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Optical characterization of the emissive properties of HDR/WCG displays using ICtCp color space and Fourier optics viewing angle instruments

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Abstract

*High Dynamic Range (HDR) and Wide Color Gamut (WCG) displays require adapted color measurements analysis. In this paper, we evaluate the viewing angle dependence of the color gamut and color volume of two HDR/WCG displays, one QLED TV and one OLED TV measured using a Fourier optics viewing angle system. The analysis is made using L*a*b* color space and ICtCp color space recently proposed by Dolby laboratories. The different interests of the ICtCp color space for direct comparison of the displays is discussed.*

Introduction

Many high dynamic range (HDR) and wide color gamut (WCG) displays made with different technologies are now commercially available. The new HD video standards such as HDR10, Dolby Vision and Hybrid Log Gamma (HLG) [1-2] take ITU-R BT.2020 as the default color gamut. In addition, HDR requires not only much extensive color gamut but also much higher luminance dynamic range than standard dynamic range (SDR). Maximum brightness for white is for example 1000cd/m2 for HDR10 [2] and up to 10000cd/m2 for Dolby vision [3]. Color gamut is always a restrictive property that do not involve the luminance range. On the contrary color volume involves both color gamut and luminance range and appear as a better descriptor to compare displays that are supposed to have large color gamut and extended luminance range. We have already proposed to use color volumes to analyze viewing angle color measurements on the displays [4-6]. In these studies the standard L*a*b* CIE 1976 and L*u*v* color spaces have been used and several parameters of the color volumes of different displays have been computed. The international committee for display metrology has also standardized the method [7].

In this paper, we use the ICtCp color space recently proposed by Dolby laboratories and which is well adapted for HDR and WCG contents [8]. We compare this new color space with the standard L*a*b* CIE 1976 color space [9], analyzing the color viewing angle properties measured on two HDR displays: one QLED TV and one OLED TV. Color measurements are made on white, black, red, green, blue, magenta, yellow and cyan states using an EZContrast Fourier optics viewing angle system with a maximum angular aperture of ±80°.

Color spaces

*CIE L*a*b* color space*

CIE L*a*b* color space is widely used by different color industries. The three coordinates of CIELAB represent the lightness of the color L* compared to a white reference, its position between red/magenta and green a* and its position between yellow and blue b*.

$$L^* = 116 * f\left({}^{Y}/_{Y_n}\right) - 16$$

$$a^* = 500 * [f\left({}^{X}/_{X_n}\right) - f\left({}^{Y}/_{Y_n}\right)]$$

$$b^* = 200 * [f\left({}^{Y}/_{Y_n}\right) - f\left({}^{Z}/_{Z_n}\right)]$$

$$f(t) = t^{1/3} \quad \text{if} \quad t > (6/29)3$$

$$\text{or} \quad f(t) = \frac{t}{3} * \left(\frac{29}{6}\right)^2 + \frac{16}{116} \text{ otherwise}$$

$X_nY_nZ_n$ is a chosen white reference and the f(t) function included some non-linearity to match the human eye response. As shown in figure 1.a reporting the Mac Adam ellipses, L*a*b* color space is reasonably perceptually uniform except in the blue region and discernibility rules in terms of Euclidian distance can be defined [9].

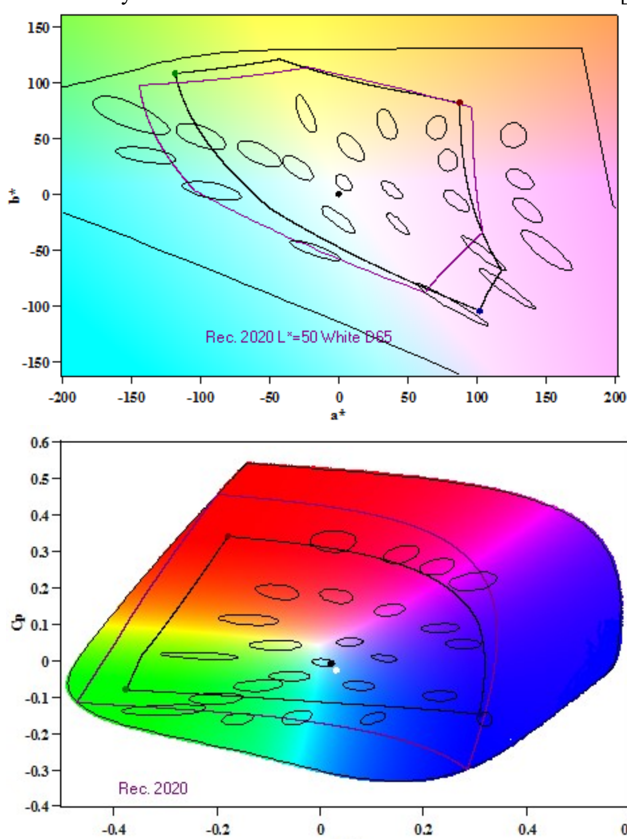

*Figure 1. Color gamut of QLED display at normal incidence in the a*b* (top) and CtCp (bottom) chromatic plan: Rec.2020 gamut and Mac Adam ellipses (x10) are included*

ICtCp color space

ICtCp color space has been introduced by Dolby laboratories in order to match the new video format for HDR/WCG video compression [3, 8]. The transformation from XYZ CIE components to ICtCp space consists in three successive operations; conversion to three cones human response space LMS; nonlinear conversion to reduce dynamic range and color differencing equations:

$$\begin{pmatrix} L \\ M \\ S \end{pmatrix} = \begin{pmatrix} 0.3592 & 0.6976 & -0.0358 \\ -0.1922 & 1.1004 & 0.0755 \\ 0.0070 & 0.0749 & 0.8434 \end{pmatrix} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}$$

$$L'M'S' = EOTF_{PQ}^{-1}(LMS)$$

$$\begin{pmatrix} I \\ Ct \\ Cp \end{pmatrix} = \begin{pmatrix} 0.5 & 0.5 & 0 \\ 1.6137 & -3.3234 & 1.7097 \\ 4.3780 & -4.2455 & -0.1325 \end{pmatrix} \begin{pmatrix} L' \\ Y \\ Z \end{pmatrix}$$

and scaling using:

$$(I \quad Ct \quad Cp)_{Scaled} = (I \quad Ct \quad Cp) \begin{pmatrix} 2048 \\ 1024 \\ 2048 \end{pmatrix}$$

The corresponding CtCp chromatic plane is reported in figure 1.b with the same MacAdam ellipses and the monochromatic color locus. The space is perceptually uniform in the entire plane. Depending on the selected maximum brightness of the white (10000cd/m^2 for BT.2100 used in the following, 1000cd/m^2 for DCIP3, and 100cd/m^2 for BT.709), the ICtCp parameters can be scaled to obtain directly the volume in number of distinguishable colors, a capacity that is very useful for direct quantitative comparison of different displays. It can be also applied both for HDR (10bits) and SDR (8bits) displays.

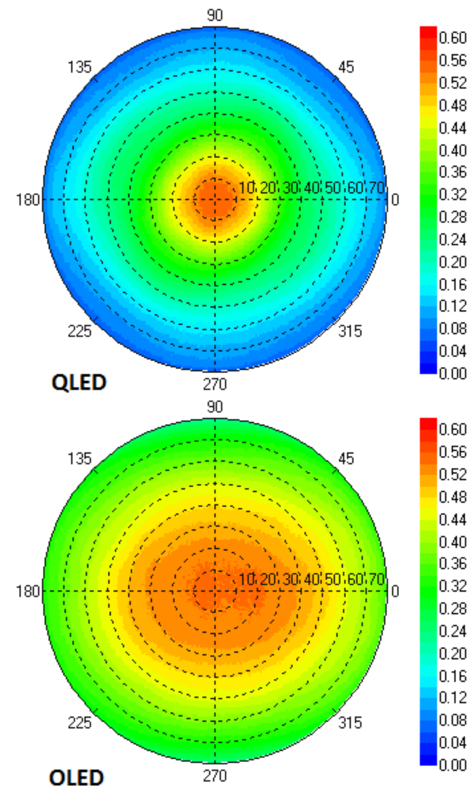

*Figure 2. Color gamut ratio to Rec.2020 of QLED (top) and OLED (bottom) displays at all angles in the a*b*chromatic plane*

Experimental results

Color gamut

a*b* chromatic plane

The color gamut measured at normal incidence on the QLED TV compared to the Rec.2020 reference gamut is reported in Figure 1.a and 1.b for the L*a*b* and ICtCp chromatic planes respectively. The white reference is taken as the white luminance measured on the samples at normal incidence for the L*a*b* color space. Even if the gamut shapes are very different for the two color spaces, the difference with the reference is comparable. The gamut ratios to Rec.2020 computed at all angles using the two-color spaces for the QLED and OLED TVs are reported in Figures 2 and 3. The white reference for the L*a*b* space is taken as the sample value at normal incidence. To get comparable values, it is fixed for all the angles and the strong reduction outside normal incidence is due to the lightness reduction and not to color change.

CtCp chromatic plane

On the contrary, one advantage of the ICtCp color space is that the CtCp values can be normalized to the XYZ maximum at all angles and the gamut behavior observed on Figure 3 is in this case only due to the color variations making this color space more appropriated to compare color gamuts. The u'v' color space is also naturally normalized and often used for gamut evaluation.

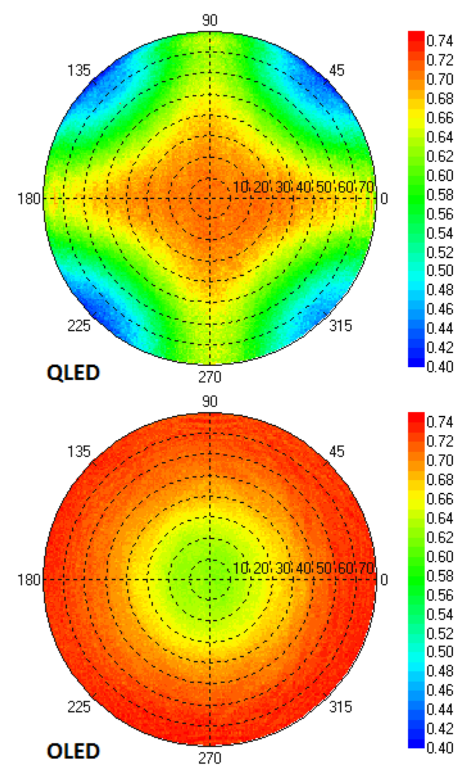

Figure 3. Color gamut ratio to Rec.2020 of QLED (top) and OLED (bottom) displays at all angles in the CtCp chromatic plane

Color volume

L*a*b* chromatic space

L*a*b* color space is useful to compare the shape of the color volumes of different displays using measured white values as reference values. The color volumes of the QLED and OLED TVs measured at normal incidence are reported in figure 4 with the Rec.2020 volume computed with the same reference. The shape of the two-color volumes is slightly different but quantitative differences in terms of color between the two displays cannot be obtained directly because of the different white references. The angular dependence of the color volume of the two displays is reported in figure 5. The strong decrease of the color volume of the QLED display with incidence angle is due to the strong luminance reduction. In this sense, the OLED display is clearly better than the QLED display.

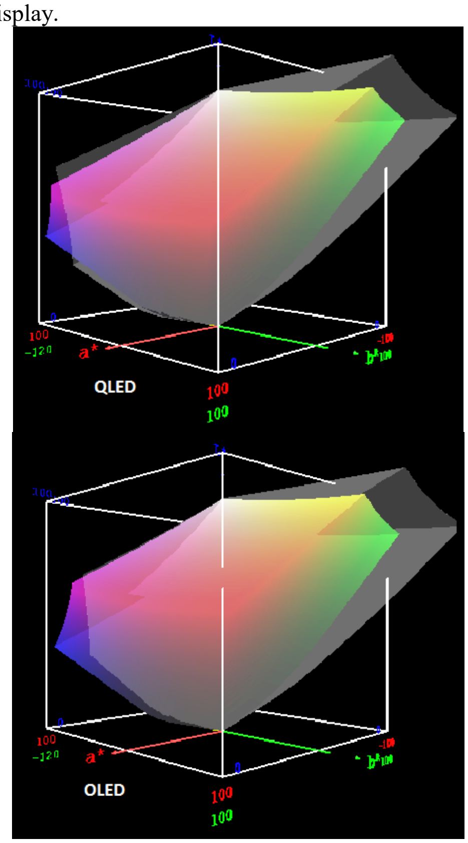

Figure 4. Color Volumes in Lab color space of QLED (top) and OLED (bottom) displays at normal incidence. Reference color volume Rec.2020 is reported in grey

ICtCp chromatic space

In the ICtCp color space, the color volumes scaled to units of distinguishable colors can be directly compared. We have reported the color volumes of the two displays measured at normal incidence in figure 6. The Rec.2020 reference volume in number of distinguishable colors and scaled to a white level of 10000cd/m^2 is also reported in grey on the same figure. We see immediately that the two displays suffer from an intensity level much lower than the Rec.2020 reference for all the colors and that the two color volumes are comparable at normal incidence even if there are much smaller than Rec.2020 reference.

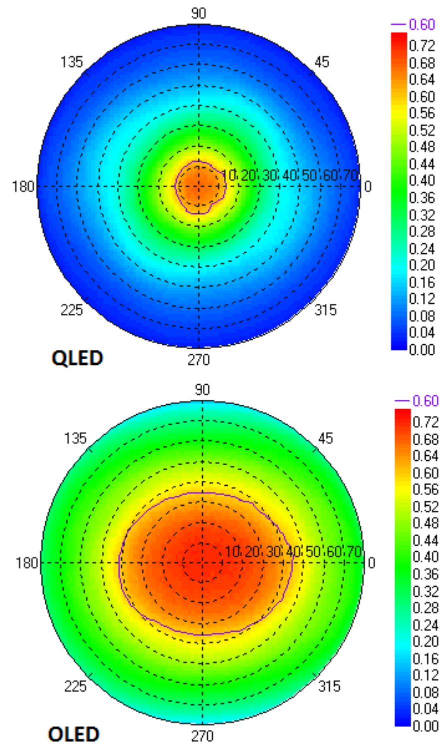

*Figure 5. Color Volume ratio to Rec.2020 in the L*a*b* color space of QLED (top) and OLED (bottom) displays at all angles. Reference illuminant is the white value measured at normal incidence*

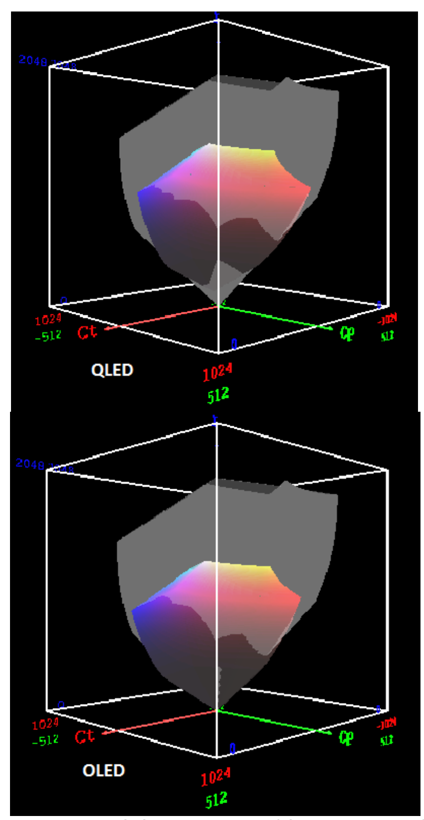

Figure 6. Color Volumes in ICtCp color space of QLED (top) and OLED (bottom) displays at normal incidence. Reference color volume Rec.2020 is reported in grey

To compare more easily the two displays we have computed the angular behavior of the volume ratio to Rec.2020 reference and the color volume gravity center in the ICtCp color space. Angular behaviors of the volume ratio, gravity center intensity and Ct and Cp coordinates are reported in figure 7 for the two displays with the same scales. As reported above, the two displays have comparable properties at normal incidence except that the global color shift is slightly different for the two displays (more important red shift for the QLED display at normal incidence). Nevertheless, the angular dependence is very different for the two displays. The OLED display is much more efficient in terms of color because it maintains a high color volume in the entire viewing angle and the color properties are more stable than those of the QLED display.

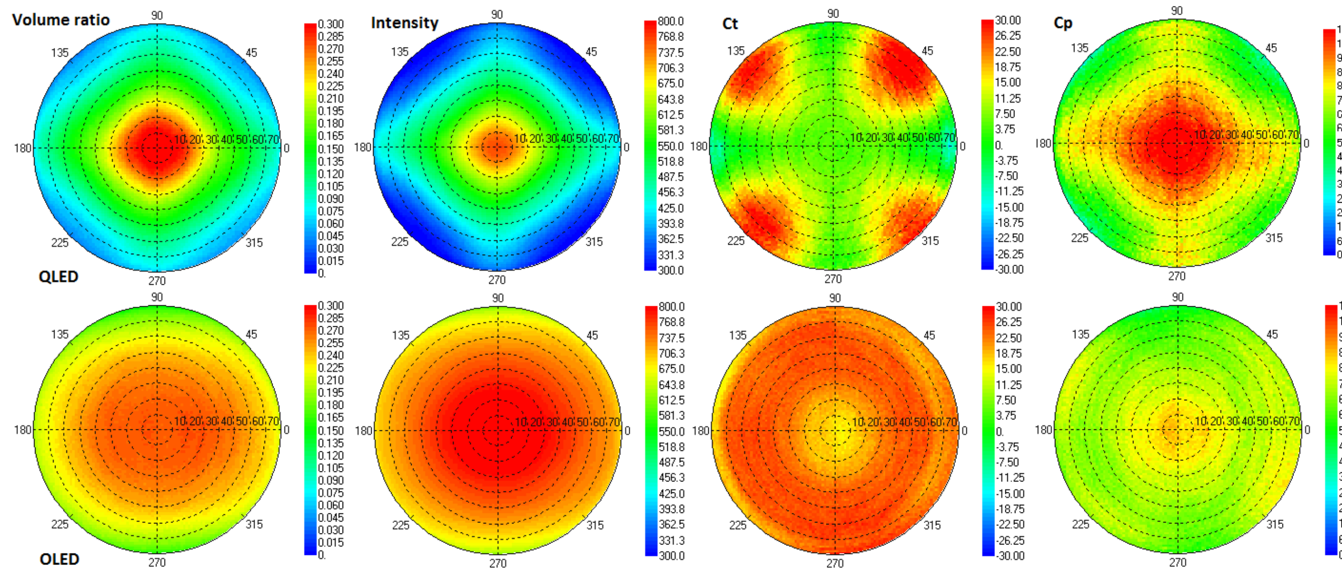

Figure 7. Color volume and gravity center parameters of the QLED (top) and OLED (bottom) displays in the ICtCp color space at all angles: volume ratio to Rec2020 (left), gravity center I (left-center), Ct(right center) and Cp (right)

Conclusions

Analysis of viewing angle color measurements using the ICtCp color space is really innovative and interesting for more efficient comparison of HDR/WCG displays whatever the display technology. Compared to standard L*a*b* color space, it does not need any choice of white reference and presents several advantages: it can be used for gamut evaluation (without scaling) and for color volume quantification in millions of distinguishable color (MDC) (with scaling).

We have compared one QLED and one OLED TV using this new color space. Even if the luminance level is much smaller than the reference (volume ratio to Rec.2020 below 30%), the two displays have comparable color properties at normal incidence. Nevertheless, the OLED display is much better at angles above 20-30° where the QLED display shows a strong decrease of the color volume. In addition the stability of the color properties is better for the OLED display. This is particularly obvious when comparing the gravity centers angular behaviors of the two displays (cf. figure 7).

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Author Biography

Pierre Boher earned an Engineer degree at ECP, "Ecole Centrale des Arts et Manufactures" in 1982. He obtained his Ph.D. in material sciences in 1984 and his ability to research management at "University Pierre et Marie Curie" in 1991. He worked in the French Philips Laboratories during nine years on the deposition and characterization of very thin films and multilayers. R&D manager at SOPRA between 1995 and 2002, he developed different metrology tools for non-destructive characterization mainly for microelectronics. He joined ELDIM as R&D manager in 2003.

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