Chapter

Picture Quality and Sound Quality of OLED TVs

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Abstract

Unlike the past when cathode-ray tube (CRT) dominated display industry, many different types of flat panel displays (FPDs) are now leading the industry. Of these, organic light-emitting diode (OLED) display has recently become a next-generation display since this display is recognised as having advantages over other competing technologies in picture quality and form factor. With major attributes of picture quality considered, a series of evaluations based on objective measures was performed with an OLED TV compared to an LCD TV. OLED TV outperformed LCD TV 100 times in black, 20 times in colour contrast, 30% in dynamic range coverage, 50 times in local contrast and 20 times in viewing angle. In addition, sound quality of the OLED TV was assessed using both objective and subjective evaluation methods compared to conventional TV speakers since OLED panel speaker technology was recently commercialised. The OLED panel speaker showed better performance both in objective and subjective methods.

Keywords: OLED TV, OLED panel speaker, picture quality, sound quality, emissive display, HDR

1. Introduction

Although there are many different types of displays nowadays, displays can be mainly categorised as projection, off-screen, direct view and so on (**Figure 1**). Most of all, many FPDs of direct view displays have been commercialised very successfully. These FPDs can be also categorised in many ways, but the author will categorise them as an emissive display (or self-emissive display) and a non-emissive display in order to discuss picture quality of them because this kind of categorisation is highly related to picture quality.

Non-emissive displays need additional ambient light or illumination emitting light as a light source because colour and light level could not be expressed with the panel. In this category, there are electrophoretic display (EPD), electrochromic display (ECD) and so on, and the most successful one ever is liquid crystal display (LCD). For LCD, backlighting system is used as an illumination and each pixel of its panel controls colour and light level as an optical shutter [1].

On the other hand, an emissive display stands for the display which each pixel of its panel emits light with light level and colour controlled by itself [2]. For example,

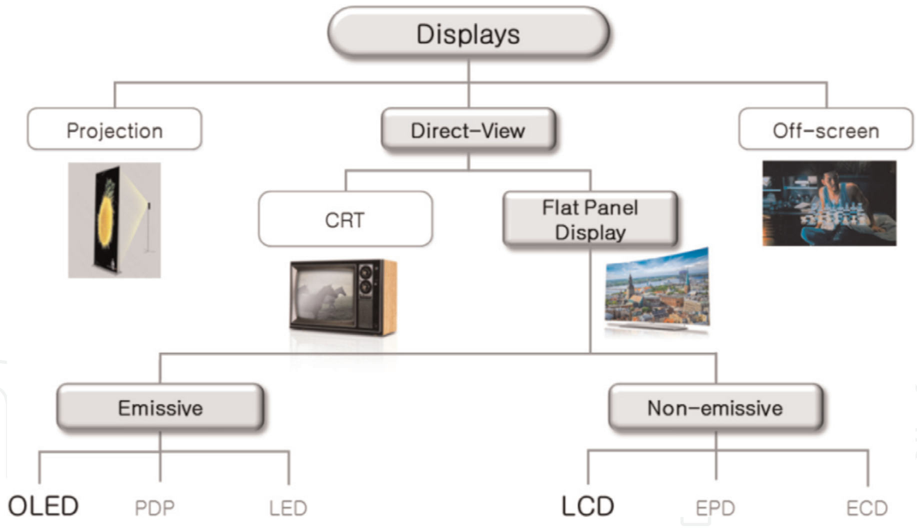

Figure 1.
Display category.

in this emissive display, there are plasma display panel (PDP), light-emitting diode (LED) and OLED which will be investigated in this chapter. OLED technology has been recently adopted for large TV displays and commercial displays as well as mobile displays [3].

This fundamental way of displaying causes the difference in picture quality. This chapter will introduce picture quality attributes and evaluation methods for high-end TV displays and assess the picture quality of OLED TV as an emissive display with the reference to LCD TV as a non-emissive display which is a current major TV display technology, and sound quality of OLED TV using OLED panel speaker will be also investigated.

2. Picture quality of OLED TVs

2.1 Evaluation method

In order to understand how to evaluate picture quality of OLED TVs, it is better to start with a well-known concept "image quality circle [4]". This concept says that three steps—technology variables (display design factor), physical image parameters (physical measures) and customer perceptions (perceptual attributes)—are important for foreseeing customer image quality rating (picture quality that consumers consider), and these are organically linked and influence sequentially. Of these, physical measure and perceptual attribute, also called objective measure and subjective measure, respectively, should be measured together for an appropriate picture quality evaluation. In other words, these two measures should be linked for a perfect picture quality modelling [5].

In this study, only objective measure was considered. It will be also helpful to refer to a number of product reviews from various consumer reports in order to see a trend of subjective measure. Black, colour, viewing angle and HDR property were selected as the objective measures. Because recent high-end TVs have the identical specifications in resolution, colour bit depth, frame rate, etc., which were traditionally compared, other attributes causing differences in picture quality were chosen. The OLED TV used in this evaluation has 65 inches of diagonal size and 4 K ultra-high-definition (UHD) resolution. Also, 4 K UHD LCD TVs with the identical 65-inch size were compared to see a typical difference in picture quality between emissive display and non-emissive display. For the LCD TVs, two different backlighting types according to local dimming method were evaluated—edge-lit and direct-lit.

2.2 Evaluation result

2.2.1 Black

2.2.1.1 Pixel dimming vs. local dimming

First of all, the most fundamental performance of OLED TV which makes difference in picture quality is black level and pixel dimming. These performances could affect most of perceived picture quality attributes—colourfulness, brightness, sharpness, contrast and so on. That is why LCD manufacturers attempt to develop display technologies for lower black level with more number of dimming blocks.

For LCD, the technology which enables lower black level is called local dimming for backlight. The LCD TVs which were evaluated in this chapter have 12 dimming blocks for edge-lit backlight and 150 dimming blocks for direct-lit backlight (**Figure 2**). Since more dimming blocks secure lower black level and better picture quality, LCD manufacturers tend to increase the number of dimming blocks. Recent premium LCD TVs adopted over 500 dimming blocks. However, more dimming blocks mean more expensive cost for backlight and relevant electronic parts. Furthermore, direct-lit LCD for more dimming blocks should sacrifice thinner display thickness compared to edge-lit LCD showing better design.

However, OLED TV can inherently realise lowest black level because every single pixel can emit no light when black signal is applied. In terms of number of dimming blocks, OLED TV has more than 33 million blocks when 4 K UHD is considered (WRGB $\times$ 3840 $\times$ 2160). This is called pixel dimming because every sub-pixel (white, red, green and blue sub-pixels) is dimmable. Pixel dimming using emissive sub-pixels can reproduce peak highlight without halo artefact which normally appears in LCDs (**Figure 3**).

To increase brightness of peak highlight in LCDs, brightness of the LEDs in the dimming blocks corresponding to the peak highlight zone should be increased, and it will cause halo artefact around the peak highlight zone. On the contrary, if the brightness of the LEDs is decreased, the halo artefact could be reduced, but the peak highlight will get darker, and it will be difficult to reproduce the creative intent.

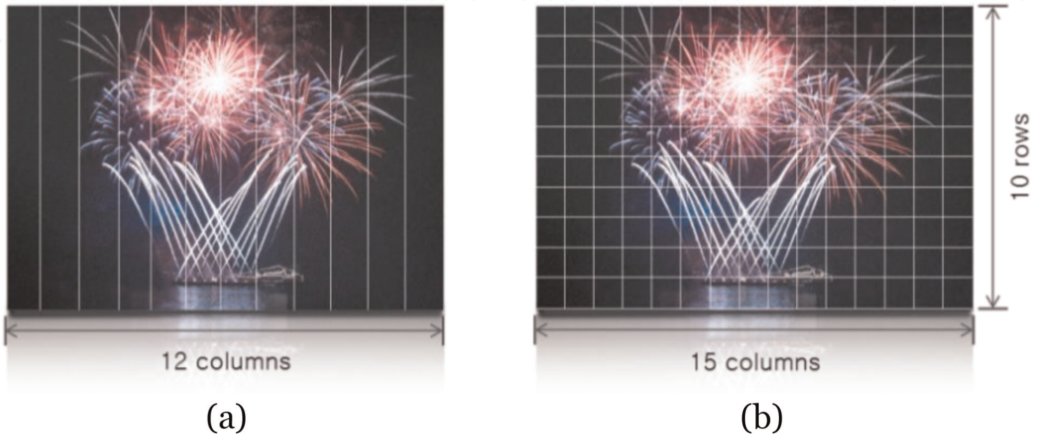

Figure 2.
LCD TVs according to local dimming method. (a) LCD TV with edge-lit backlight. (b) LCD TV with direct-lit backlight.

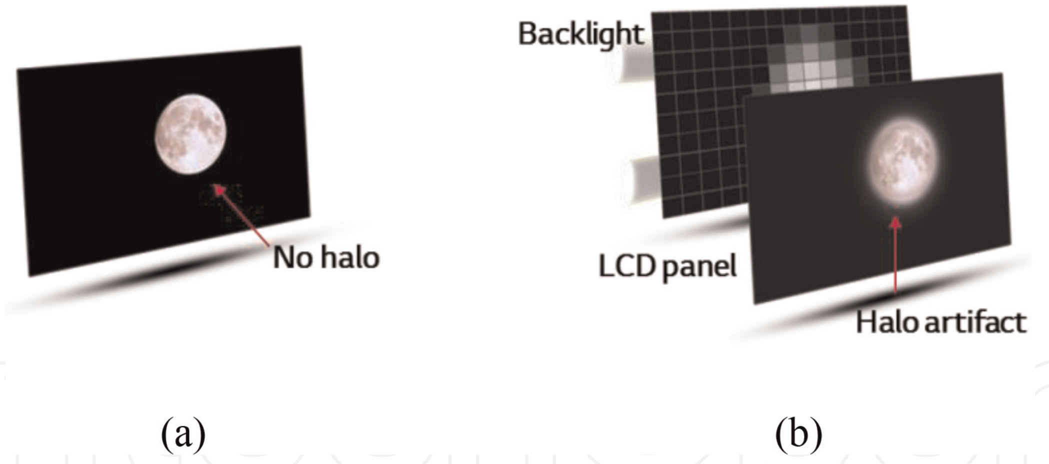

Figure 3.
Dimming performance comparison between OLED TV and LCD TV. (a) Pixel dimming (OLED TV) and (b) local dimming (LCD TV).

Figure 4.
Example of various colours around black signals in complex images and conventional black test pattern. (a) Black signals in complex images and (b) full-screen black [6].

2.2.1.2 Black level and black constancy

In this section, two objective measures for black performance described in the above section will be introduced. As can be seen in **Figure 4**, most complex images we face contain a variety of colour signals around black signals (or darker level signals). But conventional test patterns [6] in **Figure 4b** for measuring black performance of displays could not reflect the real situation like this. Thus a set of new test patterns as shown in **Figure 5** were proposed in the International Electrotechnical Commission (IEC) [7].

This set consists of five different test patterns with different grey levels of backgrounds (0, 255, 511, 767 and 1023 grey levels of overall 1024 grey levels) and a centred black box for measuring black level. Furthermore, black constancy value can be also evaluated with these patterns. This test shows how consistently the black level remains depending on neighboured colour signals. The black constancy C shown in Eq. (1) is defined as the difference between maximum black luminance and minimum black luminance.

$$\mathrm{C} = \max[|L_{k,0} - L_{k,i}|] \tag{1}$$

where $L_{k,0}$ is the black luminance of the centre at the 0th grey background level; $L_{k,i}$ is the black luminance of the centre at the ith grey background level (i = 255, 511, 767 and 1023).

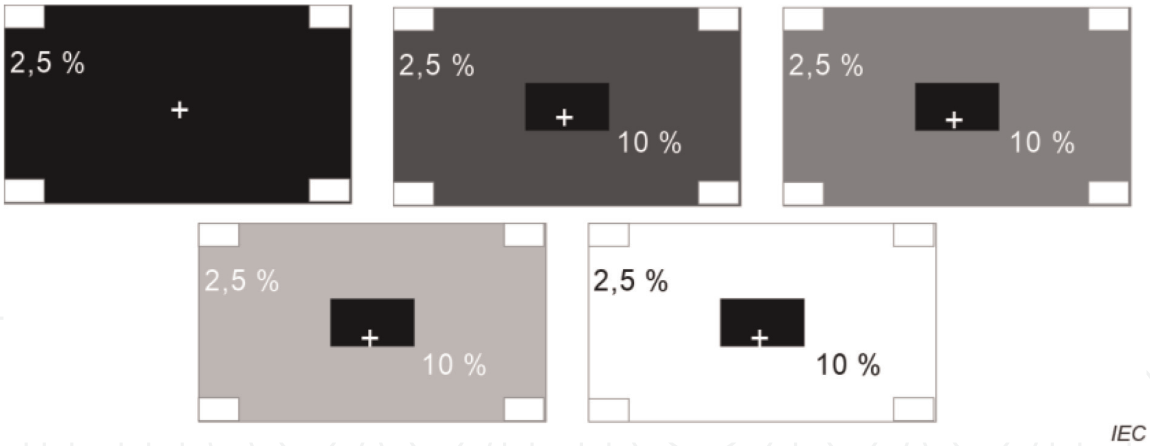

Figure 5.
Test patterns for black level and constancy measurement.

Black luminance (cd/m^2)	OLED TV	LCD TV (edge-lit)	LCD TV (direct-lit)
Max	8.3×10^{-4}	6.5×10^{-2}	8.2×10^{-2}
Min	5.6×10^{-6}	1.3×10^{-3}	1.7×10^{-3}
Ave	4.2×10^{-4}	$4.4 \times 10^{--2}$	5.1×10^{-2}
Constancy (Max-Min)	8.2×10^{-4}	6.4×10^{-2}	8.0×10^{-2}

Table 1.
Black luminance and black constancy of the OLED TV and the LCD TVs.

These black luminance data and black constancy values are summarised in **Table 1** and **Figure 6**. As can be seen, the black levels of LCD TVs are strongly influenced by the neighboured colour signals. However, OLED TV's black level remains comparatively constant showing 8.2×10^{-4} cd/m^2 black constancy. It was also found that direct-lit LCD showed bigger constancy than edge-lit LCD, which could be caused by higher brightness of direct-lit LCD.

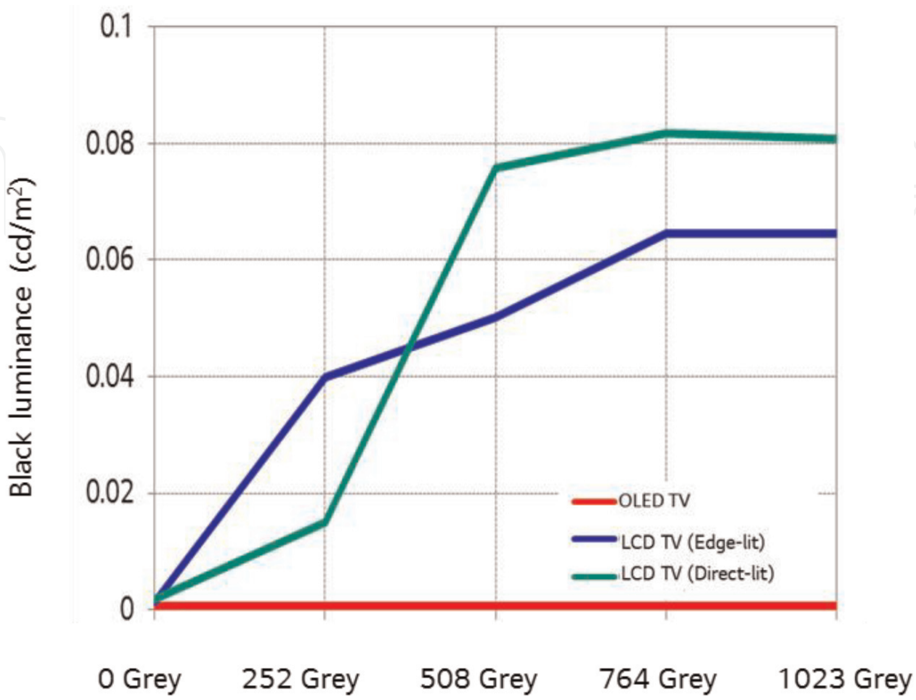

Figure 6.
Black luminance according to background grey levels.

2.2.2 Colour

2.2.2.1 Colour gamut

To investigate colour capability of OLED TV, colour gamut was evaluated in terms of both area ratio and coverage to standard colour spaces. Both area ratios with reference to BT.709 [8] and BT.2020 [9] show almost similar values for OLED TV and LCD TVs. Coverage values with reference to DCI-P3 [10] and BT.2020 also show similar for both displays. The coverage values for DCI-P3 exceed 95% in all the TVs compared. This indicates those TVs could reproduce similar colour capability for digital cinema.

Is it sufficient to explain the colour performance of those TVs with this evaluation? Since OLED TV is generally assessed more colourful at the similar colour gamut than LCD TVs [11], the reason will be discussed in the next section (**Figure 7**).

2.2.2.2 Colour contrast

Simultaneous contrast is one of well-known colour appearance phenomena which is easily perceived and experienced in our daily life [12]. **Figure 8** illustrates simultaneous contrast. The two identical grey patches presented on different backgrounds appear distinct. The darker background causes the grey patch to appear lighter, while the less dark background causes the white patch to appear less light. Although the centred colours have the identical luminance values, those two colours could appear different. This phenomenon can be found between TVs with different black levels.

To quantify this difference considering the relation between black level and colour, it is suggested to use colour contrast. The test pattern has black background and centred colour, and colour contrast is evaluated with the ratio of luminance of the colour to average luminance of the background (Eq. (2)) (**Figure 9**).

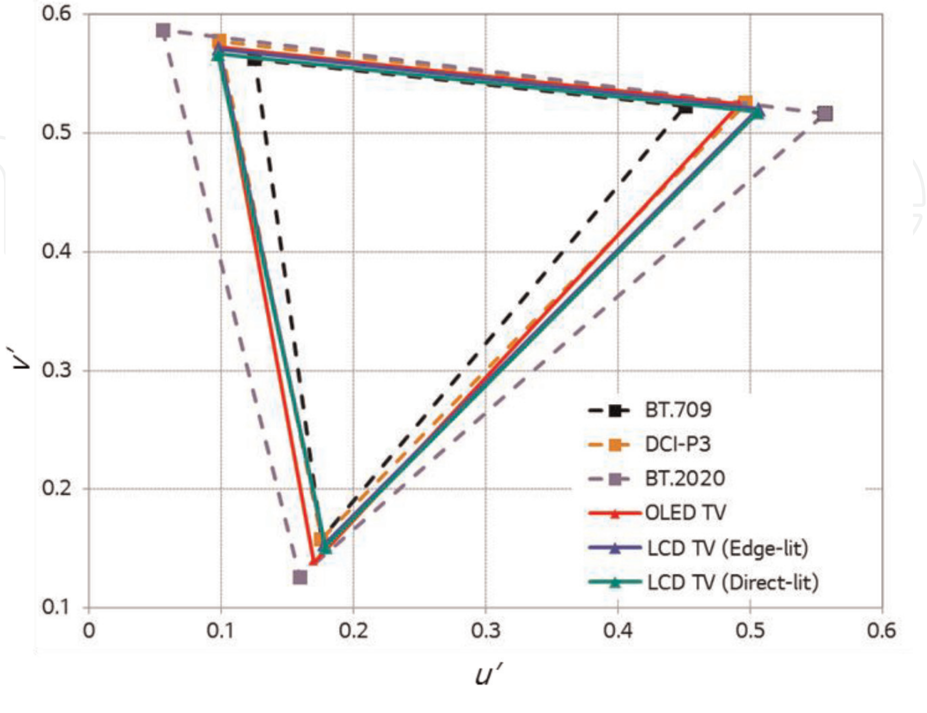

Figure 7.
*Colour gamut comparison of the OLED TV and the LCD TVs with reference to BT.709, DCI-p3 and BT.2020 colour spaces (**Table 2**).*

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Figure 8.
Simultaneous contrast phenomenon perceived at the different dark backgrounds in luminance values.

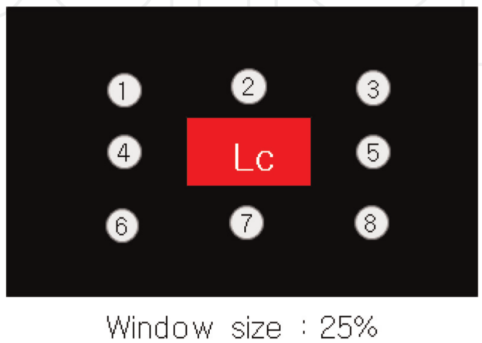

Figure 9.
Test pattern and measurement locations for colour contrast.

Colour gamut (in CIE1976)		OLED TV	LCD TV (edge-lit)	LCD TV (direct-lit)
Area ratio (%)	BT.709	129	128	128
	BT.2020	75	74	74
Coverage (%)	DCI-P3	99	97	96
	BT.2020	75	74	74

Table 2.
Colour gamut area ratio and coverage of the OLED TV and the LCD TVs.

$$\text{Colour contrast} = \frac{L_c}{L_k}, L_k = \frac{\sum_i^8 (L_i)}{8} \tag{2}$$

where L_c is the luminance of the centre and L_i is the black surround at the eight locations.

Colour contrast result was summarised in **Table 3**. OLED TV shows 60 times higher colour contrast than edge-lit LCD TV and around 20 times higher colour contrast than direct-lit LCD TV. This indicates that two TVs which have the same

Colour contrast	OLED TV	LCD TV (edge-lit)	LCD TV (direct-lit)
Red	120,000:1	1800:1	4700:1
Green	400,000:1	6500:1	17,000:1
Blue	64,000:1	790:1	2300:1

Table 3.
Colour contrast of the OLED TV and the LCD TVs.

colour gamut performance could show distinct perception depending on each black level, and this is one of the evidences in which black level affects many picture quality attributes such as brightness, contrast, sharpness, colourfulness, etc. as mentioned in the previous section.

2.2.3 High dynamic range (HDR)

HDR displays are recently becoming premium displays as more and more HDR contents are produced and they are rapidly distributed to the consumer market. HDR means a dynamic range higher than what is considered to be SDR (standard dynamic range) or LDR (low dynamic range) [13]. HDR generally offers better visual experience than SDR. In other words, HDR content could appear more similar to what human vision perceives. Especially, both bright details and dark details are expressed more naturally compared to SDR. Therefore, HDR TV should reproduce such highlight and dark zones more precisely.

Commercial HDR TV was first defined and announced by UHD Alliance (UHDA) in 2016 [14]. The UHDA announced their certification requirements for a HDR TV. According to the requirements, the HDR TV should have both a peak brightness of over 1000 cd/m^2 and a black level less than 0.05 cd/m^2 for LCD TV or a peak brightness of over 540 cd/m^2 and a black level less than 0.0005 cd/m^2 for OLED TV. These specifications are only the minimum requirement for HDR TV. After this logo programme was set up, many international standard bodies—IEC, International Committee for Display Metrology (ICDM), Video Electronics Standards Association (VESA), etc.—have made an effort to standardise metrologies or requirements. In this section, deeper consideration and evaluation of HDR properties for OLED TV will be made by a recent established international standard [7].

2.2.3.1 Dynamic range coverage

It is well known that human vision can perceive very wide range of brightness and darkness. There is some agreement that human vision can adapt to a value of 14 log units ranging from 10^{-6} to 10^8 cd/m^2 [15]. For a HDR content based on SMPTE ST.2084 [16], the code value ranges from o to 10^4 cd/m^2. If a reference dynamic range is given, a display's dynamic range coverage to the reference can be easily evaluated by measuring peak black luminance and peak luminance with the test patterns in **Figures 5** and **10**, respectively. That is, after measuring peak luminance using four patterns, the highest peak luminance is decided. Also the lowest black is decided with five black luminance patterns. Maximum dynamic range coverage (Eq. (3)) is obtained comparing the peak luminance value and black luminance value of reference [7]:

$$C_{dr.\max}[\%] = \frac{R_{dr.\max}}{\left(\log L_{w.ref} - \log L_{k.ref}\right)} \times 100 \tag{3}$$

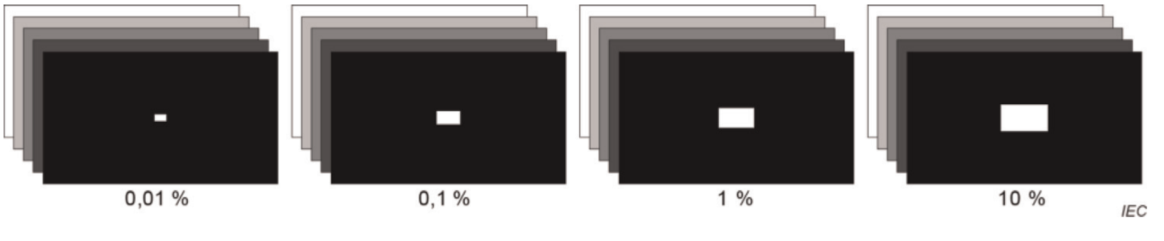

Figure 10.
Test patterns for peak luminance measurement.

$$R_{dr.\max} = \log L_{w.\max} - \log L_{k.\min} \tag{4}$$

where $L_{w,\max}$ is the maximum value of measured peak luminance and $L_{k,\min}$ is the minimum value of measured black luminance.

As a result, dynamic range coverages of OLED TV and LCD TVs are compared with reference to human vision and SMPTE ST.2084 content (**Table 4**). For the black level of SMPTE ST.2084, human vision's black was used instead of 0 cd/m^2. The OLED TV shows 61% of dynamic range coverage over human vision and 80% over SMPTE ST.2084 content, while LCD TVs show comparatively lower dynamic range coverage values. When the UHDA's required values are considered, two displays also show a big difference (OLED TV, 60%; LCD TV, 43%). From this result, it is clear that OLED TV still needs to achieve higher peak luminance in addition that the LCD TVs need to have lower black level and higher peak luminance in order to be a better HDR TV and cover higher dynamic range of human vision and HDR content. When, however, higher peak luminance is considered, visual fatigue needs to be considered as well [17].

2.2.3.2 Peak luminance and constancy

One of the great advantages of an ideal HDR TV is that it can express shiny peak highlights that cannot be experienced on SDR TVs. Therefore, peak luminance of HDR TV is very important to express such peak highlight zones properly. As shown in **Figure 11**, peak highlight appears in real images in a variety of sizes (**Figure 12**).

To see how large the peak highlights are distributed in the HDR content, all of the peak highlights of the content were detected, and statistical analysis was conducted [18, 19]. According to the analysis, it was found that the size of peak highlight, which appeared the most frequently, was 0.01% in area ratio and that the cumulative 90% of peak highlights was 0.2% in area ratio. This result indicates a very important point. That is, HDR displays should express small peak highlights within about 0.2% very well.

Dynamic range coverage (%)	UHDA (OLED)	UHDA (LCD)	OLED TV	LCD TV (edge-lit)	LCD TV (direct-lit)
Human vision	46	33	61	46	46
SMPTE ST.2084	60	43	80	60	60

Table 4.
Dynamic coverage of UHDA required displays, the OLED TV and the LCD TVs with reference to human vision and a HDR standard.

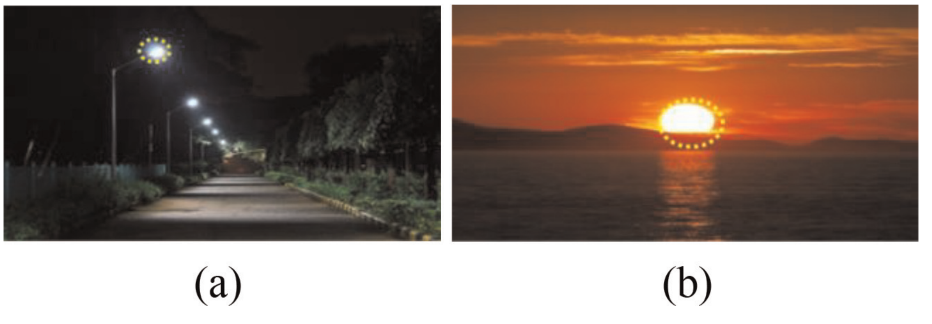

Figure 11.
Example of peak highlights in actual HDR images. (a) Peak size of 0.06% and (b) peak size of 1%.

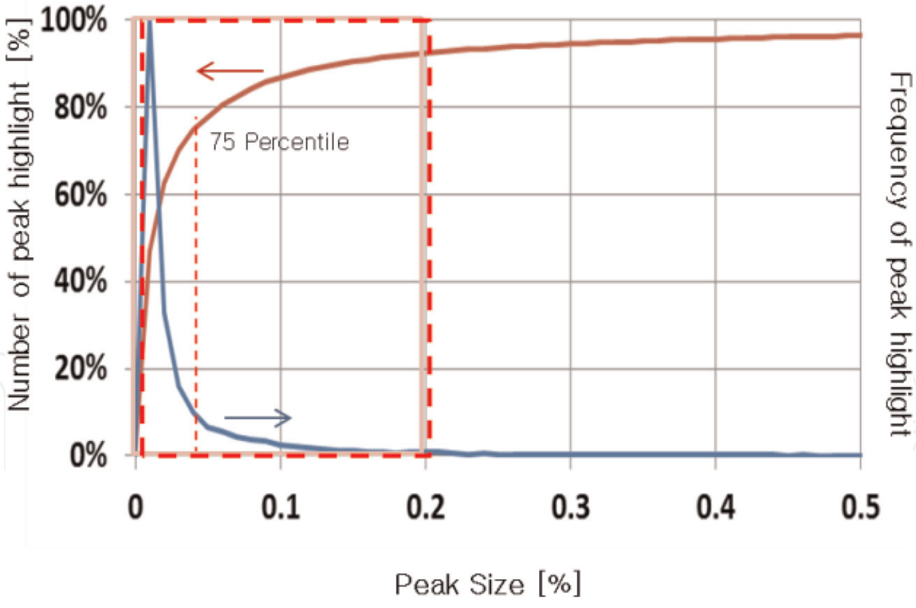

Figure 12.
Distribution of the size of peak highlights in actual images.

To evaluate these characteristics, peak luminance patterns introduced in **Figure 10** were used, and 20, 30, 40 and 100% patterns were additionally used. The peak luminance characteristics of the display can be well displayed according to peak highlight size. The results of the measurements are detailed in **Figure 13**. LCD TVs had higher luminance values than OLED TVs at peak highlight, which is larger than 1% size. On the other hand, OLED TV showed almost constant peak luminance values at smaller peak highlight size than 10%.

As mentioned about the UHDA requirement in the preceding section, the peak luminance of LCDs 1000 cd/m^2 is taken equivalent to 540 cd/m^2 of OLED TV because of the high contrast characteristic of OLED TVs. Given this fact, OLED TV can be said to have consistently high peak luminance not only at 10% of the peak highlight but also at smaller than 0.01% size. However, only from 1 to 10% size, LCD TVs have high peak luminance of 1000 cd/m^2. As noted in the previous

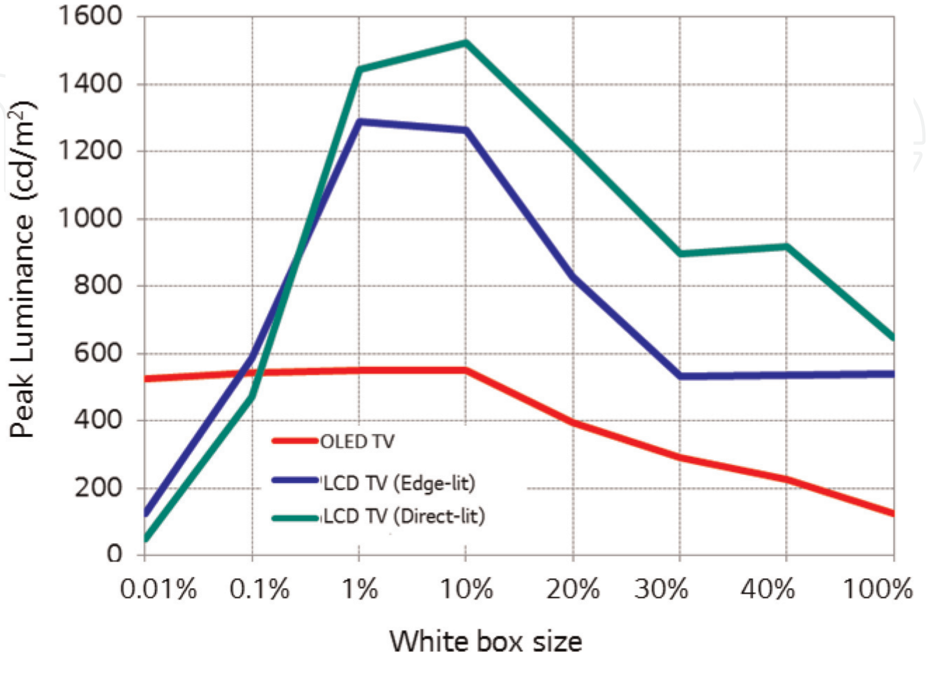

Figure 13.
Peak luminance of the OLED TV and the LCD TVs according to the size of the white boxes.

Size (%)	OLED TV	LCD TV (edge-lit)	LCD TV (direct-lit)
0.01	526	123	49
0.1	544	587	470
1	549	1288	1444
10	548	1263	1523

Table 5.
Peak luminance according to the size of white box.

section, it can be said that OLED TV is very advantageous in expressing peak highlight because peak luminance is very important in smaller peak highlight size than 0.2% (**Table 5**).

In addition, the results of measuring peak luminance were plotted by varying the grey level around the white box in the measurement pattern (**Figure 14**). As can be seen, the OLED TV implements the maximum peak luminance regardless of the surrounding signal compared to the LCD TV, while the LCD TV implements the maximum peak luminance within a relatively small range. In the actual video, where various signals are inputted, an OLED TV can show consistently bright peak luminance.

2.2.3.3 Local contrast

Sequential contrast measurement methods, which used to be mainly used, measure the black luminance and peak luminance values of the display in different patterns and then determine the contrast ratio by the ratio of those values. However, with this value, it is difficult to represent the local contrast characteristic frequently encountered in actual content because dark and bright parts usually appear at the same time in real life (**Figure 15**).

In order to measure another important characteristic of HDR, a local contrast, a measurement method was proposed using the pattern shown in **Figure 16** and Eq. (5) [7]. Measurements showed that OLED TV showed local contrast values 50 times larger than LCD TVs (**Table 6**):

$$CR_L = \frac{8L_C}{L_1 + L_2 + L_3 + L_4 + L_6 + L_7 + L_8 + L_9} \tag{5}$$

where L_c is the luminance of the centre; L_i is the black surround at the eight locations.

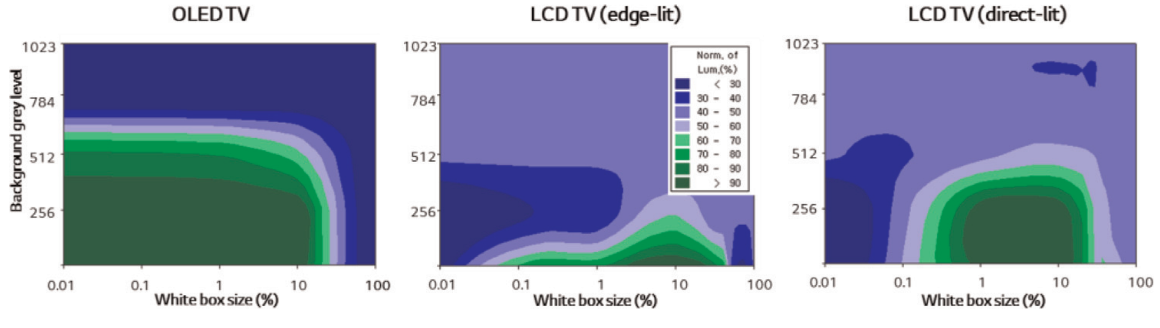

Figure 14.
Peak luminance of the OLED TV and the LCD TVs influenced by grey level of background.

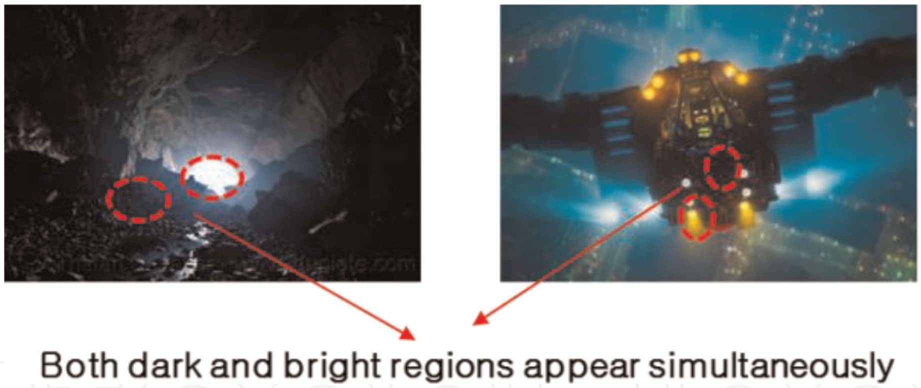

Figure 15.
Example of the images that local contrast measurement is important.

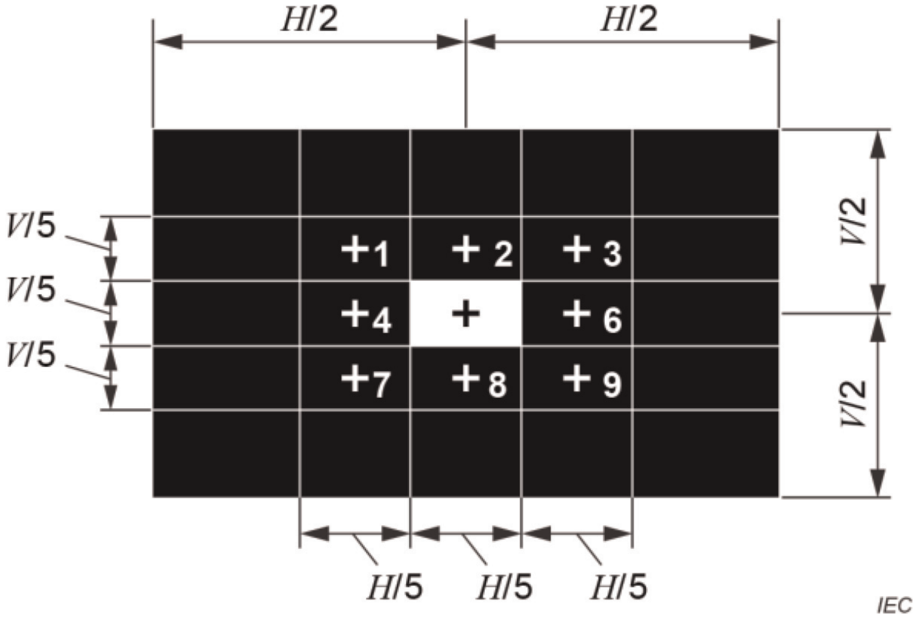

Figure 16.
Test pattern for local contrast.

	OLED TV	LCD TV (edge-lit)	LCD TV (direct-lit)
White luminance	544	1280	1420
Ave. black luminance	0.0005	0.0936	0.0729
Local contrast	1088K:1	13.6K:1	19.5K:1

Table 6.
Local contrast of the OLED TV and the LCD TVs (cd/m²).

2.2.4 Viewing angle

Another big difference between emissive display and non-emissive display is the performance of the viewing angle. OLED TV has relatively constant optical properties in the entire direction as light emits from each pixel of OLED panel.

On the other hand, LCD TVs have different displaying ways from OLED TV because the light emitted from backlight passes through liquid crystal layer which is optically anisotropic. When the light enters the pixelated liquid crystal layer, it is polarised. The polarised light goes through phase retardation because of optical anisotropic property of liquid crystal layer. The phase retardation depends strongly on the incident angle. Therefore, picture quality is influenced by the viewing angle. That is, colour, gamma, luminance and black characteristics will vary depending on the viewing angle (**Figure 17**).

For colour shift criteria ($\Delta u'v' < 0.02$), OLED TV is 120°, while LCD TV is 92°. For half-luminance angle where luminance is reduced by half to the front luminance, OLED TV is measured 132°, while LCD TV is 62°. In addition, for gamma shift ratio (GSR), which measures the extent of gamma variation at off-axis to the normal direction, the OLED TV showed 1% variation, while LCD TVs showed around 20% shift (**Table 7**). This numerical difference causes colour distortion as shown in **Figure 18**.

Next, black performance and HDR properties that were examined in the previous section were compared at 45° viewing angle. The result is summarised in **Table 8**. While the OLED TV showed the identical black luminance value to the value at the normal direction, the black luminance values of LCD TVs have increased by four times and six times, respectively. For peak luminance, although the OLED TV maintained at 94% at off-axis compared to normal direction, the LCD TVs showed around 50% or less of peak luminance compared to normal direction.

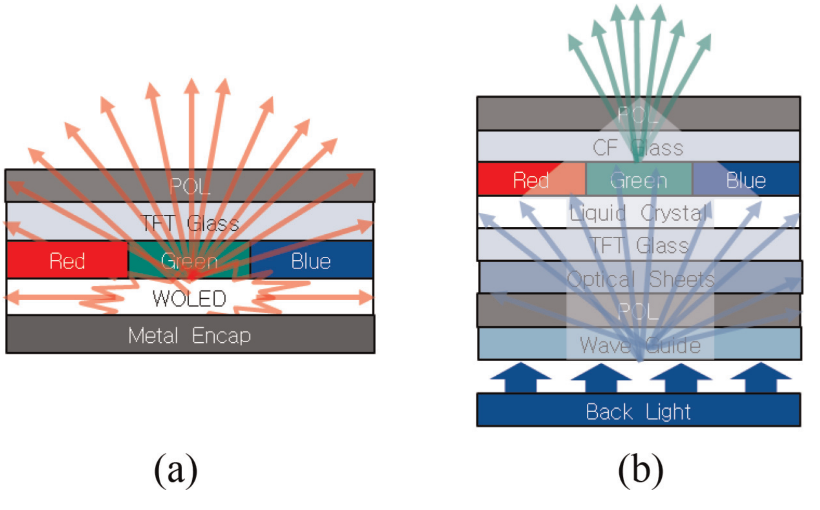

Figure 17.
Conceptual diagrams of light path of OLED TV and LCD TV. (a) OLED TV and (b) LCD TV.

Gamma shift ratio	OLED TV	LCD TV (edge-lit)	LCD TV (direct-lit)
0° vs. 45° (%)	1.0	19.6	23.0

Table 7.
Gamma shift ratio of the OLED TV and the LCD TVs.

Figure 18.
Picture quality change at the off-axis of the OLED TV and the LCD TVs.

Picture quality attributes	OLED TV			LCD TV (edge-lit)			LCD TV (direct-lit)		
	0°		45°	0°		45°	0°		45°
Black luminance (cd/m^2)	5.6E−6	100% →	5.6E−6	1.3E−3	640% →	8.3E−3	1.7E−3	440% →	7.4E−3
Peak luminance (cd/m^2)	548	94% →	516	1263	34% →	430	1523	49% →	749
Dynamic range coverage (%)	80	100% →	80	60	78% →	47	60	83% →	50
Local contrast (:1)	1.1M	91% →	1.0M	13K	7.7% →	1K	19K	11% →	2K

Table 8.
Black and HDR properties of viewing angle of the OLED TV and the LCD TVs.

In addition, the dynamic range coverage and local contrast of the OLED TV were also relatively maintained compared to the normal direction, whereas LCD TVs have deteriorated at the 45° viewing angles. In summary, the OLED TV generally maintains picture quality at the off-axis direction.

3. Sound quality of the OLED TV using OLED panel speaker

OLED panel speaker has been recently developed by LG Display, which vibrates the thin OLED panel itself with actuator or piezo materials to make a sound on the viewing screen to deliver directly to consumers. The sound reproduced on the centre of panel not only increases sound quality but also keeps the borderless and thin TV design. The OLED panel speaker can maximise vibration transfer efficiency compared to non-emissive panel speakers which have optical sheet, reflector and light guide plate in addition to the panel.

At the Consumer Electronics Show (CES) in 2017, LG Display also demonstrated a technology called Crystal Sound OLED (CSO), which has surpassed the limitations of conventional TVs using indirect reflected sound. This technology makes consumers feel like they hear the sound coming directly from the OLED TV screen, not the reflected sound coming from a separate speaker built into the TV.

By combining the technology to transmit its own sound with the OLED technology, only the advantages of both external and internal speakers applied to TV have been secured with the differentiated CSO technology.

In this section, the level of sound quality was confirmed through objective and subjective evaluation based on the difference between the position and radiation direction of TV speaker. Moreover the sound quality was evaluated between CSO and conventional TVs [20].

3.1 Objective measures

3.1.1 Preliminary experiment by speaker position

Prior to evaluating the speaker performance of a TV product, the sound quality of one channel was quantitatively measured by viewer's location as shown in **Figure 19** with a 65-inch TV product, whose speaker is located at the bottom and has a structure that radiates sound forward.

For this experiment, the x axis in **Figure 20** represents the frequency and the y axis the frequency response, which is the sound pressure level. The experiment was

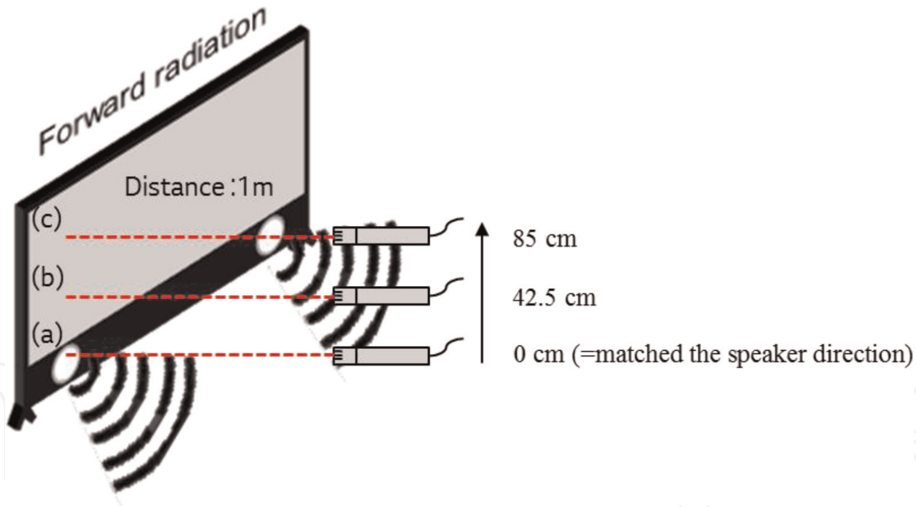

Figure 19.
Forward radiation structure, test positions and the distance for the TV sample.

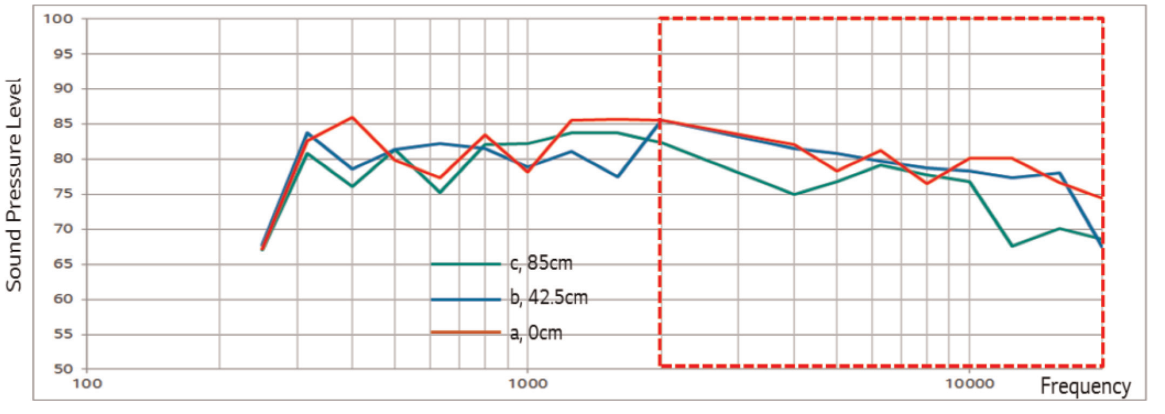

Figure 20.
Frequency response results by speaker height.

conducted in an anechoic chamber to rule out the space characteristics, and the frequency band has been limited from 250 Hz to 20 kHz to reflect the space characteristics of the real anechoic chamber. Also, a stepped signal with 1/6 octave of 20 Hz to 20 kHz has been used as a test signal, and the measurement distance is 1 metre, and the measurement position is shown in **Figure 19**.

"(a)" is located on the principal axis of the speaker, and "(b)" and "(c)" indicate positions that are increasingly distant from the speaker. As can be seen in **Figure 20**, the measured results show that the sound pressure level in the band larger than 3 kHz was kept flat without decreasing at "(a)". On the other hand, the sound pressure level was drastically reduced in the band larger than 15 kHz at "(b)". At "(c)", the sound pressure level was reduced more in the band from 2 to 10 kHz when compared to "(a)" and "(b)", and the sensitivity decreased by about 10 dB in the band larger than 10 kHz. This result shows that it is difficult for the consumer to experience the original sound quality of the speaker when performance degradation occurs in the high frequency band with increasingly receding viewing position and speaker height position in terms of TV user experience.

3.1.2 Sound quality evaluation of OLED panel speaker

Thus, the frequency responses of the following three products were measured to be compared—OLED panel speaker (A), a product with a speaker at the bottom that radiates sound forward (B) and a product with a speaker at the bottom that radiates sound downward (C).

The speaker position and the radiation structure of the measurement samples are shown in **Figure 21**. The conditions of the experiment are the same as the previous one. Also, in the case of the measurement position, the screen has been divided into the speaker channels in order to simulate the situation based on audiovisual standards in accordance with the scenario where the consumers used to be measured, respectively, by the centre of the divided screen.

The measurement results for products A, B and C are shown in **Figure 22**. As can be seen in the graph, the sound pressure level of the OLED panel speaker tends to be flat in the band from 2 to 20 kHz. On the other hand, B and C products tend to have a lower sound pressure level in the band larger than 8 kHz when compared to product A. This graph also shows that product A with an OLED panel speaker has the advantage of the physical location of the speaker, which allowed the characteristics of the frequency response to remain flat up to the high frequency band at the measuring position for viewing.

3.2 Subjective measures

3.2.1 Preliminary experiment by speaker position

Two subjective measures have been made to compare the sound quality of an OLED panel speaker with that of a conventional TV speaker. Prior to comparing the products, the sound quality by the speaker's position has been compared for TV products whose speakers are located at the bottom and radiate sound forward to increase the reliability of this experiment. That is, the speaker is located at the ear height of the viewer (condition A), 30 cm below the viewer's ear height (condition B)

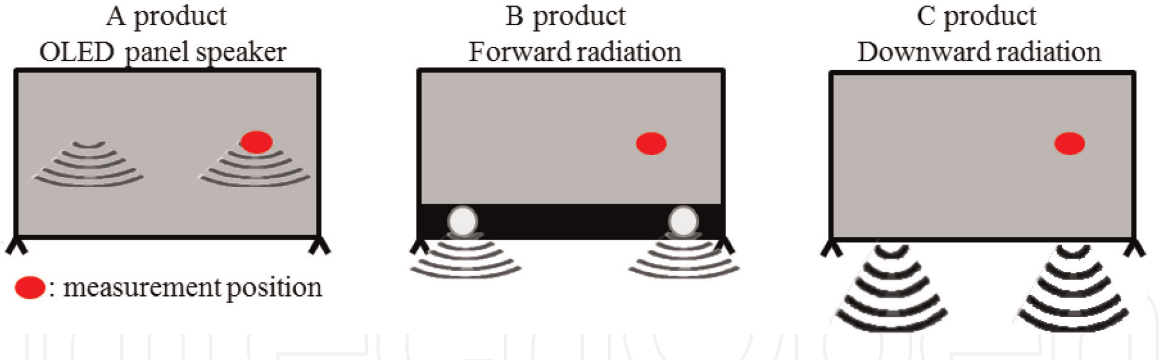

Figure 21.
Speaker position and radiation structure for the TV samples.

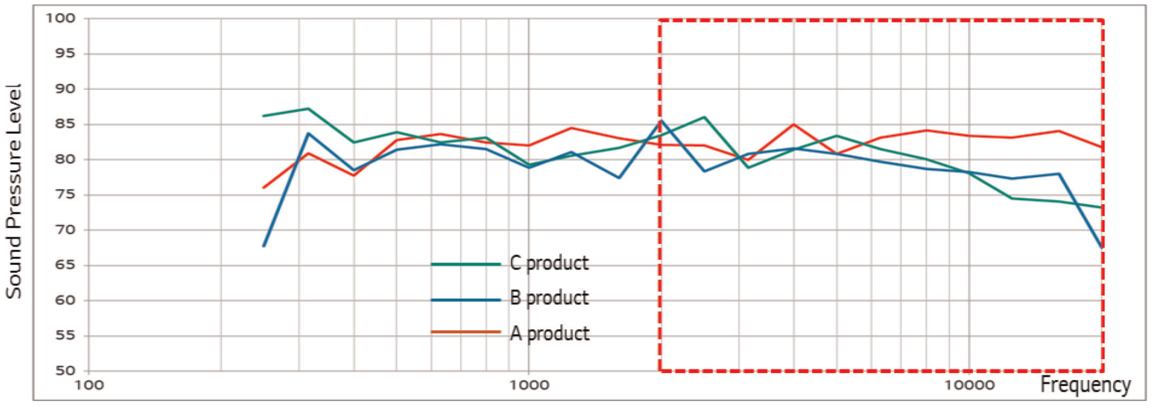

Figure 22.
Frequency response results. (A) OLED panel speaker, (B) forward radiation and (C) downward radiation.

and 60 cm below the viewer's ear height (condition C). **Figure 23** shows that a player called foobar2000 was used on the PC, the PC and TV were connected with HDMI, the height of the assessment samples was designed to be adjusted quickly with an automated electric table and a 9-point scale was used for assessment. Test sound loudness was 63 dB (C), and source type was FLAC, 44.1 kHz, and 16 bit. The items in **Table 9** based on EBU document Tech.3286 have been adopted for the assessment [21]. A, B and C conditions were applied rotationally to eliminate the influence of the experimental procedure [22].

As shown in **Figure 24**, condition A (where the speaker is located at the ear height of the viewer) has had higher scores in preference by about 1.5 points, in sound location accuracy and timbre by about 2 points and in sound balance by about 1.5 points when compared to condition C (where the speaker is located 60 cm below the viewer's ear height). However, the correlation r for spatial impression was 0.26, which indicates that there is no significant difference within the range of 60 cm downward. As a result, it can be deduced that in an environment where you watch TV, the increasing difference between the height of the TV speaker and that of your ears negatively affects the sound quality factor of preference, sound location accuracy, timbre and sound balance. This experiment has improved the reliability of the subjective assessment of the sound quality of three TV speakers with different speaker drive units.

3.2.2 Sound quality evaluation of OLED panel speaker

Next, an evaluation was carried out on the following three TV products for subjective assessment: product A whose speaker is located at the bottom and radiates sound forward, product B with an OLED panel speaker and product C whose speaker is located at the bottom and radiates sound downward. The experimental

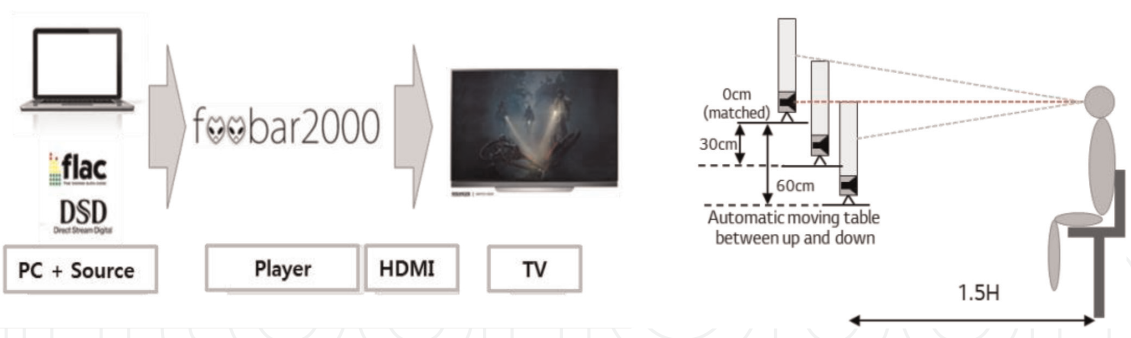

Figure 23.
Test conditions for subjective assessment according to the speaker height.

Parameter	Check point	Test programme
Spatial impression	Spatial size, balance	Classic, POP
Sound location accuracy	Location accuracy	Classic
Transparency	Sound source definition	Classic, piano solo
Sound balance	Dynamic range	Classic
Timbre	Sound colour, frequency	Guitar, POP
Overall preference	Preference	All

Table 9.
Test parameter and programme for subjective assessment.

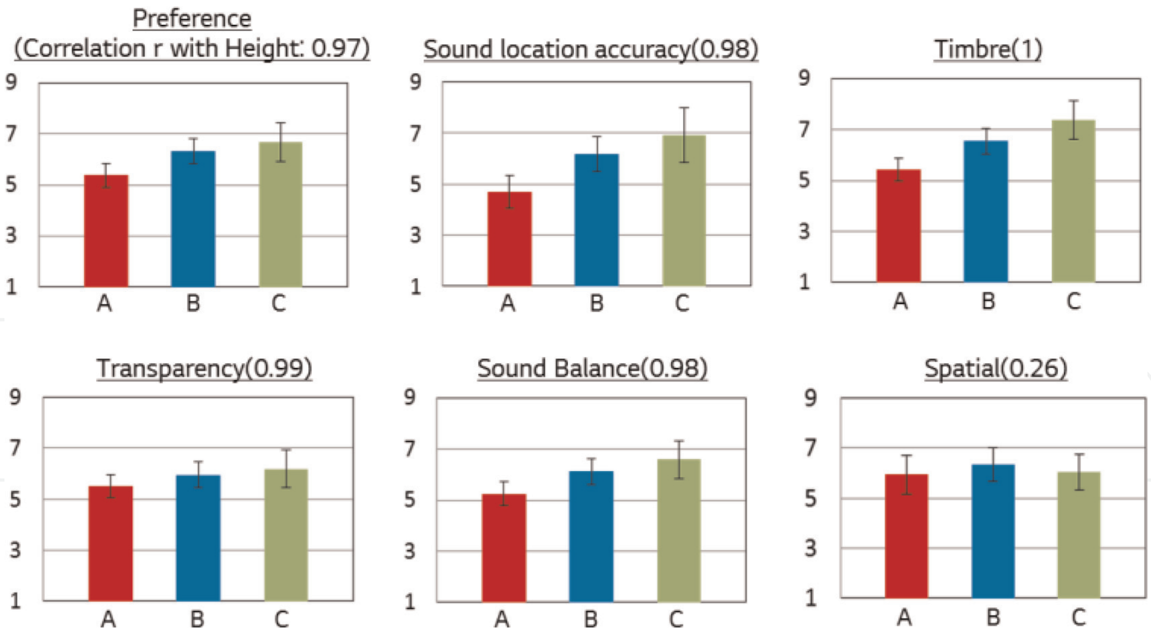

Figure 24.
Results of the subjective assessments by speaker height.

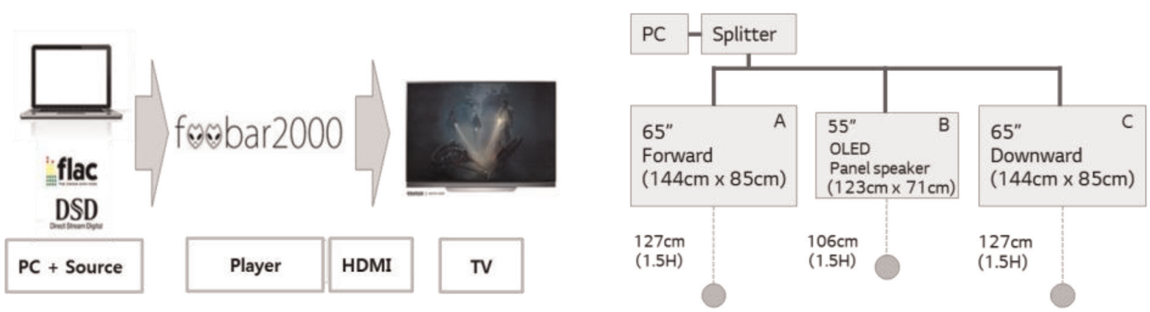

Figure 25.
Test conditions for subjective assessment according to speaker radiation structure of the TV samples.

conditions are shown in **Figure 25**. The viewing distance has been set to 1.5H (H referring to the vertical length of the TV panel) depending on the size of each TV screen. Both the assessment items and the source programme have been set the same as in **Table 9**.

According to **Figure 26**, product B with an OLED panel speaker has received the highest score for sound location accuracy, timbre and transparency. Moreover, a higher score was received for overall preference in descending order of B, A and C, which is the order where the ears and the screen coincide with each other on the horizontal axis.

For spatial impression, however, there was no significant difference between the three products just as in the previous experiment. As a result, it can be deduced that in an environment where you watch TV, the increasing difference between the height of the TV speaker and that of your ears negatively affects the sound quality factor of preference, sound location accuracy, timbre and sound balance.

Based on the above two experiments, it has been shown that observers would have the best sound quality and preference when the height of their ears matches that at which the speaker radiates sound, at a distance of less than 60 cm, the speaker height does not significantly affect spatial impression and at the moment, most speakers applied to TVs are located at the bottom and radiate sound downward to have poor sound quality for timbre, transparency and preference.

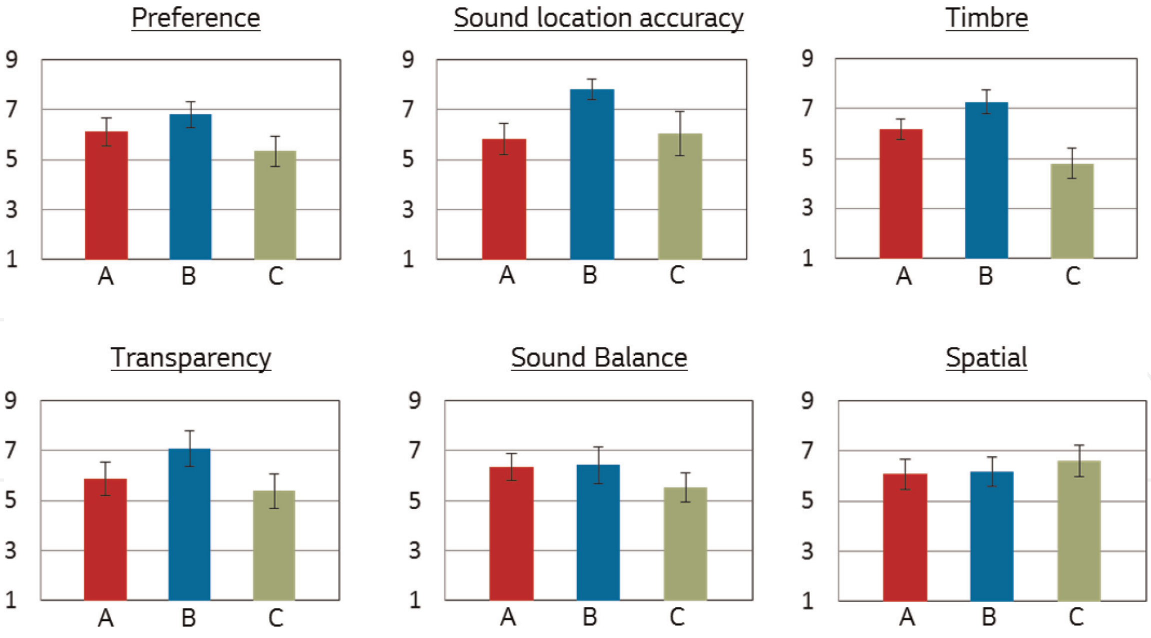

Figure 26.
Results of the subjective assessments according to speaker radiation structure of the TV samples.

4. Conclusions

This chapter dealt with picture quality of OLED TV and sound quality of the OLED TV using the OLED panel speaker. Reasonable picture quality attributes for the evaluation were introduced, and this evaluation was performed using the measurement methods based on several international standards. The OLED TV evaluated here showed better performance in black, colour, HDR and viewing angle properties compared to high-end LCD TVs. It was also proved that the fundamental reason of the difference is due to the emissive display which emits light at every single pixel.

Sound quality of the OLED panel speaker was then evaluated in both objective and subjective ways. It showed better quality particularly in higher frequency and was evaluated better in most subjective assessment attributes when compared to the conventional TV speakers, which indicates this technology is one of the good solutions for on-screen sound.

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