Study of Perceived Bit-depth on TV with High Dynamic Range

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Abstract

One of important objectives on display market is to provide natural and realistic images. Specifications which are high dynamic range, high bit-depth, large gamut size, efficient data compression, etc. are demanded for achieving this objective. For high dynamic range (HDR), increase of maximum luminance is needed to present the brilliant sun realistically. Lower minimum luminance is better for complete darkness. As dynamic range is increased, dis-continuous perception of luminance difference between adjacent gray levels can be presented in display. Bit-depth is related to luminance difference between adjacent gray levels. Dis-continuous perception due to HDR can be reduced by high bit-depth. But, high bit-depth is caused of high cost for manufacturing display. Therefore, minimally required bit-depth should be determined for prohibiting contour. The objective of this paper is to present perceived bit-depth on display for TV with HDR. To achieve the objective, methods for visual test are proposed in this paper. As experimental results, bit-depth of 12 bit is enough to prohibit contour perceptually in OLED TV which has dynamic range over 100000 : 1 .

Introduction

One of important objectives on display market is to provide natural and realistic images. Specifications which are high dynamic range, high bit-depth, large gamut size, efficient data compression, etc. are demanded for achieving this objective. Dynamic range is ratio that maximum luminance divided by minimum luminance. In high dynamic range (HDR), increase of maximum luminance is needed to present the brilliant sun realistically. Lower minimum luminance is better for complete darkness. Bit-depth is related to the number of displayable gray level between maximum and minimum luminance. Suppose that displayable luminance levels are L_0, …, L_n, L_{n+1}, …, L_N from black to white sequentially. n is integer and denoted as gray level. N is represented as maximum value of n. So, L_0 and L_N are represented as minimum and maximum luminance level respectively. L_n is symbolized as luminance level of n gray level. When bit-depth is 8 bit, N is 255. If bit depth is increased from 8 to 10 bit, N is also increased from 255 to 1023. That is, the number of displayable gray level is 4 times as 2 bit increase. And if L_{255} and L_{1023} are the same, luminance difference between adjacent gray levels, (L_{n+1}-L_n), is decreased as compared to one of 8 bit. Suppose that (L_{n+1}-L_n) can be perceived by human vision in 8 bit display due to increase of dynamic range. Then, gradient images that are represented as smooth luminance variation such as a light under street lamp at night are recognized dis-continuously. Dis-continuously perceived luminance variation is caused of reducing image quality and often called by contour. In this 8 bit display, if (L_{n+1}-L_n) is smaller than threshold of human vision system as increasing bit-depth, contour can be removed and gradient images can be represented smoothly. In other words, dis-continuous perception is caused by high dynamic range can be reduced by high bit-depth. But, high bit-depth is caused of high cost for manufacturing display. Therefore, minimally required bit-depth should be determined for removing contour.

Minimally required bit-depth is determined by conditions that (L_{n+1}-L_n) is not perceived by human vision system and bit-depth is minimized. For example, if (L_{n+1}-L_n) is perceived in 8bit display but not perceived in 9bit display, bit-depth of 9bit is required. The perception of (L_{n+1}-L_n) is related to distribution of images. However, it is difficult to estimate the distribution of images, so that sinusoidal pattern is applied. Suppose that minimum value is L_n and maximum value is L_{n+1} in sinusoidal pattern. (L_{n+1}-L_n) is more perceived at lower L_n, when (L_{n+1}-L_n) is invariable. As increasing spatial frequency, perceived degree of (L_{n+1}-L_n) is decreased after increased. In order to evaluate perception of (L_{n+1}-L_n) is depended on L_n or spatial frequency of sinusoidal pattern, modulation is calculated in [1]. Modulation is that (L_{n+1}-L_n) is divided by (L_{n+1}+L_n). Also, modulation threshold is presented in [1]. When modulation is smaller than modulation threshold, (L_{n+1}-L_n) cannot be perceived.

In most of previous methods, it was determined that bit-depth of 12 bit is required [2~6]. In [2], 16 bit digital projector (L_0 is 0.0041 cd/m^2, L_N is 41 cd/m^2) was used for cinema environment. Modulation threshold was calculated in all of displayable L_n. And required bit-depth was derived by comparing modulation and modulation threshold. For verification, visual test was performed with sinusoidal test pattern whose spatial frequency was fixed by 13 cycles. In [3], [4], monitor (L_0 is 0.03 cd/m^2, L_N is 300 cd/m^2) was applied. Luminance, L_n and L_{n+1}, of square pattern were represented using dithering method. And (L_{n+1}-L_n) was evaluated in boundary of square patterns between L_n and L_{n+1}. Required bit-depth was verified by visual test in [2~4]. But results of verification is dissatisfied for TV, because luminance of displays used in [2~4] is too low as compared with TV whose maximum luminance is over 400 cd/m^2, averagely. In [5], required bit-depth was determined by mathematical calculation. Lattice for luminance JND (just noticeable difference) was defined. The number of Lattices included from L_0 to L_N was calculated. Luminance of over 3000 cd/m^2 was considered in evaluation for required bit-depth. But visual test for verification is not performed in [5].

The objective of this paper is to present perceived bit-depth on display for TV with HDR. To achieve the objective, methods for visual test are proposed in this paper. For visual test, LCD TV which has maximum luminance of 1000 cd/m^2 and OLED TV which has minimum luminance of almost zero cd/m^2 are prepared. For visual test, sinusoidal pattern whose minimum value is L_n and maximum value is L_{n+1} is generated and sinusoidal pattern which has various spatial frequencies is used in this paper. In order to represent L_n and L_{n+1} for 8~12 bit-depth and prohibit flicker, spatial-temporal error diffusion is applied in 8 bit displays.

In section 2, bit-depth is mathematically analyzed with modulation threshold of CSF. In section 3, environment for visual test is described. In section 4, three results of visual test for providing perceived bit-depth are presented. Conclusion and discussion is presented in last section.

Mathematical analysis of bit-depth based on modulation threshold of CSF

As a mentioned in introduction, bit-depth can be derived by comparing modulation of sinusoidal pattern and modulation threshold based on CSF such as method of [2]. First, relationship of L_0, L_n and L_N is presented by (1).

$$L_n = L_0 + (L_N - L_0) \times (n/N)^r \quad (1)$$

where, L_0 and L_N are represented as minimum and maximum luminance level of display respectively. n, N and r are represented as given gray level, maximum gray level according to bit-depth (ex. N is 255 at 8bit display) and gamma value, respectively. In this paper, r is 2.2. Suppose there is sinusoidal pattern whose minimum value is L_n and maximum value is L_{n+1}. Modulation of sinusoidal pattern can be calculated by (2)~(4).

$$m = L_d / L_s \quad (2)$$

$$L_d = (L_{n+1} - L_n) \quad (3)$$

$$L_s = (L_{n+1} + L_n) \quad (4)$$

where, m is represented as modulation. L_d, L_s is represented as luminance difference, luminance sum, respectively. After (3) and (4) are substituted with (1), modulation is presented by (5)~(7) again.

$$L_d = (L_N - L_0) \times \{(n+1)^r - (n)^r\} / N^r \quad (5)$$

$$L_s = 2 L_0 + (L_N - L_0) \times \{(n+1)^r + (n)^r\} / N^r \quad (6)$$

$$m = \{(n+1)^r - (n)^r\} / [\{(n+1)^r + (n)^r\} + 2 N^r / (L_N / L_0 - 1)] \quad (7)$$

In (7), m is inversely proportional to N which is determined by bit-depth. That is, as increasing bit-depth, modulation is reduced and contour can be more disappeared. Also, in (7), m is directly proportional to dynamic range, L_N/L_0. As increasing of L_N or decreasing of L_0, modulation as well as dynamic range is grown. In other word, contour can be more perceived in display with high dynamic range (HDR). Modulation threshold of [1] is presented by (8).

$$m_t(u) = 1/CSF(u) \quad (8)$$

where, $m_t(u)$ is represented as modulation threshold. CSF(u) was defined in [1]. u is denoted as spatial frequency. CSF(u) is decreased after increased as increasing u in [1]. Minimum value of $m_t(u)$ is calculated with u that maximizes CSF(u). The parameters that barten recommended for CSF calculation and X_0 (angular size of the object image) which is determined in [2] is used in this paper.

Minimum value of $m_t(u)$ is shown as black line in figure 1 ~ 4. Horizontal axis is represented as L_n. Vertical axis is represented as m. In figure 1, m which is calculated according various bit-depths at cinema environment of [2] is shown. When m is larger than minimum value of $m_t(u)$, it is evaluated that contour can be perceived at L_n. On a whole range of L_n, m for 12 bit is less than minimum value of $m_t(u)$. Therefore, bit-depth of 12 bit is required in cinema environment. That is, contour which is affected by luminance difference (L_{n+1}-L_n) cannot be perceived in 12 bit.

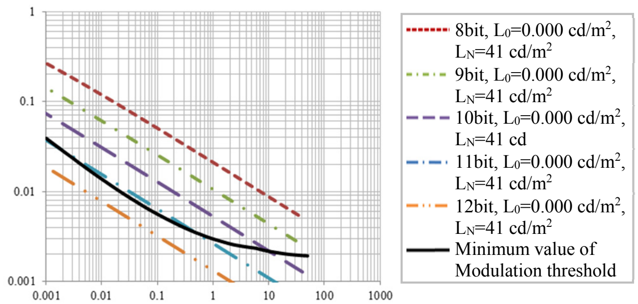


Figure 1. Minimum value of modulation threshold and modulations at various bit-depths

Results of figure 1 are analyzed in ideal case for cinema environment. Actually, L_0 is above zero cd/m^2 and L_N is much higher than display for cinema environment in TV. When L_N is fixed and L_0 is changed, m is calculated and results of calculation are shown in figure 2. When L_N is 500 cd/m^2, contour can be perceived in spite of 12 bit under 1 cd/m^2. For removing contour, bit-depth of above 14 bit is required. Range that contour can be perceived is more widen as L_0 is more decreased. When L_N is changed, calculated m is shown by figure 3. Expectably, bit-depth of above 14 bit is required. When L_N is 1000cd/m^2 and L_0 is 0.001cd/m^2 (dynamic range is 1000000:1), bit-depth of above 14 bit is required as shown in figure 4, understandably. Because implementation of 14 bit-depth demands dynamical cost rising, visual test for required bit-depth is needs for verification.

Experiment environments

In this paper, five display panels for TV are prepared for visual tests. All of these displays have 2.2 gamma values. Display's specifications, L_0, L_N and dynamic range are presented in table 1. LCD1 ~ LCD4 have different L_N each other by controlling backlight. L_N of LCD1 is highest. Value of dynamic range is similar due to backlight control. OLED are prepared to evaluate at near zero cd/m^2. Dynamic range of OLED is very higher than other displays.

Display which has bit-depth of over 9 bit is rarely produced. Therefore, it is necessary to represent luminance level corresponded with over 9 bit. Dithering or error diffusion method is mostly applied for representing luminance level. Using dithering or error diffusion method, un-displayable luminance level can be represented based on spatial or temporal low pass filtering characteristic of human vision [6]. For example, suppose that L_L and L_H are denoted as only two displayable luminance levels in w×h pixels area. When α pixels for w×h area display L_L and the rest of pixels display L_H, luminance level of $\{L_L + \alpha / (w \times h) \times (L_H - L_L)\}$ can be represented averagely by human vision. When 8bit-based spatio-temporal dithering mentioned in [4] is applied, pattern or flicker is perceived in our test environment that maximum luminance is over 1000 cd/m^2. Therefore, well-designed spatio-temporal error diffusion which is proposed to reduce perceived pattern and flicker in [7] is applied in this paper.

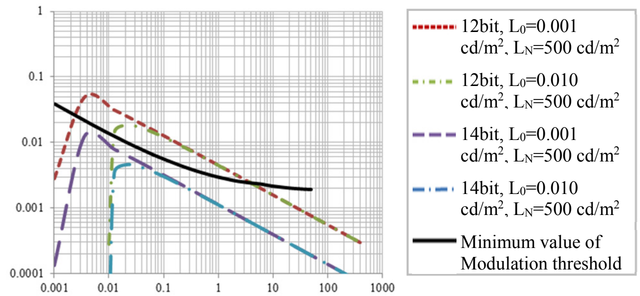


Figure 2. Modulations according to various bit-depths, L_0 at fixed L_N

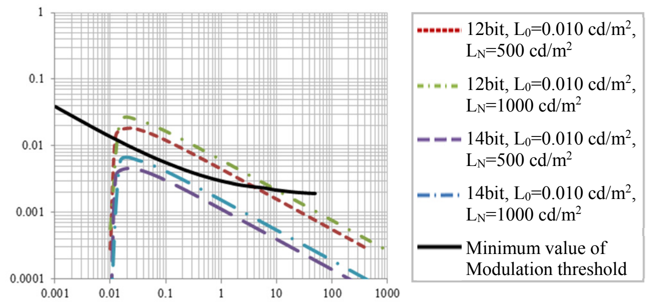


Figure 3. Modulations according to various bit-depths, L_N at fixed L_0

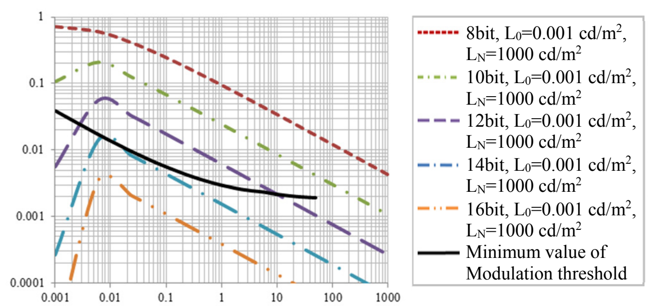


Figure 4. Modulations according to various bit-depths at fixed L_0 and L_N

Suppose that L_L is coincided with L_n in 8 bit display. And, L_C is represented as luminance level of adjacent gray level for L_L. Then, L_C is become L_{n+1} in 8bit display. Relationship between gray levels for 8 bit and 9 bit is shown in figure 5. In case of minimum and maximum luminance of display is invariant at each bit-depth, luminance difference between adjacent gray levels is reduced as increase of bit-depth. Odd value of gray level for 9 bit cannot be expressed integer value of gray level for 8bit. So, Odd values of gray level for 9 bit are replaced by (n+1/2) in 8bit. That is, L_C for 9bit is become $L_{n+1/2}$ in 8bit display. $L_{n+1/2}$ is represented as combination between L_n and L_{n+1} in 8 bit display using error diffusion method.

Table 1. Display's specifications

Index	Minimum luminance (L_0)	Maximum luminance (L_N)	Dynamic range (L_N/L_0)
LCD1	0.697	1012.900	1453 : 1
LCD2	0.404	480.850	1190 : 1
LCD3	0.234	291.410	1245 : 1
LCD4	0.075	98.341	1311 : 1
OLED	0.003	392.260	130753 : 1

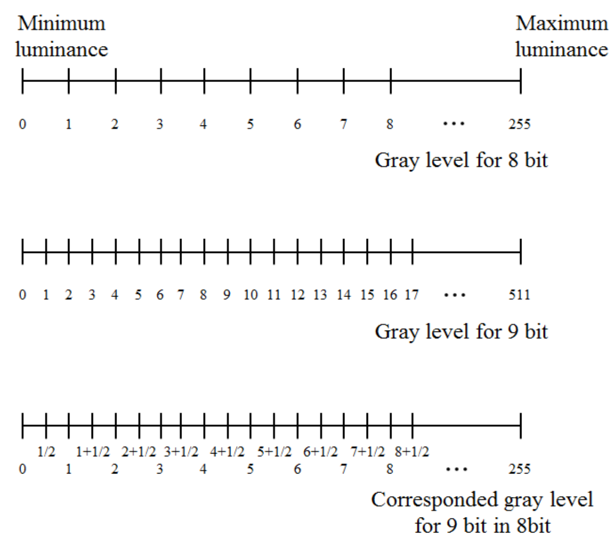


Figure 5. Relationship between gray levels for 8 bit and 9 bit

Test image is shown in figure 6. There are two kind of luminance in test image. L_L and L_C is represented as luminance level of adjacent gray levels for each bit-depth. Also, there are sinusoidal patterns which have different spatial frequency in test image. In pattern of minimum spatial frequency, L_L and L_C are alternated at every 4 pixels. Thus, spatial frequencies of sinusoidal patterns are 8, 16, 24, 32, 40 and 48, sequentially. In order to easily evaluate the pattern, phase is changed in same spatial frequency.

In table 2, L_L, L_C and L_H are listed for our visual test. The number of L_L is 32. Based on theory that JND for low gray level area is lower than one for middle or high gray level area, gray level is increased by 1 step under 16 gray level and 16 step between 16 and 240 gray levels. Maximum value of gray level for L_L is decided by 254, because n+1 is less than or equal to N which is 255 at 8 bit display.

Perception of sinusoidal patterns is evaluated by observers in darkroom. Observer is forced to evaluate that contour is perceived on boundary between L_L and L_C. The observers are 10 experts. Distance between observer and display is 30 cm.

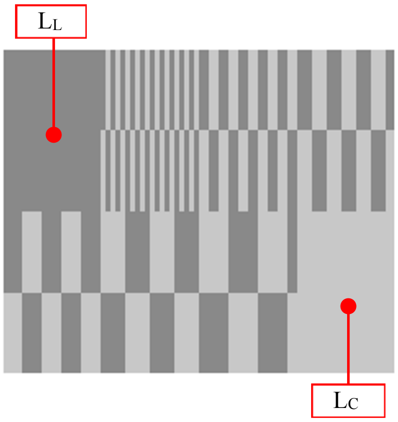


Figure 6. Example of test images

Table 2. L_L, L_C and L_H are listed for visual test image

L_L	L_C					L_H
	12 bit	11 bit	10 bit	9 bit	8 bit	
L_0	$L_{0+1/16}$	$L_{0+1/8}$	$L_{0+1/4}$	$L_{0+1/2}$	L_{0+1}	L_1
L_1	$L_{1+1/16}$	$L_{1+1/8}$	$L_{1+1/4}$	$L_{1+1/2}$	L_{1+1}	L_2
…	…	…	…	…	…	…
L_{15}	$L_{15+1/16}$	$L_{15+1/8}$	$L_{15+1/4}$	$L_{15+1/2}$	L_{15+1}	L_{16}
L_{16}	$L_{16+1/16}$	$L_{16+1/8}$	$L_{16+1/4}$	$L_{16+1/2}$	L_{16+1}	L_{17}
L_{32}	$L_{32+1/16}$	$L_{32+1/8}$	$L_{32+1/4}$	$L_{32+1/2}$	L_{32+1}	L_{33}
…	…	…	…	…	…	…
L_{240}	$L_{240+1/16}$	$L_{240+1/8}$	$L_{240+1/4}$	$L_{240+1/2}$	L_{240+1}	L_{241}
L_{254}	$L_{254+1/16}$	$L_{254+1/8}$	$L_{254+1/4}$	$L_{254+1/2}$	L_{254+1}	L_{255}

Experiment Results

Three experiments were performed in this paper. In first experiments, perceived bit-depth is analyzed according to spatial frequencies. In second experiments, perceived bit-depth is analyzed according to increase of maximum luminance (L_N). In last experiments, in case of minimum luminance (L_0) is much lower than one of LCD4, perceived bit-depth is analyzed with OLED.

(1) Perceived bit-depth according to spatial frequencies

In figure 7, result of visual test which is performed according to spatial frequencies in LCD1~LCD4 and OLED is shown. Response ratio is represented on the vertical axis. Response ratio is 100%, when all observers can perceive contour. L_L is represented on the horizontal axis. Response ratio is above 50 % at less than 10 bits at any spatial frequencies. Otherwise, Response ratio is decreased as increasing spatial frequency at 11 bit. Response ratio is below 10 % at 12 bit. As a result, it can be assured that contour is not perceived at any spatial frequencies, when bit-depth of display becomes 12 bit.

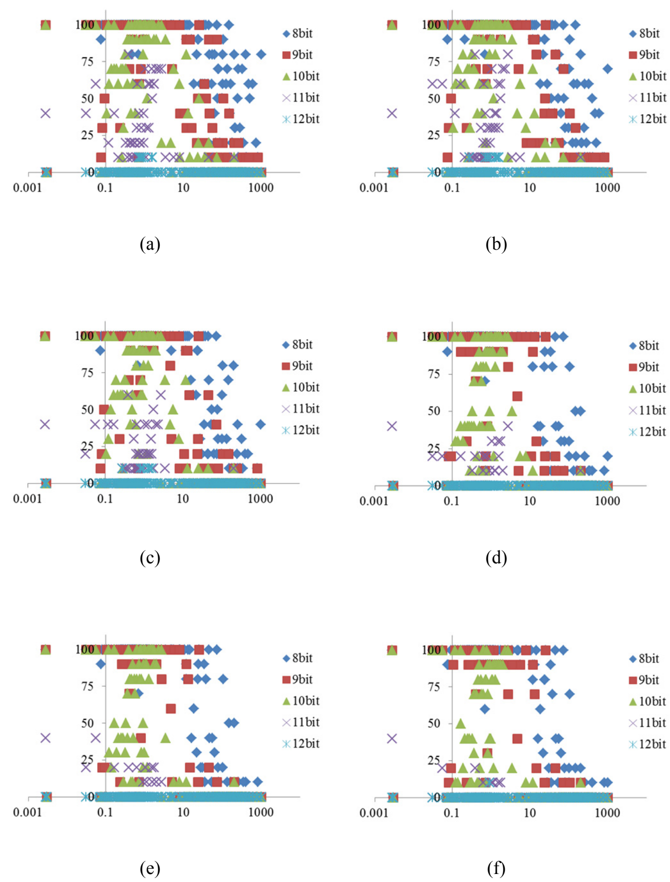
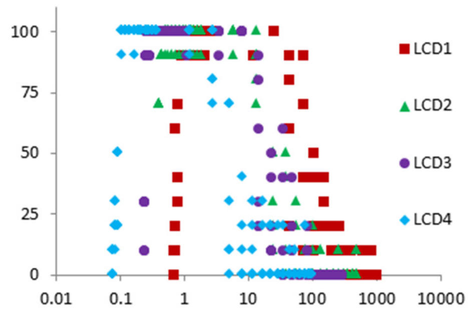


Figure 7. Experimental result according to spatial frequencies (a) 8, (b) 16, (c) 24, (d) 32, (e) 40, (f) 48 spatial frequencies

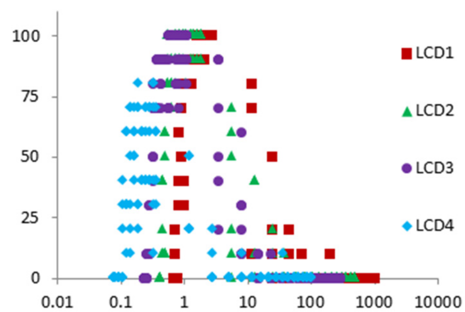
(2) Perceived bit-depth according to maximum luminance

In figure 8, result of visual test which is performed according to increase of maximum luminance (L_N) at each bit-depth is shown. Contour can be perceived at under 10 bit in all of LCD, because response ratio is above 50% in figure 8(a), (b). When bit-depth of display becomes 11 bit in figure 8(c), response ratio is decreased below 50% and it can be decided that contour be not perceived in

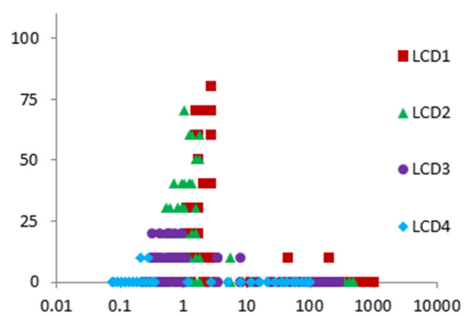
LCD3 and LCD4. Such as a result represented in figure 8(d), 12 bit is required for removing contour in LCD1 and LCD2 which have over about 500 cd/m^2 of maximum luminance, unlike mathematical results of figure 3 and 4.



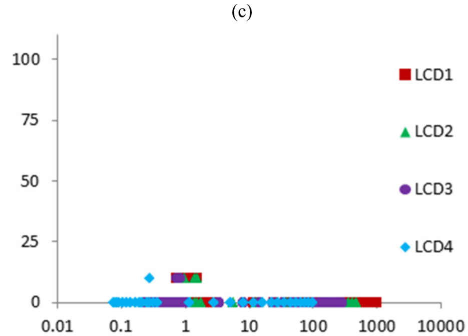
(a)



(b)



(c)



(d)

Figure 8. Experimental result according to maximum luminance (a) 9bit, (b)10 bit, (c) 11 bit, (d)12 bit.

(3) Perceived bit-depth at minimum luminance

In figure 9, result of visual test which is performed according to bit-depth in OLED. In low luminance under 1cd/m^2, response ratio is almost 100% in 9 and 10 bit. Contour can be still perceived in 11bit. But, if bit-depth of display becomes 12 bit, there is no more perception of contour. In figure 10, result of visual test which is performed according to bit-depth in LCD2 is shown. Maximum luminance of LCD2 is higher than one of OLED. Contrariwise, minimum luminance of OLED is much lower. In OLED, dark area under about 0.5cd/m^2 can be displayed. In LCD2, it is difficult to display dark area. Therefore, smooth and gradient black image can be more displayed than LCD2 in OLED, when display has high bit-depth.

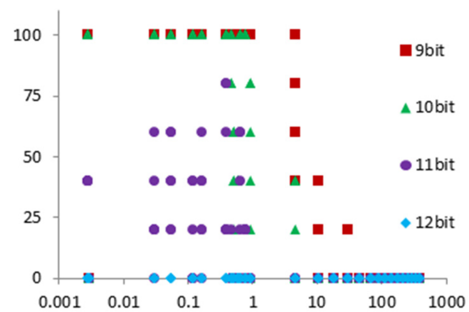


Figure 9. Experimental result in OLED (L_0 is 0.003 cd/m^2, L_N is 392.260 cd/m^2)

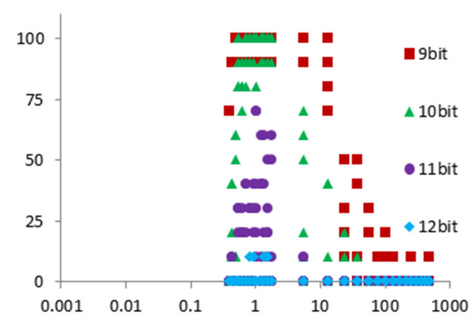


Figure 10. Experimental result in LCD2 (L_0 is 0.404 cd/m^2, L_N is 480.850 cd/m^2)

Discussion and conclusion

Bit-depth of 14 bit is required to prohibit contour in display with high dynamic range, when bit-depths are calculated based on threshold modulation mathematically. Because implementation of 14 bit-depth demands dynamical cost rising, visual test for perceived bit-depth is needs. Two types of displays are prepared for visual test. LCD1~LCD4 have different maximum luminance each other by backlight control. Maximum luminance of LCD4 is highest. And OLED are prepared to evaluate at near zero cd/m^2. There are 3 experimental results of visual test. In first result, it can be assured that contour is not perceived at any spatial frequencies, when bit-depth of display becomes 12 bit. In second result, 12 bit is required for removing contour, unlike mathematical results that required bit-depth is 14 bit. In last result, it can be assured that contour is not perceived at any luminance in OLED, when bit-depth of display becomes 12 bit. If experimental results are accumulated, bit-depth of 12 bit is enough to prohibit contour perceptually. And, when bit-depth of display becomes 12 bit. When OLED which can be displayed dark area under about 0.5cd/m^2 has 12 bit-depth, smooth and gradient black image can be more displayed than LCD.

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