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The Characterization of HDR OLED Display

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Abstract

This study was focused on the characterization of a new OLED TV under high dynamic range (HDR) and wide colour gamut (WCG) condition. Two aspects were covered. The colorimetric characteristics were first measured, analyzed and evaluated. The data were used to derive a novel characterization model. The present results showed that OLED displays had some better characteristics over ordinary display in both colour gamut and contrast ratio.

Introduction

The organic light emitting diode (OLED) display is becoming the most promising candidate for replacing the liquid crystal display (LCD) that is widely used in the daily life. OLED displays have superior qualities such as wide colour gamut (WCG), high dynamic range (HDR), and thinner panel thickness. It has now been utilized in several commercial productions including smart phones, and televisions. One of the most desirable properties of an OLED display is its high rendering performance to provide a life-like appearance in terms of colour and image quality.

However, most of previous studies were mainly focused on the traditional CRT and LCD technology [1, 2], and little work has been performed for OLED displays. Perales *et. al.* [3] studied an OLED display in regards to its luminance range, primary constancy, the additivity and channel dependence to determine whether a traditional characterization is applicable or not. They then found the OLED display was suffering from serious additive failure problems and cannot be well calibrated using a GOG model. Baek *et. al.* [4] compared a 2.2-inch OLED display with a LCD display in terms of spectral power distribution, tone reproduction curve (TRC), luminance, contrast, correlated color temperature, 2D color gamut and spatial uniformity. It was found that the OLED gave better performance in the former four aspects but similar quality for the other attributes. Sun *et. al.* [5] proposed two characterization models and compared them with some classic display models. Although both models were reported to work well in the test, they used some empirical formulas based on some assumptions. It is uncertain whether they were applicable to other OLED devices. Ye *et. al.* [6] evaluated an OLED TV and two LCD TVs in terms of their performance in rendering image. Seven types of image attributes as well as overall preference were evaluated and OLED TV was found to has a superiority over LCD TVs on the most of attributes studied, especially for peak brightness and contrast.

It can be clearly depicted that OLED TV could provide better visual experience than LCD and CRT displays. But it still has problems in some aspects such as channel dependence. Hence, it is of interest to fully understand its colorimetric characteristics, as well as its characterization model for accurate colour reproduction or management for imaging applications.

Objective

The colour characteristics data were collected in the first place to give an overall impression of the OLED TV. The colour characteristics including peak luminance curve (PLC), channel dependence, tone reproduction curve (TRC), 2D and 3D colour gamut and blackness and contrast were investigated, and compared with a QD-LCD display. Finally, a characterization model was proposed based on its unique characteristics, and its performance to predict the colour of the HDR OLED display was evaluated and compared with some other commonly used models.

Colorimetric Characteristics Evaluation

Measurement conditions

Two types of the state of the art TVs were studied here. They represent the mainstream technologies in display industry, OLED and QD-LCD.

A 65" Sony A1 OLED TV was adopted in this study. Its physical size was 1451 mm by 834 mm by 86 mm with a diagonal length of 1639 mm and its spatial resolution was 3840 pixels by 2160 pixels. It could achieve a luminance up to over 700 cd/m^2 and a quite low black level. Default settings were adopted when taken measurement under Cinema Pro mode. The TV settings for contrast enhancement were turned off. HDR and WCG functions were turned on and the OLED TV then approximate the BT.2020 standard [7] at this condition. Due to the limitation of present technology, the real 'BT.2020' specification can only be approximately achieved.

In addition to the OLED TV, a 65" QD-LCD TV was also included. QD-LCD had the same resolution as the OLED and a larger dynamic range due to its high peak luminance. However, its black level was also much higher, leading to a reduction of contrast. It was serving as the anchor to better understand the performance of OLED TV.

The total measurement was implemented in a darkened room (Reflectance for the wall is 8%) using a tele-spectradiometer (TSR), Konica Minolta CS-2000A Spectroradiometer (referred as CS2000 later). CS2000 had a larger luminance range from 0.0005 to 5,000 cd/m^2, giving great accuracy for measuring dark colours. This means CS2000 was quite suitable for measuring display and could cover the dynamic range of the two displays studied in this paper.

The whole testing condition followed the instruction of IEC 62341-6-1[8] for OLED and QD-LCD. Fig. 1 illustrates the measurement setting. Its measurement distance was set at 2.5 times the width, equaling to 1.7m. A 4% window size was adopted thorough out the whole study to avoid the interference of the embedded power saving function. The background was set at middle grey if not specifically noted. This is to avoid the involvement of white channel embedded (no white boost technology) in the OLED TV, which was intended to increase its luminance range. In this condition, the peak lumiance of the OLED TV was constrained below 450 cd/m^2.

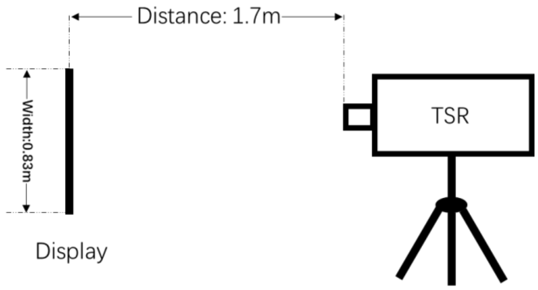

Figure 1. The measurement condition for OLED. All the lights were turned off when taking measurement

Colour characteristics

Some most important colour characteristics were studied. They were introduced in detail as follows,

Peak Luminance Curve (PLC)

The PLC was introduced first to explain the inner power saving function embedded in the OLED TV. For CRT and LCD displays, intensity levels were controlled by the voltage level, i.e. proportion to the input RGB signal. However, this was totally different for OLED displays. The average luminance output for an OLED was dependent on the window size displayed, i.e. the total output is influenced not only by the input values, but also by window sizes. This means the power increases with the increase of window size and the input RGB signal level. As a result, a power saving function was embedded in the OLED panel to automatically control the total output.

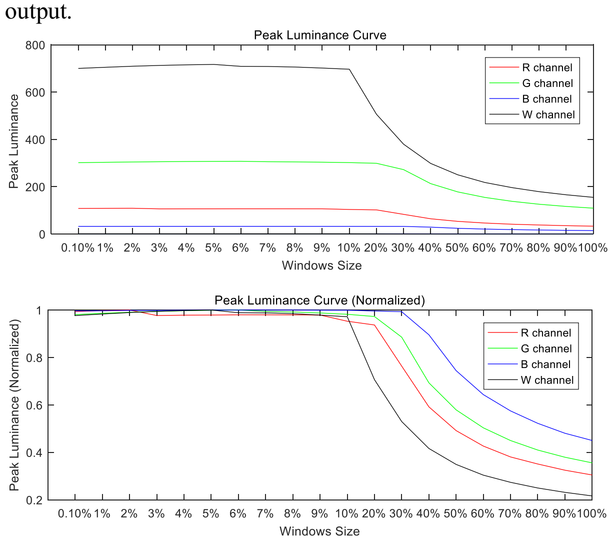

Figure 2. The luminance output with the change of window size

Fig. 2 clearly shows a luminance drop with the increase of window size. It can be seen that the output luminance was stable at first. However, it was then dropped quickly when the window size was over 10%. Based on this fact, the whole measurement of this study was fixed at a windows size of 4%, which ensures a constant luminance output. The 4% window size adopted in this study is only for the characterization under this specific grey background. For other cases incuding different window sizes or backgrounds, the average pixel level should be adopted to accurately simulate its real power saving function.

Channel dependence

The traditional way to test channel dependency was compare the agreement of XYZ values for grey channel with the sum of that for R-, G- and B- channels. In this manner, each channel was measured from 0 to 255 digital inputs with an interval of 15. A mean colour difference of 5.5 ΔE_{00}^{*} was found for both displays studied. Note that no white boost technology was involved in this test.

However, this is not a proper testing method for HDR displays. Primary chromaticities have been pre-set in the BT.2020 standard, which is beyond the capability of the technology by now. Hence, a tone mapping algorithm was applied for each channel to match the PQ curve, leading to an unavoidable additivity failure.

Channel dependency was the underlying assumption for classical characterization models. Since it was not met by the HDR displays, classical models were not applicable to HDR devices. Hence, a new characterization was proposed and was to be discussed later.

Tone reproduction curve (TRC)

TRC is an important characteristic for a HDR display, representing its intrinsic properties in rendering colours. As is mentioned before, it is hard to achieve the up-to-date standard, BT.2020, for the present HDR displays, where the PQ curve [9] is adopted.

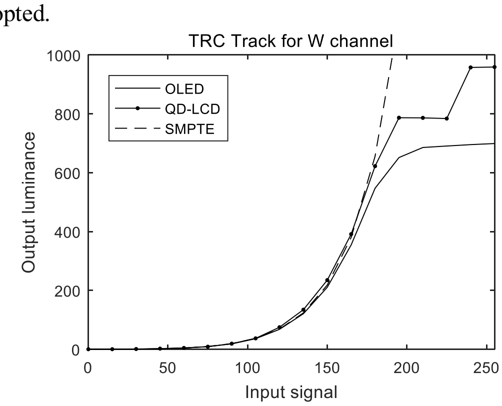

Figure 3. TRC tracks of each individual channel

In this study, an investigation was performed between the white channel with the PQ curve under a black background. The results are shown in Fig. 3. It is obvious that the present HDR display cannot obtain a high luminance as defined in the standard. Hence, a cut-off value for each channel was found for both displays, beyond which no luminance increase was observed. In addition, a precise TRC track was achieved when input signal was at low level for all channels, indicating the good performance of both displays. For input signal above a certain value, departure was found for both displays. This adoption of roll-off algorithm was intended to improve the picture quality and was in accordance with the UHD Alliance Technical Specification (Version 1.0, November 23, 2015)[10], where EOTF accuracy was confirmed up to 60% of display's maximum luminance. And for data above 60%, it's the TV manufacturer's own decision to make a suitable TRC to achieve a better image quality.

2D gamut in 1976 u'v' diagram

Fig. 4 shows the 2D gamut of all the displays studied in 1976 $u'v'$ diagram as well as a DCI-P3 gamut, which is most mobile device and digital cinema based. Each display's R, G and B primaries were drawn when the driving signal at maxmium (255), e.g. chromacity of R channel was obtained for a input RGB value of [255,0,0]. One can find that OLED had the largest gamuts. DCI-P3 was fully enclosed by OLED. They had the same coordinates except for blue primary. QD-LCD had the smallest gamut among all and was completely encompassed by DCI-P3.

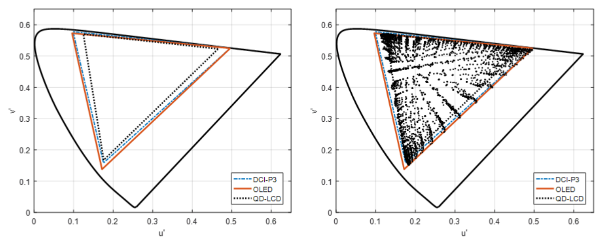

Figure 4. *2D gamut of the OLED TV in 1976 u'v' diagram (left). The black points in the right were the measured data of QD-LCD.*

3D colour gamut

2D gamut was not a good indicator to reveal the rendering capability of a display since no luminance information was involved. Hence, 3D gamuts for both displays against a grey background were illustrated in Fig.5 in $J_za_zb_z$[11] uniform colour space (UCS). $J_za_zb_z$ is a UCS specially developed for HDR and WCG applications and allows for a luminance range from 0.001 to 10,000 cd/m^2. It adopts a fixed white point, i.e. D65 at 10,000 cd/m^2. CIELAB, CIECAM02 and other UCSs were not selected just because they were developed using SDR datasets and their performance in HDR and WCG conditions have not been fully studied [13]. It is important to notify that the whole analysis is under a grey background where no white boost technology is involved, representing the typical usage scenario of TVs. It is obvious that the results would vary according to different average luminance levels (a combination of background and window size).

From Fig. 5, it is clearly observed that QD-LCD in this condition showed a large colour gamut for its peak luminance and was comparable with that of OLED. Gamut for OLED was still quite large due to its relatively high luminance and chromatic primaries. Their gamuts were summarized in Table 1, where gamut for the OLED was normalized to 1.

Black and Contrast

Previous studies advised that contrast was a quite important factor for image rendering using a display[6, 12]. Table 1 shows that OLED had a remarkably high contrast, which could go over a hundred thousand for grey background in luminance unit (cd/m^2). However, this number may not be realistic for human perception due to poor uniformity of the luminance scale. Hence, it was re-calculated in $J_za_zb_z$ and its value was still outstanding among all the displays. In addition, contrast for QD-LCD was not bad although it was not comparable with that of OLED.

Such a high contrast for OLED was due to its low black level. Technologies for OLED and QD-LCD are quite different. OLED was self-illuminance, indicating each pixel could be easily turn-off to achieve a complete black. However, QD-LCD used local dimming technology, implying it was more difficult to control the backlight to avoid any light leakage.

From the above analysis, both OLED and QD-LCD showed some colour characteristics different from ordinary LCD display. QD-LCD had a larger gamut volume while OLED had a higher contrast ratio.

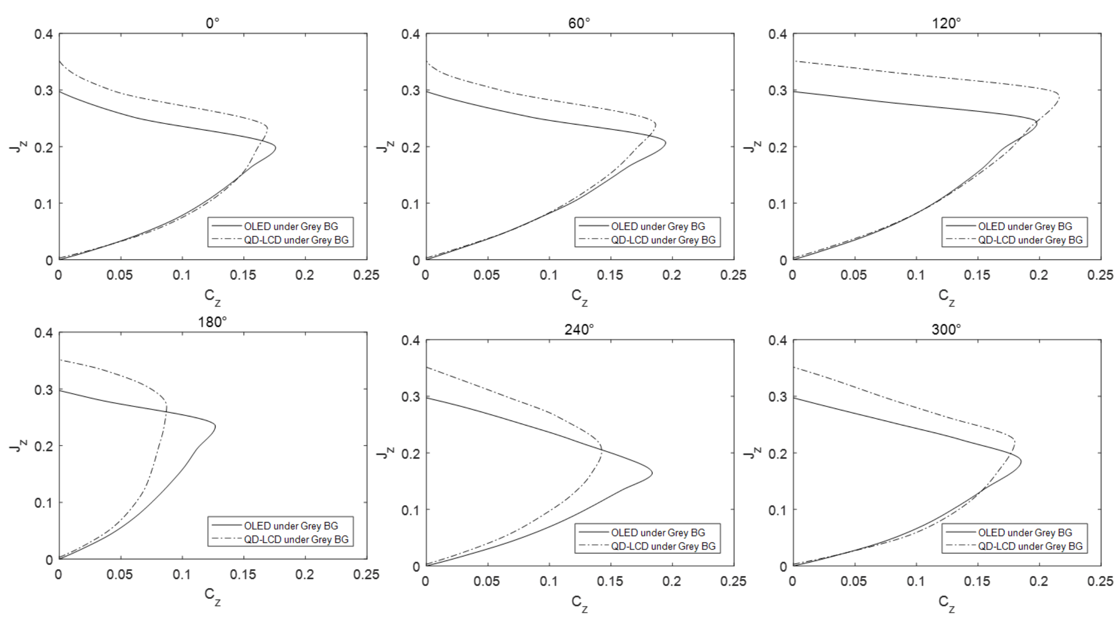

Figure 5. *Gamuts comparison of OLED and QD-LCD displays under and grey background*

Table 1. A summary of the display properties. Two types of contrast were included. One was calculated using luminance (cd/m^2) and the other one was calculated using J_z (brightness) values. Gamut of OLED was normalized to 1.

	Peak white (cd/m^2)	CCT(K)	Black (cd/m^2)	Luminance Contrast (log cd/m^2)	Brightness Contrast (log $J_za_zb_z$ unit)	Relative Gamut Volume
QD-LCD	669.15	7255	0.76	3.946	2.037	1.12
OLED	427.55	7337	0.00056	5.886	3.822	1

Display characterization

Most of the colorimetric characterization models are based upon two underlying assumptions of colorimetric characteristics, i.e. channel independence and chromaticity constancy. However, as discussed above, OLED displays do not meet these two assumptions. Hence, a novel model, i.e. *PLCC based compensation model,* referred as *PC model,* was then proposed by combining two classic models, i.e. PLCC and 3D-LUT. PC model includes two major parts, linearization and compensation. The former part was to apply the traditional PLCC model for any input colour and thus the predicted output, XYZ_{PLCC}, could be obtained. Afterwards, a 3D-LUT was adopted to estimate the amount of compensated XYZ values, ΔXYZ_{Cmp}, to be added back to the XYZ_{PLCC}. Finally, the output for the input colour was the sum of XYZ_{PLCC} and ΔXYZ_{Cmp}.

An important step of PC model was to build a 3D-LUT for XYZ compensation. Initially, N sampling points per channel are defined. Subsequently, N*N*N training samples are displayed on the OLED TV in question and their XYZ output, XYZ_m, are measured via a TSR. Meanwhile, their XYZ_p were obtained by applying the PLCC model. Finally, the 3D-LUT can be established by Eq. 1.

$$\Delta XYZ_{3D-LUT} = XYZ_m - XYZ_p \qquad (1)$$

To test the model's performance, Macbeth ColorChecker chart (MCCC) consisting of 24 colours were adopted. There are 2 sets of test colours. One had a white luminance (the 24th patch on MCCC) of 100 cd/m^2, giving a well prediction accuracy for traditional displays. However, its dynamic range was somehow narrow when applied to HDR displays. Hence, they were further extended to 400 cd/m^2 by simply multiplying by four to the XYZ values. Hence, two sets of MCCC testing datasets were obtained.

The training dataset for both 3D-LUT and PC model was a 5*5*5 colour dataset. PLCC had an even sampling of 18 samples per channel, indicating 54 training samples in total. SMPTE model was complied with the calculation procedure as defined in SMPTE 2084 standard. Models' performance in terms of prediction accuracy in CIEDE2000 unit were summarized in Fig. 6.

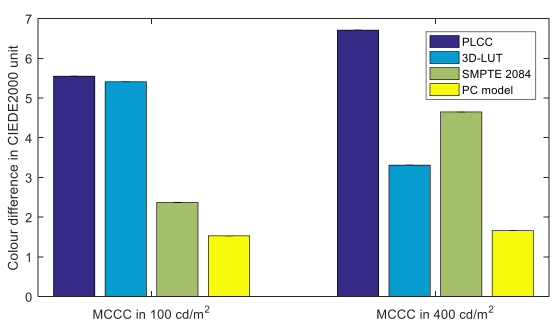

Figure 6*. Model performance in terms of color difference*

Fig. 6 shows that the present PC model outperformed all the other models tested, giving an acceptable average colour difference within or around $2\Delta E^*_{00}$. Accuracy of PLCC model was limited by the channel independency (5.24 ΔE^*_{00}) and could not give a higher prediction accuracy. Performance for 3D-LUT was merely up to the number of training samples. The more samples used, better performance that could be achieved. SMPTE model was defined in the SMPTE 2084 standard, and it was truly performed better than the classic models (PLCC and 3D-LUT) in most cases. Its predictive accuracy in general gave good agreement for most of the coloursbut not so well for some saturated colours.

Conclusion

A study on characterization of OLED TV was successfully conducted. The OLED TV was found to have high overall contrast and large colour gamut, indicating its potential to give a high image quality. A novel characterization model was proposed to perform display characterization and its performance was outstanding among all the models investigated.

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