn't very well designed, the dot optical parameters weren't properly chosen, as the resulting real image was very similar up until the middle but the simulated far side pattern did not match the measurements.

At this first design it was foreseen that the pattern parameters may not have been 100% accurate. The first step should have been to create a design, produce it and compare results. Comparing the simulation to the production of a design with light concentrated somewhere on the panel could have yielded false results. This is why care was taken to design a uniform pattern with these starting parameters.

The next step then is to compare the measurements taken from the panel with the bins' value taken from the simulation and optimize the dot's optical parameters.

The values of the measurement were entered into the mesh values tab and this table was set as the "Merit Function". This means the results of the simulation should meet these values by changing the optimization parameters. The optimization parameters will be set as the pattern's optical properties. And the resulting properties are as follows:


Illuminance Mesh

y \ x	-425.635	-411.905	-398.175	-384.444	-370.714	-356.984	-343.254
238.486	2173.9	2207.1	2458.4	2764.6	2984.9	3180.3	3431.0
224.457	2320.7	2389.1	2690.2	3077.7	3394.0	3650.2	3930.3
210.429	2371.2	2477.1	2861.3	3372.1	3772.6	4034.3	4305.2
196.4	2216.4	2349.0	2780.4	3365.6	3847.7	4113.7	4272.8
182.371	2050.5	2233.5	2683.0	3276.9	3857.8	4226.9	4277.1
168.343	2095.9	2246.7	2612.7	3135.4	3732.6	4181.5	4276.7
154.314	2136.8	2243.9	2544.1	3014.4	3556.8	4011.5	4215.6
140.286	2057.3	2189.3	2540.0	3000.8	3457.7	3863.8	4096.1
126.257	1858.6	2071.1	2505.2	2968.0	3395.7	3802.8	3971.8
112.229	1755.7	2043.6	2483.7	2863.8	3274.6	3724.0	3885.9
98.2	1796.1	2095.5	2525.2	2897.4	3317.9	3719.0	3879.9
84.1714	1871.3	2128.5	2561.3	2977.5	3351.6	3655.5	3852.8
70.1429	1884.1	2103.7	2486.7	2897.1	3231.0	3543.4	3795.6
56.1143	1878.5	2097.1	2426.7	2764.2	3074.5	3434.0	3735.8
42.0857	1808.9	2062.9	2410.0	2734.0	3070.1	3409.6	3675.8
28.0571	1708.0	2028.6	2449.2	2770.2	3080.0	3387.9	3640.9
14.0286	1685.8	2025.3	2486.0	2824.0	3126.2	3437.8	3652.4
0	1761.3	2049.9	2456.6	2812.0	3184.4	3546.7	3731.4
-14.0286	1813.9	2066.2	2414.5	2764.7	3218.3	3624.8	3767.0
-28.0571	1824.2	2047.0	2424.3	2838.6	3289.2	3594.6	3686.6
-42.0857	1842.6	2034.9	2458.3	2932.1	3331.6	3533.8	3659.7
-56.1143	1894.0	2052.3	2453.1	2935.1	3311.3	3528.4	3712.7
-70.1429	1860.2	2024.6	2447.0	2951.1	3299.6	3553.2	3756.3
-84.1714	1830.4	2003.7	2451.7	3007.4	3359.9	3565.4	3756.8
-98.2	1837.0	2026.2	2446.4	2953.6	3362.6	3598.0	3860.0
-112.229	1842.0	2067.6	2479.8	2932.1	3404.4	3722.4	3999.5

Figure 123: Mesh Results

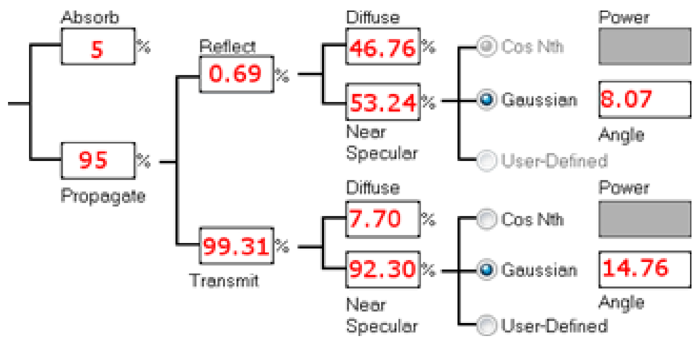


Figure 124: Complete Scattering Model

For all simulation from this point on, these values are utilized.

5.2 Second Step

In the second step, after using the first step to compare the optical parameters to the real measurements and optimizing these parameters, a new, more uniform and brighter panel is designed.

In addition to general distribution, 9 measurement points were enhanced to a level that would increase the measurement values but would not be perceivable by the end user.

This is called the 9 points study. It was achieved by increasing the dot size at the 9 measurement points' vicinity. Figure 125, figure 126 and figure 127 represent the panel without the study, with the study as it should be and an exaggerated study that would be noticeable by the end user.

Figure 125: Without 9 Pts Study

Figure 126: Subtle 9 Pts Study

Figure 127: Excessive 9 Pts Study

The simulation results are shown below. To be able to do that, the size of the dots closer to the LEDs were shrunk. Also the dots at the sides were shrunk in order to take into account the reflectors on the sides that might cause light leakage. To compensate for the extra light loss (extraction) from the center, the dots on the far side were enlarged.

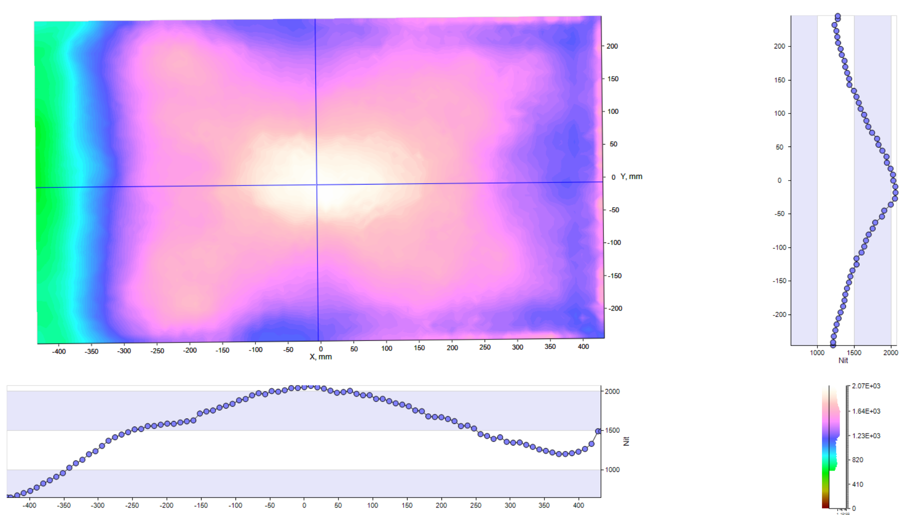


Figure 128: Simulation result of the 2^{nd} Step

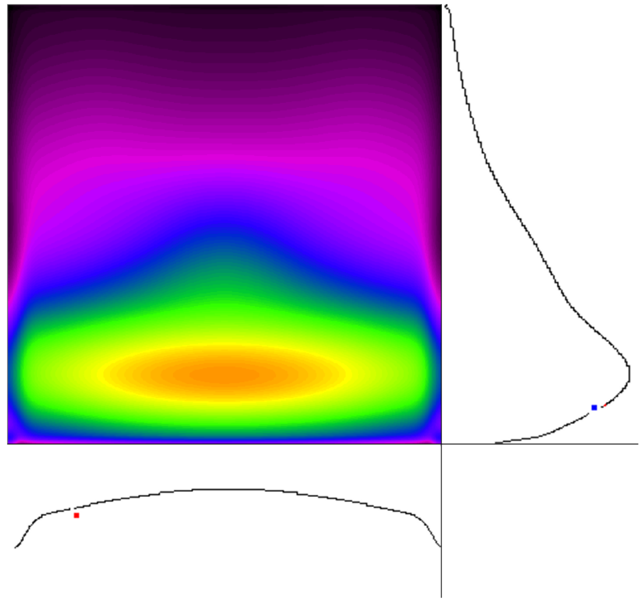


Figure 129: Distribution of the Dots and Horizontal and Vertical Cross Sections with the LEDs on top

5.3 Third Step

The third step is amelioration upon the 2^{nd} pattern. It was intended to be more uniform and pleasant to the end-user. The top and bottom mid parts increased and the very middle part decreased. The light leakage problem was alleviated by erasing extra lines (2 lines) from the top and bottom of the pattern and the remaining border dots were shrunk to the point that they do cause neither leakage nor darkness. The area between the middle of the panel and the LEDs was increased a little to increase the brightness of this area but not to effect the middle. The middle was decreased to let more energy to the far side. The 9 point study points on the far side are moved away from the LEDs as they previously didn't coincide with the measurement points. The area close to the connectors was increased to compensate for the LEDs being replaced by the connectors.

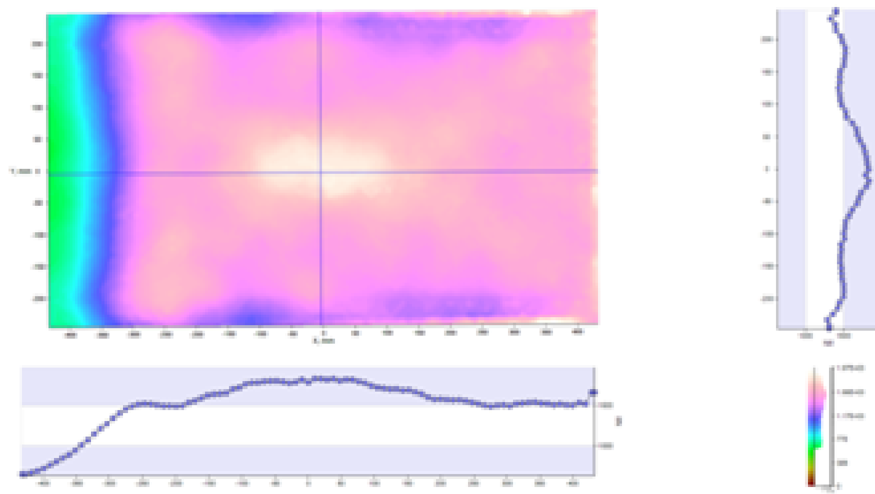


Figure 130: Simulation result of the 3^{rd} Step

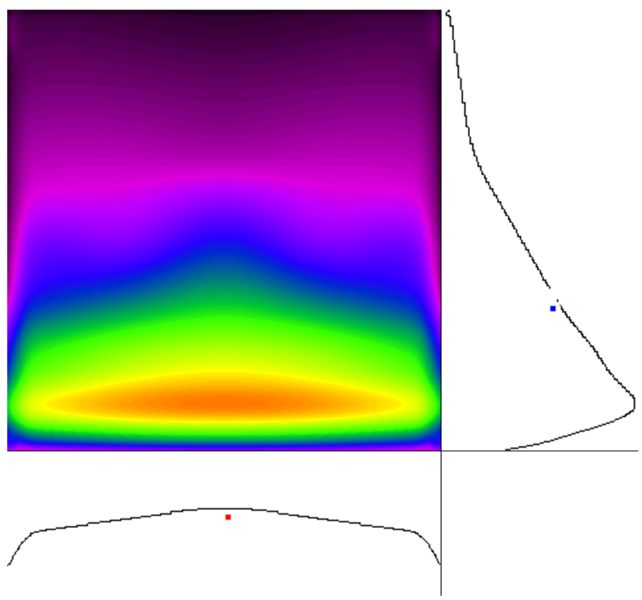


Figure 131: Distribution of the Dots and Horizontal and Vertical Cross Sections with the LEDs on top

5.4 *Final Step*

The dark parts closer to connectors was ameliorated by the study on the 3rd step but required further modification therefore, these points were further enlarged. The light leakage wasn't resolved with pattern modification thus 2 more lines were deleted. This action did not reflect on the pattern as the dots remain in simulation but by preventing loss of light (leakage) the rest become brighter. To minimize the dark strip on the far side, this part's dots were enlarged to the limit and the enlarged area was also increased. The dots between the LEDs and the middle were enhanced to brighten up this part. The deviation between the middle of the screen and the top and bottom parts was smoothened.

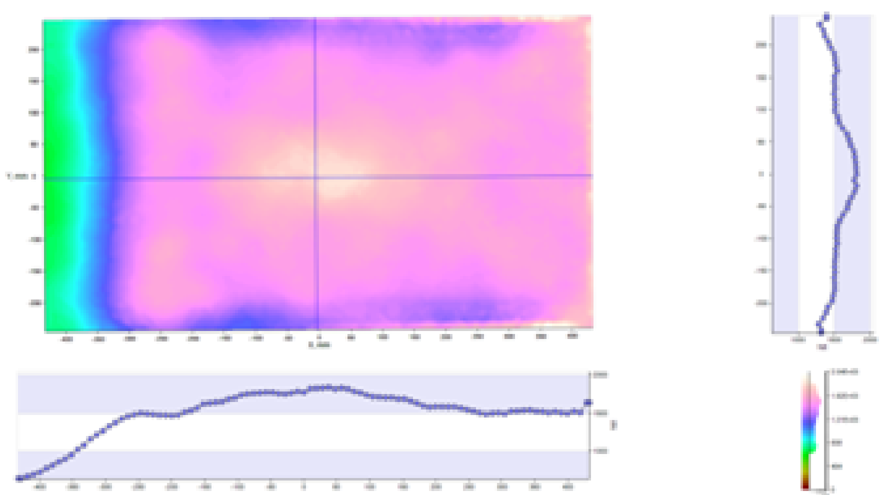


Figure 132: Simulation result of the 4^{th} Step

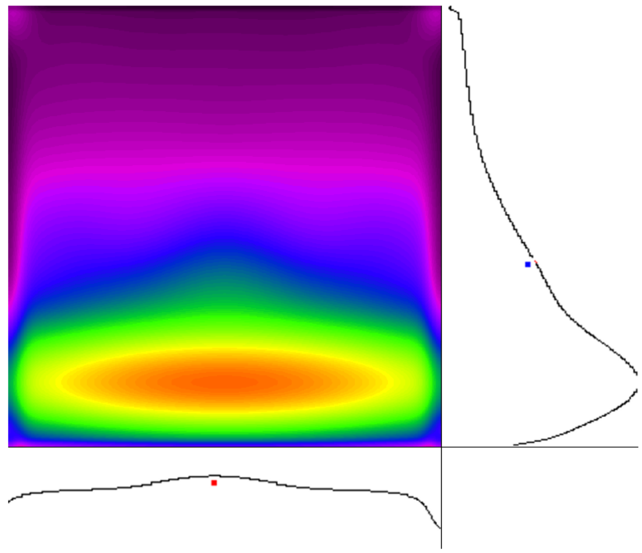


Figure 133: Distribution of the Dots and Horizontal and Vertical Cross Sections with the LEDs on top

CHAPTER VI

RESULTS & DISCUSSIONS

6.1 First Step

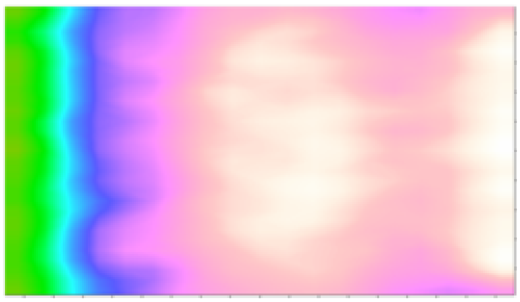


Figure 134: Simulation Results of the 1^{st} Step

Figure 135: Photo of the Panel Assembled with the 1^{st} Step LGP

This step was an initial step to understand the relation between the simulation and the reality. Although the parameters of the dot pattern were not yet optimized, the results' similarity to the simulation is remarkable.

The measurement results are taken via SR3A and are as follows:

Point								
01	02	03	04	05	06	07	08	09
Values								
155	192	167	135	221	198	154	200	210

Max	Min	Avg.	Unif
221	135	181	61.09%

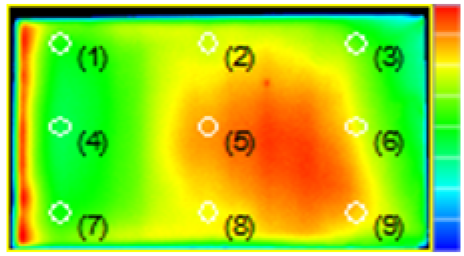


Figure 136: Resulting Light Distribution Measured with CA2000

The uniformity was far below the target and so is the central brightness. The reason that the results were so far off the target was because of the leakages i.e., loss of light. Figure 136 is the measurement of the panel with red the brightest and blue is the dimmest part.

6.2 *Second Step*

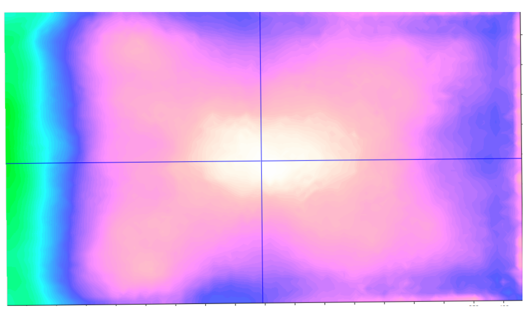


Figure 137: Simulation Results of the 2^{nd} Step

Figure 138: Photo of the Panel Assembled with the 2^{nd} Step LGP

Trying to increase the brightness of the 9 measurement points, the middle point (pts 5) was too much increased. Therefore, the top and bottom mid parts are too dark. Similarly, decrease in size of the part between middle and LEDs, this part was also too dark. As the center was too exaggerated, the uniformity became very low. Increase in the size of the mid part resulted in too much light extracted there and as a result the far side was too dark, no matter how big the dots were set. The darkness just before the LEDs increased the contrast and made the light leakage from this part much more visible. The 9 point study missed the measurement point. It is not far enough. The measurement results are as below.

The measurement results are taken via SR-3A and are as follows:

Point								
01	02	03	04	05	06	07	08	09
Values								
214	207	191	206	299	199	221	205	203

Max	Min	Avg.	Unif
299	191	216	63.88%

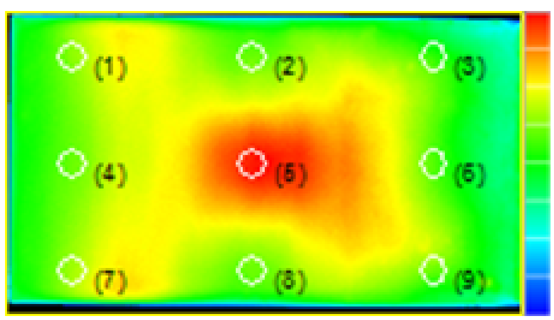


Figure 139: Resulting Light Distribution Measured with CA2000

The uniformity is still below the target but the central brightness is closer to the target. Still there are leakages resulting in the non optimal results. Figure 139 is the measurement of the panel with red the brightest and blue is the dimmest part.

6.3 Third Step

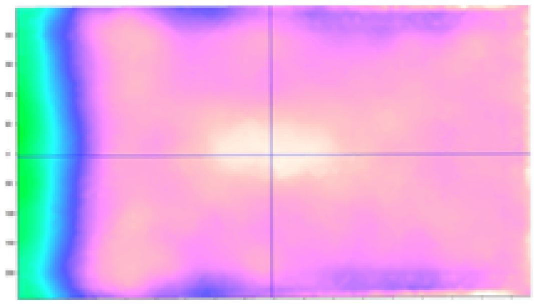


Figure 140: Simulation Results of the 3^{rd} Step

Figure 141: Results of the 3^{rd} Step LGP

The area closer to the connector was increased to see the effect. There is improvement but the improvement in the uniformity was not enough. Same is valid for the light leakages. The 9 point study is still visible though there is improvement. The measurement points and the 9 point studies now overlap. The uniformity was closer to the requirements and the central brightness reached the target.

The measurement results are taken via SR-3A and are as follows:

Point								
01	02	03	04	05	06	07	08	09
Values								
241	254	242	225	305	282	251	267	256

Max	Min	Avg.	Unif
305	225	258	73.77%

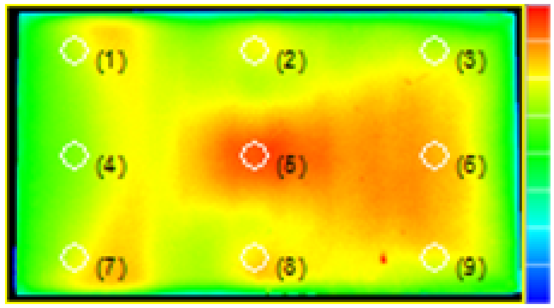


Figure 142: Resulting Light Distribution Measured with CA2000

6.4 Final Step

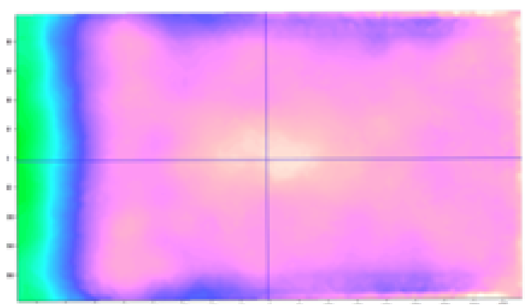


Figure 143: Final Step Simulation

Figure 144: Results of the Final Step

As the result of the connector area study, the brightness of this part was increased to the point which is no longer noticeable. The erased lines solved the light leakage problem. The transition between the measurement points and the rest wasn't noticeable anymore. The targets for the brightness of 300 nits and uniformity of 75% were met and visually the panel was free from any problems.

For all intents and purposes the result of this design was within the specified targets.

Point								
01	02	03	04	05	06	07	08	09
Values								
278	286	264	269	333	288	302	294	277

Max	Min	Avg.	Unif
333	264	288	79.28%

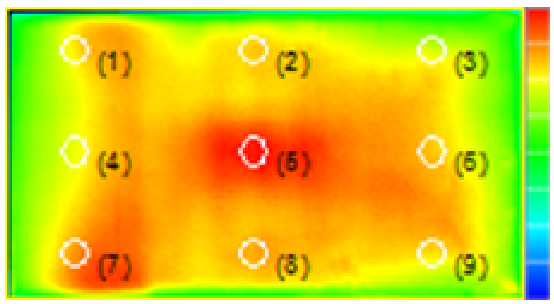


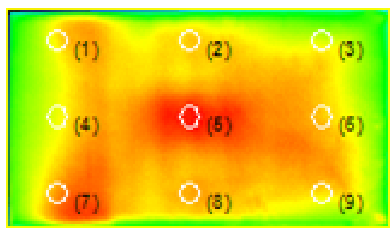
Figure 145: Final Light Distribution

As this was the final pattern and was a candidate for approval, multiple samples were needed for evaluation. Three sample panels were evaluated and the results of all three panels were all within required specification(>300nits, 75% uniformity). The results are as follows:

Sample 01

Point								
01	02	03	04	05	06	07	08	09
Values								
278	286	264	269	333	288	302	294	277

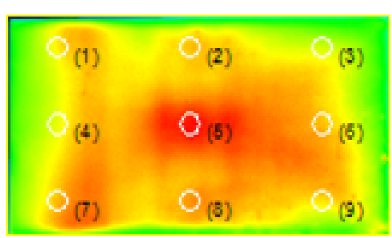
Max	Min	Avg.	Unif
333	264	288	79.28%



Sample 02

Point								
01	02	03	04	05	06	07	08	09
Values								
267	278	253	260	322	280	282	289	268

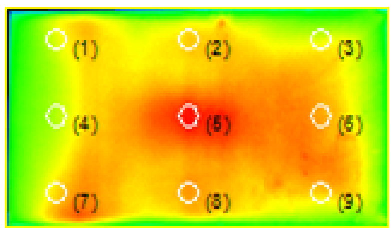
Max	Min	Avg.	Unif
322	253	278	78.57%



Sample 03

Point								
01	02	03	04	05	06	07	08	09
Values								
269	290	272	259	338	301	289	302	287

Max	Min	Avg.	Unif
338	259	290	76.63%



CHAPTER VII

CONCLUSION

As the penetration of the LCD TVs increases in the market, the market becomes more and more competitive and it is getting harder to obtain an edge to compete with the others. To be able to have a good share in the market and to meet the demand, one also has to be able to produce fast, cheap, efficient and good quality products. As a result, the design of the products can no longer be empirical but the capability to simulate and design the panels in virtual environment thus having flexibility and faster design capabilities in house must be acquired.

The most critical component in an edge type LED LCD TV is the LGP and the ability to design the LGP is crucial. That was the motivation behind this work. This work was started from scratch and the resulting point is a very good one, not only meeting the measureable values such as the brightness but also displaying a pleasant general view.

The studies made on the subject of LGP dot pattern design are most often tackle small sizes such as 2", 7", etc... The fact that this work was done on a panel of considerable size (39") and the LEDs were on the vertical side along with the power consumption and optical stack requirement (without DBEF) made it one of the most difficult studies on the matter.

In summary, in this study an LGP panel that performs to the specs was developed. In addition, a new process of LGP design method was also demonstrated. The new process flow requires involment of various engineering groups during the design phase.

Both mechanical and optical aspects of the design were developed in parallel. As a result of this approach, both mechanical and optical design was finished at the same time. Therefore, at the end of the engineering phase, an LGP design that can be transferred to production quickly was completed.

If in the future this design proves to be over the specs, further studies to decrease the cost of the optical film structure and/or lowering the current to have a better, i.e., lower, power consumption thus obtaining better classes such as A^{++} may be conducted.

CHAPTER VIII

APPENDIX

8.1 *Specs of the Instruments Used*

These Specs are taken from the supplier websites [54, 55].

8.1.1 SR-3AR

Photo detector	Electronically cooled linear CCD
Dispersing element	Diffraction grating
Measurement angle	2°/1°/0.2°/0.1°selectable (Motor moved)
Minimum measurement area	2°: 10.0, 1°: 4.99 0.2°: 1.00 0.1°: 0.50 (mm)
Measurement distance	350mm - (distance from metallic tip of objective lens)
Spectral bandwidth	5 - 8nm *Half bandwidth
Wavelength accuracy	0.3nm *Hg emission lamp
Wavelength range	380 - 780nm
Wavelength resolution	1nm
Measurement mode	Auto/Manual (integral time/frequency) / External vertical sync signal input
Measurement object	Spectral radiance : $W.sr^{-1}m^{-2}.nm^{-1}$

Calculation function	Radiance Le : $W.sr^{-1}m^{-2}$, Luminance Lv : $cd.m^{-2}$, CIE1931 chromaticity coordinates xy, CIE1976 chromaticity coordinates u' v', Tristimulus value XYZ, Correlated color temperature and Deviation, CIE standard observer 2°/ 10°
Range of guaranteed illuminance accuracy	2°: 0.1 - 3,000 1°: 0.3 - 9,000 0.2°: 7.5 - 70,000 0.1°: 30 - 300,000
Accuracy in luminance	±2% or less
Accuracy in chromaticity(x,y)	±0.002
Repeatability in luminance	0.3% (0.1cd/m^2 or more)
Repeatability in chromaticity	0.0005 (0.1cd/m^2 or more)
Polarization error	Luminance1% or less,Spectral radiance2% or less (400 - 780nm)
Measurement time	NORMAL Mode: about 1 - 31sec, HIGH SPEED Mode: about 1 - 17sec
Interface	USB2.0 / RS-232C selectable
Power supply	Dedicated AC adapter AC100V-240V, 50/60Hz, DC12V 36W
Power consumption	about 34W
Use conditions	Temperature: 5 - 35°C, Humidity: 80%RH or less (no condensation)
Outer dimensions (WDH)	150x406x239mm
Weight	5.5kg

Measurement area (Diameter ϕ)					
Measurement Angle	Measurement distance(*1)				
	350mm	500mm	800mm	1000mm	2000mm
2°	10	15.1	25.4	32.2	66.4
1°	4.99	7.55	12.7	16.1	33.2
0.2°	1	1.51	2.54	3.22	6.64
0.1°	0.5	0.76	1.27	1.61	3.32

8.1.2 CA 2000

Lens	Standard lens	Wide lens	Telephoto lens*
Light receptor	2/3-inch CCD image sensor (monochrome); Effective number of pixels: 1000×1000 (Measurement points: 980×980); Equipped with XYZ filter (closely matches CIE 1931 color-matching functions) and ND filter		
Typical measurement sizes/distances (Approx. length per side of square/distance)			
Measurement luminance range (including when ND filter is used)	0.1 to 100,000cd/m^2		
Size – **Body only**	160 (W)×64 (H)×199 (D) mm (Height including handle: 211mm)		
Size – **With lens/lens hood attached**			
Weight	Approx. 3.5kg (when Standard lens and lens hood are attached)		
Power source	Included AC adapter: 100 to 240V AC, 50/60Hz		

[54]

8.2 Pattern Creation & SWs Utilization

8.2.1 DS Design Tool

8.2.1.1 New Project

First step in order to create a new file is to press "NEW" from the opening screen (Figure 146) of "DS Pattern Design Tool" which will open the next screen (Figure

147)

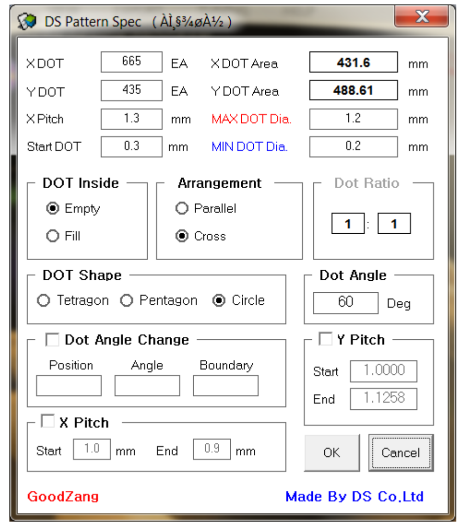


Figure 146: Opening Screen

Figure 147: New Project

In this screen the initial values for the design are defined e.g., the distance between dots (XPitch), smallest dot size, biggest dot size etc...

XPitch

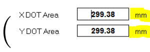
This is the distance between the dots in the X axis and this number must be a divisor of the LED Pitch value e.g., if Led pitch is 7.8 XPitch may be 1.3 ($\frac{7.8}{1.3} = 6$). Otherwise the amount of dots in front of each LED will not be the same causing problems such as "hot spot".

- By experience the value of dot pitch should be between 1.3 and 1.6.
- At the beginning of each project, the LED pitch and the distance between strings must be appropriately chosen and the LED supplier along with the mechanical group shall be informed. Otherwise the distances chosen might cause problems.

Dot Angle

This is the angle between the dots of the two consecutive lines. Generally for big size TVs this value is 60° and 30° or 60° for small sizes

XDOT, YDOT, XDOT Area and YDOT Area

After XPitch and Dot Angle are correctly defined, the dimensions of the LGP is entered (XDOT Area & YDOT Area) and the "mm" is clicked (

) leading to the program calculating XDOT and YDOT.

If the LGP is symmetrical then it is possible to design the half (or quarter) of it and duplicating later. For example, if the panel is lit from top or bottom, only the left (or right) part would be designed.

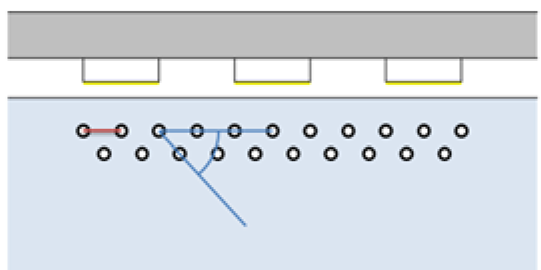


Figure 148: LEDs, XPitch and Dot Angle

Max Dot Dia

This is the biggest diameter value a dot may have. It should be at least 1 mm smaller than $\frac{XPitch}{2\ x\ Cos(DotAngle)}$ (Figure 149).

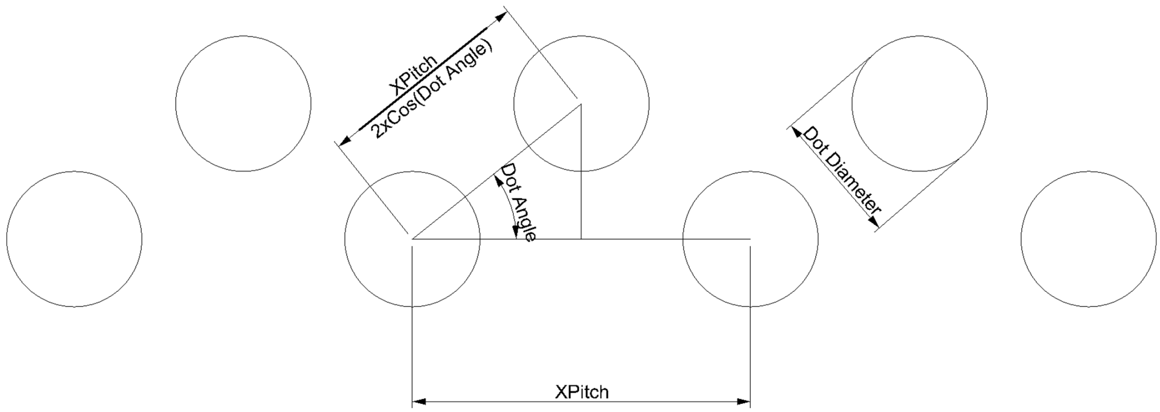


Figure 149: XPitch, Dot Angle, Dot Diameter and Max Dot Diameter

Min Dot Dia

This is the minimum dot diameter allowed at any point. Even if a smaller value is entered in "tuning table" it will be replaced by this value.

Start Dot

At the beginning, if no input has been made to "tuning table" all the dots will have this size.

Dot Inside

This is to indicate whether the dots are filled or empty. By default this value should be kept "Empty".

Arrangement

This is the arrangement of the dots. It should be "Cross". If it is set to be "parallel" the cell pattern will cause an effect called Moiré.

DOT Ratio

This is the width-to-height ratio of the dots' size (Figures 150, 151 and 152).

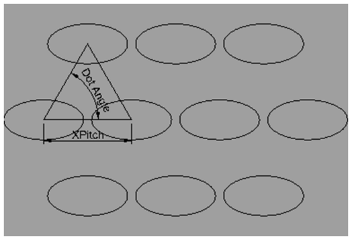


Figure 150: 2:1 Dot Ratio

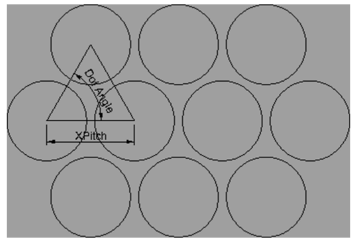


Figure 151: 1:1 Dot Ratio

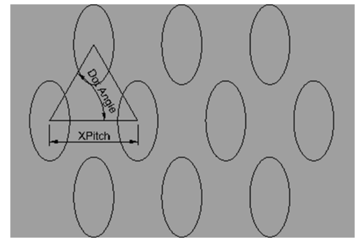


Figure 152: 1:2 Dot Ratio

Dot Shape

This is the shape of the dots. The most common shape is "circle".

8.2.1.2 Design Steps

When all the parameters for a new project are set, "OK" is pressed and the "Curve" interface is called (Figure 153). Pressing the "Table" button calls the "Tuning Table" interface (Figure 154).

Curve interface is where the distribution of the dot diameter size is visualized. Tuning Table is where these values (sizes and positions) are entered. The color scale on the left of the table is the color coding of the different sizes. 100% corresponds to the Max Dot Size

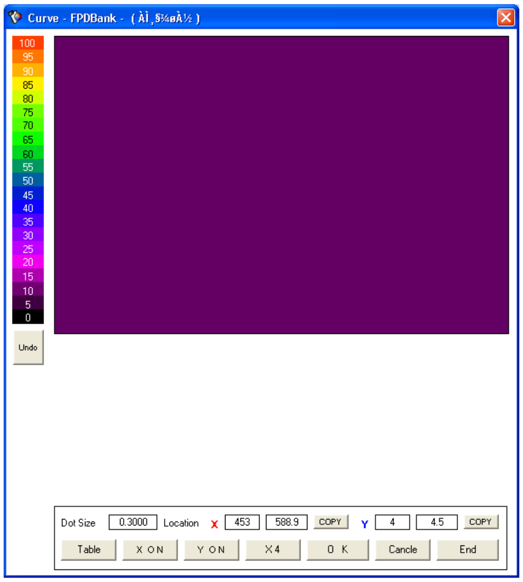


Figure 153: Curve

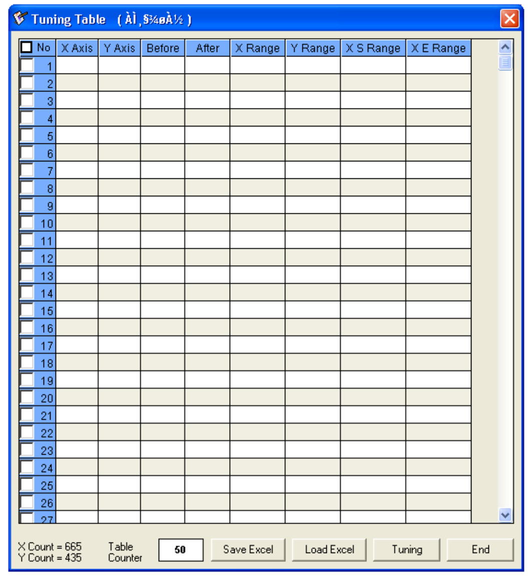


Figure 154: Tuning Table

Curve Interface

Table	:	Calls the Tuning Table interface.
X ON	:	Horizontal cross section of the dot size distribution.
Y ON	:	Vertical cross section of the dot size distribution.
X 4	:	Quadruples the visible Dot Map.
		The visible part is the top left corner (Figure 155).

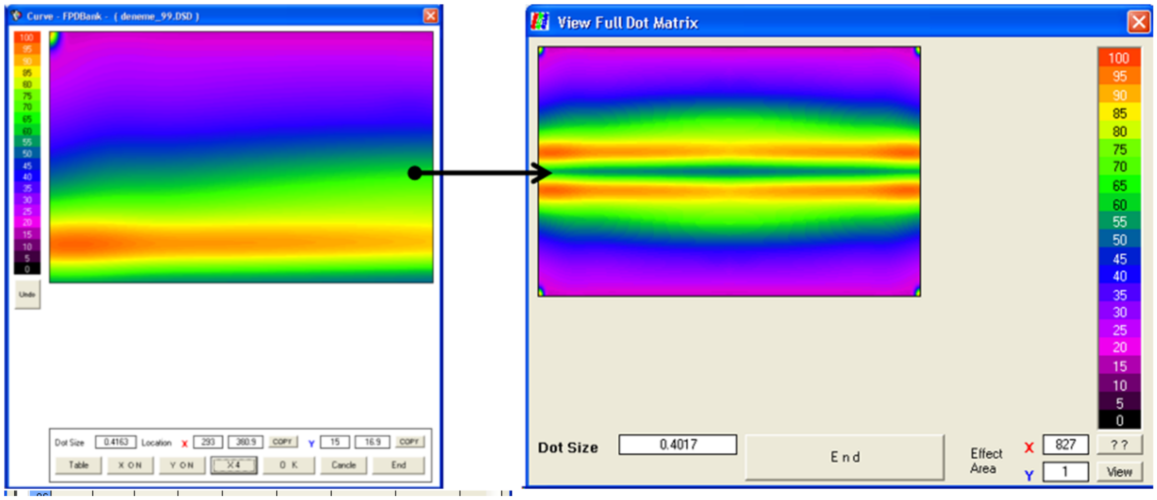


Figure 155: X4

No : Row number. Facilitates exporting to excel, editing etc...

X Axis : The position of the dot to be modified from left.

Y Axis : The position of the dot to be modified from top.

Before : The dot size prior to tuning. This value is automatically updated.

After : The dot size post tuning

X Range : The reach of the modification in the horizontal.

Y Range : The reach of the modification in the vertical.

X S Range : Start range for triangular tuning areas

X E Range : End range for triangular tuning areas

Table Interface

"Save Excel" command allows the table to be exported into excel. But the file shall be manually saved. It is possible to modify a file saved this way and import back with the "Load Excel" command. The excel file should have the extension .xls (Office 2003 or prior) not .xlsx.

Target Distribution

The dots size should increase as the distance from LEDs increase but the reflections from the reflector at the end of the LGP must be taken into account and the dot size should decrease (Figure 8.2.1.2).

Also, the end of LED Bars and the connectors at the end may cause shadows. The dots at the corners must be bigger.

If at the end of the design, the panel exhibits "hot spot", special pattern must be created for the shadows in these areas.

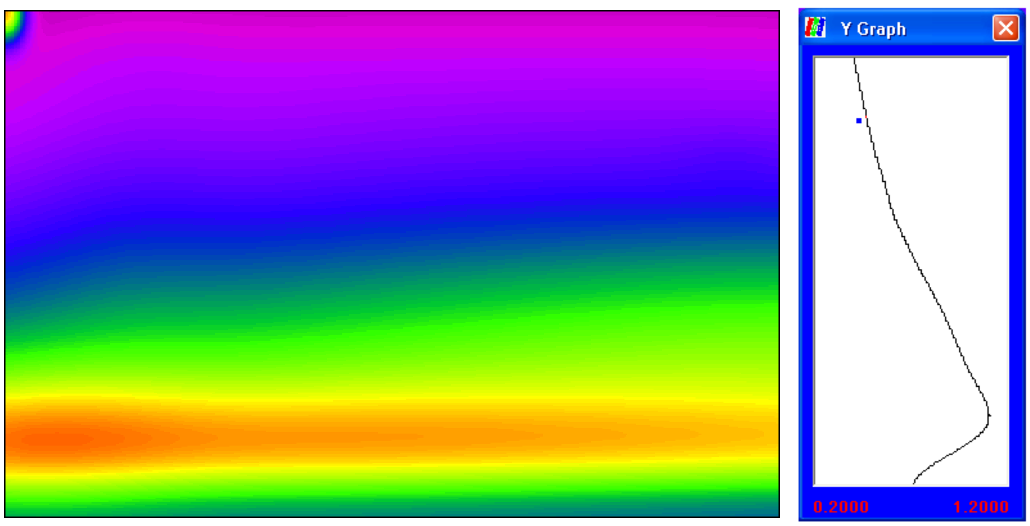


Figure 156: General and Vertical Distribution

Saving the Data

The end project must be saved both as .DSD and .DSC files. The .DSD file may be opened with DS Tools later. The .DSC file will be used to export the data into AutoCAD.

Turning Saved Data into Pattern

In order to load the pattern into ACAD, the ACAD application developed shall be used. The command "Pattern" will open the prompt window where the .DSC file will be chosen. If the pattern is not the entire pattern but a part of it, all the point are chosen and the command "mirror" is used to duplicate (or quadruplicate).

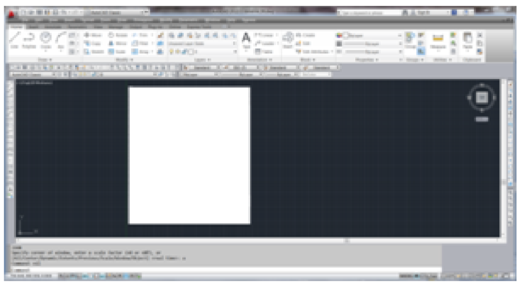


Figure 157: After import into ACAD

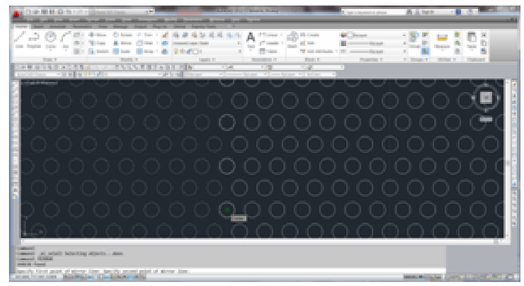


Figure 158: Mirroring

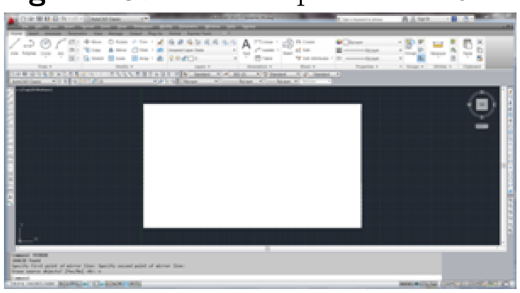


Figure 159: Pattern after Mirroring

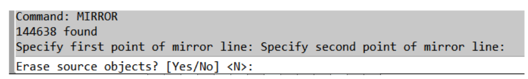


Figure 160: Prompt to Erase the Original Data

DATAEXTRACTION is used in ACAD later to extract the data about the pattern (x_position, y_position, radius).

Before doing so the LEDs should be imported and coincided with the pattern to check that each and every LED has the same number of dots.

In the UI after the data extraction command one can create a new extraction or use a readily created one.

Data Extraction Steps

- "Create a new data extraction" prompt is answered with "next" and enter the address where we are going to save the template.
- "Next" to the next prompt.
- On the 3rd window the patterns that are to be taken are chosen. If the file only has the pattern then the only features will be circles. In another file there may be other features, only circles should be chosen.
- In the next prompt, the following boxes should be unchecked : "3D visualization", "Drawing", "General" and only the followings shall remain "Center X", "Center Y" and "Radius".
- Next step would be to reduce the data to only "Center X", "Center Y" and "Radius".
- "Output data to external file" is clicked and the name to be saved is entered. As result, a .csv and a .dxe file are created.

Changing Data Format for Light Tools

The data in this .csv file is copied into the excel file that has been created for the purpose. From this excel file, the pattern is extracted as a .txt file by using the save as command.

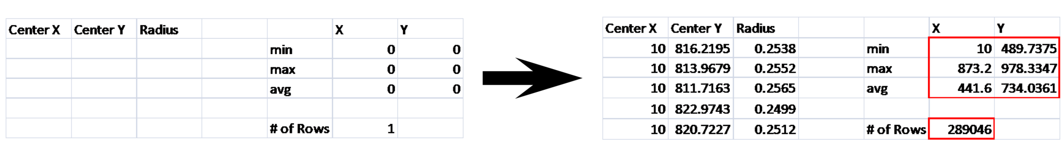


Figure 161: Copying to Excel

8.2.2 Inspection and Processing of the Mechanical Files

8.2.2.1 Inspection of the Files

To be able to start the design and to create the pattern following data must be at hand:

- 2D drawings of the system. The requirements for this drawing are:
  - The LEDs and LGP must be aligned
  - Optical sheets must exist
    - In later stages, when the pattern is being edited, the optical films will be necessary to crop the pattern
  - Active area should be defined.
    - Active area is the area from which the light may be extracted
- 3D drawings of the system
  - All optical components must be included
    - LGP
    - Optical films
    - LEDs, LED Bars and connectors
      - LEDs and LED Bars should be separately defined
      - LED Bar and the heat sink should be separate entities
    - Reflector Sheet
      - There must be 0.01 mm distance between the reflector and the LGP.
    - Reflector strips under the middle frame (the plastic frame that holds the optical sheets down and provides base for the cell)
    - Pieces like sponge, Mylar etc... if any

    * Back cover

- Any other parts that would have optical impact on the system.
    * These parts should be correctly aligned
    * They should be separate entities
- The back cover, which will not be included in the simulation but will only hold information on the alignment and possible holes, should be a separate entity as well that can be deleted while running the simulation.

8.2.2.2 Processing of the Files

After due examination, any inconsistencies, inappropriate parts etc... should be modified.

The most common problem is to have the LEDs and LED Bars to be one entity (LEDs extruded from LED Bar) and the distance between LGP and reflector to be zero. These are easy to solve problems.

Insertion of Space between LGP and Reflector

This distance can be introduced by opening the file with any CAD program and moving the reflector (with move command) 0.01mm away from the LGP. It can also be done by opening the properties of the reflector in LT and changing the appropriate position (most commonly y_axis) by 0.01.

This distance may be bigger or smaller within the limits of reason. The height of the pattern dots should be kept in mind while setting this distance (0.007mm). Otherwise the pattern will be immersed in the reflector and the simulation will fail as the optical properties of the pattern will be overwritten by the optical properties of the reflector (95% lambertian reflector with 5% absorption).

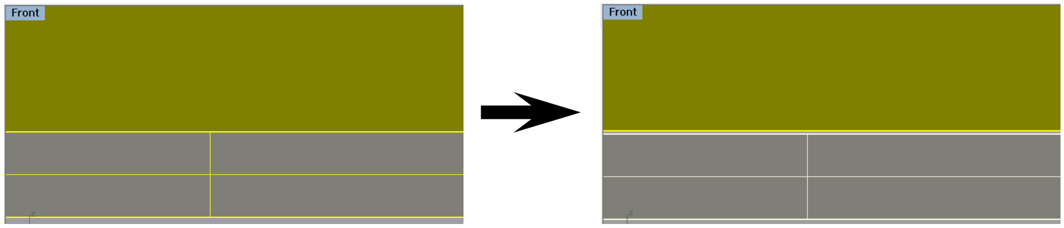


Figure 162: Moving the Reflector

Definitions of LEDs

In order to define the sources, the LEDs must be individual entities each and every one of them. Otherwise, the LED Bar will radiate from all its faces and the ones that will not radiate shall be chosen and turned off. If the 3D is a single entity, the ”explode” command may be used to separate the sub entities that make up the LED Bars, namely the LEDs and the PCB. If this operation does not separate them, they should be redesigned in LT.

Generation of LEDs

In case the LEDs will be recreated, the 3D files should be edited with a CAD program and LEDs and LED Bars should be separated e.g., in Rhino, the command ”box” is used to create a rectangular prism that will act as the LED and emit from its top face (Figures 163 - 166) and duplicate it with the array command (Figures 167 - 172).

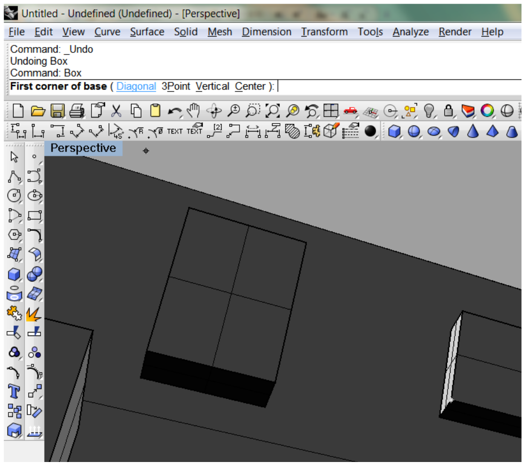


Figure 163: LED Creation Step 01

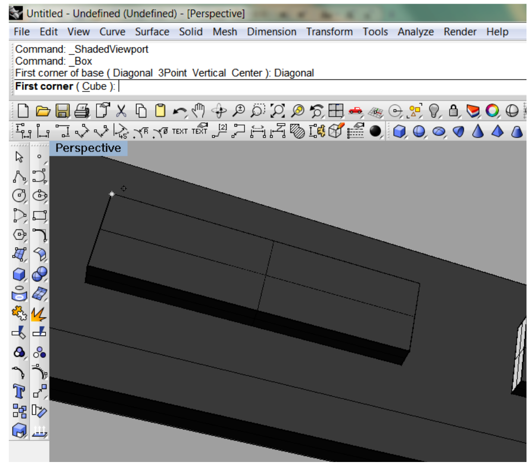


Figure 164: LED Creation Step 02

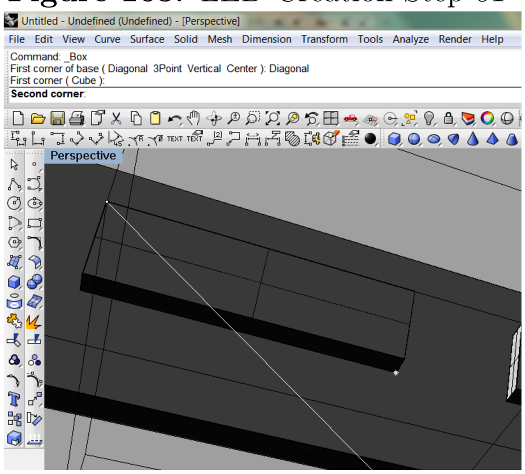


Figure 165: LED Creation Step 03

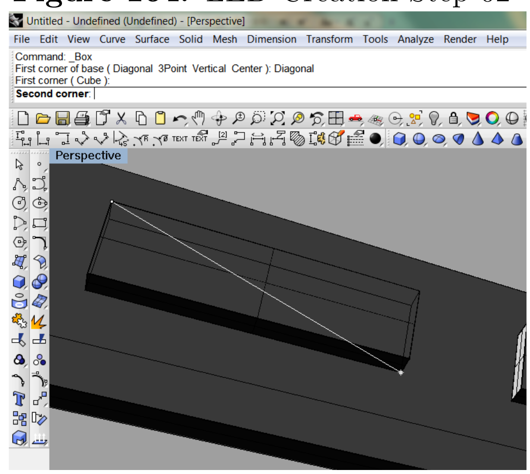


Figure 166: LED Creation Step 04

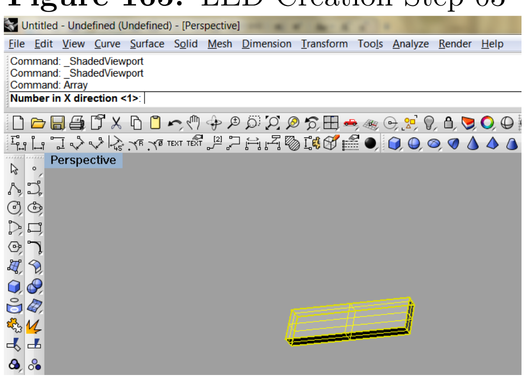


Figure 167: Array Step 01

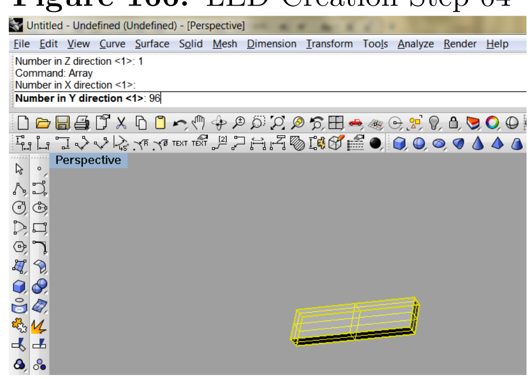


Figure 168: Array Step 02

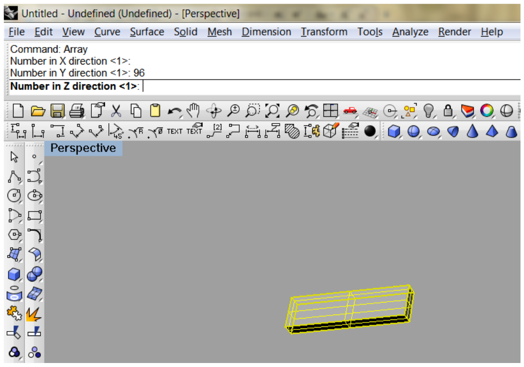


Figure 169: Array Step 03

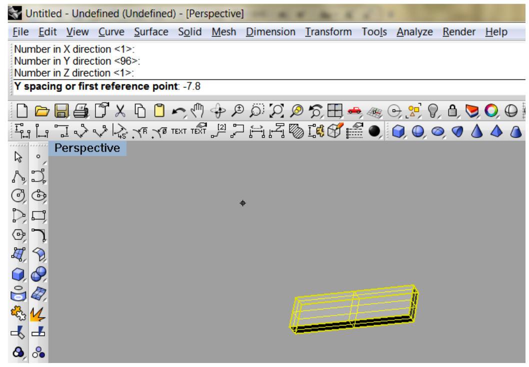


Figure 170: Array Step 04

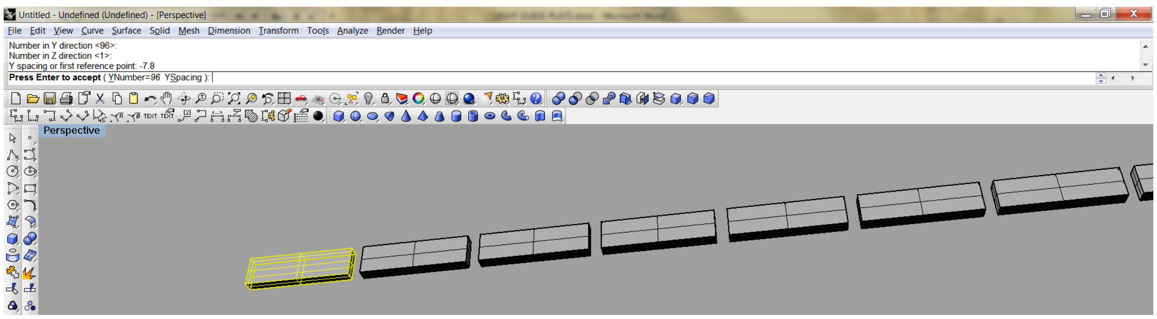


Figure 171: Checking and Accepting the Array 01

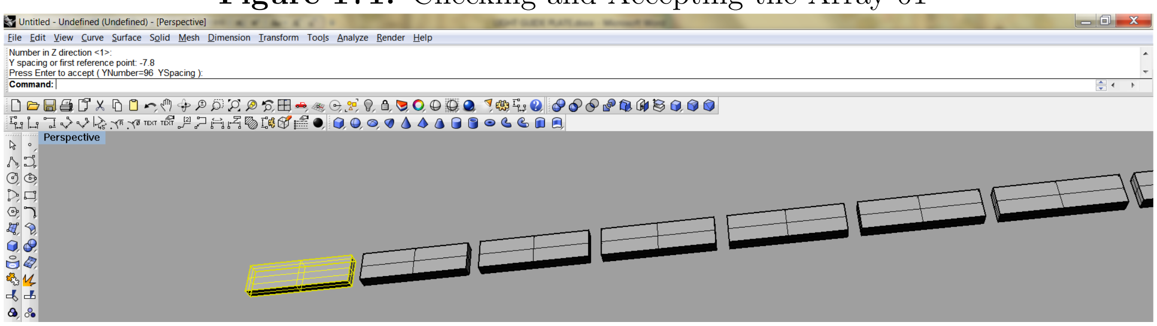


Figure 172: Checking and Accepting the Array 02

8.2.3 Lighttools

8.2.3.1 New Project

At the beginning of a new project, the following path should be taken from the menu : "File" → "Import" → "Step..." to select the 3D object. The field "Use Entity Names from File" should be clicked to use entity names from file. This way if during the design the components have been correctly named, the same name will be used (Figure 173).

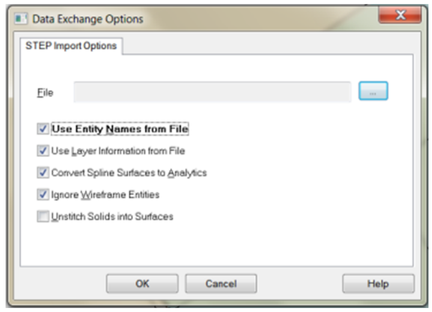


Figure 173: Importing 3D Drawings

8.2.3.2 Attaching Pattern to the LGP

On the back surface of the LGP, occluded by the reflector, right click will bring the menu from which the option "Add 3D Texture Zone" will be chosen. To be able to reach this face of the LGP, a right click on the reflector and the command "hide" must be performed. From the menu on left, under the components, a right click on the "texture" will bring the menu from where the properties will be chosen to edit. From the tab "Geometry", "Element Shape" will be set as "Cone". By right clicking on the pattern and choosing "Load Parameter/Placement Data" option the .txt file with the position and size of the pattern, created with the excel sheet will be loaded. Next is checking whether or not the pattern is aligned to the LGP. To do so the pattern should be made visible from the "View Preferences". This will significantly cause the computer to slow down as 1 million dots will be visible.

- The pattern is usually 90° off. From the properties the angle will be changed by -90°

- The width and height of the pattern region should be changed to accommodate the new, rotated region.

- To speed the processing, the pattern should be turned off again and by right clicking the optical properties must be assigned (Figures 176 - 179)

The reason the dots are chosen as cone and not cylinder is that the program treats the cylinder as half barrels on the side (Figure 174). If the pattern is chosen as cones of taper value of 1, the cones will become cylinders (Figure 175). Since the dots are very thin and wide cylinders (0.007mm height and > 0.2mm radius) this model works fine.

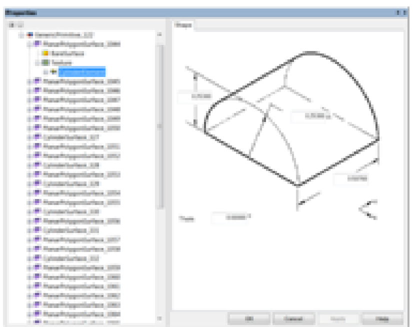


Figure 174: Cylinder Dot Shape

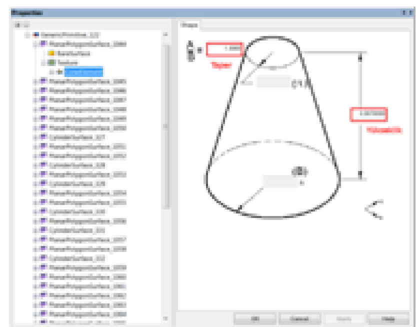


Figure 175: Cone Dot Shape

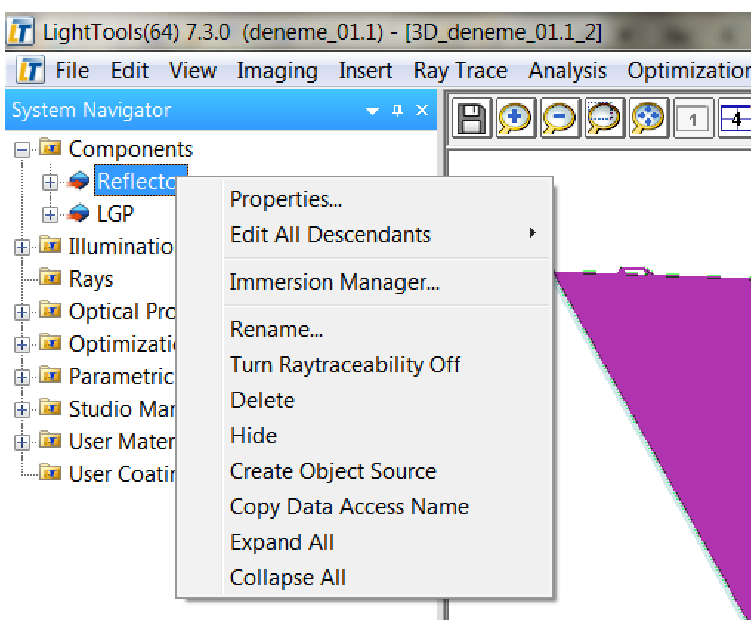


Figure 176: Assigning Optical Properties

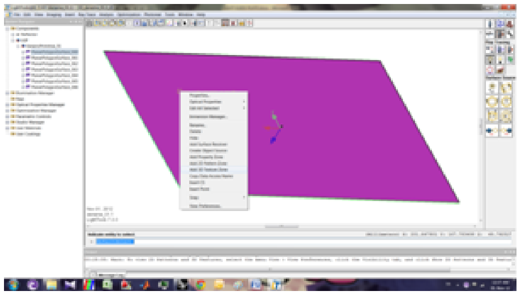


Figure 177: Assigning 3D Texture Zone 01

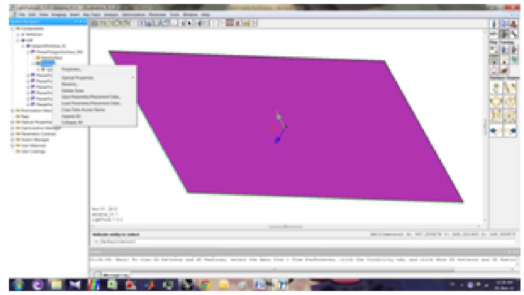


Figure 178: Assigning 3D Texture Zone 02

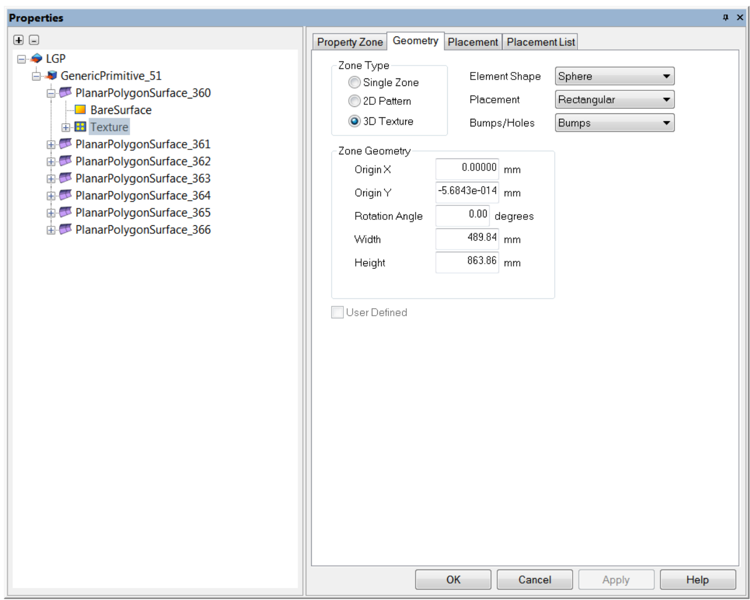


Figure 179: Creating Texture and Assigning Properties

8.2.4 Assigning Optical Properties

8.2.4.1 Optical Properties of the LEDs

Under the "System Navigator" and "Components" LEDs are chosen and highlighted. The menu on the right contains the items "Ray Tracing" → "Surface Source" → "SurfSource". By clicking this item, the LEDs are defined as surface sources. Next step is to select the LEDs (all of them) from the following path: "Illumination Manager" → "Source List" and "Edit All Descendants" →"Sources" is clicked. From the

"Emittance" tab, "Photometric Flux" is chosen and the flux of the LED is set and the thick is moved from "Measured Over" into "Aim Region". From the "Aim Sphere" tab, the field called "Orientation" is used for setting the emission region. The values "0" and "90" values are set for "Angle" values.

Optical Properties of the Reflector

Reflector is chosen from the components and right clicked. The path "Edit All Descendant" → "Optical Properties" → "Create and Assign New Optical Property" is followed. This is the way to create a new optical property and assign it to the chosen component. If an already created optical property will be assigned then it is simply chosen from under the "Optical Properties".

The suitable model for the reflector is "Simple Scattering". After choosing this model either "Apply" is clicked or enter button is pressed thus activating the tab for simple scattering. Here the reflectance is set as 95% for reasons explained in the thesis.

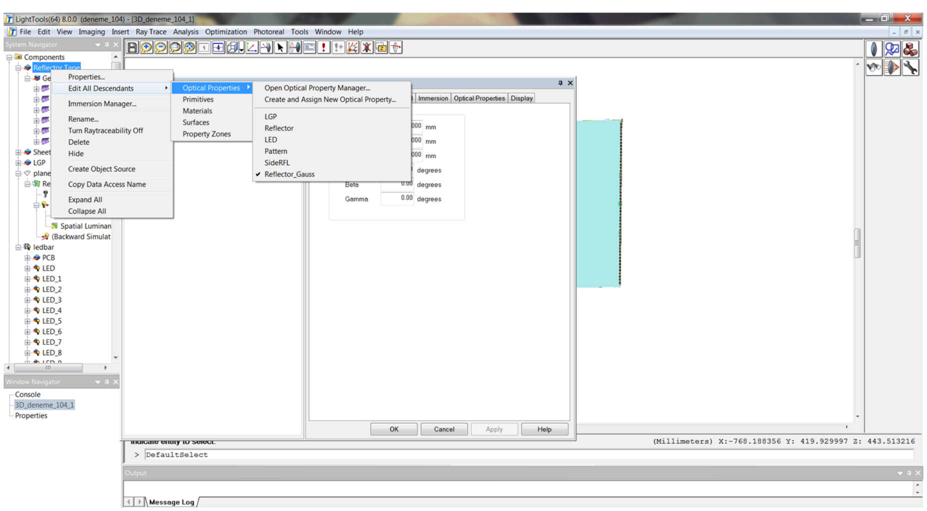


Figure 180: Optical Properties Assignment

Optical Properties of the LED Bars

The dielectric mask on the LED Bars acts as a reflector. Thus it must have the same properties. The measurement yielded the result that the reflectance of this mask is about 85%.

8.2.4.2 Definition of the Receiver

It is possible to set the receiver on any surface. But to prevent any possible problems / artifacts, the receiver is better assigned to a dummy plane. This way it is possible to modify the parameters of the receiver and thus gain flexibility.

In order to do this first the plane must be created. It is done via "Elements" → "Dummy Surfaces" → "Dummy Plane" and two arbitrary points are selected on the screen thus creating the plane randomly (Figure 181).

Figure 181: Dummy Plane

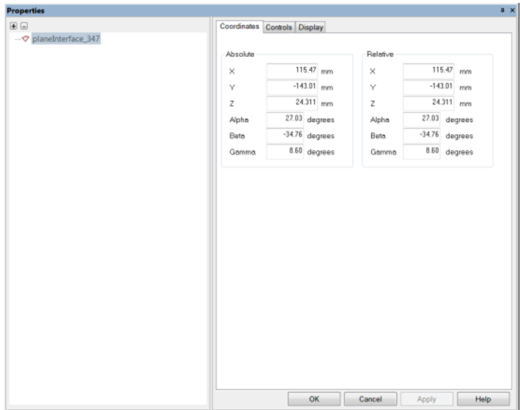


Figure 182: Plane at the Moment of Creation

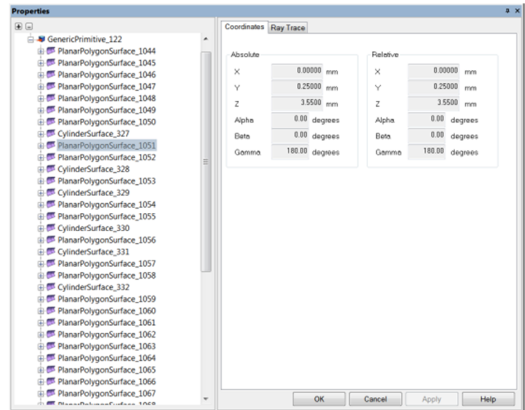


Figure 183: Position and Orientation of the Top Surface of the LGP

After setting the plane's position and rotation to coincide with the top surface of the LGP and setting the plane a little higher to prevent problems and artifacts it is right clicked and the comment "Add Surface Receiver" is executed. The plane is again right clicked and from the left side, manager's "+" is hit and Receiver is visible. Similarly going forward, "Forward Simulation" is found. Here "Spatial Luminance" box is selected and the other is un-selected. By applying or entering, the tabs "Spatial Luminance" and "Spatial Lum Meter" are made visible.

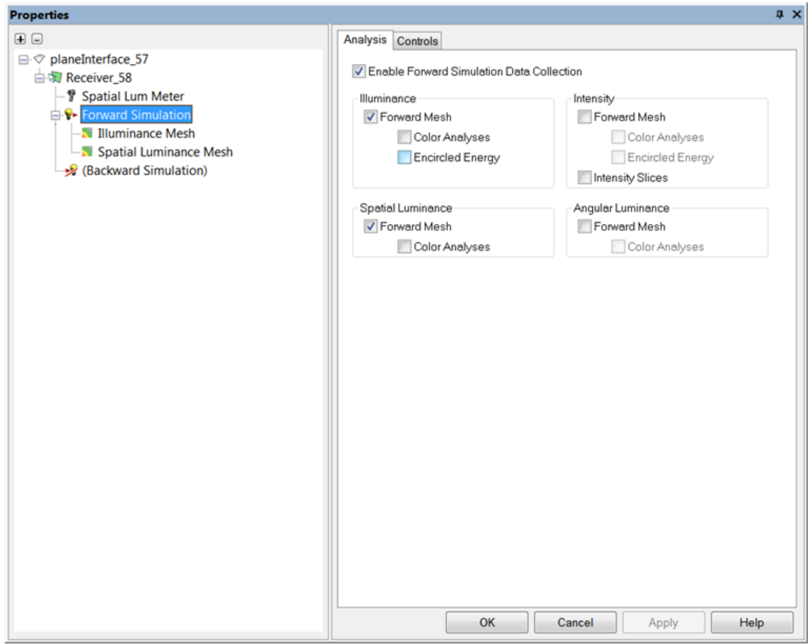


Figure 184: Receiver Assignment

8.2.5 Modification of the Pattern in AutoCAD

After the pattern is deemed suitable, the pattern's .dwg file is opened with to AutoCAD and the command "import" is used to import the LGP drawing. The dots and the LGP are aligned and the excess of the pattern is trimmed.

8.2.5.1 Alignment of the Pattern to the Optical Structure

Using the "line" command, opposing corners of the pattern is united. The intersection of these two lines is considered to be the middle of the pattern. After importing the optical structure (LGP) this drawing is selected and the blue square in the middle is clicked thus selected. By moving this square to the center of the pattern and waiting for it to "snap" the pattern and the LGP will have been aligned.

The next step should be to check that the same number of dots are before each LEDs and the alignment is the same and symmetrical in front of all LEDs.

8.2.5.2 Cropping of the Pattern

Pattern must be made suitable for production of the ”screen mask”. Therefore, some of the dots must be erased, e.g., the part where there will be the connectors, the LGP will have an indent. This part will be free of dots. Similarly, on the edges, to prevent light leakage dot rows may be erased. Initially the distance from the edges of the LGP to the start of the dots must be between 2 mm and 4 mm but the empty area should not pass the active area or the alignment of the optical films. This value may be reset after tries.

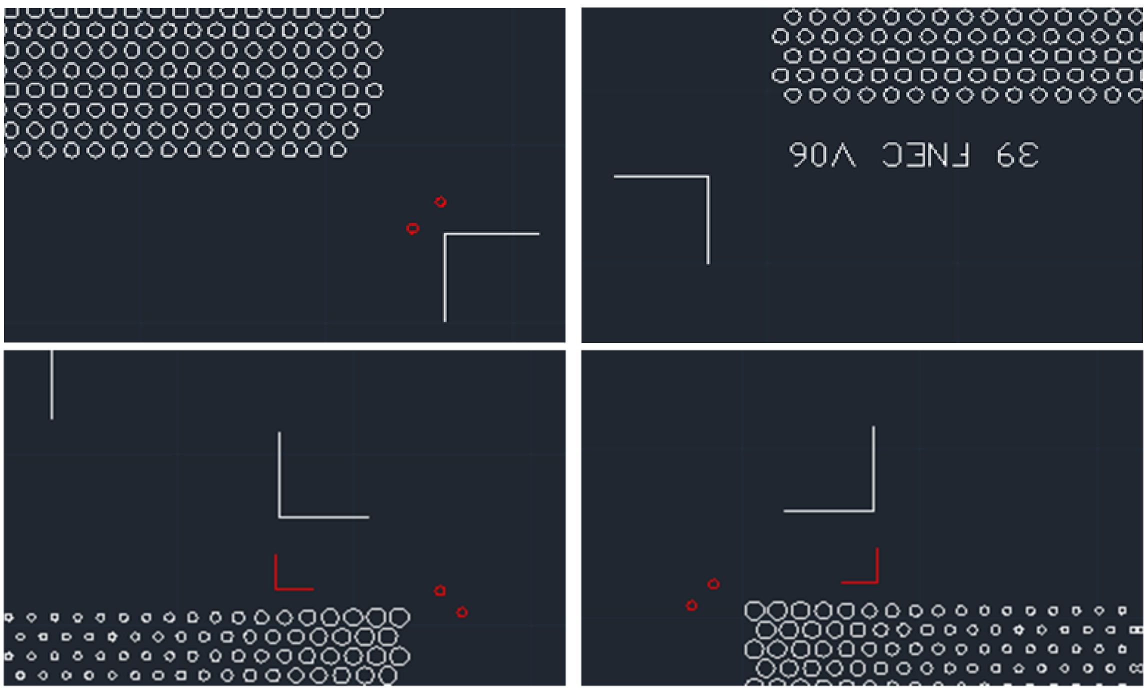


Figure 185: Corners of the LGP and the Trimmed Pattern with the Connector Study

8.3 The Last Approved Pattern's Tune Table Values

No.	X Axis	Y Axis	Before	After	X Range	Y Range	X S Range	X E Range
1	323	548	0.3000	1.1200	1500	300		
3	323	25	0.3000	0.3200	6000	350		
5	323	300	0.3170	0.5450	2500	450		
7	323	150	0.4303	0.4350	15000	250		
8	323	200	0.4807	0.4750	200	250		
10	323	425	0.7597	0.8000	800	700		
12	323	410	0.7462	0.8400	500	150		
14	323	580	1.1236	1.4000	1500	200		
15	323	500	1.2442	1.1800	1500	200		
16	323	350	0.6532	0.7500	250	200		
18	1	500	0.9628	0.7500	50	750		
19	645	500	0.9628	0.7500	50	750		
21	323	5	0.3447	0.3250	15000	7		
22	1	328	0.3901	0.3800	12	15000		
23	645	328	0.3901	0.3800	12	15000		
24	323	657	0.8307	0.7000	15000	16		
26	1	657	0.3941	0.6000	30	50		
27	645	657	0.3941	0.6000	30	50		
29	590	30	0.3515	0.4100	400	300		
30	60	30	0.3517	0.4100	400	300		
31	323	30	0.3658	0.4100	400	300		
32	323	220	0.5310	0.5200	400	200		
34	80	350	0.5900	0.6650	250	200		
35	570	350	0.5884	0.6650	250	200		
	1	15	0.3800	0.4500	100	150		
	645	15	0.3810	0.4500	100	150		
40	323	1	0.3871	0.3500	15000	10		
42	1	1	0.3176	0.4500	75	120		
43	645	1	0.3185	0.4500	75	120		

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