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Achieving 12-bit perceptual quantizer curve with liquid crystal display

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Abstract: We proposed a scheme to drive the light emitting diode (LED) backlight and liquid crystal (LC) panel simultaneously to achieve 10,000-nit 12-bit perceptual quantizer (PQ) curve, which is required by high dynamic range (HDR) displays. Besides the relative fast response time and low driving voltage, this approach can also mitigate image noises.

OCIS codes: (230.3720) Liquid-crystal devices; (160.3710) Liquid crystals.

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Research Article | Vol. 25, No. 10 | 15 May 2017 | OPTICS EXPRESS 10940
Optics EXPRESS

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1. Introduction

High dynamic range (HDR) [1] is regarded as the next big thing for display industry, as it provides supreme image qualities that standard dynamic range (SDR) displays cannot offer [2–4]. To qualify as an HDR display, both peak brightness and dark state of the display have to be improved [1, 5]. At the same time, professional HDR contents are encoded with BT. 2020 color gamut [6, 7]. Thus, the color gamut of the display has to be widened to reproduce highly saturated colors [8]. Moreover, the bit depth of the display has to be increased simultaneously to accommodate for the enlarged luminance range [9]. For HDR displays, the conventional gamma encoding is no longer suitable as it may cause quantization errors and thus new electro-optical transfer functions (EOTFs) have been proposed to replace the gamma encoding. The most widely used EOTF for HDR content is the 12-bit perceptual quantizer (PQ) curve [10], also known as the ST. 2084 standard that covers 0 to 10,000 nits.

Two display technologies can be implemented for HDR. The first one is organic light emitting diode (OLED) display [11]. OLED is possible to achieve perfect black level, however, because of the material lifetime concern, its peak brightness is usually below 1000 nits. The second approach is to use dimmable light-emitting diode (LED) array as liquid crystal display (LCD) backlight to dynamically control the dark state of the device [5]. Currently, the peak brightness of LCD using local dimming backlight can achieve 4000 nits. With the emergence of high brightness LEDs, it is possible to achieve 10,000 nits in the near future. Therefore, achieving 12-bit PQ curve will become more and more critical for the display system.

In this paper, we examine the approaches needed to achieve 12-bit PQ curve up to 10,000 nits with a local dimming LCD. Our results indicate that addressing the LEDs or the LC panel alone is inadequate to realize this goal. As a result, we propose a new scheme to address the LC and the LED simultaneously to enable 12-bit PQ curve.

2. Achieving 12-bit PQ curve: Driving the LC and LED separately

Figure 1 depicts the 12-bit PQ curve together with a 12-bit gamma 2.2 curve. The detailed equation for describing the PQ curve can be found in [10]. From Fig. 1 we can see that compared with the traditional gamma curve, the PQ curve increases much more slowly. And there are ~2000 gray levels in the low luminance range (i.e. 0-100 nits). Assuming the peak brightness of the system is L and the contrast ratio of the LC panel is C, then the minimum brightness of the LCD without local dimming is L/C. This gives us an intuitive and straightforward driving method for the local dimming system:

1) For the luminance between L/C and L, the LED backlight is working at full brightness and we could control the LC panel to get the required luminance range.

2) For the luminance under L/C, the LC is turned to off-state whereas the LED is dimmed to achieve the target luminance range.

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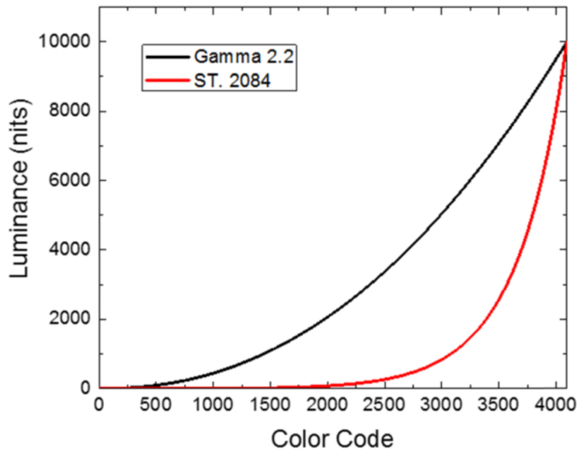

Fig. 1. The 12-bit ST-2084 curve displayed together with the 12-bit gamma 2.2 curve.

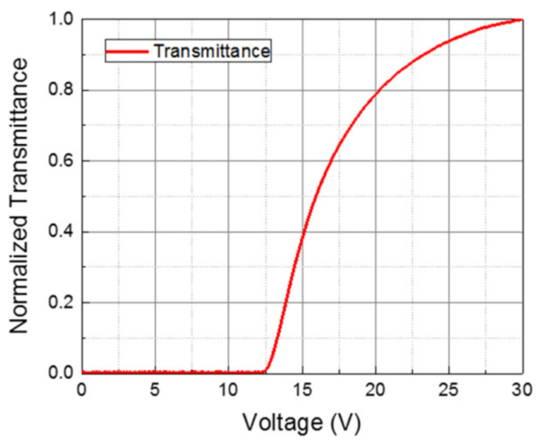

Fig. 2. Measured VT curve of the LC cell: d = 3.3 μm and λ = 633 nm.

Throughout this paper, we assume the system peak brightness L is 10,000 nits. For the LC part, we choose vertical alignment (VA) mode [12] because of its high contrast ratio. Considering the capability of current TFT technology, we set the voltage interval between two adjacent gray level at 5 mV, thus for a 12-bit display, the voltage swing ($\Delta V = V_{on} - V_{th}$) should be ~20 V. To achieve this ΔV, in experiment we mixed a negative dielectric anisotropy ($\Delta\varepsilon$) LC material ZOC-7033 (JNC, Japan) [13] with a positive $\Delta\varepsilon$ LC material MLC-6686 (Merck). The recipes for the new LC mixture are listed in Table 1. The obtained new LC mixture exhibits a rotational viscosity of 97 mPas at 22°C and a small but negative $\Delta\varepsilon$ (= –0.89), so that a large voltage swing (ΔV ~20 V) can be achieved.

Table 1. Recipe for the new LC mixture.

Component	ratio	Δn	Δε
ZOC-7003	75.2%	0.103	–4.36
MLC-6686	24.8%	0.0983	10.00

Next, we filled this new LC mixture into a commercial VA test cell with cell gap d = 3.3 μm. The cell is a single domain VA cell with rubbed surface alignment. Figure 2 shows the measured voltage-transmittance (VT) curve of the mixture, in which the threshold voltage V_{th} is 11.12V and on-state voltage V_{on} ≈30V. The measured contrast ratio of the LC cell is

~5000:1. This indicates that driving the LC alone we can get 2 nits to 10000 nits; below 2 nits we need to dim the LEDs to achieve the target luminance.

To analyze the performance of the LC cell, we selected 24 gray levels based on the 12-bit PQ-curve. The 24 gray levels are listed in Table 2.

Table 2. The selected 24 gray levels.

Gray level	Luminance (nits)	Corresponding transmittance (%)	Gray level	Luminance (nits)	Corresponding transmittance (%)
771	2.002	0.020	2303	170.274	1.703
865	2.904	0.029	2462	246.848	2.468
965	4.197	0.042	2623	357.454	3.575
1073	6.090	0.061	2785	516.542	5.165
1187	8.817	0.088	2950	749.196	7.492
1307	12.747	0.127	3115	1084.617	10.846
1434	18.473	0.185	3280	1569.166	15.692
1566	26.705	0.267	3446	2276.360	22.764
1705	38.762	0.388	3610	3292.626	32.926
1848	56.101	0.561	3773	4764.176	47.642
1996	81.278	0.813	3935	6902.473	69.025
2148	117.722	1.177	4095	10000.000	100.000

As discussed above, ~50% gray levels are in the low luminance region. For such a low transmittance, the driving voltage is only slightly above the threshold, thus, the response time would be slow [14]. To confirm this, we measured the gray-to-gray (GTG) response time between these twenty-four gray levels, and results are tabulated in Table 3. The average GTG rise time of the LC cell is 33 ms, which is too sluggish for practical applications. This indicates driving the LC and the LED separately isn't really suitable for the 12-bit display.

Table 3. The gray-to-gray response time of the LC cell. (Unit: ms)

		Rise time (ms)																							
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Decay time (ms)	1		123.6	120.8	116.4	111.7	106.3	93.0	89.1	83.1	79.2	72.3	66.2	60.3	54.1	40.3	39.7	36.1	32.4	29.3	26.9	17.4	13.0	8.0	2.5
	2	2.5		105.0	96.6	86.0	76.4	76.2	72.5	68.8	67.4	62.4	58.2	52.6	48.9	43.7	38.6	32.7	29.1	25.0	20.3	15.7	11.8	7.7	2.4
	3	2.6	88.8		95.8	89.4	85.2	79.8	75.0	71.3	66.4	62.6	58.3	53.4	49.1	41.9	38.8	35.1	28.9	23.9	19.6	15.7	11.6	7.7	2.4
	4	2.6	85.8	95.2		78.7	76.0	74.3	74.1	69.6	67.8	62.8	58.8	54.1	49.2	41.4	40.9	32.6	28.6	24.5	19.8	15.7	11.6	7.6	2.4
	5	2.6	83.2	76.0	84.6		76.8	74.4	72.1	70.6	69.1	64.2	58.0	53.0	48.2	41.6	40.3	32.9	28.4	24.2	19.8	15.4	11.5	7.5	2.4
	6	2.6	80.2	78.4	80.2	80.3		73.8	68.4	67.7	66.6	60.5	57.3	52.3	48.1	41.0	37.5	35.4	28.2	23.9	19.3	15.5	11.4	7.5	2.4
	7	2.7	73.1	71.7	75.3	70.7	71.9		67.8	61.2	60.3	59.4	54.0	49.8	47.2	40.1	35.0	33.7	28.2	23.2	19.6	15.3	11.6	7.6	2.4
	8	2.7	68.5	69.5	73.0	70.3	71.9	66.0		63.0	60.0	57.6	53.7	48.8	45.1	40.6	34.7	33.1	28.5	22.3	18.8	14.7	11.3	7.4	2.4
	9	2.8	66.3	67.4	68.6	68.6	68.2	61.1	59.3		58.2	55.3	50.8	48.0	43.8	40.0	36.7	31.3	26.5	23.0	18.4	14.9	11.1	7.4	2.4
	10	2.8	62.7	64.0	63.8	63.8	63.3	60.2	58.7	57.1		54.2	50.8	47.0	42.7	40.6	37.0	31.0	26.7	22.1	18.2	14.5	11.0	7.3	2.3
	11	2.8	58.4	59.2	58.5	57.9	58.0	57.1	55.4	56.7	57.3		48.6	43.8	40.2	34.1	33.7	28.8	25.7	22.3	17.5	14.4	10.9	7.1	2.3
	12	2.9	54.7	54.8	55.2	55.8	54.6	52.1	52.1	51.6	48.4	49.7		42.0	39.7	35.9	33.1	29.9	25.9	21.5	18.0	14.3	10.6	7.1	2.3
	13	2.8	50.1	51.1	50.7	50.5	50.5	49.3	47.6	47.5	45.4	43.9	42.5		39.0	32.3	30.4	26.2	23.6	21.1	17.3	13.6	10.4	6.9	2.2
	14	2.9	46.1	46.5	46.5	46.4	46.0	45.9	44.6	44.0	43.4	42.2	41.6	38.1		32.2	33.7	26.3	24.4	19.7	17.0	13.8	10.3	6.8	2.2
	15	3.0	43.4	39.2	42.2	41.5	42.2	45.2	44.0	44.3	38.6	39.6	39.4	39.3	34.9		31.7	27.9	22.8	19.2	16.2	13.4	9.9	6.6	2.2
	16	3.1	39.4	37.2	40.6	40.2	37.3	37.2	39.5	38.2	37.9	35.7	32.5	31.4	33.0	28.0		27.0	21.7	19.5	15.6	12.5	9.9	6.5	2.2
	17	3.2	35.7	36.9	35.2	33.5	36.5	36.2	38.5	37.2	33.9	32.2	32.5	29.3	30.7	26.9	29.0		24.4	17.4	15.4	12.7	9.3	6.3	2.1
	18	3.4	33.5	31.4	31.3	31.2	31.1	31.6	34.2	33.0	30.8	30.0	31.1	30.5	29.0	26.5	23.7	21.8		18.2	14.8	12.2	9.1	6.2	2.1
	19	3.6	30.2	27.8	29.3	29.0	29.2	28.7	27.9	29.1	27.6	28.7	27.8	26.0	25.9	25.3	24.2	21.2	19.2		15.6	12.0	8.7	6.2	2.0
	20	3.7	25.9	25.5	27.0	26.9	26.5	26.0	27.3	27.3	26.0	25.4	26.0	24.1	24.4	23.0	21.6	20.2	19.0	16.6		10.8	8.6	5.7	2.0
	21	3.9	23.8	23.1	24.1	24.1	23.9	23.9	23.3	24.6	23.8	23.2	23.8	23.0	22.7	21.3	20.5	19.2	16.6	15.6	14.2		8.7	5.8	1.9
	22	4.1	20.7	20.9	21.8	21.8	21.5	21.5	22.1	21.7	21.7	22.2	21.9	21.9	21.2	19.7	19.1	17.8	16.2	14.8	12.9	10.4		5.8	1.9
	23	4.4	18.2	19.0	19.7	19.7	19.6	20.1	20.3	20.2	20.4	20.2	20.4	20.3	19.8	19.2	18.1	17.2	15.5	13.9	12.1	10.2	8.0		1.7
	24	4.9	16.5	17.0	17.3	17.5	17.3	17.9	17.9	18.1	18.2	18.1	18.1	18.1	17.9	17.7	16.6	16.2	14.8	13.4	11.6	9.8	7.9	5.5	

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3. Achieving 12-bit PQ curve: Driving the LC and LED simultaneously

As analyzed above, driving the LC panel or the backlight LEDs alone is not suitable for achieving the 12-bit PQ curve. Thus, we need to drive the LC and the LEDs simultaneously. The most intuitive approach can be explained by Eq. (1):

$$L(G_1, G_2) = L(G_1)T(G_2). \tag{1}$$

Here, G_1 and G_2 represent the gray level of the LED and the LC, respectively, L is the luminance of the system, and T is the transmittance of the LC. By controlling the gray level of the LC and the LED simultaneously, it is possible to achieve 12-bit PQ curve. Assuming the LEDs and the LC panel have S_1 and S_2 gray levels, respectively, in theory the system will have $S_1 \times S_2$ gray levels. An example is that the LEDs are 4-bit (16 gray levels) and the LC panel is 8-bit (256 gray levels), and then ideally the whole system will be 12-bit (4096 gray levels). For a real system, because of the potential overlap between these gray levels, the required gray levels for the LEDs are usually more than 4 bits.

The abovementioned approach is quite straightforward; however, a severe flaw of this approach is that the same luminance may be achieved by different gray level combinations. This reduces the overall gray levels of the system. At the same time, without careful gray level selection, this approach will introduce severe image noises. This can be explained by the following thought experiment: the display is required to show two adjacent achromatic pixels and the target luminance for the two pixels are 100 and 93.88 nits, respectively. Assuming the LC panel follows the 8-bit gamma 2.2 curve, at least two possible gray level combinations can achieve the targets:

1) For both pixels the LEDs work at 100 nits, and the LC works at gray level 255 for the first pixel and gray level 248 for the second pixel. The actual luminance for the two pixels are 100 and 94.06 nits, respectively.
2) For the first pixel, the LED works at 100 nits and the LC works at gray level 255; for the second pixel, the LED works at 1000 nits whereas the LC works at gray level 87. The actual luminance for the two pixels are 100 nits and 93.88 nits, respectively.

At first glance, the two combinations seem identical and the second combinations seems even closer to the target luminance. However, in real applications the first combination is superior to the second one. The first reason is that in local dimming LCDs, most of the time it is not possible to do pixelated local dimming [11, 15, 16], thus the two pixels might belong to the same section where only one LED is available. The second reason is that even if it is possible to do pixelated local dimming, because of the point spread effect [15], there will be crosstalk between the adjacent pixels, and the second configuration will introduce salt-and-pepper noises [17] to the displayed image. In this sense, a driving scheme where there is no sudden jump in gray level combinations is preferred. Based on this requirement, we propose a new driving scheme with the following steps:

1) Predetermine a tone response curve L_i of the LEDs, here L is the luminance and i = 0, 1, 2,..,N_1-1 is the (i + 1)-th gray level. In total, there are N_1 grey levels.
2) For the target luminance L_t that satisfies $L_i \le L_t < L_{i+1}$, the gray level of the LED for this target is set to i + 1.
3) Determine the corresponding LC transmittance T_j based on Eq. (1). After calculating all the LC transmittance for all the target luminance, it becomes possible to construct the tone response curve T_j of the LC panel. Here j is the (j + 1)-th gray level of the LC panel. In total there are N_2 gray levels.
4) Optimizing the tone response curve L_i and T_j according to the device limit and the 12-bit PQ curve.

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With the abovementioned approach, we can ensure that one target luminance corresponds to a single gray level combination, and the gray level combinations will change smoothly if properly designed. Based on this approach, we designed the tone response curve of the LEDs and the LC by comparing with the 12-bit PQ curve. The tone response curves for the LEDs and the LC are shown in Figs. 3 (a) and 3(b), respectively. Here we have 57 gray levels for the LEDs and 256 gray levels for the LC. When they are combined together, the final tone response curve is shown in Fig. 3(c) and it is clear that this curve matches well with the 12-bit PQ curve. The detailed numbers of the tone response curves are listed in the supplement materials.

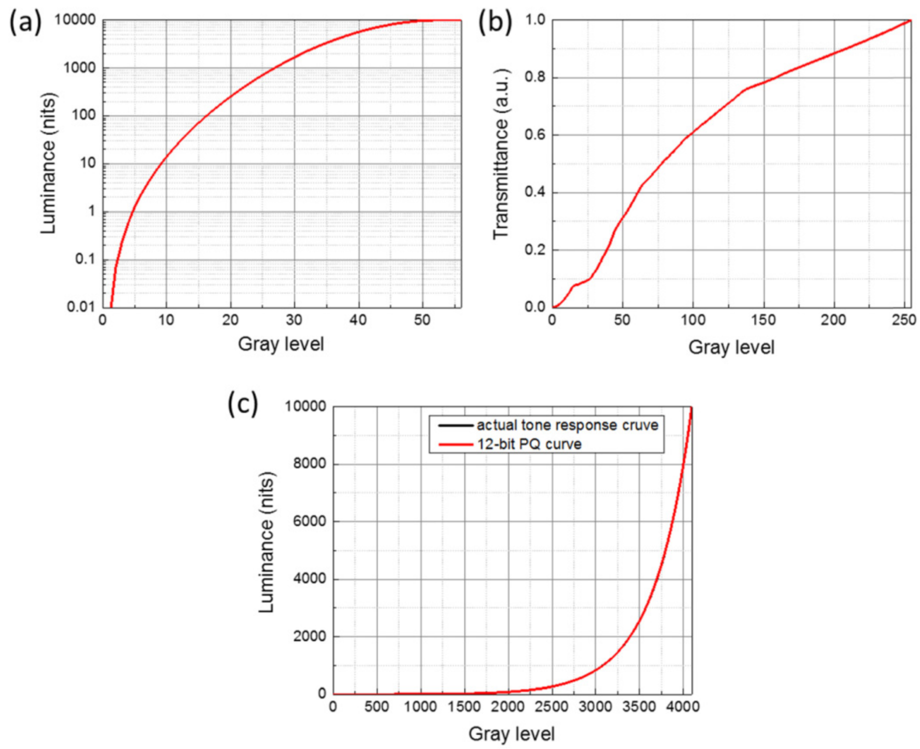

Fig. 3. Tone response curves of (a) the LEDs, (b) the LC panel and (c) the whole system in comparison with the target 12-bit PQ curve.

To quantify the difference between the actual tone response curve M and the 12-bit PQ curve R, we calculated the coefficient of variation (CV) [18] between the two curves, and the definition of CV is:

$$CV = \frac{100\%}{\bar{R}} \sqrt{\frac{\sum_{i=0}^{N-1} (M_i - R_i)^2}{N}}. \quad (2)$$

Here N is the total gray levels and $\bar{R}$ is the average luminance of the PQ curve. As can be seen from Eq. (2), the CV describes the agreement between the two data sets. The calculated CV here is 0.08%, which indicates with our proposed tone response curves shown in Fig. 3, the system can well reproduce the 12-bit PQ curve. For a practical system, because of the low transmittance of the LC panel, using 10000-nit LEDs will not give us peak brightness of 10000 nits. And thus, the CV will be greatly degraded. However, it is still possible to get small CV between the normalized tone response curve and the normalized 12-bit PQ curve. For real applications where 10000 nits display is required, there are several approaches to

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achieve this goal, such as 1) using high brightness LEDs, 2) improving the backlight design for higher optical extraction, and 3) improving the transmittance of the LC panel by using field sequential LCs [19]. For these situations, our design method is still valid to well reproduce the 10000 nits PQ curve with a small CV.

In Section 2 we have mentioned that if we drive the LEDs or the LC separately, the LC panel will have sluggish response time and high on state voltage. For our driving scheme proposed above, the response time and driving voltage of the LC panel is no longer a problem as the panel is still 8-bit except that the tone response curve is different. To prove this, we made a 3.3μm-cell-gap VA cell with ZOC-7003. The V-T curve of the cell is shown in Fig. 4. The on-stage voltage of the cell is 7.5V with a threshold voltage of 2.25V. Such driving voltage is typical for commercial LCD systems.

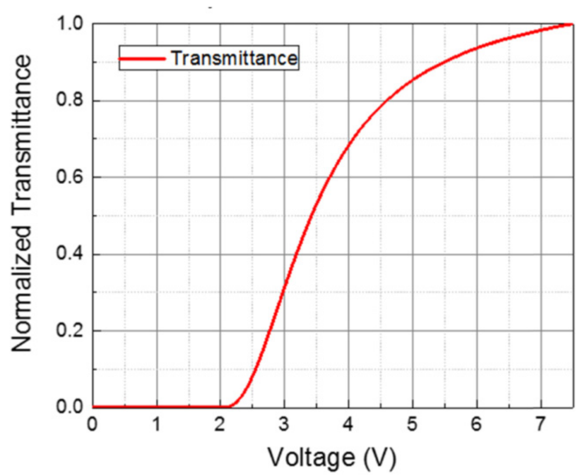

Fig. 4. The voltage-transmittance curve of VA cell using ZOC-7003.

As for the response time, the transmittance curve is equally divided into 8 gray levels and the measured GTG response times [20, 21] are shown in Table 4. The average response time of the cell is 6.17 ms. Such response time is fast enough for real applications.

Table 4. Gray-to-gray (GTG) response time of the ZOC-7003 VA cell. (ms)

		Rise time (ms)							
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Decay time (ms)	**1**		17.01	12.51	10.01	8.20	6.04	3.07	1.10
	2	2.85		11.25	9.19	7.07	4.87	2.82	0.97
	3	3.34	12.15		8.30	6.43	4.66	2.64	0.88
	4	3.65	11.82	9.61		6.09	4.39	2.51	0.83
	5	3.97	11.39	9.46	8.45		4.44	2.41	0.8
	6	4.31	11.04	9.41	7.81	6.19		2.40	0.79
	7	4.71	10.44	9.30	7.79	6.17	4.58		0.69
	8	5.15	10.55	8.96	7.51	5.86	4.21	2.20	

4. Discussion

Besides driving the LEDs and the LC panel together, another possible way to achieve the 12-bit PQ curve is to use the dual LC panel approach [22–24]. In this approach two LC panels are driven together to achieve increased bit-depth and darker black state. One common difficulty for these two approaches is the synchronization: for the first approach the synchronization between the LEDs and the LC will be the main challenge whereas for the second approach synchronizing the two LC panels will be a burden for the circuit design. Besides this challenge, each approach has its unique pros and cons. For the first approach, designing the LED backlight will be quite challenging as we have to consider the point spread

Optics EXPRESS

function [15] of the LEDs, also, the backlight design will be even more complex if we would like to use edge-lit LEDs instead of direct-lit LEDs [25]. For the second approach, the added LC panel reduces the overall optical efficiency and increases the thickness of the system. We believe these two approaches would co-exist for different requirements and user scenarios.

5. Conclusion

We have proposed an approach that drives the local dimming LED backlight and LC panel simultaneously to achieve the 12-bit PQ curve for HDR displays. Compared to driving the LEDs and LC panel separately, this approach exhibits fast response time and acceptable driving voltages. At the same time, our approach will not introduce salt-and-pepper noise to the system.

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