COLOUR GAMUT ENHANCEMENT WITH REMOTE LIGHT CONVERSION MECHANISM

A Thesis

by

Yusuf Sinan Sezer

Submitted to the

Graduate School of Sciences and Engineering
In Partial Fulfilment of the Requirements for
The Degree of

Master of Science

In the
Department of Electrical and Electronics Engineering

Özyeğin University
January 2018

COLOUR GAMUT ENHANCEMENT WITH REMOTE LIGHT CONVERSION MECHANISM

Advisor: Doç. Dr. Göksenin Yaralıoğlu

Co-Advisor: Dr. Devrim Köseoğlu

Approved by:

Doç. Dr. Göksenin Yaralıoğlu, Advisor,
Department of Electrical and
Electronics Engineering
Özyeğin University

Doç. Dr Fatih Uğurdağ,
Department of Electrical and
Electronics Engineering
Özyeğin University

Doç. Dr. Ayhan Bozkurt
Department of Engineering and Natural
Science
Sabancı University

Date Approved: January 2018

To my family…

ABSTRACT

The colour gamut of liquid crystal displays (LCDs) depends on the backlight unit spectrum. For the light emitting diode (LED) based backlight units, either phosphors or quantum dots are used to convert the blue light of the LEDs to red and green bands. On-chip phosphor and quantum dot configurations are optically and thermally inefficient as well as they reduce the lifetime of the LED chips. The topic of this thesis is remote backlight configurations where the light conversion is done away from the LED chips. We propose a configuration where a light conversion layer is placed in the backlight unit as a thin film in order to produce red and green bands. We matched the emission spectrum of the blue LEDs and the phosphorus layer to the colour filters of the LCD, so that the red, green, and blue bands efficiently expand the colour gamut. On the other hand, we have studied several on-chip phosphor converted LED based displays by designing a common BLU structure. On this structure, we have experimented optical and thermal design parameters by using LEDs with yellow Ce doped YAG phosphors and KSF based blend of green and red band emitting phosphors. In addition, we have also compared our results on remote phosphor light conversion layers with remote quantum dot containing films. Finally, we have compared and determined the critical display design parameters in terms of product reliability and durability.

ÖZET

Sıvı kristal ekranlardaki renk gamutu değeri, arka ışık ünitesine bağlıdır. LED tabanlı arka ışık ünitelerinde, mavi ışığı, kırmızı ve yeşil renge dönüştürmek için fosforlar ya da kuantum noktalar kullanılırlar. Çip üzerinde fosfor veya kuantum noktaların bulunduğu yapı, optik ve termal açıdan verimsizdir. Ayrıca, bu yapı LED çipin ömrünü de azaltmaktadır. Bu çalışmanın ana konusu, LED çipten uzakta bir renk dönüştürücü mekanizma kullanarak geniş renk gamutlu, uzun ömürlü bir LED tabanlı sıvı kristal ekran tasarlamaktır. Bu kapsamda, renk dönüştürücü mekanizmanın arka ışık ünitesinde ince bir film olarak yer aldığı bir yapı kullanılıp, kırmızı ve yeşil renk spektrumları elde edilmiştir. Mavi LED'nin ve fosforlu katmanın yayınım spekturumuyla, sıvı kristal ekranın renk filtre spektrumları eşleştirilerek, mavi, yeşil, kırmızı renk spektrumları oluşturulmuş ve geniş renk gamutu sağlanmıştır. Öte yandan, arka ışık ünitesi tasarlanarak, çeşitli LED çip üstüne yerleştirilmiş renk dönüştürücü katmanlar çalışılmıştır. Bu yapıda, sarı Ce katkılı YAG fosforlu LED'ler ile yeşil ve kırmızı spektrumda ışıma yapan malzemleri içeren KSF fosforlu LED'ler kullanılarak optik ve ısıl özellikleri çalışılmıştır. Buna ek olarak, uzak kuantum nokta içeren filmler ile, uzak fosfor içeren renk dönüşüm katmanları karşılaştırmalı olarak incelenmiştir. Son olarak, ekran tasarımının kritik parametreleri ürün güvenilirliği ve dayanıklılığı açısından değerlendirilmiştir.

ACKNOWLEDGMENTS

I would like to express my sincere thanks to Dr. Devrim Köseoğlu for his support, guidance and encouragements. I would like to thank the members of the examining committee, Assoc. Prof. Göksenin Yaralıoğlu, Assoc. Prof. Fatih Uğurdağ and Assoc. Prof. Ayhan Bozkurt for their comments and suggestions.

I also thank Kıvanç Karslı, Mehmet Salih Kılıç and Fevzi Sümer who has answered all my questions with their knowledge and experience. I place on record, my sincere gratitude to Emrah Bakan and Orkun Özen who were always there during my experimental works.

I would like to thank to, the display design manager of Vestel Electronics, Sedat Şengül for his support and encouragements.

This work is supported by Vestel Electronics and TÜBİTAK Teydeb programme.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

The discovery of GaN based light emitting diodes (LED) led to the use of blue LEDs in colour conversion mechanisms, especially for white light generation. Among the widespread applications, LED based liquid crystal displays (LCD) became commercially successful in a short period of time. In LCD displays, colours are generated within the LCD panel with the implementation of colour filters of three primary colours, namely Blue (B), Green (G), and Red (R). However, the gamut is not only dependent upon these filters, but also the spectrum of the backlight unit, since LCD panels themselves require a light source to generate images. LCD display design is typically determined by parameters such as luminance, uniformity, duration, and colour gamut. In this study, it is aimed to design an LCD display which has a long lifetime, wide colour gamut, the luminance value of 300nit, which is the general standard for the market, or above.

The wide colour gamut displays has become one of the primary research areas on display systems especially after the implementation of quantum dots and high performance phosphors in recent years. The gamut is defined as the sum of all colours that a display can produce. In the market, the average colour gamut value is around 72% in the National Television System Committee (NTSC) standard. However, this standard is being replaced by Digital Cinema Initiatives (DCI)-P3, colour gamut standard which is designed for 4K displays [1]. The average colour gamut value in the market is 82% according to DCI-P3 standard.

Phosphor containing LED packages made an improvement in terms of colour gamut and luminance values in comparison to cold cathode fluorescent lamp (CCFL) illumination, but they are thermally and optically inefficient. Since the phosphor layer covers just above the LED light source, this reduce the durability of phosphor encapsulation and prevents the applications of high currents. Another disadvantage of on-chip colour conversion is the cost. Thus, remote phosphor techniques have become an alternate solution in display and general lighting industry [2, 3]

Application of quantum dot (QD) containing films is another remote light conversion technique to produce wide colour gamut panels, since the emission spectra of quantum dots under blue LED excitation are very narrow which is suitable for well-matched colour filter integration. At the moment, however, these narrow band emitting commercial QDs films are mostly based on Cadmium, which is listed among the toxically materials in RoHS list. [4] Heavy metal free QD films, on the hand, emit in wider FWHM and the luminance values of the displays based on these films are lower. [5]

In display industry, reliability and durability of the products is of paramount importance. For this reason, the components of the display systems should be selected carefully. Therefore, the usage of phosphor containing films is regarded as a better option for wide colour gamut and higher brightness solutions. In this study, we have designed several display systems in order to study the performance different light conversion mechanisms. These include

- White LED with yellow phosphor,
- White LED with KSF phosphor,
- White LED with RG phosphor,
- CdSe QD film,

- InP QD film
- RG phosphor film

We have also performed optical and thermal tests to check the reliability and durability. All BLU designs are aimed to reach the colour targets CIE-x = 0.280 and CIE-y = 0.280. However, the primary concern is given mostly to gamut and brightness measurements.

In this thesis, we have designed and characterized LED based LCD displays to improve the critical performance parameters for colour gamut enhancement with remote light conversion mechanism. These critical performance parameters are explained in the next chapter.

The colour vision of human eye, colour gamut and standards in display technology, wide colour gamut solutions are summarized in Chapter 3.

LED based LCD display design, application and characterization of colour conversion layers for gamut enhancement, optical and thermal measurements, and their results are presented in Chapter 4.

In the last chapter, the experimental results of colour gamut enhancement with remote light conversion mechanism are reviewed with a discussion on possible future studies.

CHAPTER II

LED BASED LIQUID CRYSTAL DISPLAYS

Liquid crystal displays (LCDs) are used frequently in daily life in mobiles, e-book readers, video displays, game watches, kiosks, ATMs and automotive displays to televisions. For these reasons, developments on LCDs and related technologies have become an important research interest.

LCD based systems consist of several optical components. From a display design perspective, these systems can be investigated in two main structural parts. These are the backlight unit (BLU) and the liquid crystal panel. Figure 1 shows schematically a typical LCD system.

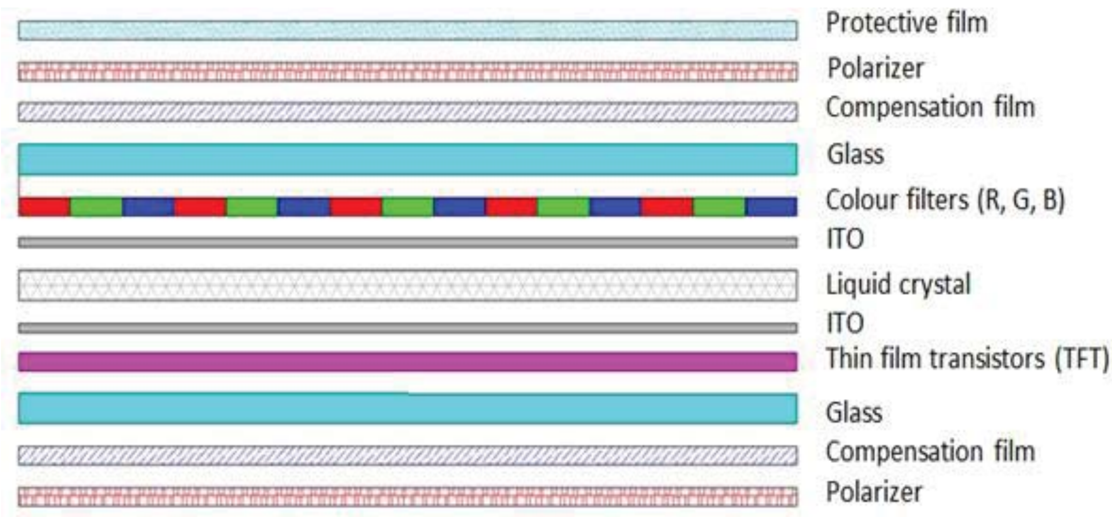

Figure 1 - The structure of liquid crystal display panel [2]

2.1. The components of LCD based systems

As mentioned above, LCDs consist of two main parts. The BLU consists of light sources, optical films (brightness enhancing sheet, diffuser sheet, and reflective polarizer), light guide plate or diffuser plate. The liquid crystal panel, on the other hand consists of polarizers, compensation films, glasses, thin film transistors, liquid crystals, and colour filters.

2.1.1 Light Source

LCDs do not emit light by themselves. They can manipulate the light generated by a source. This light is provided by a BLU either as a direct type that located under the liquid crystal cell or edge type positioned at the edge of a waveguide [6].

Before the invention of LEDs, there were light sources such as, cold cathode fluorescent lamps (CCFL), exterior electrode fluorescent lamps (EEFL) and flat fluorescent lamps (FFL) were used in display systems. The CCFL involves a glass tube coated with a fluorescent material and this tube contains an anode, a cathode and mercury gas. When a potential difference is applied to these electrodes, UV light is radiated by the gas and converted to visual spectrum by the phosphor coating inside the glass tube. A typical, CCFL spectrum is shown in Figure 2 [7].

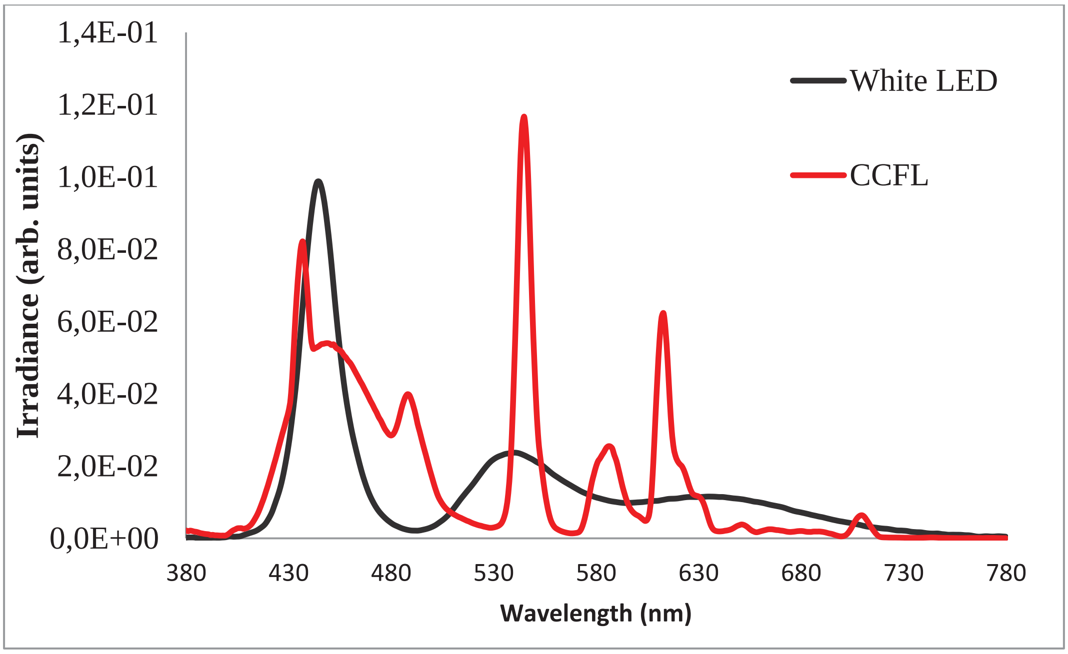

Figure 2 - White LED and CCFL spectrum **[7]**

The light emitting mechanism of EEFL is similar to CCFL. However, their electrodes are located outside the glass tube. A flat fluorescent lamp (FFL) has a rectangular shape. It contains two parallel bottom layers, and is filled with mercury and xenon gasses [7].

LEDs are made of semiconducting materials doped with impurities to form a p-n junction. When a potential difference is applied to this p-n junction, electrons and holes are produced. Recombination of these electrons and holes creates a photon which mediates throughout the semiconductor material. The frequency of this emission depends on the semiconductor material. For instance, gallium arsenide phosphide radiates red light, indium gallium nitride radiates blue light.

There are three commonly used ways to convert the light output of the LEDs to white light. One of them is using blue, green and red phosphors with UV LED. The other is to use yellow phosphors with blue LED. The last one is to use green and red phosphors with blue LED. The most common one is yellow phosphor with blue LED because of its cost advantage [7]. The spectra of blue, green, red radiations can be seen Figure 3.

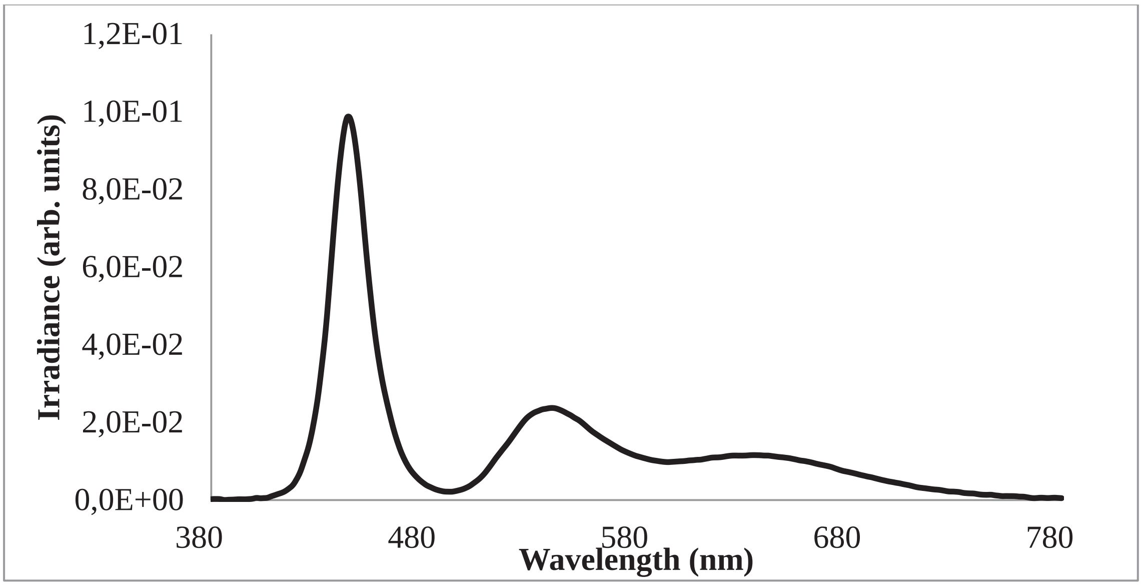

Figure 3 – The spectrum of a blue LED with yellow phosphor **[7]**

2.1.2 Light guide plate

Light guide plate (LGP) is used in LED based LCD TVs where the LEDs are located on the side of the backlight unit. These kinds of designs are called as Edge type. The typical edge type emission can be seen in Figure 4.

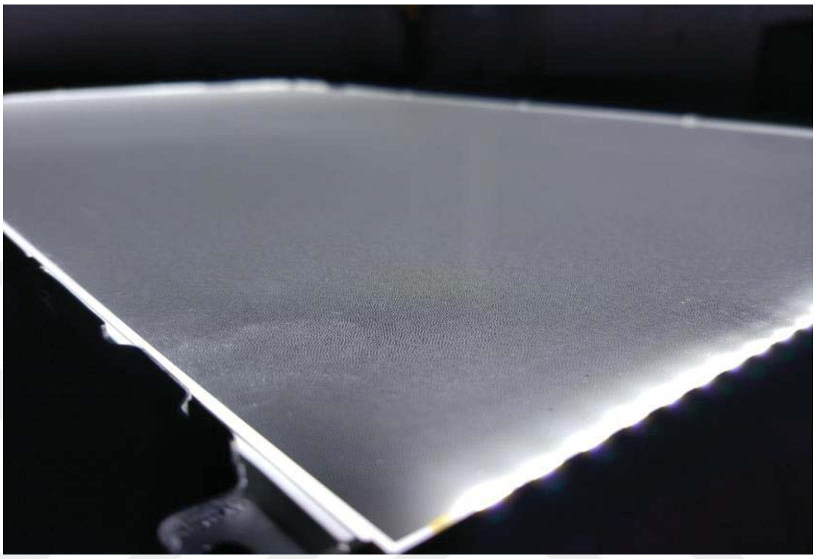

Figure 4 - Light Guide Plate of Vestel 23.6" Edge LED TV

2.1.3 Diffuser Plate

The diffuser plate is used to distribute the output of LEDs which are located at the back side of the direct type BLU homogeneously. In DLED type designs; there are two mainly used diffuser types, bulk type and surface type [8]. In this thesis, we preferred a bulk type diffuser which is described in Figure 5. These types of diffusers contain inorganic particles which are dispersed into a transparent polymer film. The size of these particles is 2-8 μm. However, these particles and polymer film have different refractive index, for this reason, the light scattered away from its original direction.

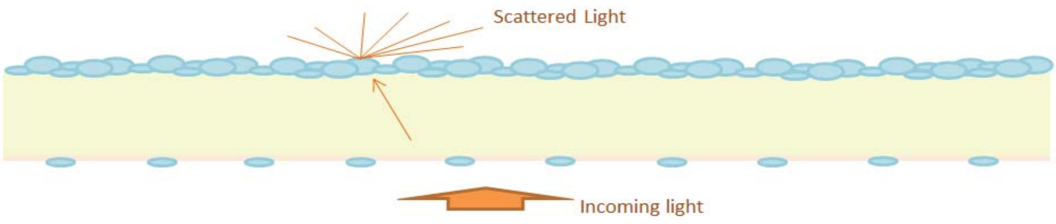

Figure 5 - The structure of diffuser plate

2.1.4 The brightness enhancing film

Brightness enhancing film (BEF) is used for increasing the brightness of LCD TVs. BEF has a prism shaped structure. Since the BLU light output should go through the LCD panel homogenously, the light should be directed to the LCD panel normal [7] [9, 10]. BEFs are sometimes called as prism sheets, and their structure is represented in Figure 6. The bottom surface of this film is flat. In addition, there is a prism shape on the top surface.

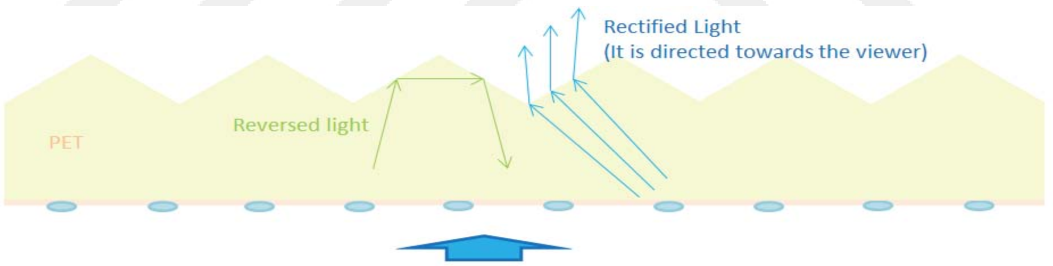

Figure 6 - The structure of BEF

2.1.5 Polarizers

In the liquid crystal panel (LCP), the liquid crystal is used to manipulate the polarized light. Since the most BLU designs produce unpolarised light, a polarizer has to be used in front of the liquid crystal layer [7]. Furthermore, an additional polarizer is needed after the liquid crystal to block the unpolarised light.

2.1.6 Compensation Films

In LCPs, due to structural and design problems, light distribution may not be optically uniformly distributed throughout the display unit. Optical path differences or delays or light leakages or directional changes may occur due to these problems. The compensation films are generally used to recover these problems. In addition, viewing angle is also improved by using these films [7].

2.1.7 Colour Filters

Colour filters (CF) have a significant effect on the gamut, brightness and colour coordinates of LCD based display system [11, 12]. The CF consists of three different colour pixels. These are generally blue (B), green (G) and red (R). In some designs, there exists an additional pixel for increasing the brightness [7].Typical colour filter structure is given seen in Figure 7 [13].

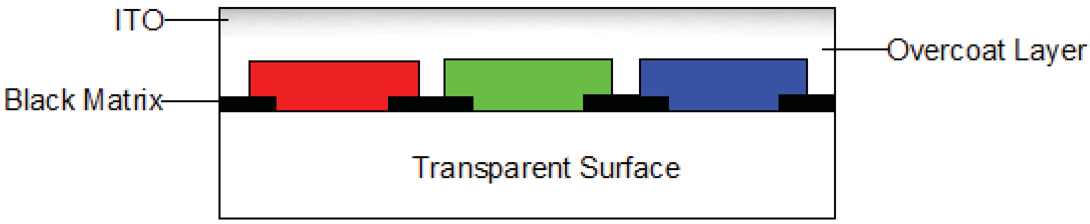

Figure 7 - The structure of typical LCD colour filter

The area between the colour pixels has a black matrix. This matrix is used to prevent light leakages and also to protect TFT drivers. There is also an upper protection layer on the colour pixels to avoid the change of function in the thickness variation and prevent from the damage of chemicals used during the production. On the overcoat layer there exists a transparent electrode made of indium-tin-oxide (ITO). The pixels are located inside the LCD substrate to prevent picture parallax problem [7].

In this thesis, the mechanism for the colour gamut enhancement is strongly depended upon the colour filter specifications. In figure 8, an example for the colour filter spectrum is given for the AU optronics (AUO) UHD LCD colour filters used in this study. This figure also shows a typical LED backlight spectrum for yellow phosphor on blue LED chip [14].

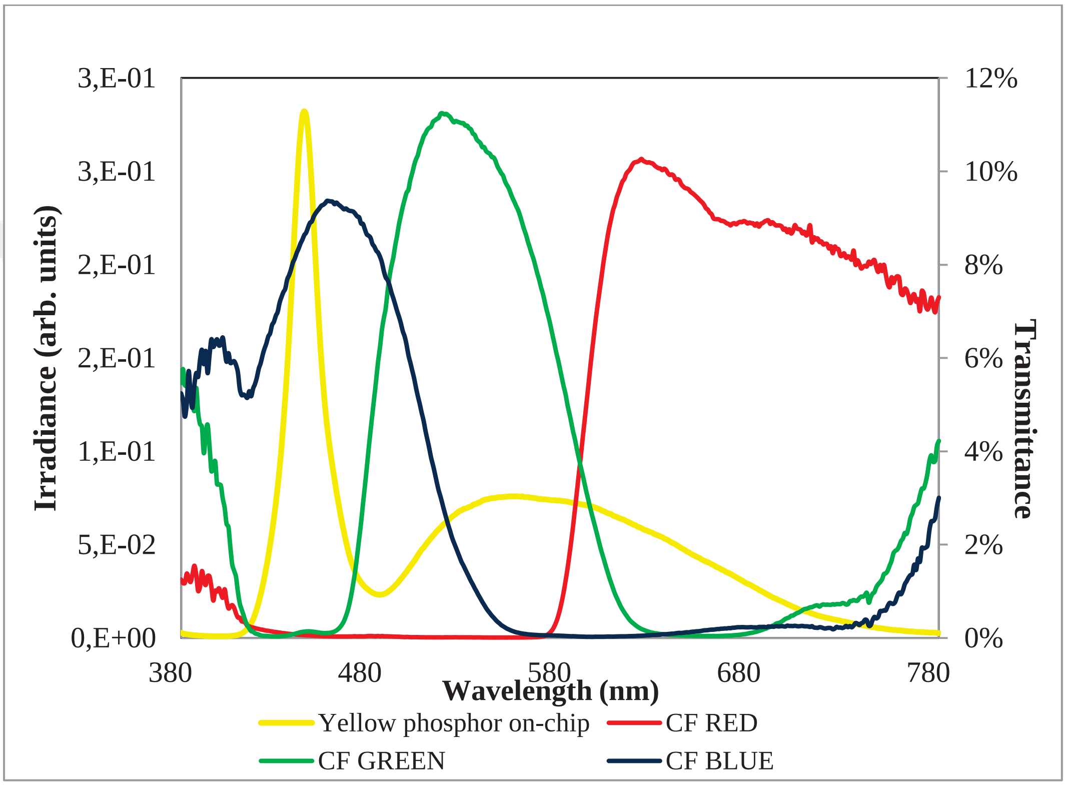

Figure 8 - The spectrums of LED backlight unit and AUO UHD LCD colour filter

2.2. The critical design parameters of LED Based LCDs

The critical design parameters of LED based LCDs are luminance, spectrum of the LEDs, light source temperature, luminance uniformity, life time and colour gamut.

2.2.1. Luminance

The LCP's transmittance value determines the required luminance value of the LCD panel. The light flux of the LEDs is depended on the specific current determined by the driving unit.

In an LED based LCD TV, there are lots of LEDs used in the backlight unit and the brightness value of each LED may vary. Therefore, it is necessary to place the LEDs on a PCB so that the luminous values of the LEDs in a bar are close to each other. Otherwise, problems such as light leakages or dark areas in the panel may occur. The flux value of the LEDs, the BLU film structure, the transmittance value of the LCP, the LED current and the amount of losses in the colour conversion mechanism may affect the panel brightness.

2.2.2. Luminance uniformity

Luminance uniformity is another critical parameter in display design. To determine BLU uniformity value; the LCD panel is divided into nine parts as shown in figure 9 and luminous values from the centre of each part are measured. Then, the uniformity value is obtained by dividing the minimum luminance value to maximum luminance value. Generally, LCDs are expected to have over 80% of the uniformity result.

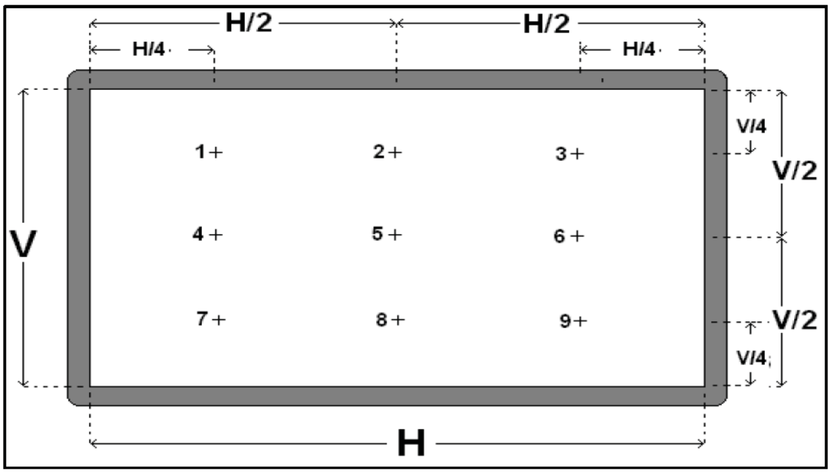

Figure 9 - Uniformity measurement points

2.2.3. Spectrum of the LEDs

The spectrum of the LED is also another important parameter of the BLU spectrum which effects affect the colour gamut and luminescence. This spectrum depends on the phosphors and / or the LED chip structures [6].

2.2.4. Temperature Dependence

Emission spectrum of the LEDs changes with the operating temperature. The luminance is depended on the LED junction temperature. The relative luminance flux of a blue LED (from Jufei Company) used in this thesis.

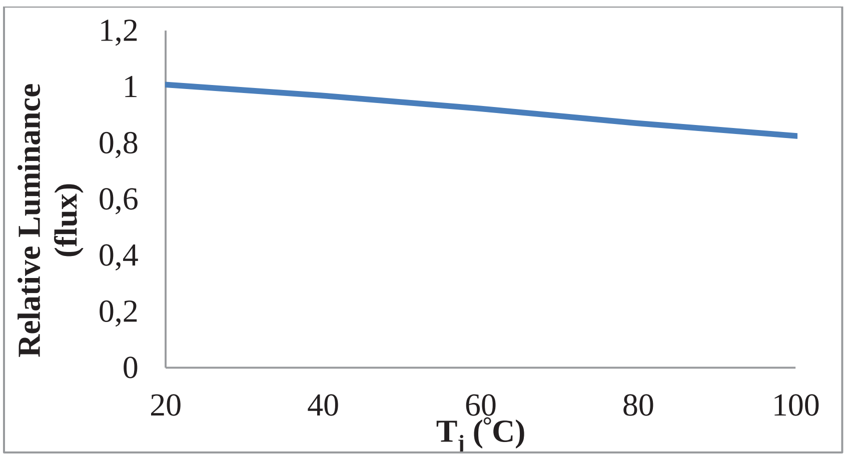

Figure 10 - Relative luminous flux against to LED junction temperature

2.2.5. Lifetime

Lifetime is defined as the period the brightness of the display reduces to half of its initial value. In LED based LCDs, the lowest lifetime belongs generally to the LEDs. Typical on chip phosphor containing LED chip packages have a lifetime of 30 000 hours [6]. This lifetime is also depended upon the driving current and the temperature of the LED. Jufei yellow phosphor on blue chip LED lifetime is shown in figure 11.

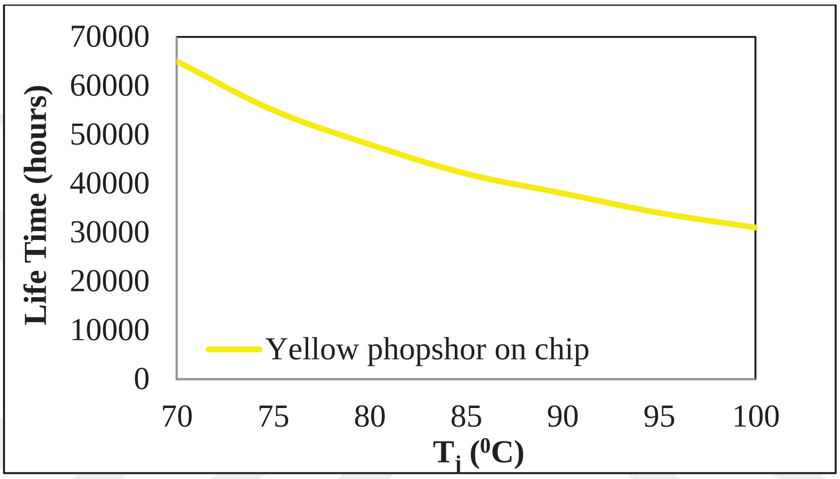

Figure 11- Life time against to LED junction temperature of yellow phosphor on chip

2.2.6. Colour Gamut

The colour gamut is mainly depended on the BLU spectrum and the colour filters of the LCP. The colour gamut value is determined by the triangles obtained from the colour coordinates of blue, green and red colours. The colour gamut for yellow phosphor on blue chip used in most LCD based TV designs on the market is around 72% in the NTSC [7].

CHAPTER III

THE DESIGN OF WIDE COLOUR GAMUT LIQUID CRYSTAL DISPLAYS

The colour gamut represents all the colours can be produced by a device. However, describing the colours produced by a display is difficult task, since the human eye perception should be modelled mathematically. There is several such colour spaces used in display industry. For example, in figure 12, horseshoe-shaped image of the CIE 1976 colour space is given for the representation of the colours that the human eye can perceive.

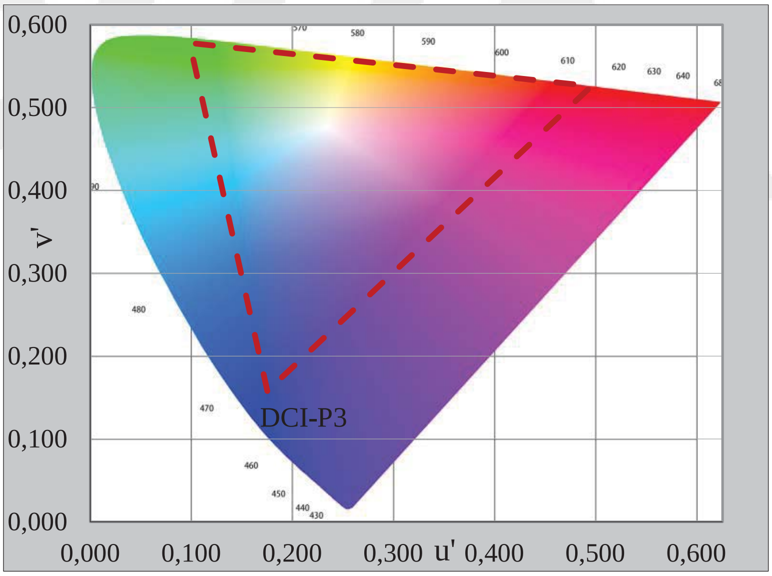

Figure 12 – CIE 1976 colour space diagram

In LCD based display systems, colours are generated by the three main colours, red, green and blue. The locations of these primary colours on the specific colour space define a triangle in the colour space system. This triangle is called a colour gamut.

Since the technological improvements in imaging and display systems directly affects the colour gamut of the devices, the colour gamut standards are being updated according to these improvements. NTSC (National Television System Committee) and PAL (Phase Variable Line) colour gamut are defined for the first colour televisions. NTSC is the first colour gamut and founded in 1953, it is also the first colour gamut used in the CIE 1931 colour system.

3.1. Wide Colour Gamut Displays

Wide colour gamut is classically defined as the colour space of a display which covers the entire AdobeRGB colour palette. Many manufacturers are able to produce products that can cover this colour space. However, with the implementation of LEDs into the BLU designs, the DCI-P3 colour palette has become widespread. Earlier examples are Retina iMac (produced in 2015) and IPad Pro (produced in 2016). DCI-P3 is becoming a standard for the motion picture industry and representing a wide colour gamut. The red and green regions of this standard extend to a wider area than AdobeRGB [1]. On the other hand, Rec 2020 (for ITU-R Recommendation BT.2020) will be the standard for UHD TV (both 4k and 8k). It specifies many broadcast image properties, including frame rate, bit depth, resolution, and aspect ratio [1]. Its colour space is wider than Adobe RGB and DCI-P3.

Achieving wide colour gamut for LCD technology is one of the most important issues. The colour gamut of LCDs depends on the backlight unit spectrum and the colour converter characteristics of the LCD panel. The narrower blue, green, red spectrum is used, the more advantageous results are obtained for colour gamut [1].

Conventional backlights use white LEDs, in which the blue colour is converted by yellow phosphor. In this case, the colour gamut value in the NTSC colour space is about 72%. The red and green emitting phosphors with a narrow spectrum are preferred for wide colour gamut. Nano materials such as quantum dots are also suitable materials for obtaining a narrow spectrum [15]. Since phosphors have better thermal resistance than quantum dots, phosphors can be used on both on LED chip package and remote solutions. However, quantum dots can only be used remotely, since they are more vulnerable to heat.

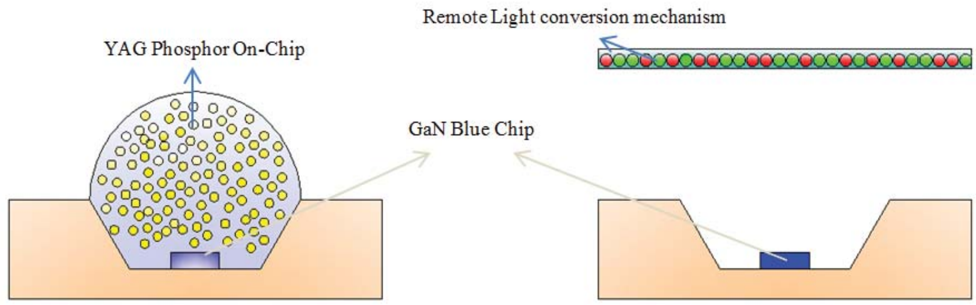

Figure 13 - LED on-chip phosphor and remote light conversion mechanism

In this study, the 65"TV prototypes were designed by using phosphors and quantum dots. These prototypes include designs with light conversion on the chip, and designs with remote light conversion by using quantum dots and phosphors (Figure 13). The colour gamut, luminescence and life time characteristics of all these designs were analysed and compared with each other.

3.2. Optical Measurements

3.2.1. The backlight unit design

In this study, two different optical structures have been used. One of them is the on-chip solution where the colour conversion mechanism is placed on the LED chip (Figure 14).

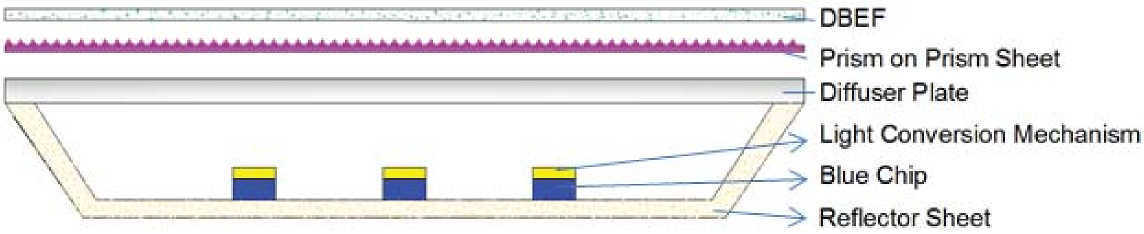

Figure 14 - Optical structure of with on-chip light conversion mechanism

The other one is that the colour conversion mechanism is placed as an optical film away from the light source (Figure 15). There are no structural differences in these BLUs except from the colour conversion mechanisms.

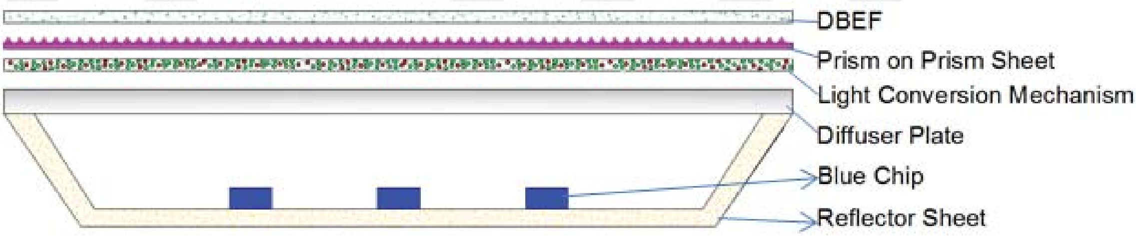

Figure 15 - BLU optical structure with remote light conversion mechanism

Both BLU designs have 2 strings, 78 LEDs and are driven at 450mA. The voltage value of each LED is 3.1V. The BLU system then consumes 108.8W of power.

Diffuser plate, prism on prism sheet and dual bright enhancement films (DBEF) have been used in that backlight unit. The optical properties of these components are shown in table 1.

Table 1 - Optical properties of light conversion mechanism BLU structure

Product Type	*Product Code*	*Thickness (mm)*	*Reflectivity 555nm (%)*	*Haze (%)*	*Transmittance (%)*	*Used Side Gloss (%)*
SMART*	POP6	0.33	N/A	99	3.00	N/A
DP	EML-R35A	1.50	N/A	99	33.00	N/A
RFL	188-RAQ3	0.188	97	N/A	N/A	20.00
DBEF	ULF-250	0.260	N/A	86	47.0	N/A

In today's LCD TV technology, the optical film structure of a typical direct LED backlight unit (BLU) consists of the diffuser plate, prism on prism sheet (POP) and diffuser sheet. In addition, a reflector sheet is used in order to collect the light scattered on the side and back surfaces of the panel. In this study, 188-RAQ3 reflector has been used. Its reflectivity value is 97% at 555nm.

The diffuser plate distributes the incoming light homogeneously in order to prevent the LEDs from being visible on the display. EML-R35A diffuser plate is used in this study, since it has a high haze.

Vertical and horizontal prism sheets are laminated to each other in order to produce a prism on prism (POP) sheet. It increases the brightness by collecting the scattered light on both the x and y axes.

Sometimes a diffuser sheet is used to distribute the light gathered by the POP film in order to allow wide viewing angles. In this study, DBEF has been used instead of the diffuser sheet in order to catch brightness in the market. It can increase the BLU luminance by 60%.

In this study, BLU has been designed and characterized by implementing RG phosphor film, CdSe QD film and InP QD film to the BLU, separately. After the film structure of the backlight unit is determined, the selection of the liquid crystal panel becomes important, since it affects the colour gamut and luminance. The more closely the BLU spectrum and colour filter spectrum match each other, the higher colour gamut and brightness is possible. In this study, 65" AU Optronics (AUO) UHD cell has been used. The transmittance with DBEF of this cell is 11.2%. In addition, the colour filter spectrum of this cell is shown in Figure 16.

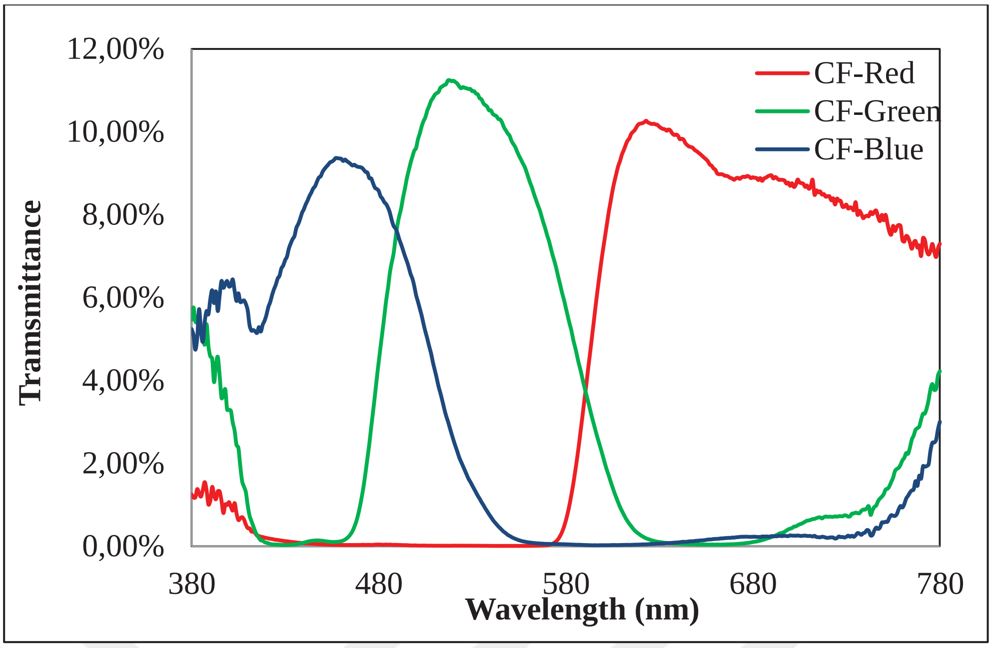

Figure 16 - Colour filter of 65" AUO UHD LCC

This colour filter data is obtained by dividing the LCP's blue, green, red spectra to the backlight spectrum. Blue, green and red spectrums should not overlap in order to obtain wider colour gamut. However, in our LCP unit, it is seen that blue and green spectra overlaps between 465 and 550 nm. In addition, a part of green and red spectra overlaps between 570 and 620nm. If these overlapping regions were smaller, it would be possible to achieve wider colour gamut.

In this thesis, the BLU has been designed and characterized with LEDs as light sources and phosphors as light converters. We have implemented several light conversion mechanisms such as yellow (Y) phosphor converted LED (on-chip), Red and Green (RG) phosphor converted LED (on-chip) and KSF phosphor converted LED (on-chip). On the other hand, for the remote light conversion mechanisms, blue LEDs with a peak wavelength of 444nm and a full width at half maximum (FWHM) value of 19nm are used as a light source. Its spectrum is given in figure 17.

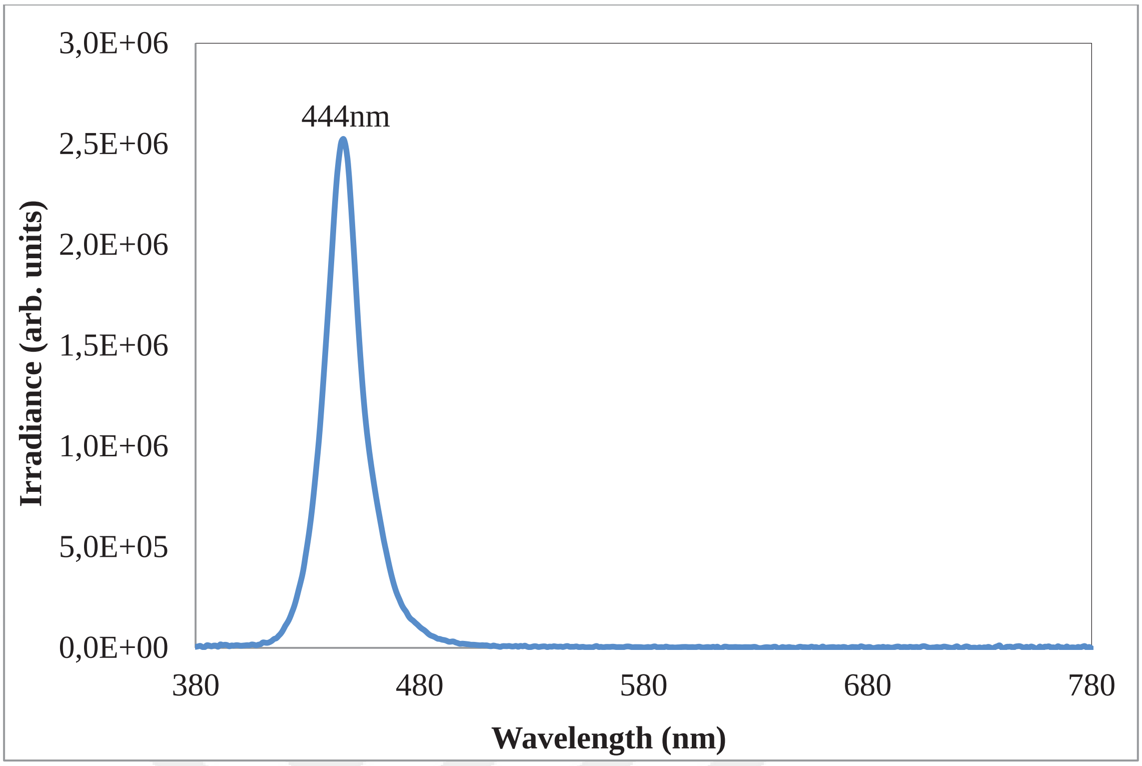

Figure 17 - Blue LED spectrum

These blue LEDs have been chosen according to the excitation response of the light conversion mechanism for the green and red wavelength range. In our configuration, the blue colour filter overlaps with green colour filter between 465nm and 550nm. Therefore, the blue region (LED excitation) should not be penetrating further than 446nm to avoid the colour gamut narrowing. For this reason, we have performed photoluminescence (PL) measurements for the RG phosphor converters under excitation wavelengths from 400 to 450 nm with 10 nm intervals by using a PL spectrometer in order to determine the optimum excitation wavelength for the blue LEDs (Figure 18).

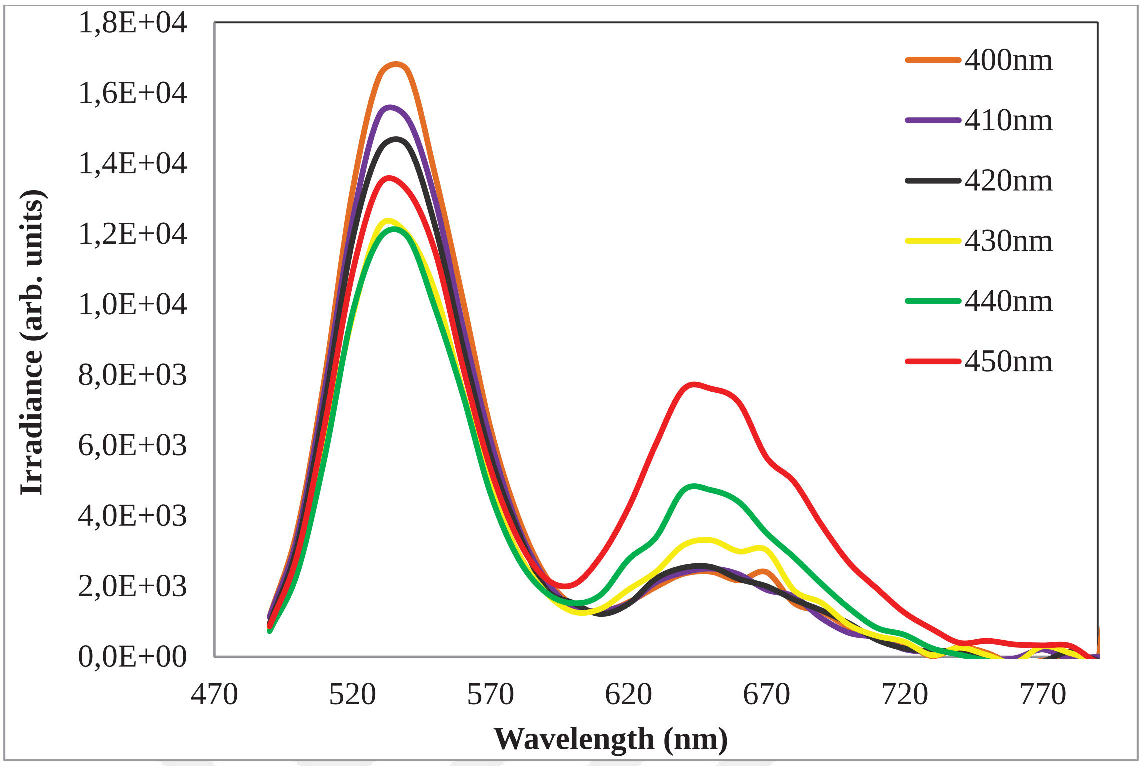

Figure 18 – Emission spectra under different excitation wavelengths

After determining the PL characteristics of RG phosphors, we have decided to use blue LEDs of 444nm, which is commercially available at the moment.

3.2.2. Preparation of remote phosphor light conversion layers

In this thesis, blended phosphor layers have been produced which can provide wide colour gamut by implementing remote phosphor technology. Phosphors are inorganic complex materials containing the rare earth elements generally from actinide and lanthanide groups. Phosphors in LED applications are used as composite materials. These materials are prepared by combining at least two different components with different properties. In phosphor containing composites, polymers are generally used as a host material for phosphors. These composites are widely used in the field of optics, optoelectronics, and exhibit adhesive or protective properties for optic elements. Transparency and stability characteristics of transparent polymers depend on the temperature. In addition, mechanical properties are critical in composite materials [16].

The type of polymer used in light converters is extremely important for the reliability and durability of phosphor containing composite materials.

The elemental composition and crystal structure of phosphors should be determined carefully in order to improve the performance of final composite structure. Due to the incorporation of phosphor material in the polymer, a composite structure with desired optic properties can be obtained by analysing optical properties such as excitation and emission spectrum, absorption, quantum yield,… etc.

Yellow phosphor with blue LED (cerium-doped yttrium aluminium garnet, YAG: Ce) is widely used in lighting applications to obtain white light. However, the emission spectrum of this phosphor spectrum is broad. For this reason, implementation of this phosphor is not suitable for wide colour gamut solutions. If red and green emitting phosphors are used instead of this phosphor, wider colour gamut solutions may be possible.

In this thesis, colour converters under GaN blue LED excitation are studied. Critical parameters such as phosphor polymer composition ratios, photoluminescence, and colour gamut have been investigated. In table 2, the characteristics of phosphors (from Mitsubishi Chemical) which can be used for wide colour gamut solutions are listed.

Table 2 - The properties of phosphors used in this thesis

Phosphor	*FWHM (nm)*	*λp (nm)*	*L (%)*	*Particle Size (μm)*
$(Si,Al)_3(O,N)_4$:Eu	53	542	127	21.8
$(Y,Ge)_3(Al,Ga)_5O_{12}$	108	535	127	15
$Lu_3Al_5O_{12}$:Ce	105	540	N/A	15
$CaAlSiN_3$:Eu	88	659	73	16
$(Sr,Ca)AlSiN_3$:Eu	76	623	137	11
$K_2SiF_6:Mn_4$+	5	632	N/A	25

In this study, Eu doped $(Si, Al)_3(O, N)_4$ (β-SiAlON) is selected for the green converter, since the FWHM value is approximately half of the others. When the FWHM value is small, a wider colour gamut can be obtained that reduce effect of colour shifting.

For the red converter, K_2SiF_6: Mn4+ (KSF) is more suitable, since it has narrow FWHM. However, we had to choose $CaAlSiN_3$ (CASN) phosphor, because it was commercially available at the moment.

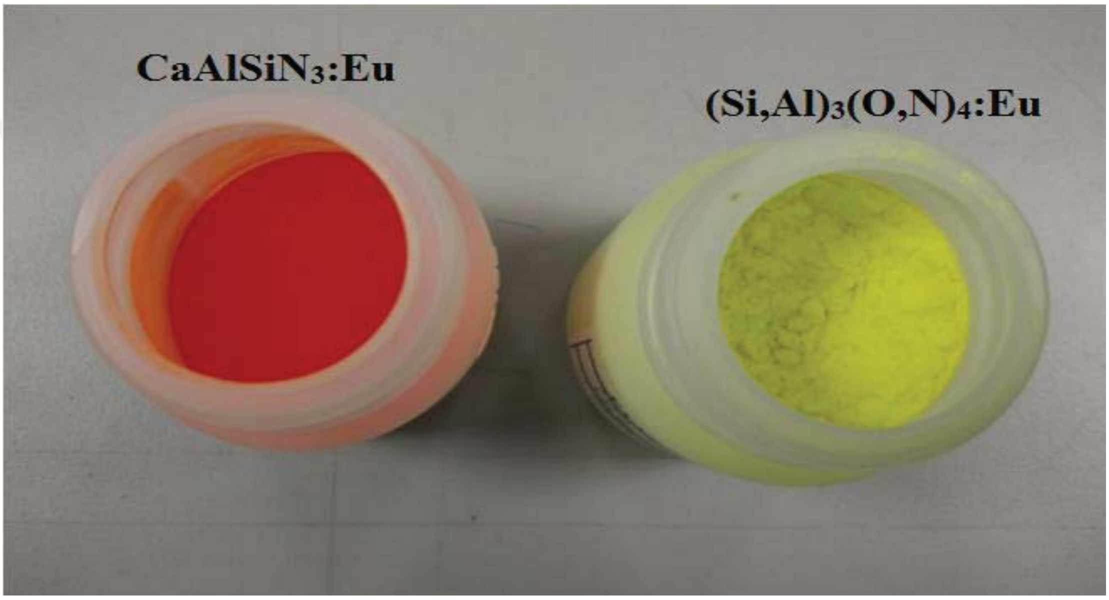

Figure 19 - $CaAlSiN_3$:Eu and $(Si,Al)_3(O,N)_4$:Eu phosphors

Suitable polymers for phosphor composites should have good optical, structural and thermal properties. In this study, we have preferred methyl phenyl silicone ($(C_7H_8OSi)_n$) (Dow Corning OE-7620). This silicone was mixed with phosphor blend (from Mitsubishi Chemical). The 90.9% of the composite is methyl phenyl silicone and the 9.1% of it is the mixture of $(Si, Al)_3(O, N)_4$: Eu and $CaAlSiN_3$: Eu phosphors. The phosphor to phosphor ratio is determined experimentally by iteration.

After the phosphor and polymer mixture is prepared, it is poured down to a polystyrene diffuser plate. Then, this mixture was flattened and distributed over the whole diffuser plate surface by the Dr. Blade [17].

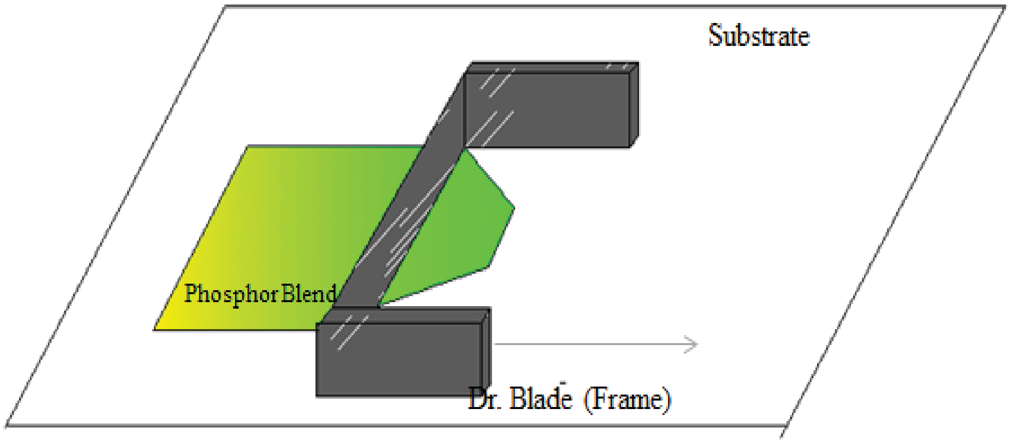

Figure 20 - Principle of the Dr. Blade coating method

Figure 20 shows the blade structure passing over the fluid by a Dr. Blade frame. The layer thickness is also adjusted by the gap between the doctor blade and the substrate as shown in Figure 21 [18].

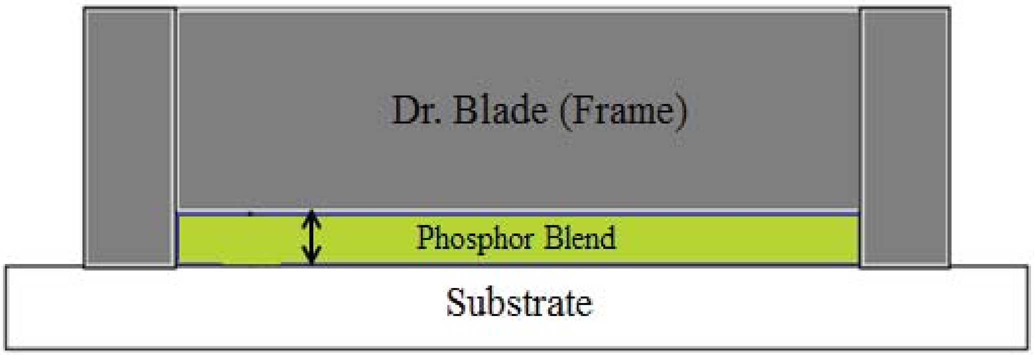

Figure 21 - Wet layer thickness control method

After the samples were prepared with this method, two stage curing process was applied. Initial curing was carried out at 70°C for one hour, later an additional curing was done at 120° C for half an hour.

Figure 22 – Sample preparation

The diffuser plate used in this thesis is made of polystyrene which has a glass transition temperature of 100°C [19]. For this reason, the curing process was repeated by preparing the samples by applying one hour at 70°C and an additional half an hour at 80°C. We have coated diffuser plates with 0.55 and 0.65 mm light converting composite layers.

3.2.3. Optical measurement devices

3.2.3.1 SR-Spectroradiometer

The spectroradiometric device, SR-LEDW spectroradiometer of Topcon Company, was used in this study is used for the measurement of colour coordinates and brightness. To be able to measure accurately, the device is positioned 50 cm from the system (Figure 23). Since the luminosity of the system decreases until the LED chip reaches thermal equilibrium; measurements were taken after the backlight unit was operated for 1 hour [20].

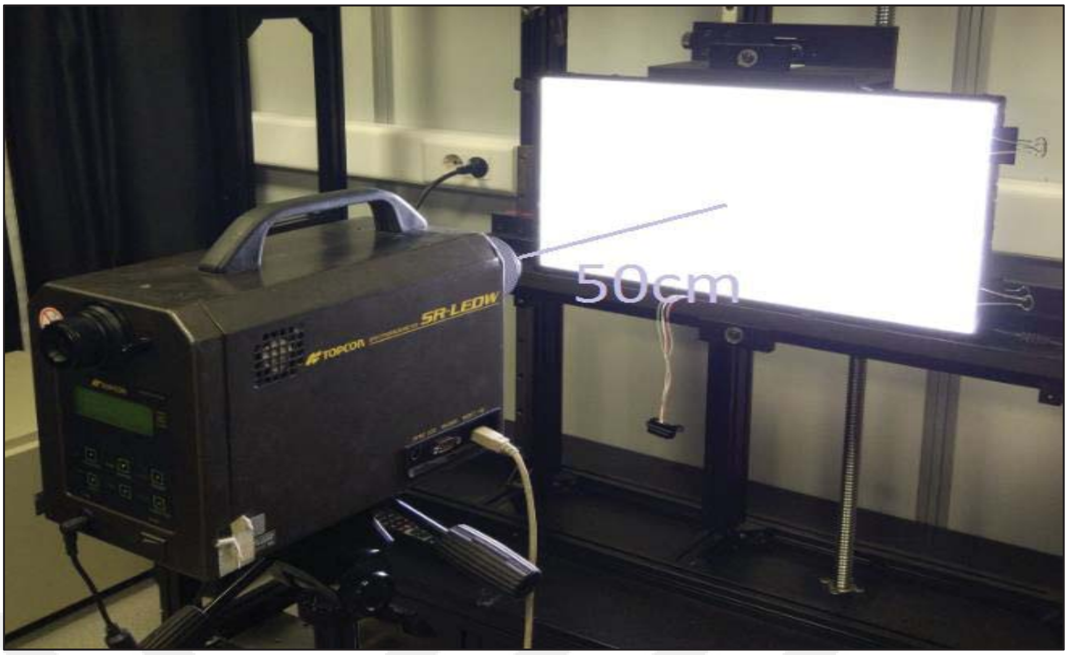

Figure 23 - Spectroradiometer measurement system

According to the measured colour coordinates, colour gamut is calculated.

3.2.3.2 PL Spectrum

The PL spectrum shows excitation and emission spectra in figure 24. The left hand side belongs to excitation; the right hand side shows the emission spectrum.

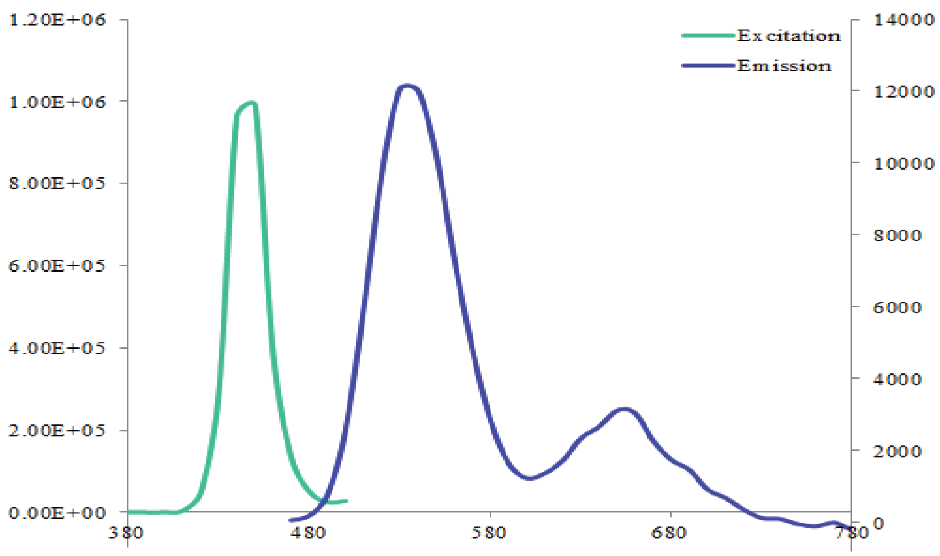

Figure 24 - Excitation and Emission spectrum of PL spectroscopy

3.2.3.3 Spectroradiometer

A spectroradiometer (of JETI Company) is used measured the luminous intensity and colour coordinates as well as the irradiance against the wavelength. The blended phosphor coatings on diffuser plates with 0.55 and 0.65mm coating thickness were characterized by using a down-light armature structure (Figure 25).

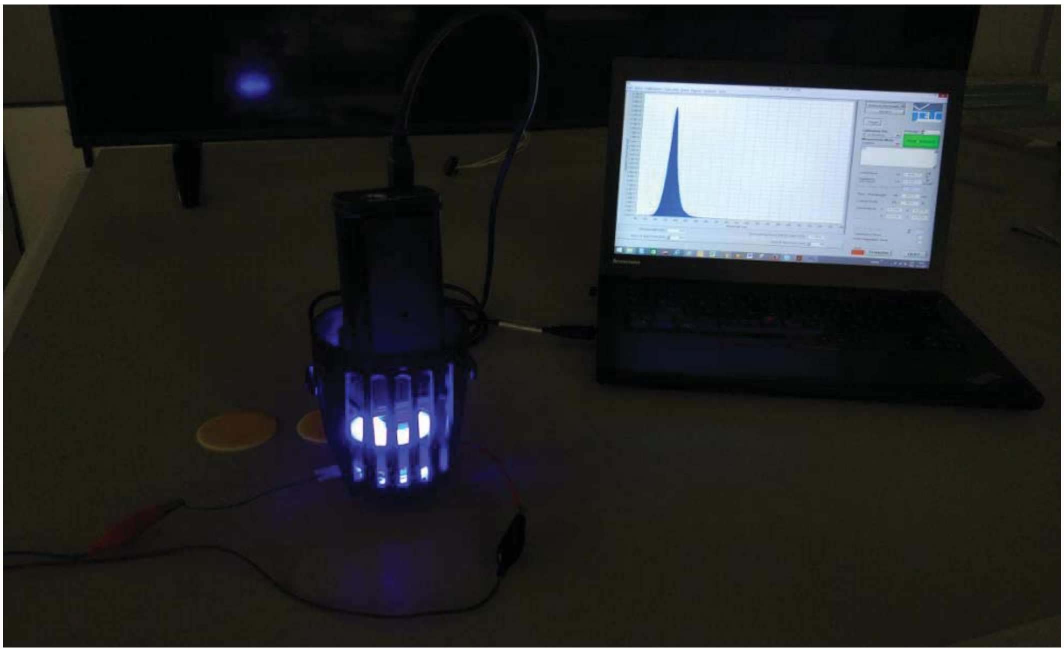

Figure 25 - Measurement system based on downlight set up

3.2.4. On-chip light conversion mechanism

3.2.4.1 Yellow Phosphor

As described in section 3.2.1, we have implemented yellow phosphor converted on-chip LED structures in our backlight design for comparison with the low-cost standard displays. The backlight unit was operated for 1 hour to reach thermal equilibrium. Then, the measurements were performed with the spectroradiometer from the centre of the backlight unit. The irradiance spectrum with respect to wavelength was obtained from this measurement. This spectrum was used to obtain the colour gamut, centre brightness, and colour coordinate values by using the CF spectrum of the 65" AUO UHD LCD panel.

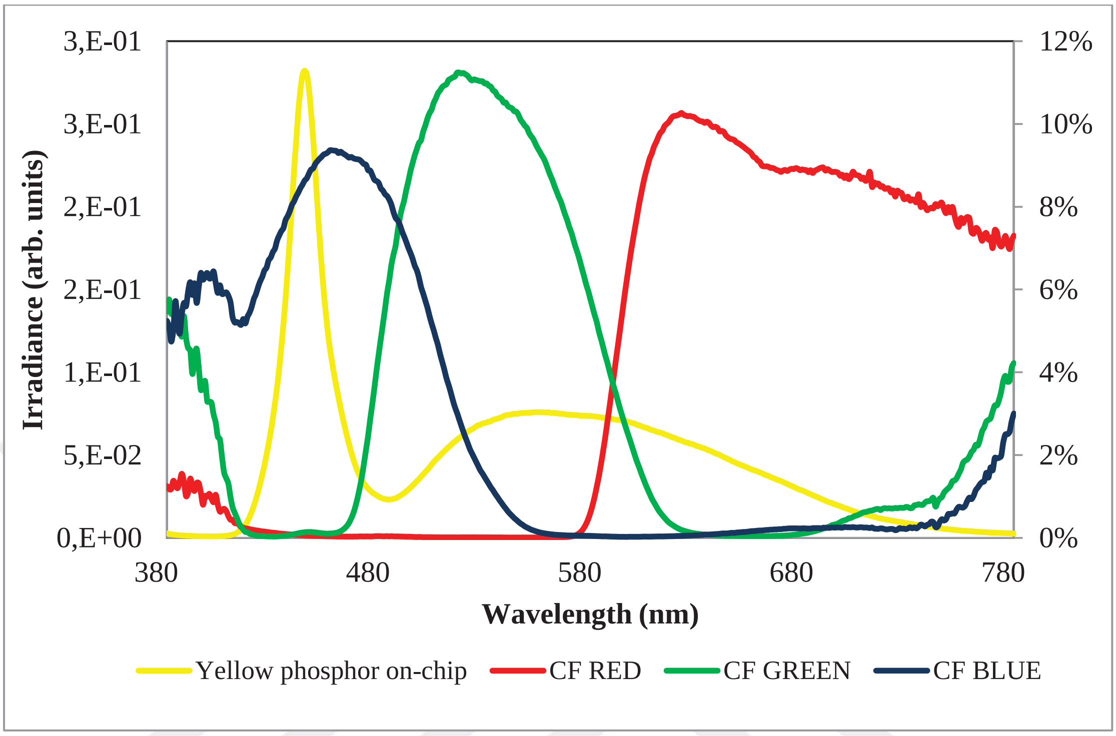

Figure 26 - BLU spectrum of yellow phosphor on chip with AUO CF

Table 3 - The colour coordinates of the panel with RG phosphor on chip LED

		CIE1931			CIE1976	
		x	y	L (nit)	u'	v'
Panel	R	0.653	0.330	96.7	0.461	0.525
	G	0.307	0.614	342	0.126	0.567
	B	0.152	0.061	51.4	0.178	0.159
NTSC	R	0.670	0.330	**DCI**	0.496	0.526
	G	0.210	0.710		0.099	0.578
	B	0.140	0.080		0.175	0.158

By using the BLU spectrum and the colour filter spectrum, the colour coordinates and luminescence values of the blue, green and red spectra were calculated in CIE 1931 colour space. By calculating the CIE 1976 colour space equivalents of these values, the colour gamut values are found in both the NTSC and DCI colour gamut standards (Table 3). In addition, white luminescence value of the panel was obtained by adding the blue, green and red luminescence values.

Table 4 - The results of the designed panel with yellow phosphor on-chip LED

	Gamut (NTSC)	*Gamut (DCI)*	*White L (nit)*
Panel	74%	83%	489

The colour gamut of the yellow phosphor on-chip LED TVs is around %72 in NTSC standard. However, the brightness value of this panel is considerably higher than the brightness value of general TV products in the market since the DBEF is used in this structure.

The spectrum of blue, green and red of the BLU should be compatible with the CF spectrum of the LCP to sustain wide colour gamut. Since on-chip yellow phosphor solution does not produce separate green and red bands, these results in narrowing of colour gamut values to 74% in NTSC and to 83% in DCI-P3.

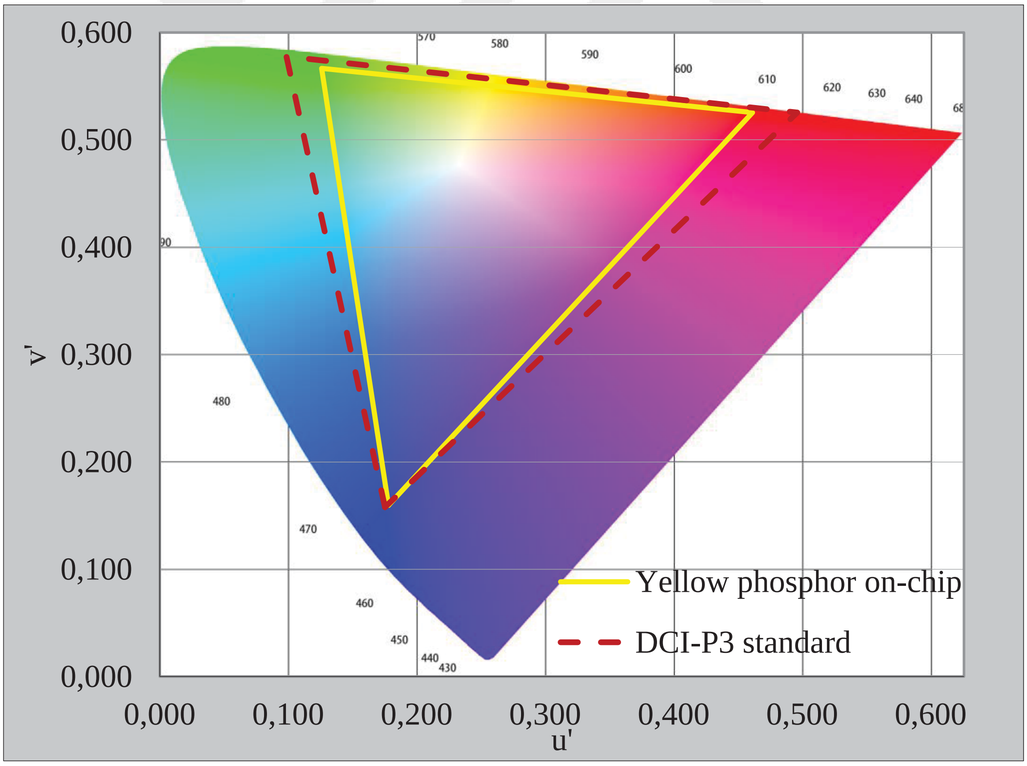

Figure 27 - Yellow phosphor on-chip colour gamut area at CIE 1976 colour space

In figure 27, the colour triangle of the panel is compared with that of the DCI-P3 standard. Here the blue corner of the panel and that of DCI-P3 triangle match each other.

If a blue chip with longer wavelength was selected, the blue u' coordinate of the panel would decrease and the v' coordinate would increase, and this consequently would narrow down the gamut further.

As can be seen in figure 26, approximately 1/4 of the area of the red region of the BLU spectrum overlaps with that of the colour filter's green region. Because of this, green colour coordinate of the panel shifts towards the red region. Similarly, approximately 1/3 of the area of the green region of the BLU spectrum overlaps with that of the colour filter's red region. For this reason, red colour colour coordinate of the panel to shift towards the green region.

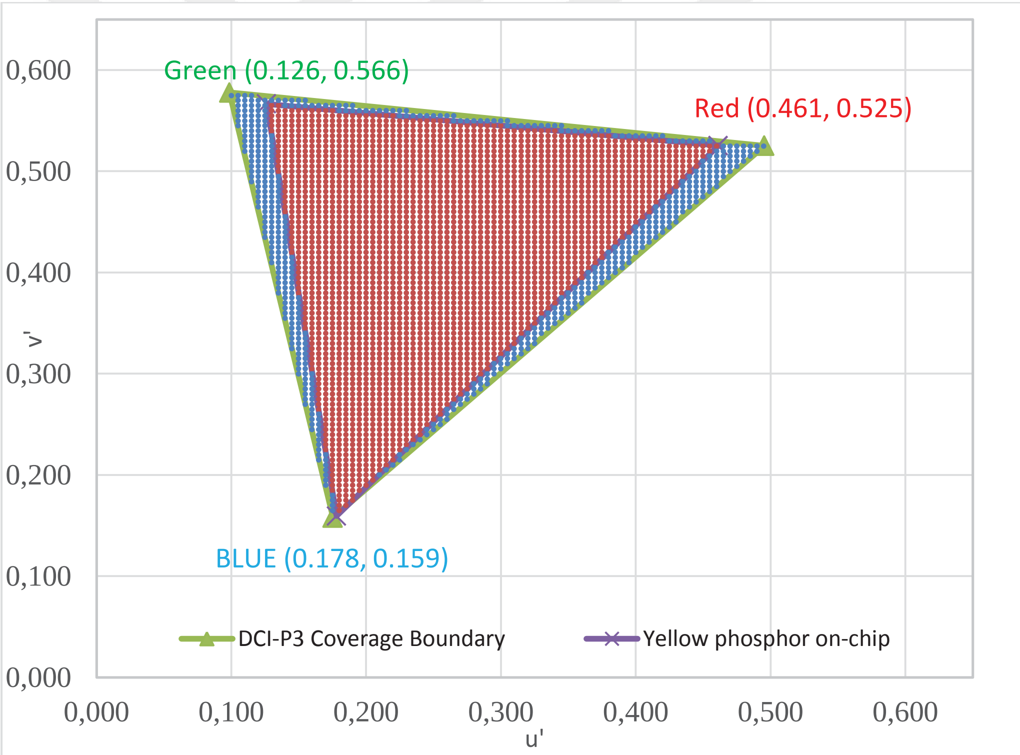

Figure 28 - The colour gamut coverage of the designed panel with yellow phosphor on-chip LED

Because of these colour shifts, approximately 83% of the DCI-P3 standard triangle had been covered with this yellow phosphor on-chip design (Figure 28).

3.2.4.2 RG Phosphor

As described in section 3.2.1, we implemented RG phosphor converted on-chip LED structures in our backlight design. To test critical performance parameters of our display design, the backlight unit was operated for 1 hour to reach thermal equilibrium. Then, the measurements were performed with the spectroradiometer from the centre of the backlight unit. The irradiance spectrum with respect to wavelength was obtained from this measurement. This spectrum was used to obtain the colour gamut, centre brightness, and colour coordinate values by using the CF spectrum of the 65" AUO UHD LCD panel.

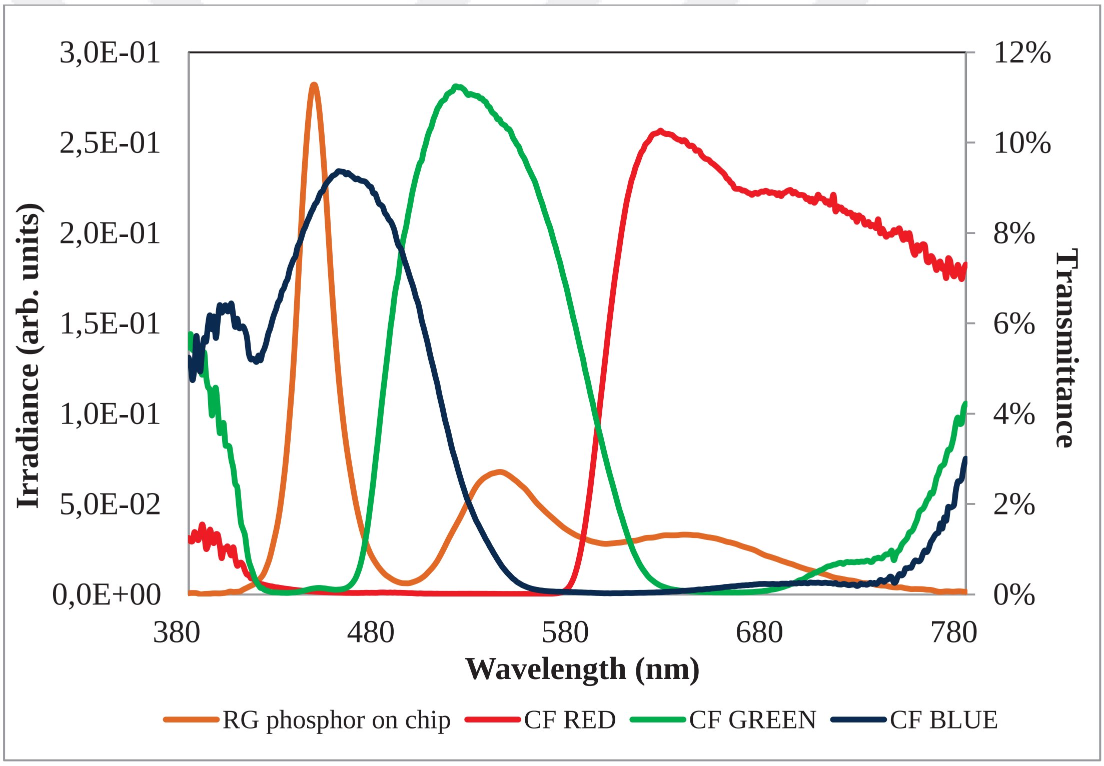

Figure 29 - BLU spectrum of RG phosphor on chip with AUO CF

By using the BLU spectrum and the colour filter spectrum, the colour coordinates and luminescence values of the blue, green and red spectra were calculated in CIE 1931 colour space. By calculating the CIE 1976 colour space equivalents of these values, the colour gamut values are found in both the NTSC and DCI colour gamut standards (Table

5). In addition, white luminescence value of the panel was obtained by adding the blue, green and red luminescence values.

Table 5 - The colour coordinates of the panel with RG phosphor on chip LED

		CIE1931			**CIE1976**	
		x	y	L (nit)	u'	v'
Panel	R	0.650	0.316	47.7	0.473	0.518
	G	0.287	0.641	233.4	0.113	0.57
	B	0.156	0.043	36.3	0.195	0.121
NTSC	R	0.670	0.330	**DCI**	0.496	0.526
	G	0.210	0.710		0.099	0.578
	B	0.140	0.080		0.175	0.158

Since the green and red FWHM of RG phosphor on-chip structure is broad, this prevents colour gamut to be widened. The luminance value is 35% lower than that of yellow phosphor on-chip structure (Table 6).

Table 6 - The results of the panel with RG phosphor on chip LED

	Gamut (NTSC)	*Gamut (DCI)*	*White L (nit)*
Panel	82%	89%	316

A shift had been observed in the coordinates of all three primary colours. Because of this, there is no significant increase in colour gamut. The blue filter and BLU spectrum overlaps between 630 and 740 nm, so the blue shift to red region has been observed. The overlap of the green filter with the regions between 610 to 630 nm and 680 to740 nm of the BLU spectrum is responsible for the shift from green to red. The red colour had been shifted to the green region, because the BLU spectrum overlaps with the red colour filter between 570nm and 610nm (Figure 30).

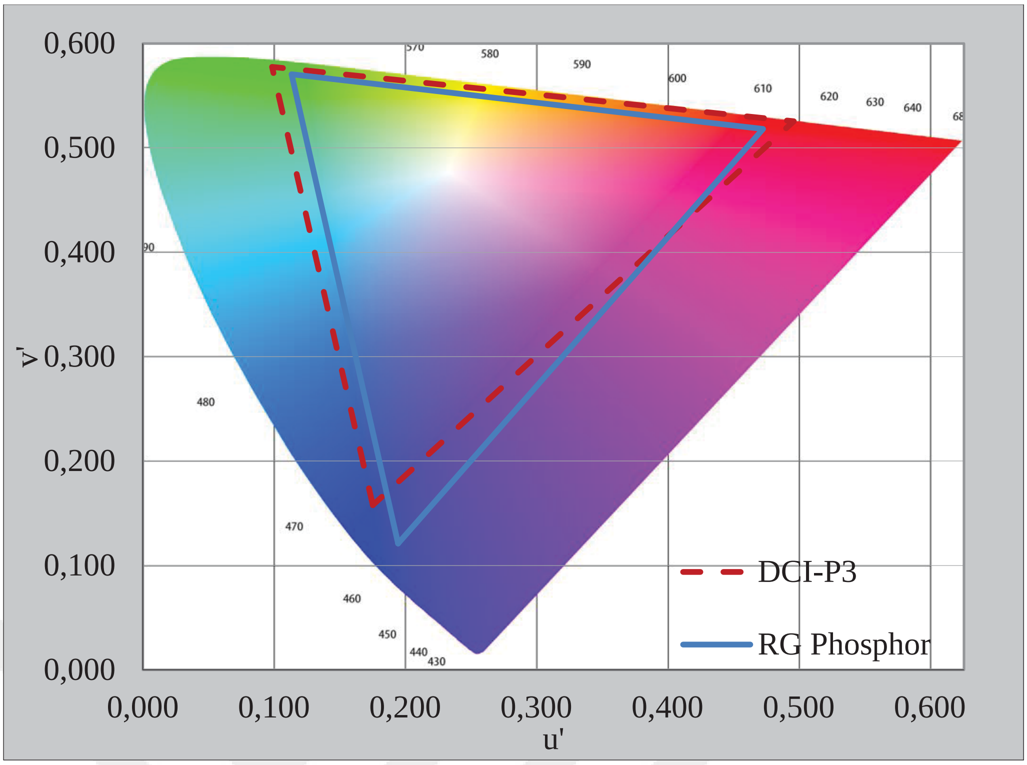

Figure 30 - Colour gamut area of the panel with RG phosphors on-chip LED

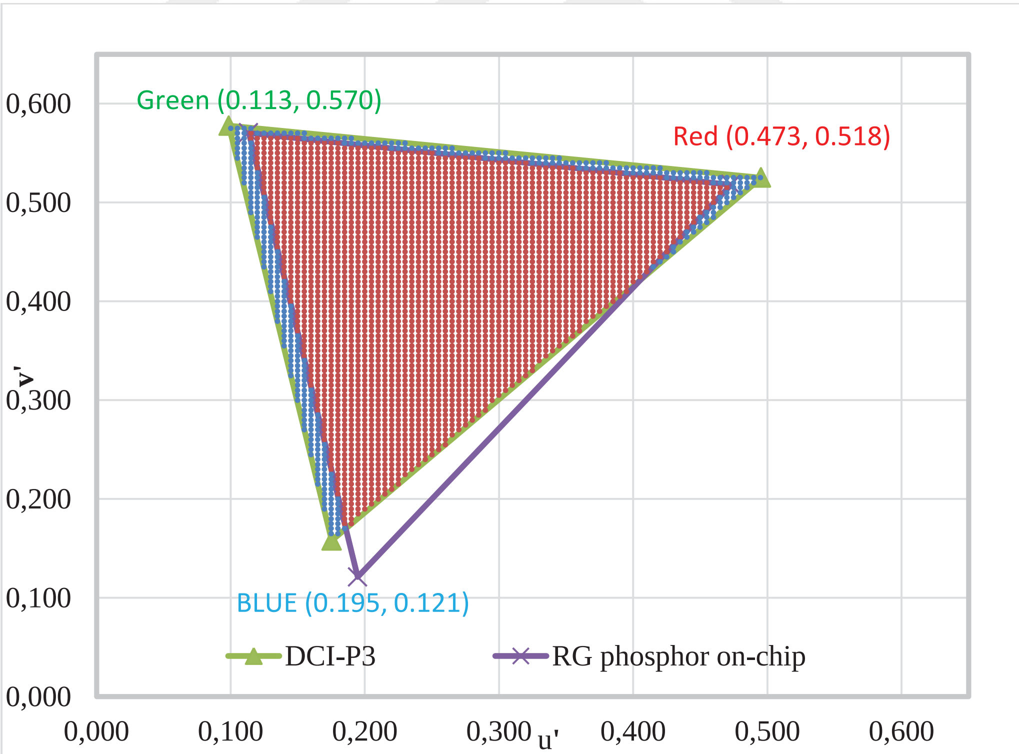

Figure 31 - Colour gamut coverage of RG on-chip LED bar in CIE 1976 colour space

Because of these colour shifts, approximately 89% of the DCI-P3 standard triangle had been covered with RG phosphor on-chip design (Figure 31).

3.2.4.3 KSF phosphor

As described in section 3.2.1, we have implemented KSF phosphor converted on-chip LED structures. To test critical performance parameters of our display design, the backlight unit was operated for 1 hour to reach thermal equilibrium. Then, the measurements were performed with the spectroradiometer from the centre of the backlight unit. The irradiance spectrum with respect to wavelength was obtained from this measurement. This spectrum was used to obtain the colour gamut, centre brightness, and colour coordinate values by using the CF spectrum of the 65" AUO UHD LCD panel.

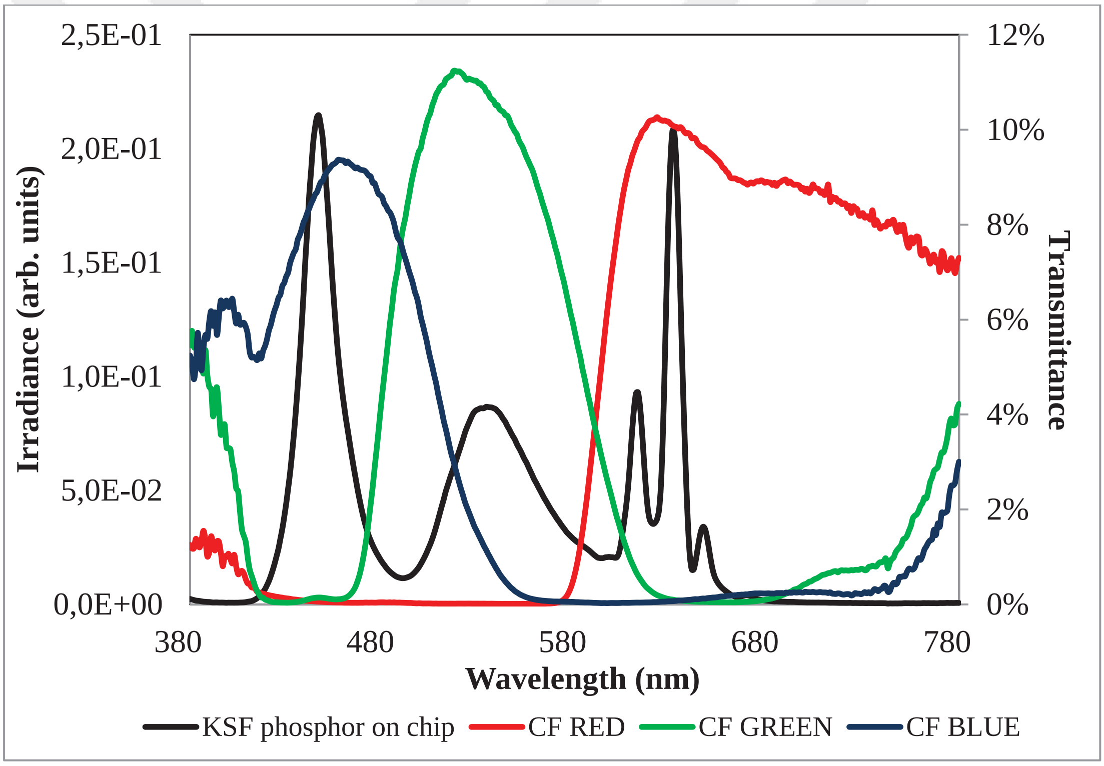

Figure 32 - BLU spectrum of KSF phosphor on chip with AUO CF

By using the BLU spectrum and the colour filter spectrum, the colour coordinates and luminescence values of the blue, green and red spectra were calculated in CIE 1931 colour space. By calculating the CIE 1976 colour space equivalents of these values, the colour gamut values were found in both the NTSC and DCI colour gamut standards

(Table 7, 8). In addition, white luminescence value of the panel was obtained by adding the blue, green and red luminescence values.

Table 7 - The colour coordinates of the panel with KSF phosphor on chip LED

		CIE1931			**CIE1976**	
		x	y	L (nit)	u'	v'
Panel	R	0.675	0.311	82.3	0.501	0.52
	G	0.262	0.661	288.4	0.101	0.572
	B	0.152	0.066	45.2	0.174	0.171
NTSC	R	0.670	0.330	**DCI**	0.496	0.526
	G	0.210	0.710		0.099	0.578
	B	0.140	0.080		0.175	0.158

Table 8 - The results of the panel with KSF phosphor on chip LED

	Gamut (NTSC)	*Gamut (DCI)*	*White L (nit)*
Panel	90%	95%	416

The colour gamut of this KSF on-chip structure is wider than the RG phosphor on-chip structure. However, the centre white luminance value of this panel was approximately 15% lower than the panel with yellow phosphor on-chip.

The FWHM of KSF phosphor used in this display design is approximately 5 nm. At the moment, among the phosphors used in LED industry, this corresponds to the lowest value [21].

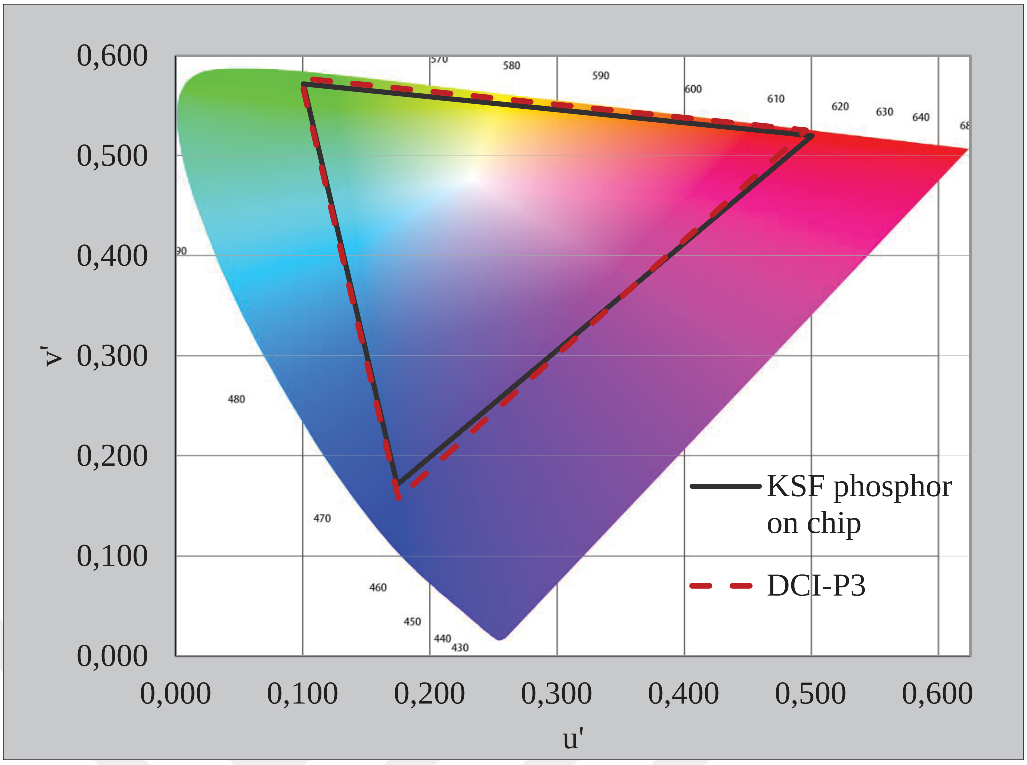

Figure 33 - Colour gamut area of the panel with KSF phosphor on chip LED

The gamut of the display with KSF phosphor on-chip design does not cover the DCI-P3 standard triangle one to one, since it slightly shifts to blue and green regions. The BLU spectrum and green colour filter overlaps between 560 and 620nm, because of this the shifts from green to red region was observed. This region corresponds to one-tenth of the BLU spectrum which overlaps with the green filter region. Therefore, the shift is lower and colour gamut is wider than the RG and yellow phosphor on-chip designs.

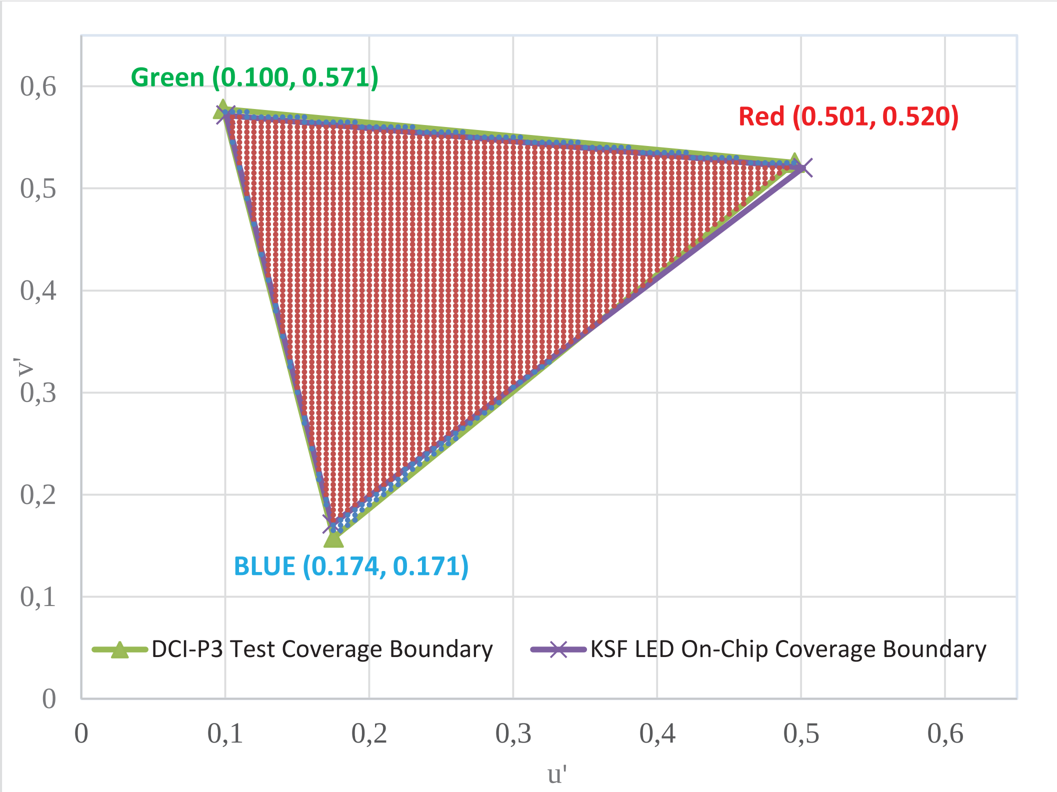

Figure 34 - Colour gamut coverage of on-chip KSF LED Bar at CIE 1976 colour space

Because of these slightly colour shifts, approximately 95% of the DCI-P3 standard triangle had been covered with RG phosphor on-chip design (Figure 34).

3.2.5.1 CdSe Quantum Dot Film

As described in section 3.2.1, we have implemented CdSe QD film in our backlight design. To test critical performance parameters of our display design, the backlight unit was operated for 1 hour to reach thermal equilibrium. Then, the measurements were performed with the spectroradiometer from the centre of the backlight unit. The irradiance spectrum with respect to wavelength was obtained from this measurement. This spectrum was used to obtain the colour gamut, centre brightness, and colour coordinate values by using the CF spectrum of the 65" AUO UHD LCD panel.

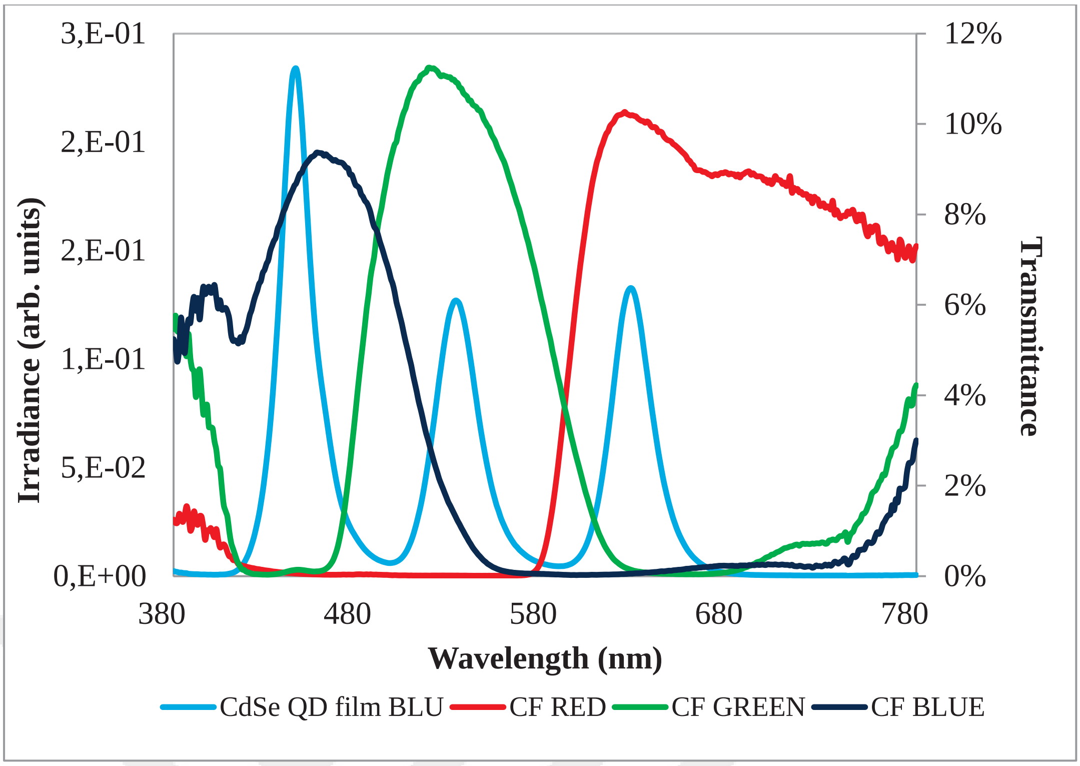

Figure 35 - BLU with CdSe QD film spectrum and AUO CF

By using the BLU spectrum and the colour filter spectrum, the colour coordinates and luminescence values of the blue, green and red spectra were calculated in CIE 1931 colour space. By calculating the CIE 1976 colour space equivalents of these values, the colour gamut values are found in both the NTSC and DCI colour gamut standards (Table 9). In addition, white luminescence value of the panel was obtained by adding the blue, green and red luminescence values.

Table 9 - The colour coordinates of the panel with CdSe QD film

		CIE1931			CIE1976	
		x	y	L (nit)	u'	v'
Panel	R	0.682	0.302	79.3	0.519	0.517
	G	0.213	0.706	251.5	0.077	0.575
	B	0.155	0.062	44.1	0.18	0.162
NTSC	R	0.670	0.330	**DCI**	0.496	0.526
	G	0.210	0.710		0.099	0.578
	B	0.140	0.080		0.175	0.158

Since the white luminance measurements result in 24% higher values than our initial design target, the CdSe QD film provide better results than the other phosphor based designs. This is mostly because the narrow bandwidth emissions from the green (FWHM ~ 28nm) and red (FWHM ~ 25 nm). Colour gamut values are 103% for NTSC and 97% for DCI-P3 standards (Table 10).

Table 10 - Colour gamut and white luminance values of panel with CdSe QD film

	Gamut (NTSC)	*Gamut (DCI)*	*White L (nit)*
Panel	103%	97%	373

The colour triangle of panel with CdSe QD film is wider than the DCI-P3 standard (figure 36). However, it is seen that the panel green is closer to the blue area of the standard.

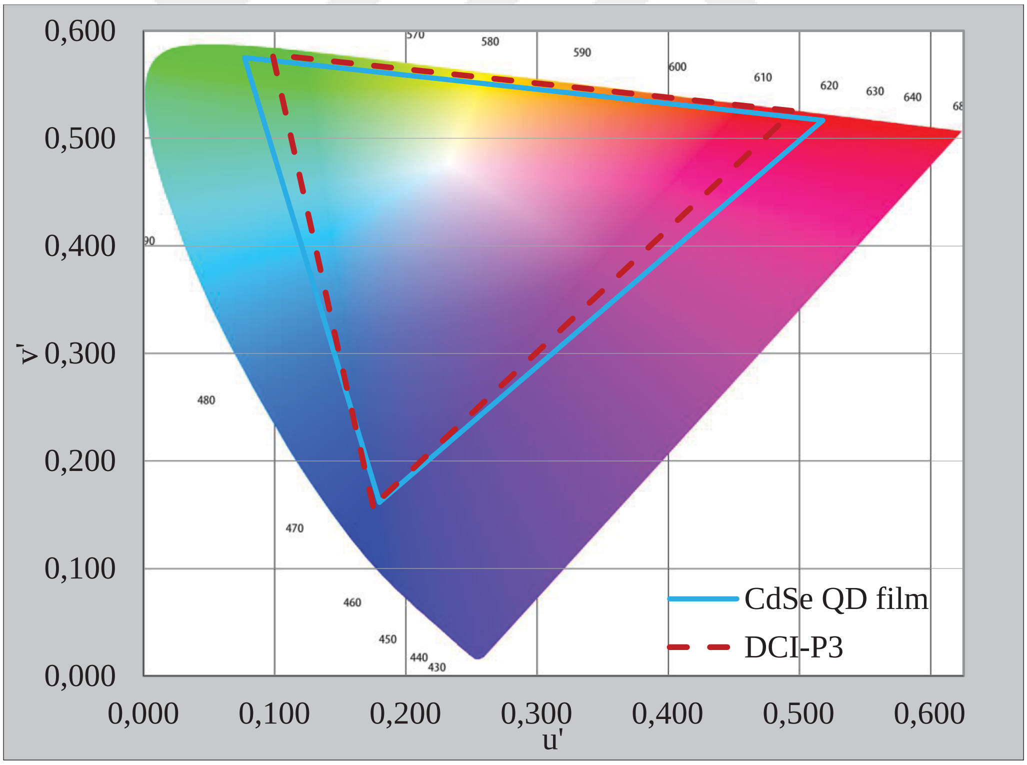

Figure 36 - Colour gamut area of the panel with CdSe QD film in CIE 1976 colour space

The green colour filter and BLU spectrum overlaps between 470 and 490 nm which is in the blue region, so this caused a shift. In addition, the panel red is close to the blue region of the standard. For this reason, a shift from red to blue is observed.

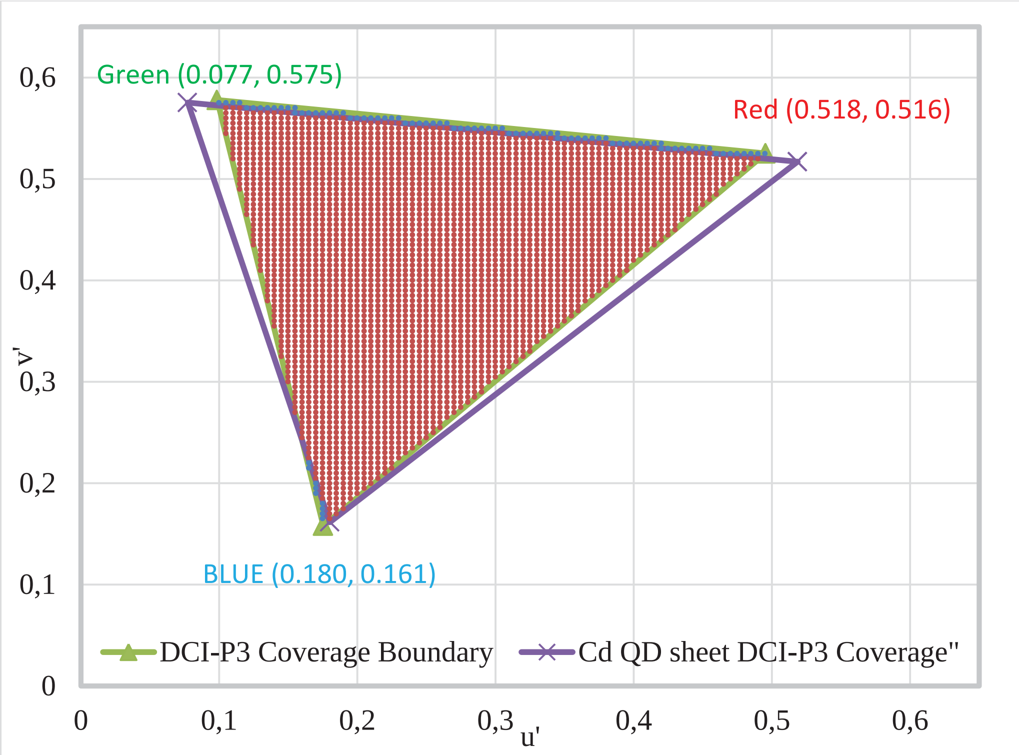

Figure 37 - Colour gamut coverage of panel with CdSe QD film

Because of these slightly colour shifts, approximately 97% of the DCI-P3 standard triangle had been covered with RG phosphor on-chip design (Figure 37).

3.2.5.2 InP Quantum Dot Film Results

As described in section 3.2.1 we have implemented InP QD film in our backlight design. To test critical performance parameters of our display design, the backlight unit was operated for 1 hour to reach thermal equilibrium. Then, the measurements were performed with the spectroradiometer from the centre of the backlight unit. The irradiance spectrum with respect to wavelength was obtained from this measurement. This spectrum was used to obtain the colour gamut, centre brightness, and colour coordinate values by using the CF spectrum of the 65" AUO UHD LCD panel.

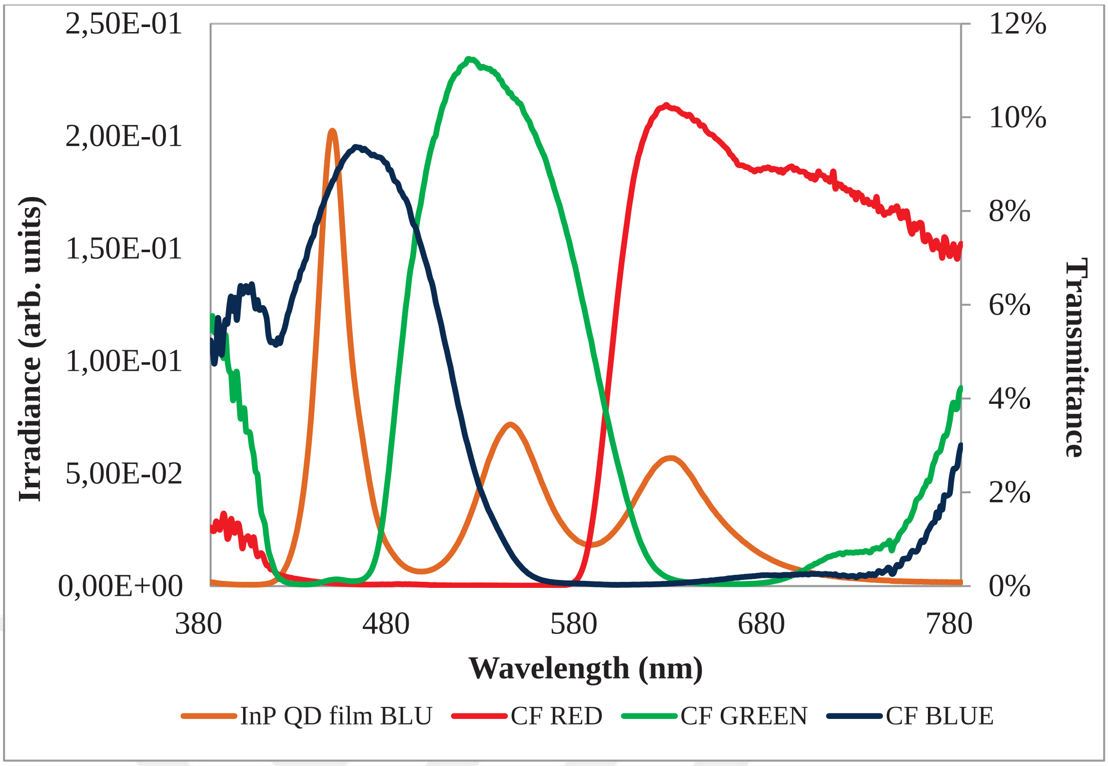

Figure 38 - BLU spectrum of InP QD film with AUO CF

By using the BLU spectrum and the colour filter spectrum, the colour coordinates and luminescence values of the blue, green and red spectra were calculated in CIE 1931 colour space. By calculating the CIE 1976 colour space equivalents of these values, the colour gamut values are found in both the NTSC and DCI colour gamut standards (Table 11). In addition, white luminescence value of the panel was obtained by adding the blue, green and red luminescence values.

Table 11 - The colour coordinates of the panel with InP QD film

		CIE1931			CIE1976	
		x	y	L (nit)	u'	v'
Panel	R	0.667	0.315	61.6	0.49	0.521
	G	0.278	0.655	206.6	0.108	0.572
	B	0.156	0.05	30.1	0.189	0.137
NTSC	R	0.670	0.330	DCI	0.496	0.526
	G	0.210	0.710		0.099	0.578
	B	0.140	0.080		0.175	0.158

Table 12 - Colour gamut and white luminance values of panel with InP QD film

	Gamut (NTSC)	*Gamut (DCI)*	*White L (nit)*
Panel	87%	93%	297.2

Figure 38 shows the green and red regions are separated from each other. The green FWHM of InP QD film is around 42nm and the red FWHM is around 57 nm. The colour gamut value is 87% in NTSC and 93% in DCI-P3 (Table 12).

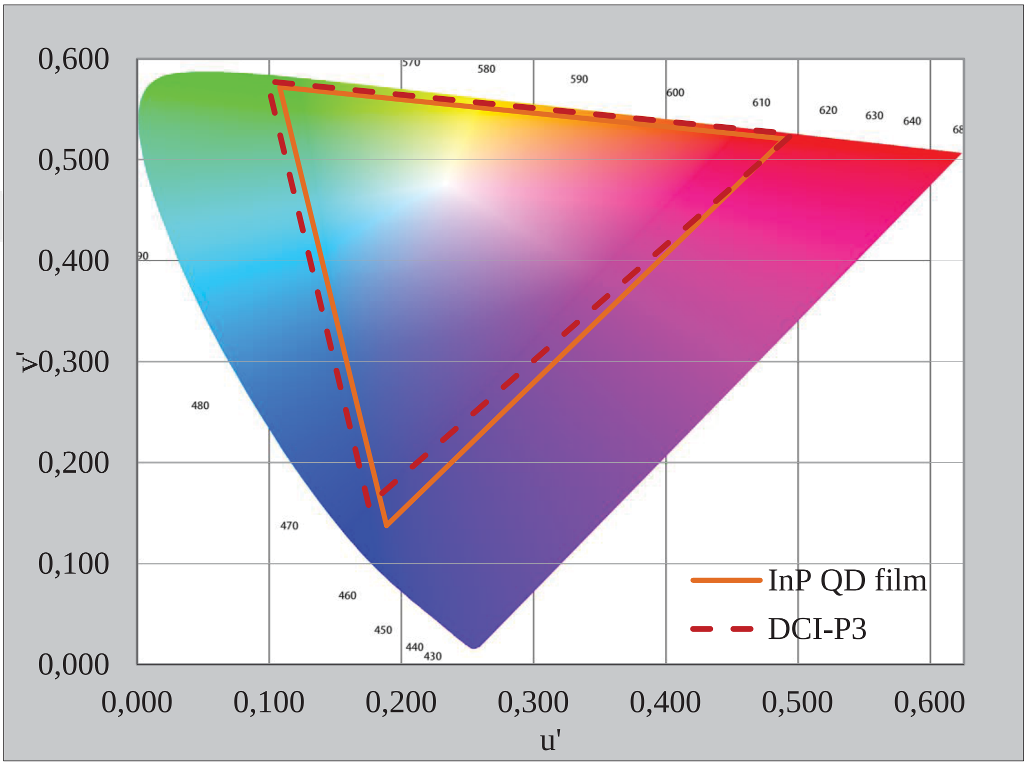

Figure 39 - Colour gamut area of panel with InP QD film

The colour gamut of the panel designed with InP QD film is narrower than the ones with CdSe QD films. In figure 39, the blue of InP QD film shifts to the red and the green of InP QD film shifts to red. As can be seen from figure 38, since the BLU spectrum and blue colour filter overlaps between 650 and 734 nm, the blue colour has shifts to red. In addition, the green colour filter and BLU spectrum overlaps between 560 nm to 620nm and from 574 nm to 734 nm. For this reason, the colour shifts from green to red is observed.

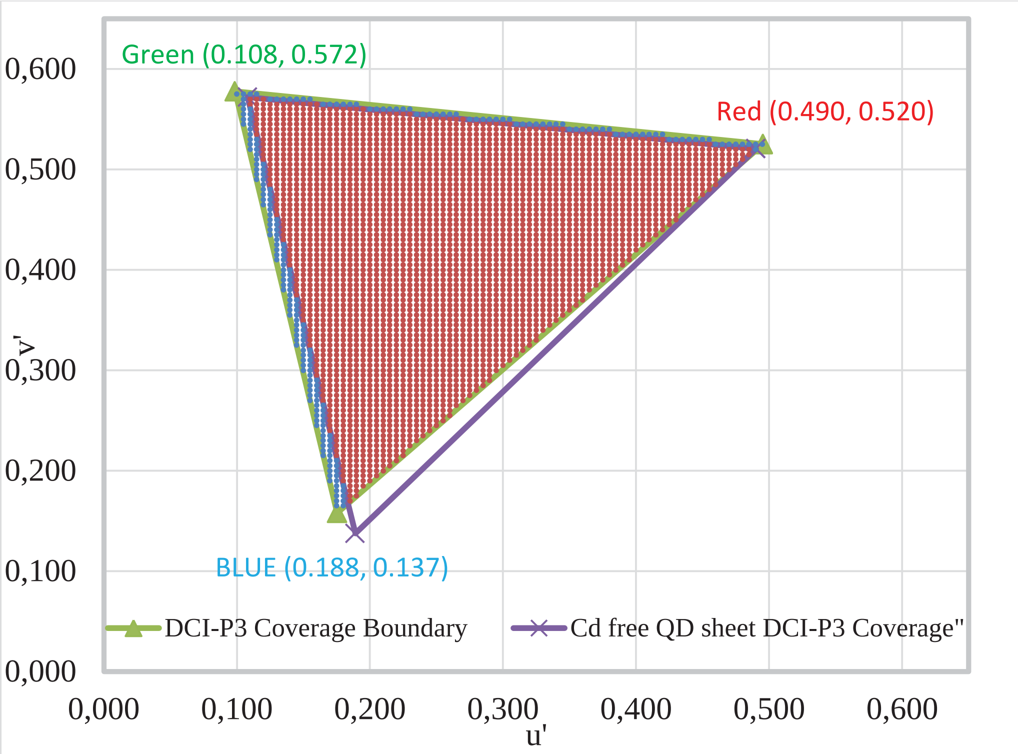

Figure 40-Colour gamut coverage of panel with InP QD film at CIE 1976 colour space

Because of these colour shifts, approximately 97% of the DCI-P3 standard colour triangle had been covered with RG phosphor on-chip design (Figure 40).

3.2.5.3 RG Phosphor Film

As described in section 3.2.1, we have implemented RG phosphor film in our backlight design. To test critical performance parameters of our display design, the backlight unit was operated for 1 hour to reach thermal equilibrium. Then, the measurements were performed with the spectroradiometer from the centre of the backlight unit. The irradiance spectrum with respect to wavelength was obtained from this measurement. This spectrum was used to obtain the colour gamut, centre brightness, and colour coordinate values by using the CF spectrum of the 65" AUO UHD LCD panel.

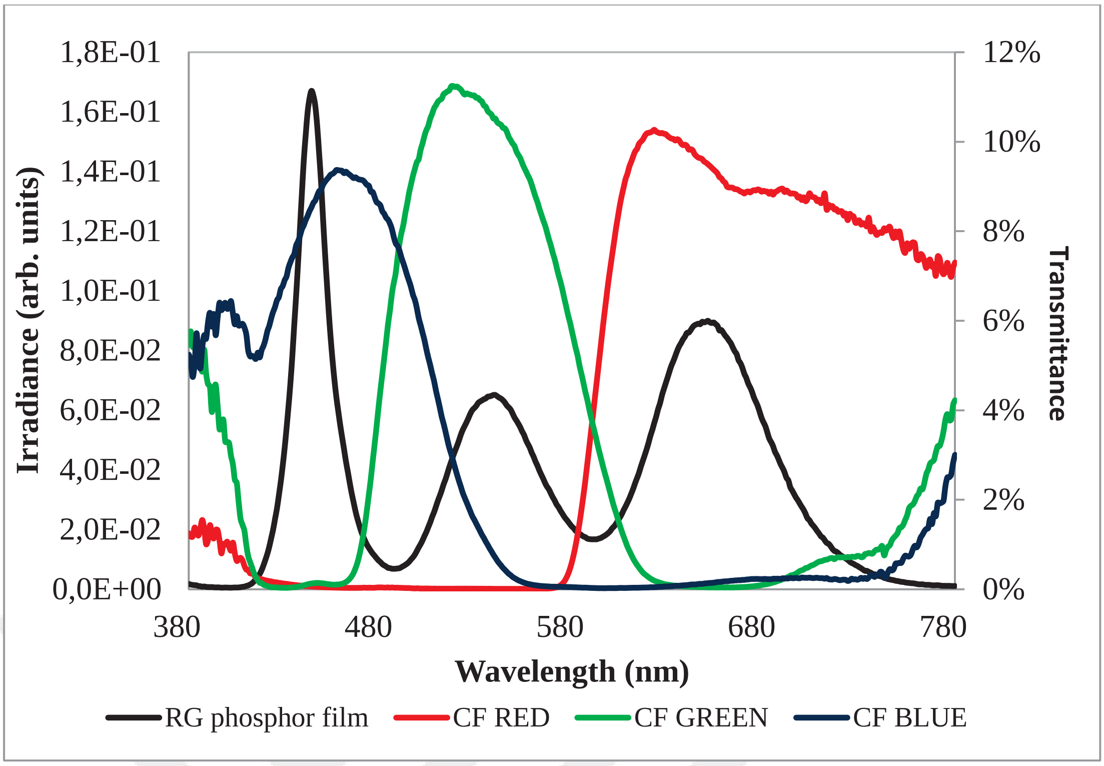

Figure 41 - BLU spectrum of RG phosphor film with AUO CF

By using the BLU spectrum and the colour filter spectrum, the colour coordinates and luminescence values of the blue, green and red spectra were calculated in CIE 1931 colour space. By calculating the CIE 1976 colour space equivalents of these values, the colour gamut values are found in both the NTSC and DCI colour gamut standards (Table 13). In addition, white luminescence value of the panel was obtained by adding the blue, green and red luminescence values.

Table 13 - The colour coordinates of the panel with RG phosphor film

		CIE1931			CIE1976	
		x	y	L (nit)	u'	v'
Panel	R	0.684	0.303	68.1	0.52	0.517
	G	0.268	0.665	220.3	0.102	0.573
	B	0.156	0.064	32	0.18	0.167
NTSC	R	0.670	0.330	**DCI**	0.496	0.526
	G	0.210	0.710		0.099	0.578
	B	0.140	0.080		0.175	0.158

Table 14 - Colour gamut and white luminance values of panel with RG phosphor film

	Gamut (NTSC)	*Gamut (DCI)*	*White L (nit)*
Panel	92%	96%	320

The white luminance of the display design with RG phosphor film is 6.6% higher than our design target (Table 14). The green FWHM value is 55 nm and the red FWHM value is 69 nm.

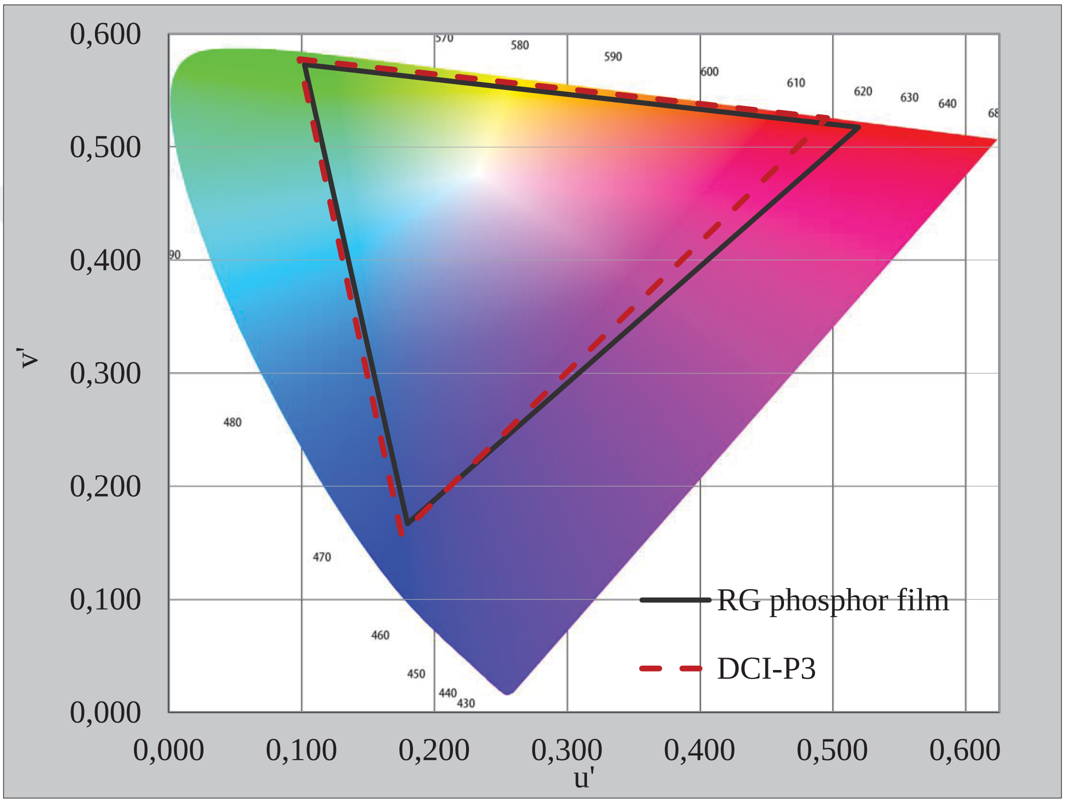

Figure 42 - Colour gamut area of RG phosphor film

As can be seen from the previous figure 41, the BLU spectrum and blue filter overlaps between 677 and 752 nm, because of this, blue shifts to red. In addition, the colour gamut value becomes narrower, because of red and green emission of RG phosphor film are broad. The BLU spectrum and the green colour filter overlaps between 560nm and 620nm, because of this, the green colour shifts to red.

Human eyes are more sensitive to green than the other colours [22]. Luminance calculations of display are done by simulating the human eye. Hence, the high intensity green colour spectrum of the panel leads to higher observed luminance. Therefore, the perspective of observed luminance, the increase in green spectrum may be preferred to the increase in the red spectrum.

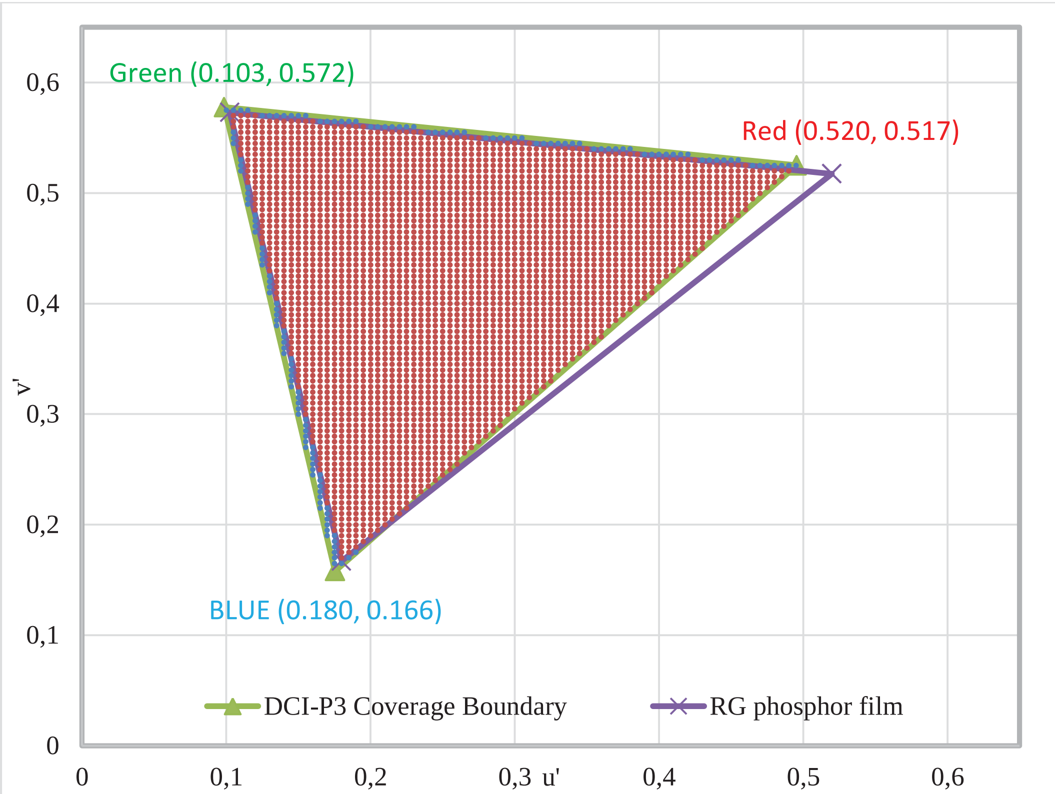

Figure 43 - Colour gamut coverage of RG phosphor film

Because of these colour shifts, approximately 97% of the DCI-P3 standard colour triangle had been covered with RG phosphor on-chip design (Figure 43).

3.2.5.4 RG phosphor film with different colour filter

As described in section 3.2.1, we have implemented RG phosphor film in our backlight design. To test critical performance parameters of our display design, the backlight unit was operated for 1 hour to reach thermal equilibrium. Then, the measurements were performed with the spectroradiometer from the centre of the backlight unit. The irradiance spectrum with respect to wavelength was obtained from this measurement. This spectrum was used to obtain the colour gamut, centre brightness, and colour coordinate values by using the CF spectrum of the 65" SAM UHD LCD panel to compare 65" AUO UHD LCD colour filter performance.

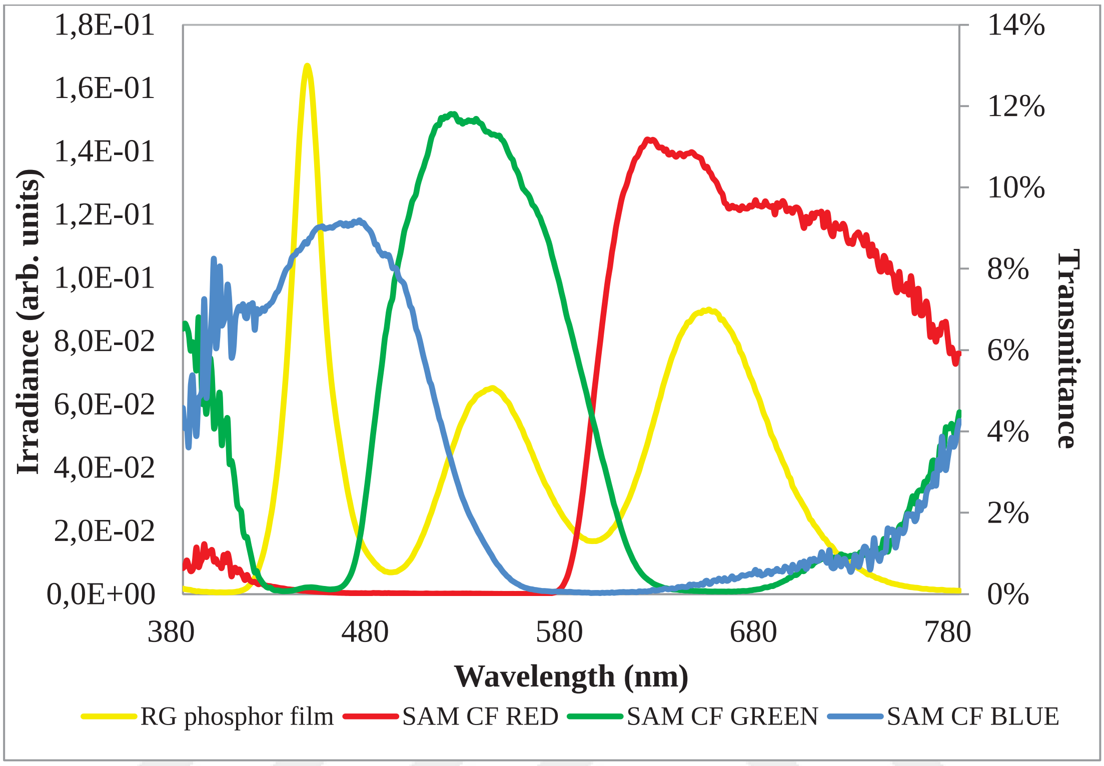

Figure 44- BLU spectrum of RG phosphor film with AUO CF

By comparing the BLU spectrum and the colour filter spectrum, the colour coordinates and luminescence values of the blue, green and red spectra were calculated in CIE 1931 colour space. By calculating the CIE 1976 colour space equivalents of these values, the colour gamut values were found in both the NTSC and DCI colour gamut standards (Table 15). In addition, white luminescence value of the panel was obtained by adding the blue, green and red luminescence values.

Table 15 - The colour coordinates of the panel with RG phosphor film

		CIE1931			CIE1976	
		x	y	L (nit)	u'	v'
Panel	R	0.683	0.303	74.6	0.519	0.517
	G	0.271	0.659	236.8	0.105	0.572
	B	0.158	0.07	36.1	0.179	0.179
NTSC	R	0.670	0.330	**DCI**	0.496	0.526
	G	0.210	0.710		0.099	0.578
	B	0.140	0.080		0.175	0.158

The white luminance value is 15.8% higher than our target value. However, the colour gamut becomes narrower (Table 16).

Table 16 - The results of the panel with SAM colour filter

	Gamut (NTSC)	*Gamut (DCI)*	*White L (nit)*
Panel	89%	93%	347.5

The reason of the narrowing the colour gamut in the SAM CF structure is the shift in blue to red and green regions. The green shift was observed because of the BLU spectrum overlaps with the blue colour filter from 460 nm to 550 nm.

In addition, they overlap between 616 nm to 780 nm, so the shift from blue to red was observed. In figure 46, there is a colour shift in the blue region. The v' value (0.179) is higher than the target v' value (0.158). The reason for this difference is the red shift in the blue. The u' value (0.179) is higher than the target v' value (0.175). The reason for this difference is the green shift in the blue. Because of these shifts, only 93% of the colour gamut was covered the DCI-P3 standard.

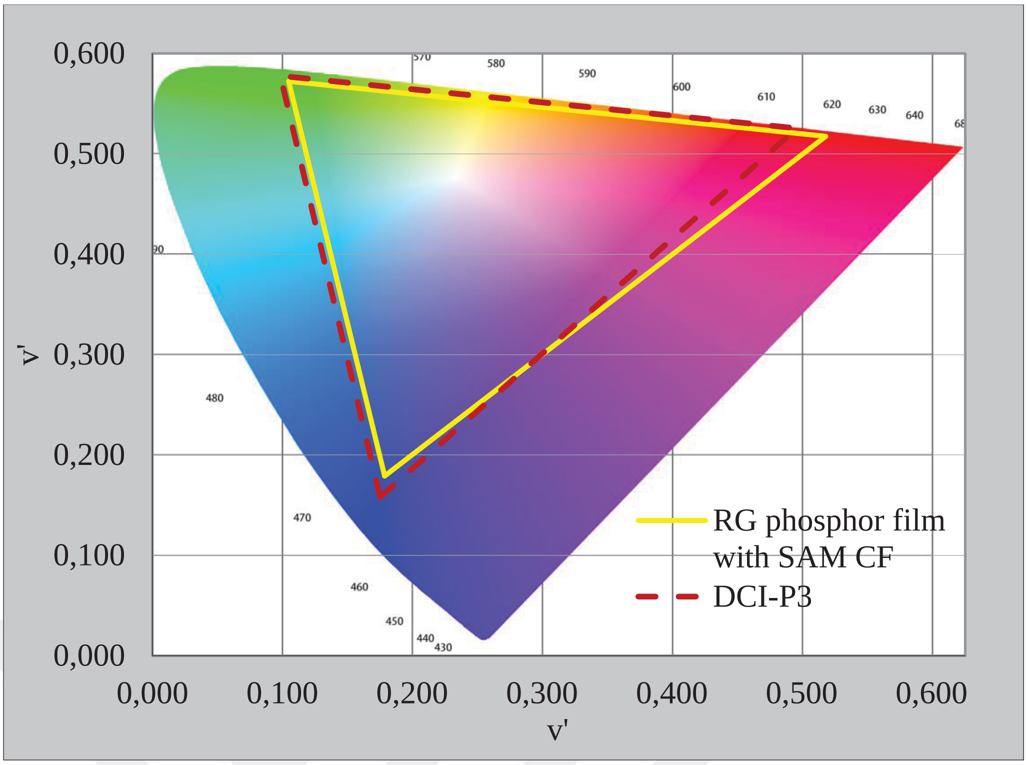

Figure 45 - Colour gamut area of RG phosphor sheet with different colour filter

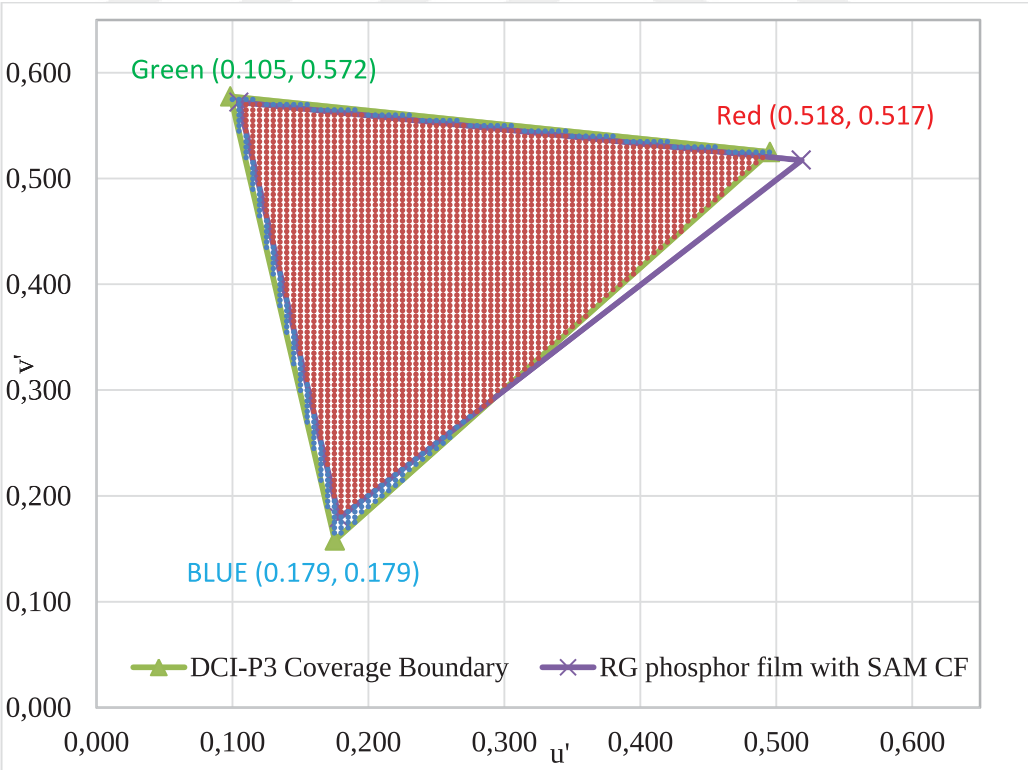

Figure 46 - Colour gamut coverage of RG phosphor film with SAM CF

3.2.5. Phosphor coatings on diffuser plate

3.2.5.5 The thickness of 0.65mm phosphor blend

As described in section 3.2.1, a diffuser plate was coated with blended RG phosphors and mounted on a down-light armature test platform. It was operated for 1 hour to reach thermal equilibrium. Then, the optical measurements were performed with the JETI spectroradiometer. The irradiance spectrum with respect to wavelength was obtained from this measurement. This spectrum was used to get the colour gamut, centre brightness, and colour coordinate values by using the CF spectrum of the 65" AUO UHD LCD panel.

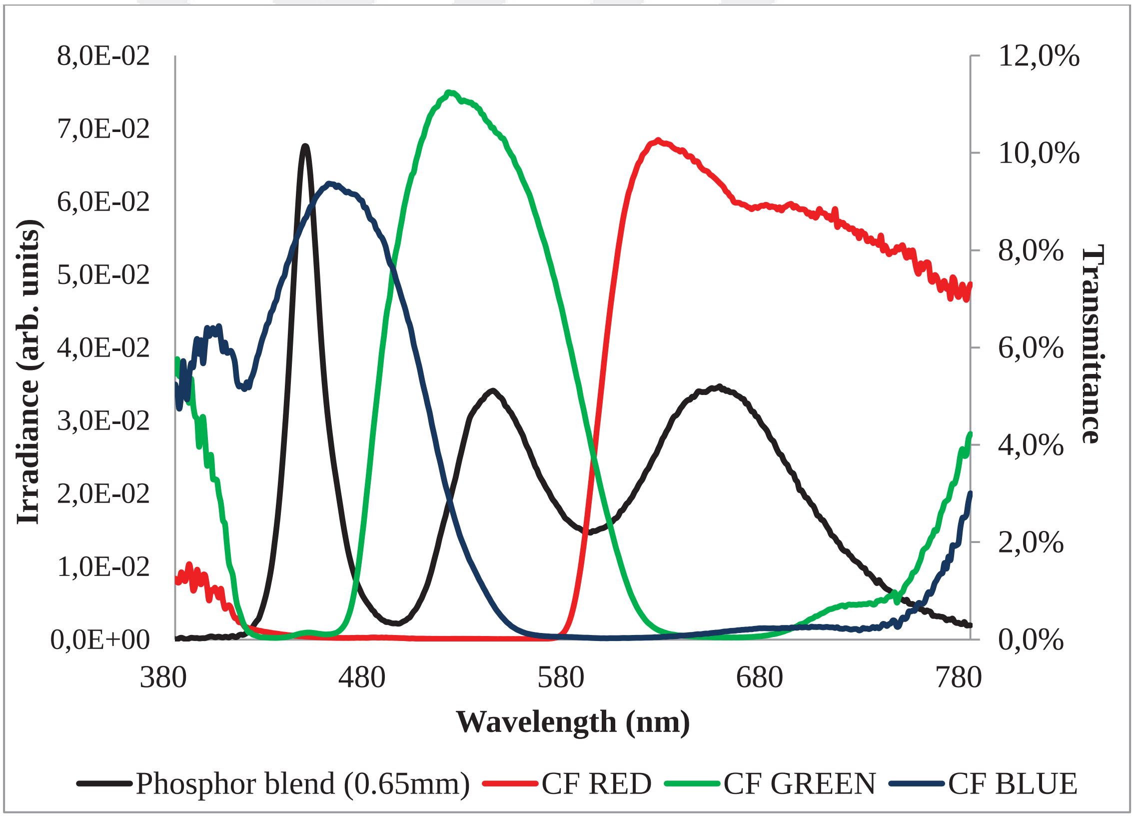

Figure 47- BLU spectrum of 0.65mm β-SiAlON+CASN phosphor blends with AUO CF

By using the BLU spectrum and the colour filter spectrum, the colour coordinates and luminescence values of the blue, green and red spectra were calculated in CIE 1931 colour space. By calculating the CIE 1976 colour space equivalents of these values, the colour gamut values were found in both the NTSC and DCI colour gamut standards (Table 17). In addition, white luminescence value of the panel was obtained by adding the blue, green and red luminescence values.

Table 17 - The colour coordinates of the panel with 0.65mm β-SiAlON+CASN phosphor

		CIE1931		L (nit)	CIE1976	
		x	y		u'	v'
Panel	R	0.676	0.314	31.70	0.499	0.522
	G	0.294	0.654	140.27	0.115	0.574
	B	0.156	0.069	20.22	0.177	0.177
NTSC	R	0.670	0.330	**DCI**	0.496	0.526
	G	0.210	0.710		0.099	0.578
	B	0.140	0.080		0.175	0.158

Table 18 - Colour gamut values of panel with phosphor blend

	Gamut (NTSC)	*Gamut (DCI)*	*Luminance (nit)*
Panel	85%	91%	164.4

The luminescence value was evaluated by comparing the thickness of coatings. It is observed that the colour gamut level in the DCI-P3 standard is over 90% for different thickness (Table 18). However, the luminance value is very lower than the designs described above.

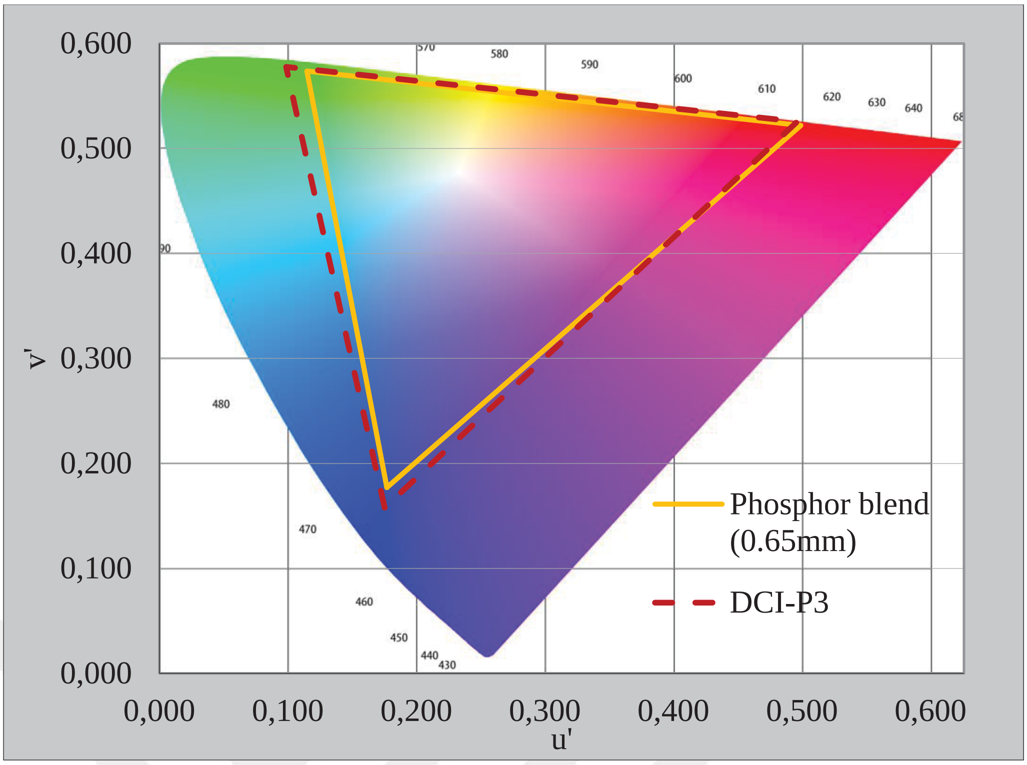

Figure 48 - Colour gamut area of 0.65mm βSiAlON+CASN phosphor blend

In figure 48, colour shifts were observed from blue to green and green to red, these shifts were the reason of gamut narrowing. In addition, the intensity of the blue peak is lower. The effect of the blue filter on the BLU spectrum between 520 and 555 nm is high in this region. Because of this effect, the shifts from blue to green were observed. The green filter and the BLU spectrum overlap between 610-630 nm and 680-780 nm; this caused the shift from red to green. There are also shifts from green to red. However, the colour gamut is still wide in DCI-P3, since the red peak wavelength is at 650 nm which is in the deeper red region.

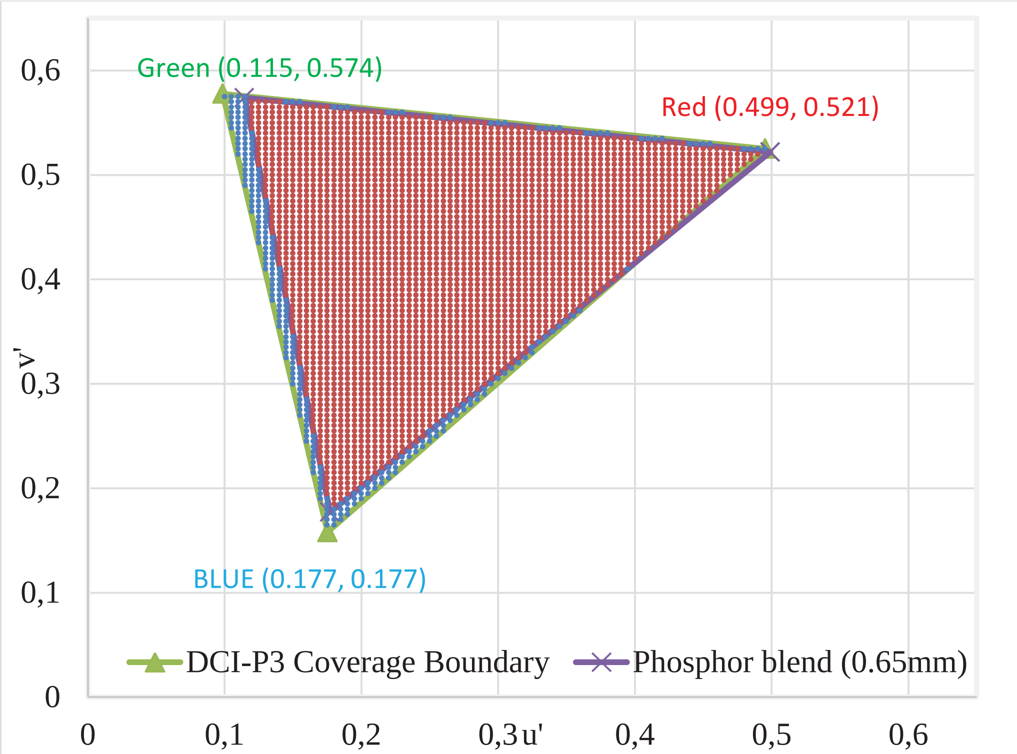

Figure 49 - Colour gamut coverage of 0.65mm βSiAlON+CASN phosphor blend

Because of these colour shifts, approximately 91% of the DCI-P3 standard colour triangle had been covered with RG phosphor on-chip design (Figure 49).

3.2.5.6 The thickness of 0.55mm phosphor blend results

As described in section 3.2.1, a diffuser plate was coated with blended RG phosphors and mounted on a down-light armature test platform. It was operated for 1 hour to reach thermal equilibrium. Then, the optical measurements were performed with the JETI spectroradiometer. The irradiance spectrum with respect to wavelength was obtained from this measurement. This spectrum was used to get the colour gamut, centre brightness, and colour coordinate values by using the CF spectrum of the 65" AUO UHD LCD panel.

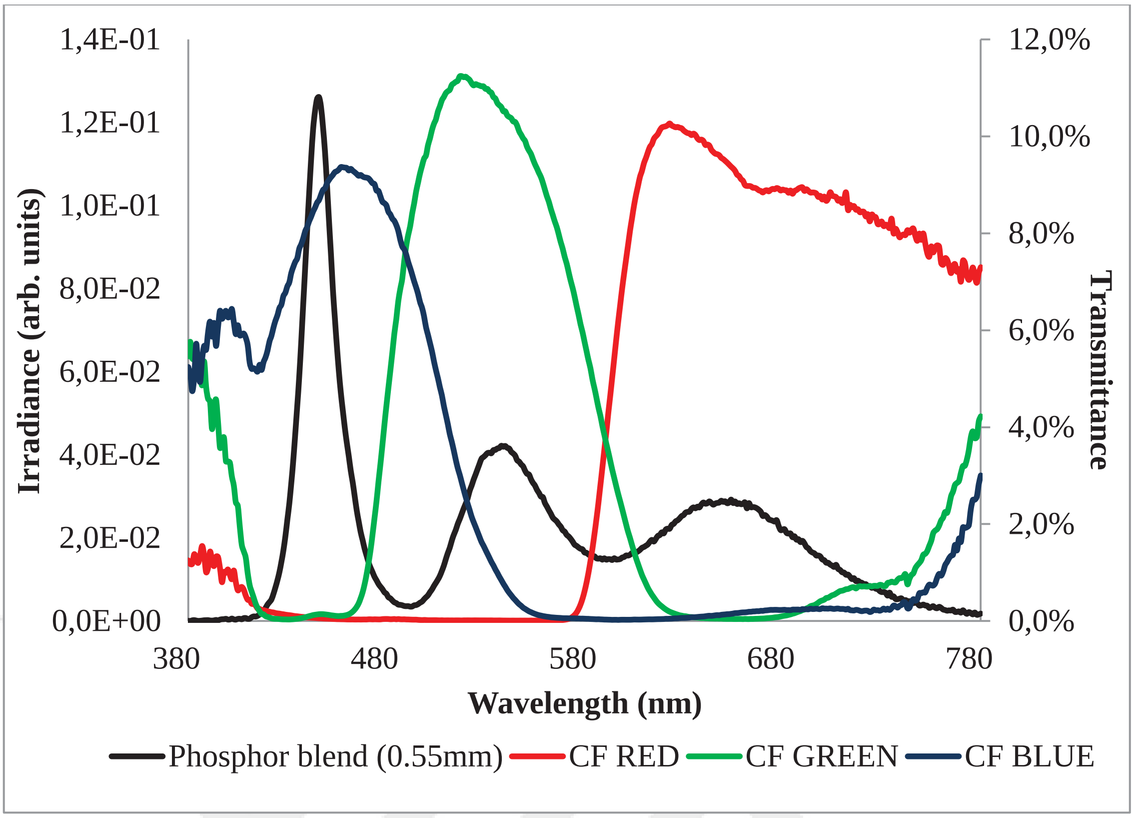

Figure 50 - BLU spectrum of 0.55mm βSiAlON+CASN phosphor blends with AUO CF

By using the BLU spectrum and the colour filter spectrum, the colour coordinates and luminescence values of the blue, green and red spectra were calculated in CIE 1931 colour space. By calculating the CIE 1976 colour space equivalents of these values, the colour gamut values were found in both the NTSC and DCI colour gamut standards (Table 19). In addition, white luminescence value of the panel was obtained by adding the blue, green and red luminescence values.

Table 19 - The colour coordinates of the panel with 0.55mm β-SiAlON+CASN phosphors

		CIE1931		L (nit)	CIE1976	
		x	y		u'	v'
Panel	R	0.667	0.313	35.52	0.492	0.52
	G	0.279	0.656	115.46	0.108	0.572
	B	0.155	0.055	13.98	0.185	0.149
NTSC	R	0.670	0.330	**DCI**	0.496	0.526
	G	0.210	0.710		0.099	0.578
	B	0.140	0.080		0.175	0.158

The colour gamut was widened, along with the lower thickness of the phosphor blended. In addition, the luminance value was increased by 17%.

Table 20 - Colour gamut values of panel with 0.55mm β-SiAlON&CASN phosphor blend

	Gamut (NTSC)	*Gamut (DCI)*	*Luminance (nit)*
Panel	88%	93%	191.1

The colour gamut value is calculated to be 93% in DCI-P3 standard. The narrower colour gamut was observed because of blue and green colour shifts to red. The BLU spectrum and blue colour filter overlaps between 630 and 780 nm, because of this the red to blue colour shift was occurred. In addition, green colour filter and BLU spectrum overlaps between 610-630 nm and 680-780 nm regions, for this reason, the green to red colour shift was observed.

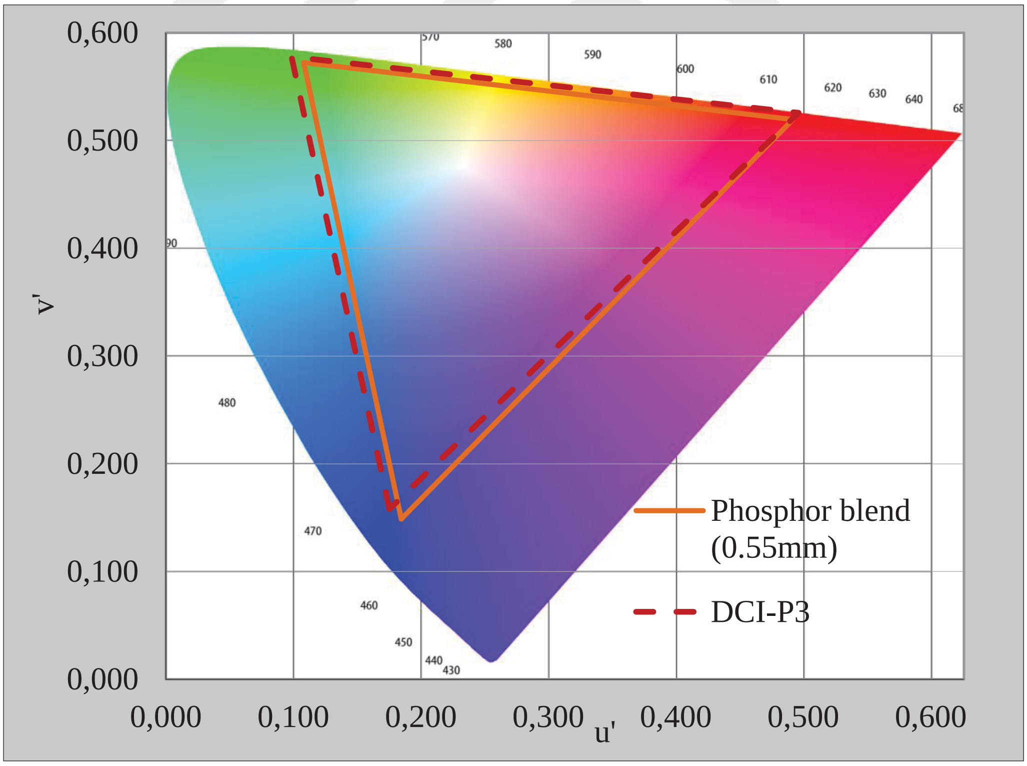

Figure 51 - Colour gamut area of 0.55mm βSiAlON+CASN phosphor blend

Because of these colour shifts, approximately 93% of the DCI-P3 standard colour triangle had been covered with RG phosphor on-chip design (Figure 52).

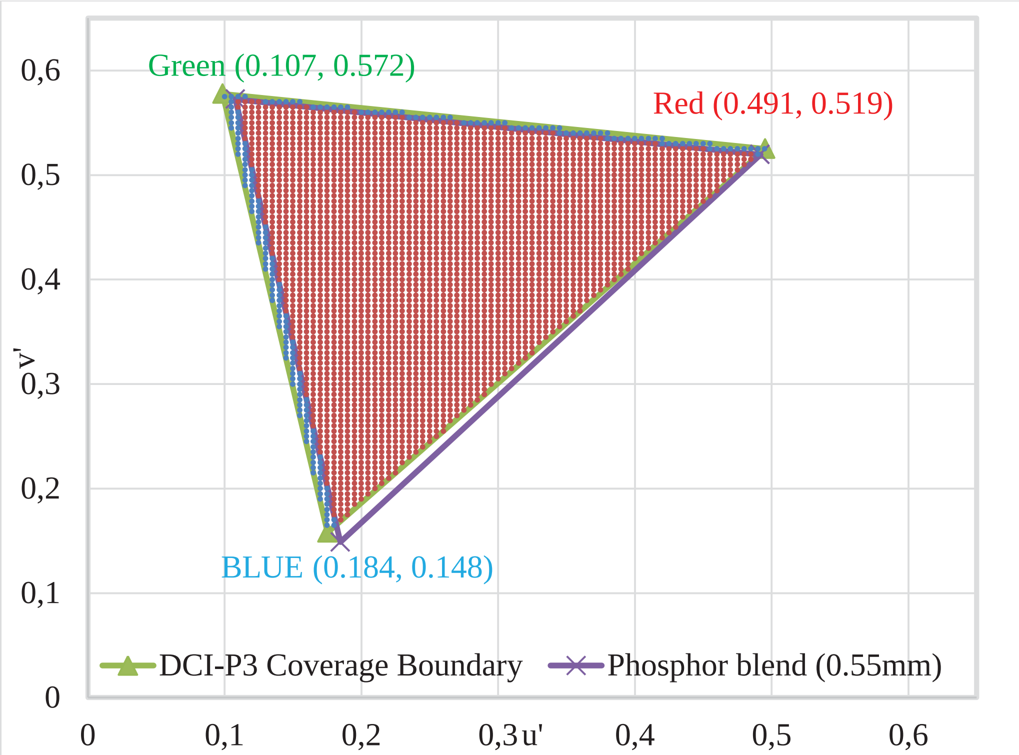

Figure 52 - Colour gamut coverage of 0.55mm βSiAlON&CASN phosphor blend

3.2.6. Comparison of the optical measurements

3.2.6.1 On Chip Phosphors

The BLU spectra of on-chip colour converters and the colour filter spectrum of the 65" AUO UHD LCC was compared in figure 53.

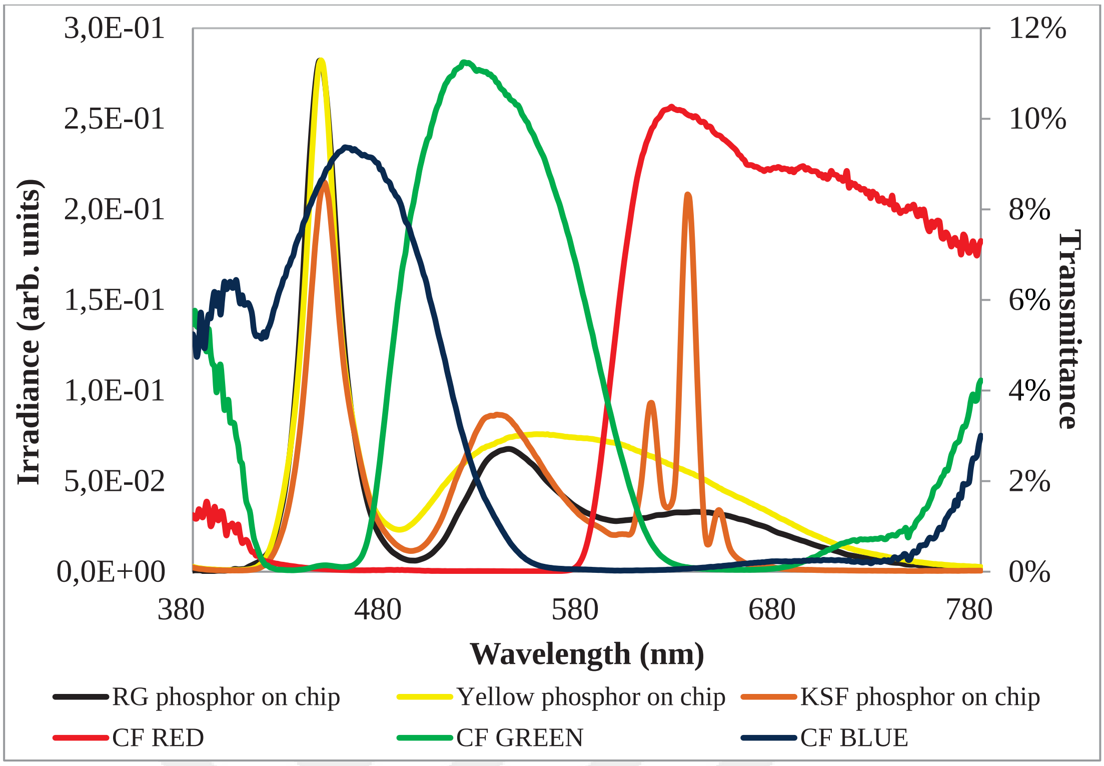

Figure 53 - BLU spectrums of phosphor on-chip structures

As can be seen in figure 53, the backlight spectrum of yellow phosphor on-chip design has wider area than the other on-chip designs in the green and red region. However, the design with yellow phosphor on-chip structure has the highest brightness value. In RG phosphor on-chip structure, green and red peaks are separated from each other, but the FWHMs are broader. The brightness value is lower in this structure. On the other hand, the red region spectrum of KSF on chip structure has a very narrow FWHM (~ 5nm) value. In addition, a narrow spectrum also was formed in the green region (~ 44 nm) of KSF on-chip. These narrow spectrums provided a wide colour gamut.

Table 21 - Colour gamut and luminance values of on-chip light conversion mechanisms

On-Chip Phosphors		u'	v'	Luminance(nit)	DCI-P3 (coverage)
Yellow	R	0.4614	0.5254	488.2	83%
	G	0.1261	0.5665		
	B	0.1781	0.1595		
RG	R	0.4729	0.5180	316.3	89%
	G	0.1135	0.5704		
	B	0.1947	0.1210		
KSF	R	0.5014	0.5201	414.2	95%
	G	0.1006	0.5717		
	B	0.1744	0.1711		
Target (DCI-P3)	R	0.4964	0.5255	300	> 90%
	G	0.0986	0.57767		
	B	0.1754	0.1579		

Although, the luminance value of KSF phosphor structure is 15% lower than yellow phosphors, its 38% higher than our initial design target. In addition, its colour gamut value is %14 higher than display design with yellow phosphor. The luminance value of the display design with RG phosphor on-chip structure is %35 lower than the yellow phosphor on-chip structure. In addition, its colour gamut level is narrower (Table 21).

In figure 53, the BLU spectrum overlaps with blue colour filter spectrum in the region between 480 nm and 530 nm. The panel with RG phosphor on-chip shows the lowest shifting ratio in this region. The main colour regions are 400 to 470nm for blue, 510 to 570nm for green and 610 to 780nm for red. The shifting ratio is defined as the division of the spectrum outside the primary colour regions to spectrum in this region. On the other hand, the highest shifting ratio was observed the panel with KSF phosphor on-chip in the same region. Therefore, the highest blue colour shift to green was observed in KSF structure. Similarly, the lowest colour shift was observed in RG phosphor structure. When the green filter and BLU spectra are compared with each other, the blue colour shifting ratios are almost same for all designs in between 460nm to 520nm. The BLU spectrum shifting ratio of the yellow phosphor on-chip design is higher in between 610 to 780nm region.

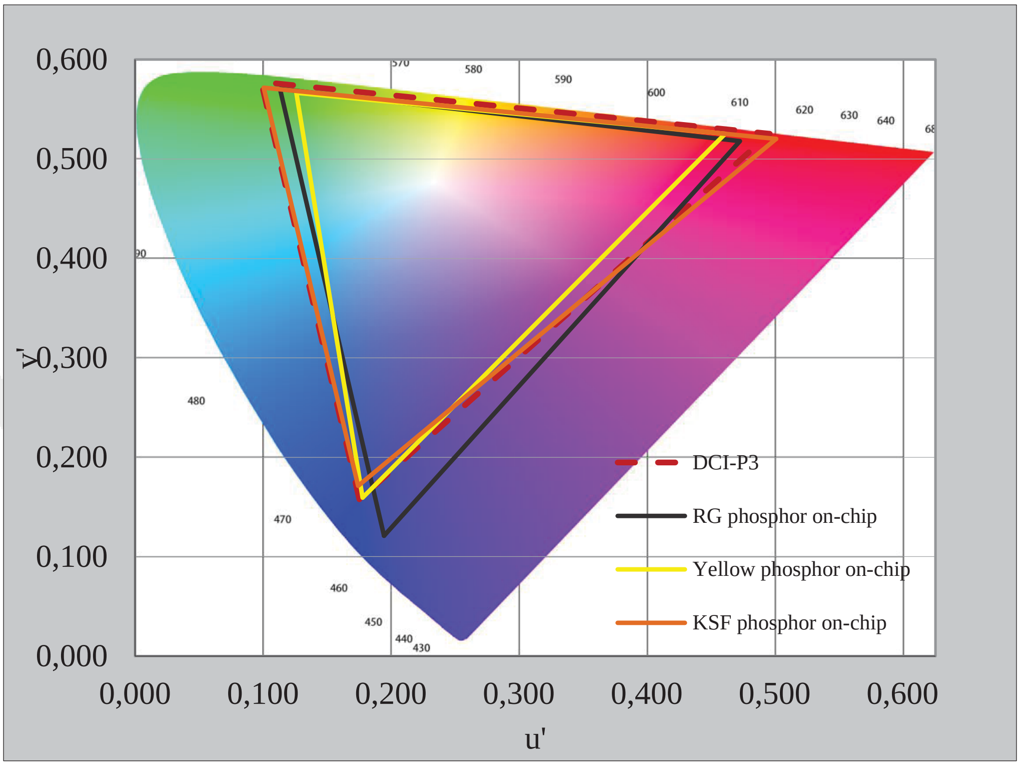

Figure 54 - Colour gamut area of on chip phosphors

The peak wavelength, λ_p and FWHM of phosphors on-chip mechanism are given in table 22.

Table 22 - Peak wavelength and FWHM values of phosphor on chip mechanism

Phosphor on chip	*Blue*		*Green*		*Yellow*		*Red*	
	λp (nm)	*FWHM (nm)*	*λp (nm)*	*FWHM (nm)*	*λp (nm)*	*FWHM (nm)*	*λp (nm)*	*FWHM (nm)*
Yellow	444	19	N/A	N/A	554	136	N/A	N/A
RG	444	19	540	60	N/A	N/A	640	N/A
KSF	445	19	534	44	N/A	N/A	631	10

Since the BLU spectra and red colour filter overlaps between 380 and 437nm the red to blue colour shifts were observed. The colour shifts from red to blue in all these three designs are almost equal. The BLU spectra and red colour filter overlap between

573nm and 610nm, which is mainly responsible from red to green colour shift. The lowest colour shift was observed in KSF phosphor on-chip structure in this region.

3.2.6.2 Comparison of Remote Light Conversion Mechanisms

The BLU spectra of on remote light conversion mechanism (RLCM) and the colour filter spectrum of the 65” AUO UHD LCC was compared in figure 55.

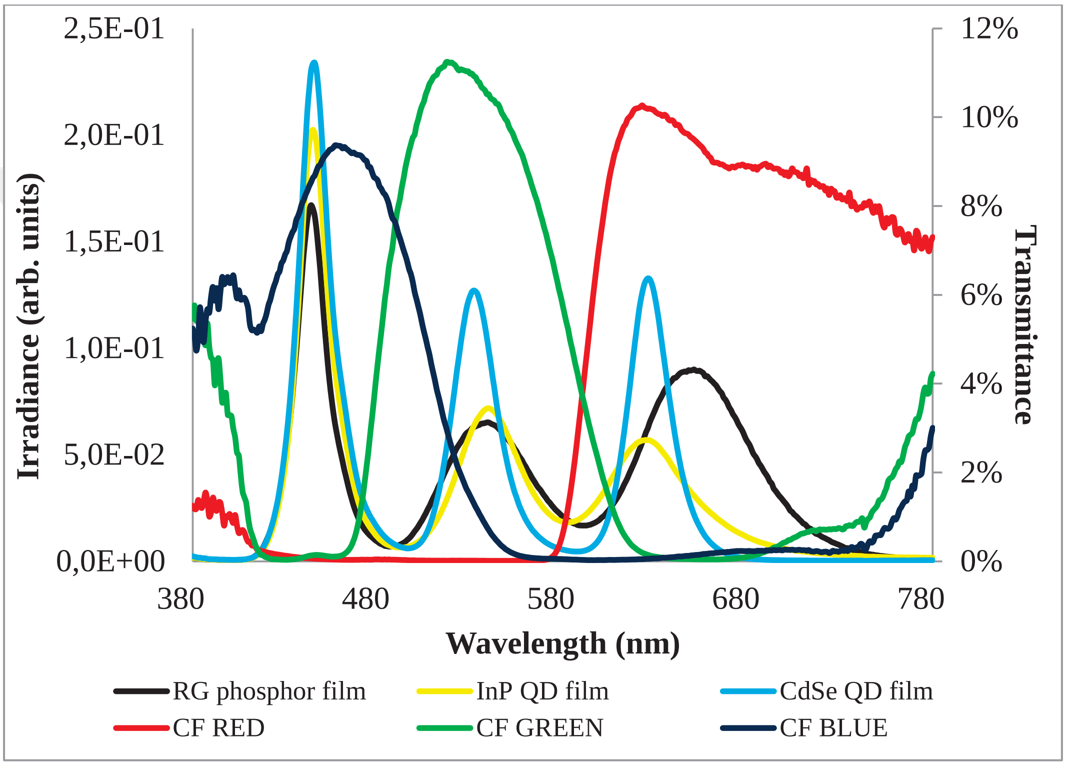

Figure 55 - BLU spectrums of remote light conversion mechanisms with AUO CF

Figure 55 shows that, the BLU spectrum of RG phosphor film has the largest colour shifting ratio between 480nm and 520nm. The lowest ratio is belong to BLU spectrum of CdSe QD film, the highest ratio is belong to BLU spectrum of InP QD film between 565 and 615nm region. When the BLU spectra and the red colour filter in the region between 570nm and 615nm are compared, InP QD film has the largest area and CdSe QD film has the lowest area. On the other hand, the BLU spectrum of CdSe QD film has the highest irradiance in the blue, green and red regions.

Table 23 - Peak wavelength and FWHM values of remote light conversion mechanism

RLCM	*Blue*		*Green*		*Red*	
	λp (nm)	*FWHM (nm)*	*λp (nm)*	*FWHM (nm)*	*λp (nm)*	*FWHM (nm)*
RG	443	19	533	58	645	70
InP	444	19	536	44	620	62
CdSe	444	19	530	27	624	26

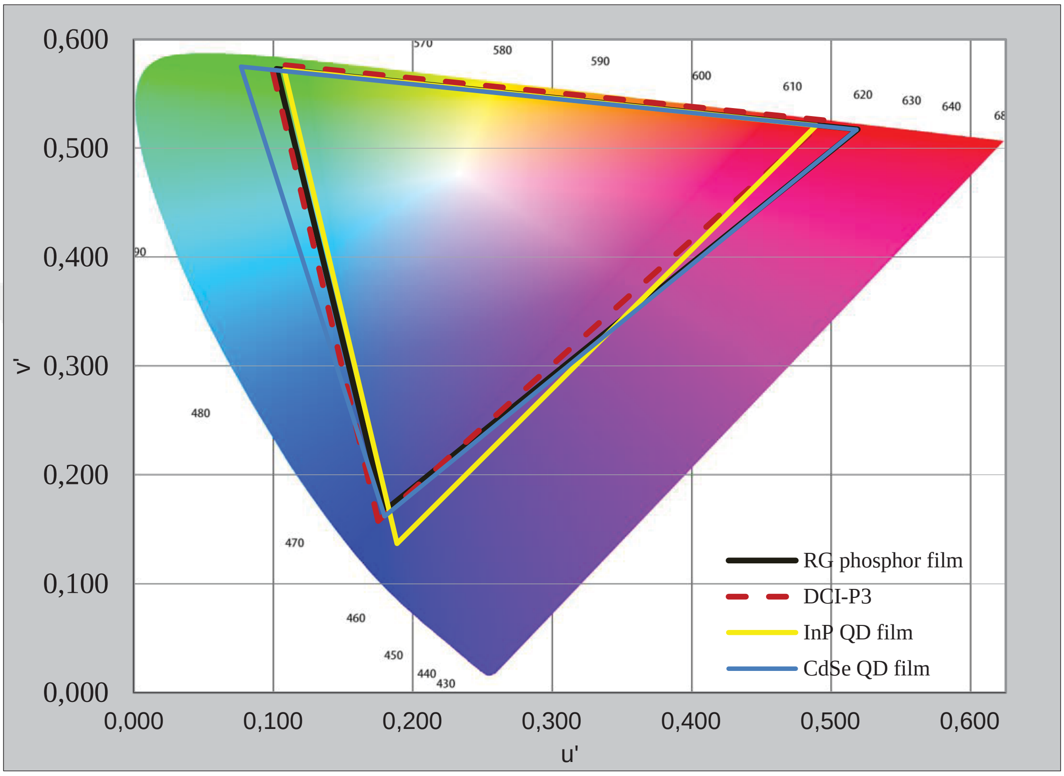

Figure 56 - Colour gamut area of panels with remote light conversion mechanism

The largest ratio under the blue colour filter of the region between 480nm and 525nm (RG phosphor film) was demonstrated the max shift from blue region to green region. The amount of red shift to the blue region is almost the same in all structures. When the green region is examined; the most shift amount green to blue region was observed in InP QD film structure. This is also due to the fact that the BLU spectrum of InP QD film under the green colour filter has the highest area in the region between 565nm and 615nm. The shift from red colour to green region, almost the same as CdSe QD film and RG phosphor film structures and these shift ratios are lower than the InP QD film. The CdSe film has much lower ratio than the RG phosphor film, in the area under the red filter between 570nm and 615 nm. However, it has shifted to green at the same level as the RG phosphor film. The reason of this, the peak wavelength in this region of the RG phosphor structure is much higher than the CdSe QD film structure (Figure 66).

Table 24 - Colour gamut and luminance values of on-chip light conversion mechanism

RLCM		u'	v'	Luminance (nit)	DCI-P3 (coverage)
InP QD film	R	0.519	0.517	297.2	97%
	G	0.077	0.575		
	B	0.18	0.162		
CdSe QD film	R	0.490	0.521	373.7	93%
	G	0.108	0.572		
	B	0.189	0.137		
RG phosphor film	R	0.520	0.517	319.3	96%
	G	0.102	0.573		
	B	0.180	0.167		
Target (DCI-P3)	R	0.496	0.526	300	> 90%
	G	0.099	0.578		
	B	0.175	0.158		

The highest luminescence was observed in the panel with CdSe QD film. Because of it has the highest irradiance value in blue, green and red regions. At the same time, the FWHM values of this structure are very narrow in green and red areas. This prevents occur of mixing colours. So, it has the widest colour gamut. Due to this superior performance of CdSe QD film which is both luminance and colour gamut, it gives the impression of the first solution that can be used to achieve wide colour gamut. However, research shows that Cd is harming human health and the environment. Because of these damages, according to ROHS standards, the entry of Cd-containing products into Europe is prohibited [23, 4]. This means that CdSe QD Film cannot be used for LED based LCD TV design. An alternative of this structure is the QD film that included InP material. However, the InP QD film structure has not provided the target luminance value. At the same time, the colour gamut is much lower than the CdSe QD film.

The RG phosphor film structure is the most preferred structure among the remote light conversion mechanisms due to the luminance value at the satisfactory level and the colour gamut value very close to the CdSe QD film structure.

3.2.6.3 Comparison of phosphor & silicon blends with different thicknesses

In this study, the production methods of remote light conversion mechanism which can ensure wide colour gamut were investigated. After this investigation, 5cm diffuser plate was coated with prepared phosphor & silicon mixture by Dr. Blade method. The coatings on the diffuser plate were prepared with same ratio in two different thicknesses. Then the effect of phosphor amount to luminance and colour gamut was investigated.

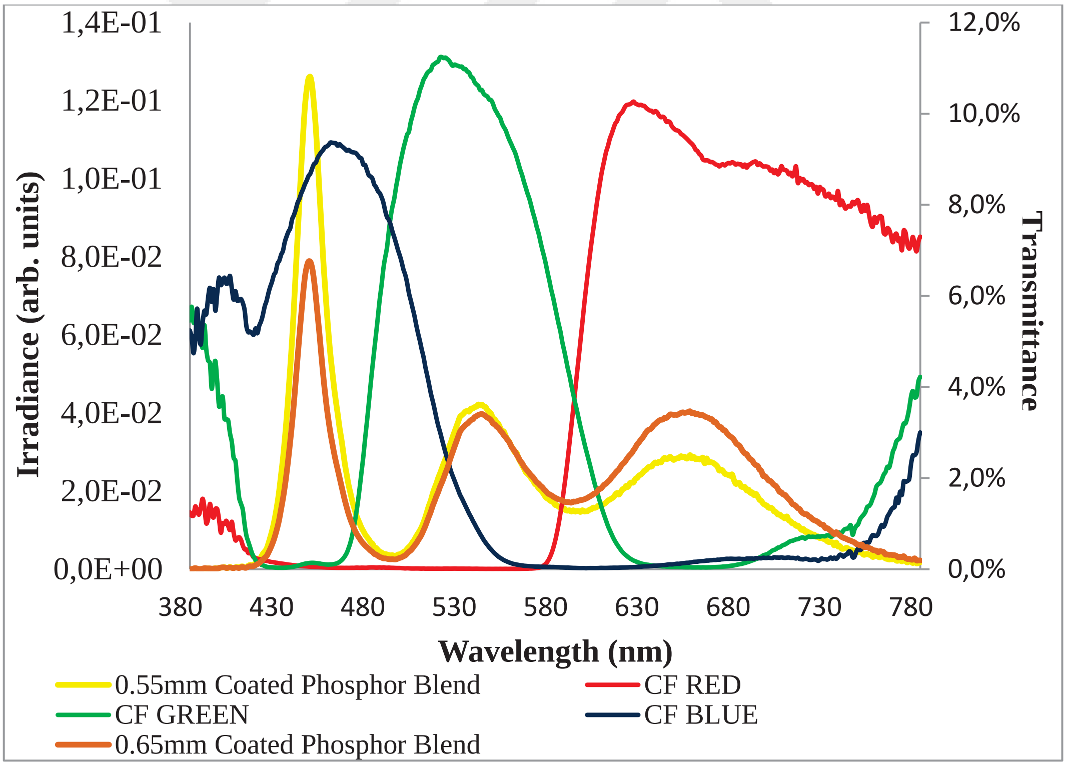

Figure 57- BLU spectrums of different thickness βSiAlON&CASN phosphor blends

The blue irradiance value of 0.65mm coating is about 50% less than the 0.55mm coating (Figure 57), since the blue excitation was further absorbed by increasing the amount of mixture. The irradiance value in the green region is also 20% lower in the 0.65mm structure.

Table 25 - Peak wavelength and FWHM values of βSiAlON&CASN phosphor blends

β-SiAlON+CASN *Phosphor Blend*	*Blue*		*Green*		*Red*	
	λp (nm)	*FWHM (nm)*	*λp (nm)*	*FWHM (nm)*	*λp (nm)*	*FWHM (nm)*
0.55mm	445	19	535	55	645	108
0.65mm	445	19	536	66	646	99

There has not been a great change with the change of thickness in peak-wavelength. However, the great changes of the green and red FWHM values are attract the attention (Table 25).

The heavy decrease in the blue irradiance value and changes of the FWHM values affected the area of the colour gamut triangle.

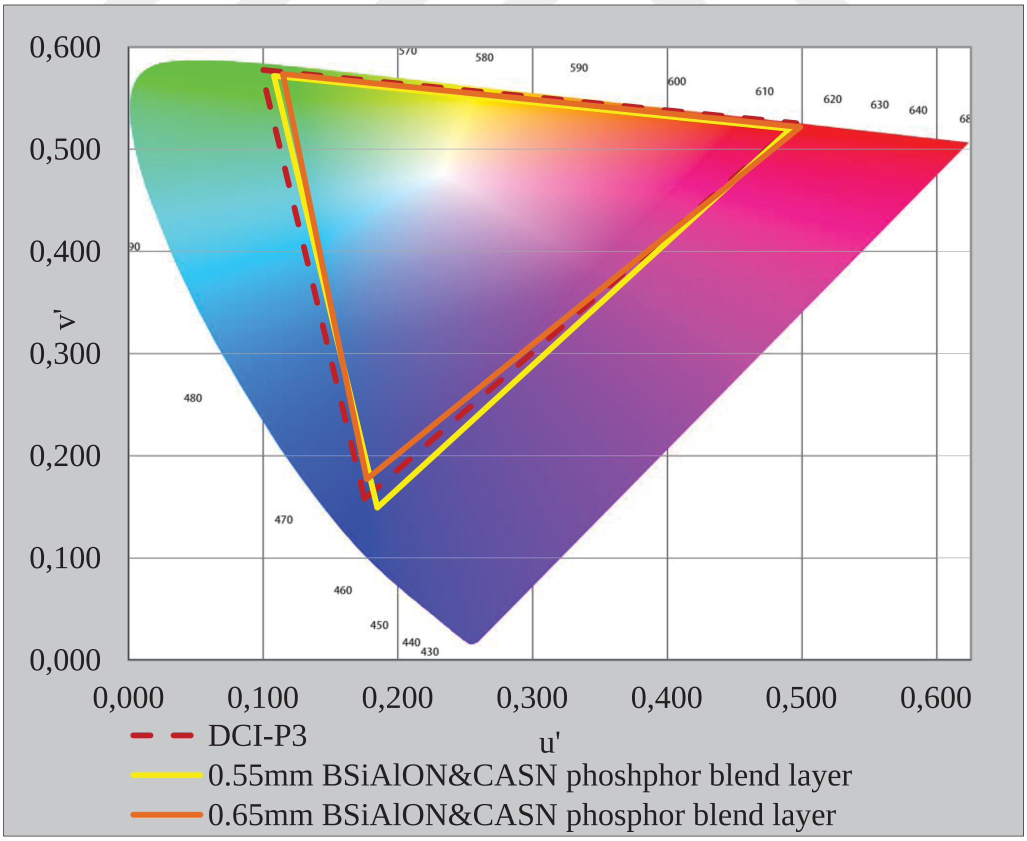

Figure 58 - Colour gamut area of βSiAlON+CASN different thickness phosphor blends

The spectrum from 480 nm to 520 nm is similar for both structures. Since the decrease in the blue irradiance value in the thick structure was too great, the shift rate of blue region to green was higher for this structure. Another shift that attracts the attention is the triangle area is the green shift to red region. Although they give the same peak wavelength values in the green zone, the higher value of the FWHM in thick structure causes this shift to be higher.

Table 26 - DCI colour gamut and luminance values of phosphor blends results

Phosphor Blends		u'	v'	Luminance (nit)	DCI-P3 (coverage)
0.55mm βSiAlON&CASN	R	0.492	0.520	191.6	93%
	G	0.108	0.572		
	B	0.185	0.149		
0.65mm βSiAlON&CASN	R	0.499	0.522	164.4	91%
	G	0.115	0.574		
	B	0.177	0.177		

The low irradiance values and the shifts caused both the luminance and the colour gamut to drop in the 0.65mm structure. Therefore, the amount of phosphor to be used in the colour conversion mechanism is a critical parameter.

3.2.6.4 0.55mm βSiAlON&CASN phosphor blends vs yellow and RG phosphor on-chip

It was compared the results of the phosphor blend layers with the RG phosphor on chip results which is a high-colour gamut solution and a yellow phosphor on chip that covers 80% of the market to see the performance in terms of colour gamut. For this comparison, the BLU spectra were matched with AUO cell CF in figure 59.

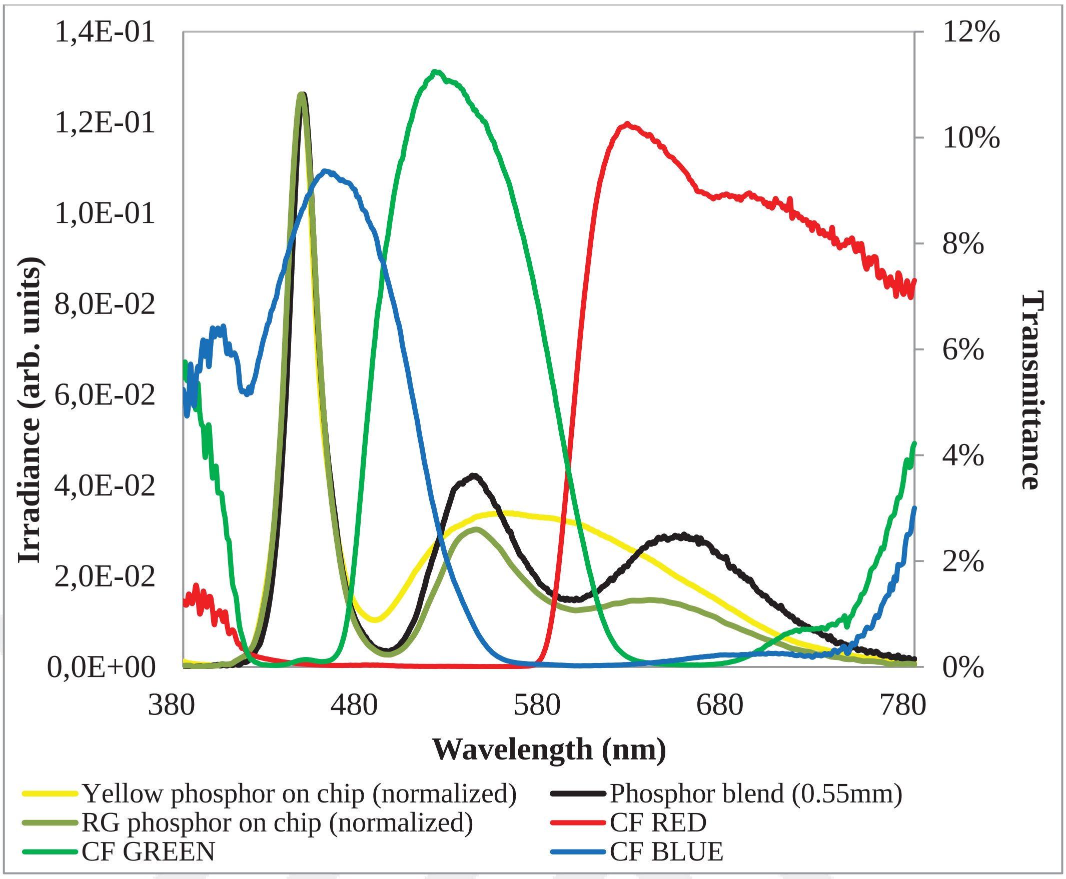

Figure 59 - BLU spectrums of 0.55mm βSiAlON&CASN and yellow and RG phosphor on chips

The green and red FWHM values of the 0.55 mm βSiAlON & CASN mixture became more apparent than the yellow phosphor on-chip structure. Compared to the RG on-chip, the FWHM value of the red region is quite narrow and a narrower spectrum is obtained in the green region (Figure 59).

Table 27 - Peak wavelength and FWHM values of βSiAlON&CASN phosphor blends

LCM	*Blue*		*Green*		*Yellow*		*Red*	
	λp (nm)	*FWHM (nm)*	*λp (nm)*	*FWHM (nm)*	*λp (nm)*	*FWHM (nm)*	*λp (nm)*	*FWHM (nm)*
Yellow	444	19	N/A	N/A	554	136	N/A	N/A
RG	444	19	540	60	N/A	N/A	640	N/A
βSiAlON&CASN	445	19	535	55	N/A	N/A	645	108

Since βSiAlON & CASN phosphor blends have the narrower FWHM values and the higher peak wavelength in the red region, this structure caused lower shifts in the green and red regions.

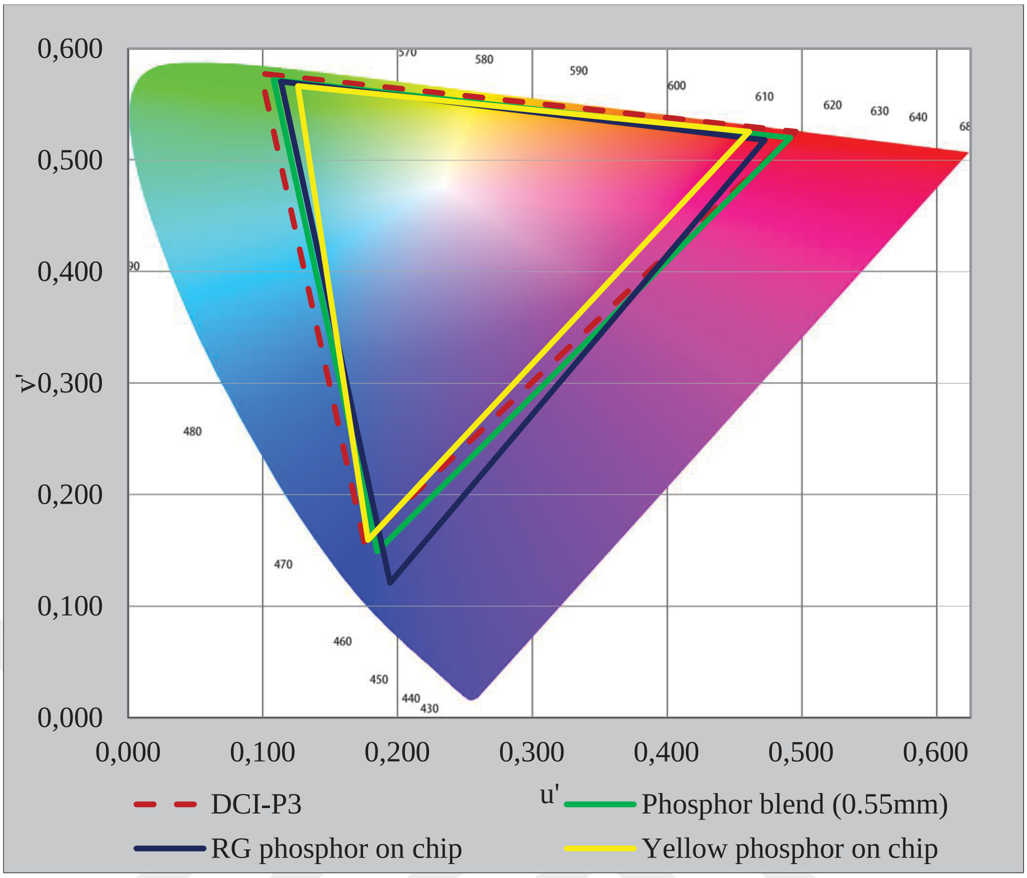

Figure 60 - Colour gamut area of phosphor blend, yellow phosphor and RG phosphor

Table 28 - Colour gamut values of phosphor blend, RG and yellow phosphor on-chip

Panel with		u'	v'	NTSC(area)	DCI-P3 (coverage)
0.55mm βSiAlON&CASN	R	0.492	0.52	87%	93%
	G	0.108	0.572		
	B	0.185	0.149		
Yellow phosphor on chip	R	0.4614	0.5254	74%	83%
	G	0.1261	0.5665		
	B	0.1781	0.1595		
RG phosphor on chip	R	0.473	0.518	82%	89%
	G	0.113	0.570		
	B	0.195	0.121		

When the results are checked, the produced βSiAlON & CASN phosphor blend layer increases the colour gamut by 12% compared to the yellow phosphor on chip structure which is covering 80% of the market. In addition, the colour gamut was 4.4% better than the RG phosphor on chip.

3.2.6.5 Colour filter effects on the optical measurement

At the beginning of this thesis study, BLU spectrum of RG phosphor film was matched with colour filters which are belong to AUO and Samsung companies to decide LCD cell to be used for wide colour gamut panel design which convenient to ROHS standard and has long life.

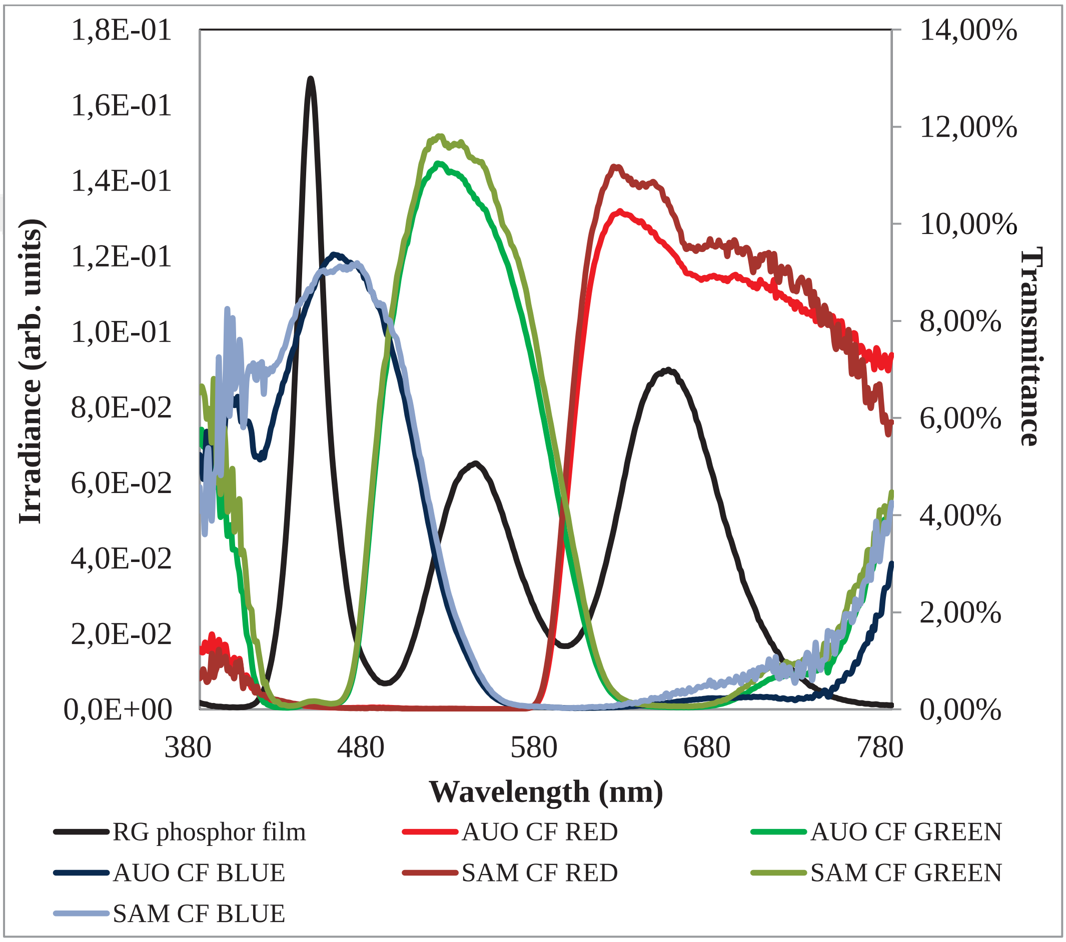

Figure 61 - BLU spectrum of RG phosphor film with different colour filters

The most obvious difference between colour filters is the change of the amount in transmittance. The Samsung colour filter has an approximately 8.4% higher transmittance value. This positive feature of transmittance causes an increase to centre luminance. However, it shows the transmittance property in the region between 630nm and 780nm which is not the blue colour region. The transmittance of this region is similar with AUO cell, but it is not totally same, blue filter spectrum of AUO cell begins near from the region where the BLU spectrum is damped. Therefore, blue shift to red region is seen lower in AUO cell.

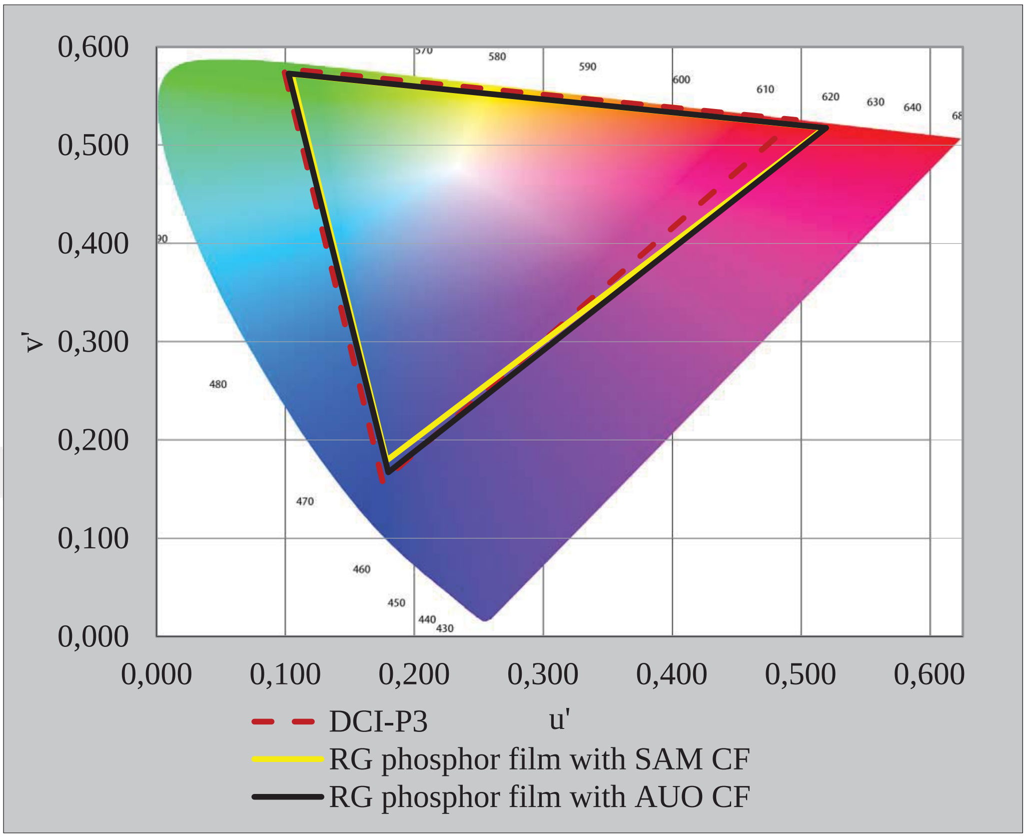

Figure 62 - Colour gamut area of RG phosphor film with AUO and SAM CF

When the colour gamut area is examined, we can see that the blue shifts to green and red region are higher for SAM cell.

Table 29 - DCI colour gamut values of RG phosphor film with AUO and SAM CF

RG phosphor film		u'	v'	Luminance (nit)	DCI-P3 (coverage)
with SAM CF	R	0.519	0.517	347.5	93%
	G	0.105	0.572		
	B	0.179	0.179		
with AUO CF	R	0.496	0.526	319.3	96%
	G	0.099	0.578		
	B	0.175	0.158		
Target	R	0.496	0.526	300	> 90%
	G	0.099	0.578		
	B	0.175	0.158		

The colour gamut area of the panel with SAM cell is 3.2% lower. Therefore, all designs in this study have been evaluated using the AUO colour filter.

3.3. Thermal Measurements

TV life time feature such as colour gamut and luminance parameters in LED TV technology is also very critical. The life time of the TV product is determined by the temperature values of the light source and thermal durability of the colour conversion mechanism. The graph of the Figure 63 shows the change life time with the junction temperature of the LEDs used in this study.

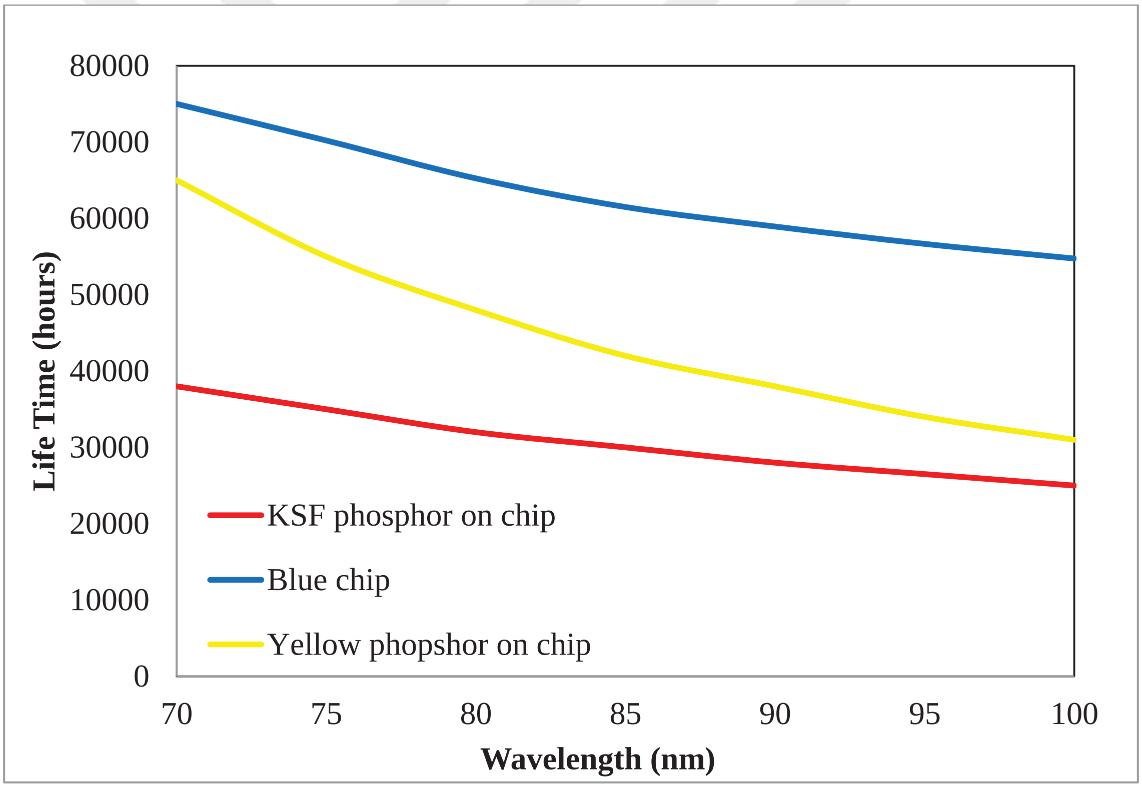

Figure 63 - Junction temperature vs life time of different LEDs

Since there is no phosphor decay, blue LED has the longest life time. Because of the KSF phosphor is easily influenced by temperature [21], the lifetime of this structure is very short.

In this study, thermal measurements were taken each LED solder via midi logger GL220 thermocouple for calculate life time of designed products. K-type thermocouple cable was used and pasted to the solder point of the LED as figure 64.

Figure 64 - Thermocouple arrangements of attaches the LEDs.

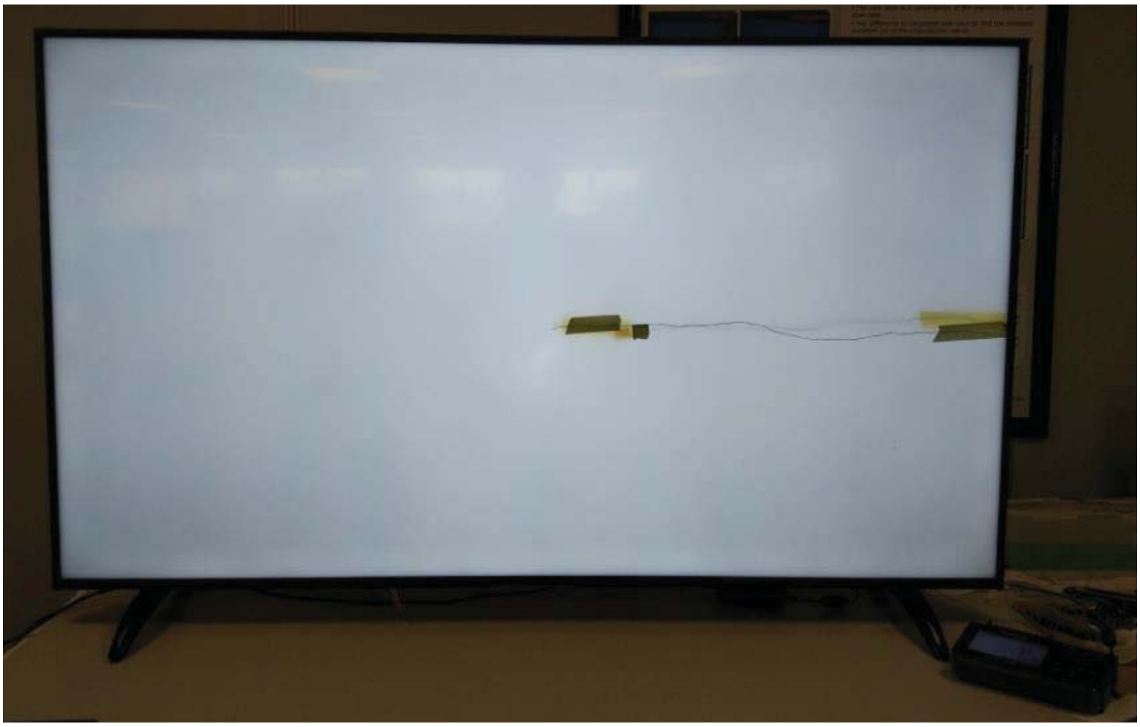

Figure 65 - Thermocouple arrangements of attaches the diffuser plate.

The final measurement mechanism is shown in figure 75. The panel has been left to warm up at 24.8°C ambient temperature. And the time-dependent Ts graph has been drawn (Figure 66). The constant temperature was determined as the Ts point of each LED.

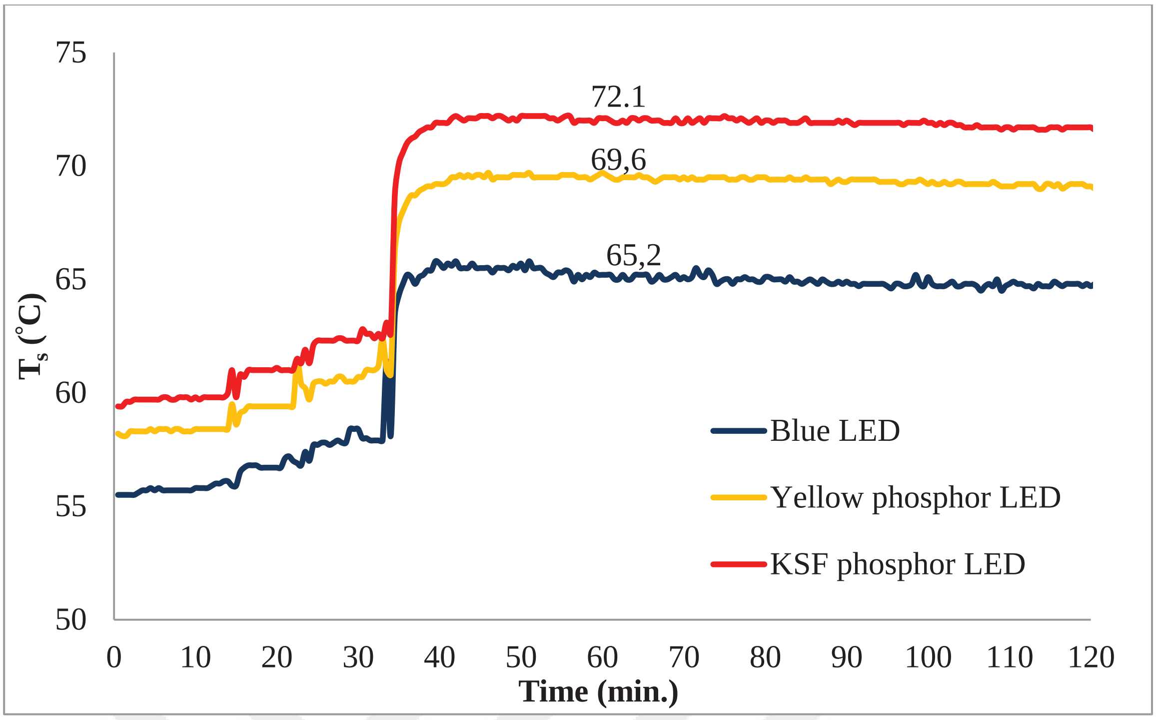

Figure 66 - Solder temperature values of LEDs with changing warm up time

The solder temperature of each LED showed a high increase between the 30th and 40th minutes and remained constant from the 40th minute. The highest temperature was observed in the KSF phosphor LED, which contained the most amount of phosphor on the chip (Figure 66).

The T_j value was calculated after the T_s point was measured.

$$T_j = T_s + (R_{th} \text{ x } W), \quad (4.1)$$

T_j: Soldering temperature

R_{th}: Thermal resistance from the chip to Ts measuring point

W: Input power consumption ($= I_F \text{ x } V_F$)

I_F: Forward current

V_F: Forward voltage

Table 30 - Tj values of blue, yellow phosphor and KSF phosphor LEDs

	Rth (°C /W)	*Voltage (V)*	*Current (A)*	*Ts (°C)*	*Tj (°C)*
Blue LED	10	3.3	0.45	65.2	80.0
Yellow Phosphor LED	10	3.3	0.45	69.6	84.5
KSF Phosphor LED	10	3.3	0.45	72.1	87.0

In addition, in the structure containing the remote RG phosphor film, a thermal measurement was also taken on the film in order to see the temperature that the exposed of phosphor. As it can be seen from figure 67, the temperature of the RG phosphor film is stabilized at 37.3°C after 1 hour. This value is much lower than the junction temperature value of the blue LED (80°C) so the life time of products with remote light conversion mechanisms (RLCM) is determined by the junction temperature of the blue LED.

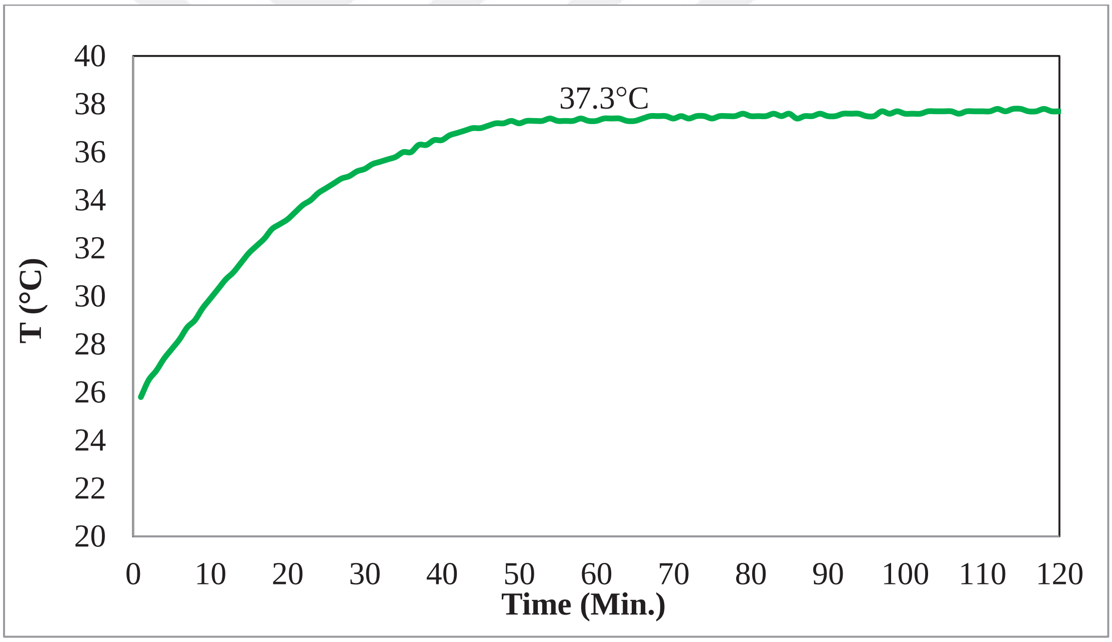

Figure 67 - Temperature values of remote light conversion mechanism

When the LED Tj values were added to the life time curves in figure 67, the life time of each TV products are determined.

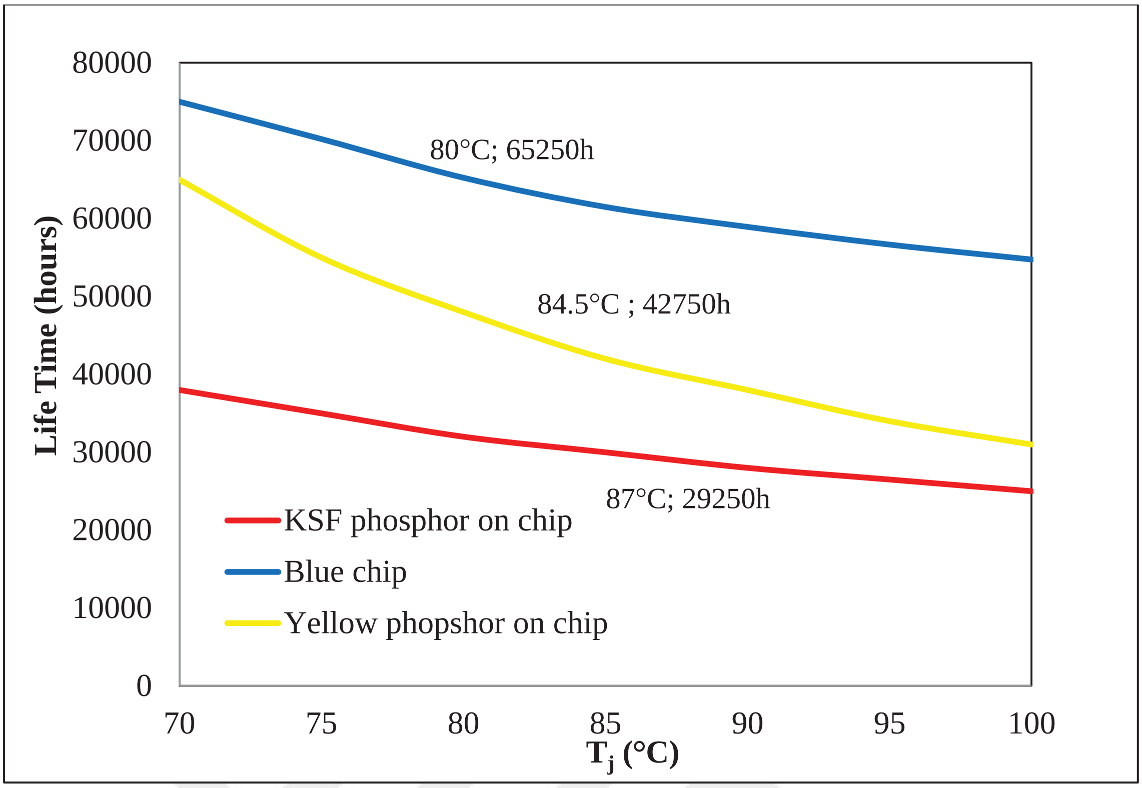

Figure 68 - Life time curves due to T_j of blue, yellow phosphor and KSF phosphor LED

Table 31 - Life time comparison results

LCD type	*Tj (°C)*	*Life Time (hours)*
LCD with phosphor film	80.0	65250
LCD with yellow phosphor LED	84.5	42750
LCD with KSF phosphor LED	87.0	29250

The life time of the LCD product with remote phosphor colour conversion film is 53% higher than the conventional LCD product with the yellow phosphor LED and also it is 123% higher than the TV product with KSF phosphor LED (Table 31).

CHAPTER IV

CONCLUSION

In this thesis, we have studied the design parameters critical in LED based LCD systems in order to define a high performance, long life, and reliably wide colour gamut display. Several wide colour gamut displays were designed and characterized with different colour conversion mechanisms. The results of colour gamut, luminance and life time of all these designs are summarized in table 32 below.

Table 32- Colour gamut, luminance and life time values of all structures

AUO UHD LCD with	*NTSC (Area)*	*DCI-P3 (coverage)*	*Luminance (nit)*	*Life time (hours)*
Yellow phosphor on-chip	74%	83%	489	42750
RG phosphor on-chip	82%	89%	316	N/A
KSF phosphor on-chip	90%	95%	416	29250
CdSe QD film	103%	97%	373	65250
InP QD film	87%	93%	297	65250
RG phosphor film	92%	96%	320	65250
Phosphor blend (0.55mm)	87%	93%	192	N/A
Phosphor blend (0.65mm)	85%	91%	164	N/A

Comparison of different colour conversion mechanisms reveals that the panel with KSF phosphor on-chip structure shows better performance in terms of colour gamut and brightness. However, the thermal behaviour of the KSF is not as good as the others, so the life time of the display with KSF on-chip structure is the lowest one. In this respect, remote colour conversion mechanisms offer longer life time products which are an important parameter in product development.

Quantum dot based remote conversion mechanisms are also suitable for wide colour gamut solutions. The display design with CdSe QD film offers better results for gamut and brightness. However, the heavy metal content (namely Cadmium, Cd) in the film is highly toxic, and will be restricted according to the RoHS in 2018.

To sum up, the display design with RG phosphor film provides a reliable and durable wide colour gamut solution, since it has a long life time, RoHS compliance, and a brightness value of over 300 nits and an impressive colour gamut of 96%. Therefore, the phosphor blend made of red (CASN) and green (β-SiAlON) phosphors can be effectively used as a remote film or coating inside the backlight unit. However, the ratio of the phosphor combination and the host material (silicone) is a critical parameter in defining the spectral output of the light conversion layer.

REFERENCES

[1] P. Service, "Pointer's Gamut, MacAdam Limits, and Wide Gamut Displays," Arizona, 2016.

[2] D. Köseoğlu, Y. S. Sezer and E. Bakan, "Colour gamut enhancement with remote light conversion mechanism," in *Nanophotonics 2017*, Barcelona, 2017.

[3] J. J. Joos, S. Abe, L. I. Martin, Z. Hens and P. F. Smet, "Hybrid remote quantum dot/powder phosphor designs for display backlights," *Light: Science & Applications,* 2017.

[4] "Rohs Guide," 26 12 2017. [Online]. Available: www.rohsguide.com/rohs-substances.htm.

[5] H. Chen, J. He and S.-T. Wu, "Recent Advances on Quantum-Dot-Enhanced Liquid-Crystal Displays," *IEEE Journal of Selected Topics in Quantum Electronics ,* vol. 23, no. 5, 2017.

[6] S. Kobayashi, S. Mikoshiba and S. Lim, LCD Backlights, John Wiley and Sons, 2009.

[7] D. K. Y. Wu and S. Tson, Fundamentals of Liquid Crystal Devices, John Wiley & Sons Ltd., 2015.

[8] M. Tjahjadi, G. Hay, D. J. Coyle and E. G. Olczak, "Advances in LCD backlight film and plate technology," *Information Display,* vol. 10, p. 22, 2006.

[9] M. W. Tseng, "Analysis and fabrication of a prism film with roll-to-roll fabrication," *Opt. Express,,* vol. 4718, p. 17, 2009.

[10] J. Lee, S. C. Meissner and R. J. Sudol, "Optical film to enhance cosmetic appearance and brightness in liquid," *Opt. Express,,* vol. 8609, p. 15, 2007.

[11] E. Chino, K. Tajiri and H. Kawakami, "Development of wide-color-gamut mobile displays with fourprimary-color LCDs," *SID Tech. Digest,* vol. 1221, p. 37, 2006.

[12] T. Sugiura, "EBU color filter for LCDs,," *SID Tech. Digest,,* vol. 146, p. 32, 2001.

[13] R. W. Sabnis, "Color filter technology for liquid crystal displays," *Displays,* vol. 20, p. 119, 1999.

[14] K. Kakinuma, M. Shinoda and T. Arai, "Technology of wide color gamut backlight with RGB lightemitting diode for liquid crystal display television," *SID Tech. Digest,* p. 1232, 2007.

[15] J. V. Derlofske, G. Benoit, A. Lathrop and D. Lamb, “Quantum Dot Enhancement of Color for LCD Systems,” *Optical Systems Division* .

[16] D. Koseoglu, “Uzak fosfor teknolojisi temelli geniş renk uzaylı ekran geliştirilmesi,” Manisa, 2017.

[17] P. Gaskell, B. Rand, J. Summers and H. Thompson, “The effect of reservoir geometry on the flow within ceramic tape casters,” *J. of the Europ. Ceram. Soc.,* vol. 17, p. 1185, 1997.

[18] R. Runk and M. Andrejco, “A precision tape casting machine for fabricating thin ceramic tapes,” *A.Ceram. Soc. Bull.,* vol. 54, p. 199, 1975.

[19] J. Rieger, “The glass transition temperature of polystyrene,” *Springer Link,* vol. 46, no. 3-4, p. 965, 1996.

[20] Y. Gu and N. Narendran, “A non-contact merhod for determing junction temperature of phosphor-converted white LEDs,” *Third International Conference on Solid State Lighting, Proceedings of SPIE,,* vol. 5187, pp. 107-114, 2004.

[21] L. Wang, X. Wang, T. Kohsei, K.-i. Yoshimura and M. Izumi, “Highly efficient narrow-band green and red phosphors enabling wider color-gamut LED backlight for more brilliant displays,” *Optical Society of America,* vol. 23, 2015.

[22] M. D. Fairchild, Color Appearance Models, John Wiley & Sons, Ltd, 2005.

[23] I. J. M. Res., “Cadmium & its adverse effects on human health,” *NCBI,* vol. 128, pp. 557-564, 2008.

VITA

Yusuf Sinan Sezer is born in 1988, in Izmır, Turkey. He graduated from Physics Department of Hacettepe University in 2012. He has been working at VESTEL as Optical Design Engineer since 2013. He has started his M.Sc.education at Ozyegin University in 2013. His current research interests are in quantum dots, phosphors, nanotechnology and optical system design.