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Luminance Compensation and Optimization to Delay OLED Degradation Based on Equivalent Lifetime Detection

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ABSTRACT In this paper, luminance compensation and optimization without internal or external sensing circuits to delay OLED degradation based on equivalent lifetime detection is proposed. The proposed method can estimate the dynamic luminance degradation with the equivalent lifetime equation derived by converting display time of any OLED cell at different luminance to a reference display time at a certain luminance. According to the calculated equivalent lifetime, luminance compensation is carried out by increasing drive current. In order to obtain a better lifetime extension of the OLED, three key parameters, such as compensation iteration m, compensation goal value L_{goal}, and compensation origin value L_{origin} are optimized. Experimental results indicate that the relative error of dynamic luminance degradation estimation is about 2.2% with the proposed method. The lifetime of OLED cells can be prolonged by 32.64% with the optimized parameters $m = 5$, $L_{origin}/L_0 = 0.75$, and $L_{goal}/L_0 = 0.83$.

INDEX TERMS Equivalent lifetime, luminance compensation, lifetime extension, OLEDs.

I. INTRODUCTION

Organic Light Emitting Diode (OLED) has attracted significant attention due to its high contrast, low power consumption, self-light emission, high color reproduction ranges and other advantages [1]. However, the OLED display suffers from severe luminance degradation as usage time increasing [2]–[4]. The mechanistic of the OLED luminance degradation mainly focused on thermal stability, trap, luminescence quencher formation, and interface degradation [5]–[8]. OLED lifetime is usually defined as the consumed time when the luminance drops to half of initial luminance, which means OLED lifetime is determined directly by the luminance decrease [9]. Therefore, most of the methods for retarding lifetime degradation of the OLED mainly focus on delaying and compensating luminance degradation.

Luminance compensation is usually implemented after the degree of luminance degradation is obtained. Currently there are a few external circuits compensation methods, which need sensing circuits and additional circuit components to delay the luminance degradation. These methods adjust the driving current to an expected value based on the detected current [10]–[12]. On the other hand, the internal compensation methods can delay luminance degradation by designing 5T1C or 4T0.5C pixel circuits. However, these pixels have strict requirements of well-designed new pixel circuits and high complexity of manufacturing to maintain the pixel size [3], [13]. And the luminance for AMOLED displays using integrated MIS (metal-insulator-semiconductor) sensor was conducted. The luminance adjusting algorithm is based on realistic models for pixel circuit elements to predict the relation between the programming voltage and OLED luminance [14]. All of the above methods require additional sensor circuits to detect the degradation degree of OLED [15], [16], which needs a period of time setting aside before the display cycle for detection. The pulsed driven internal circuits combined with external circuits can prolong the OLED lifetime by 20%. In addition, the pulsed driven circuits combined with the reverse bias can achieve a better lifetime extension, however, the specific lifetime extensions are not provided [3], [12], [13].

Luminance compensation based on lifetime prediction does not need additional sensor circuits. OLED lifetime estimation based on mathematical modeling has been studied. For example, lifetime estimation based on Weibull distribution and experimental test has been studied [17], [18]. However, this method is not conductive to obtain the aging status of OLED in real time. Currently, some researches can predict the lifetime based on the luminance degradation models, such as coulombic degradation and stretched exponential decay (SED) model [19], [20]. Compared with SED model, the coulomb model has deviations in case of high luminance. And they cannot be directly used for lifetime prediction of actual variable luminance. The lifetime extension method for active matrix OLED using a modified stretched exponential decay model can compensate the luminance by increasing the duty ratio of digital driving. The lifetime is significantly improved while the test time is 40 hours [21]. In addition, the luminance compensation is significant if the balance is obtained among the display quality, lifetime extension, and hardware cost.

In this paper, we propose a novel luminance compensation and optimization method by calculating the degradation degree of the OLED. The method can calculate the luminance degradation without any internal or external sensor circuits based on a proposed equivalent lifetime method. And the proposed equivalent lifetime method of OLED can convert display time at different luminance to a reference display time at a certain luminance. Primarily, the parameters of the luminance degradation model are calculated while the OLED is driven by a constant current. Then, using an equivalent lifetime equation, the estimated dynamic degradation with the calculated parameters is converted to the static degradation degree (The degradation is calculated by luminance decay curve driven by constant current). To improve the OLED lifetime, the driven voltage is changed to compensate the luminance degradation based on the converted static degradation degree. To obtain a better OLED lifetime extension, three key parameters, i.e., compensation iteration m, compensation goal value L_{goal}, and compensation origin value L_{origin} are optimized. The proposed lifetime extension method can obtain balance among cost, real time performance, and the lifetime of OLED.

The rest of this paper is organized as follows: Section II describes the process of estimating dynamic luminance degradation and proposes the equivalent lifetime method. Section III elaborates on the compensation optimization of OLED lifetime. Experimental results and discussions are presented in Section IV. Section V gives the conclusions.

II. EQUIVALENT LIFETIME METHOD

The OLED luminance degradation curve should be ascertained before estimating degradation degree of dynamic images. The parameters of luminance degradation curve can be calculated by measuring the OLED luminance degradation and fitting the degradation curve at a constant drive current. Based on these parameters, the equivalent lifetime method to estimate dynamic degradation degree is proposed and the details are given in the following sections.

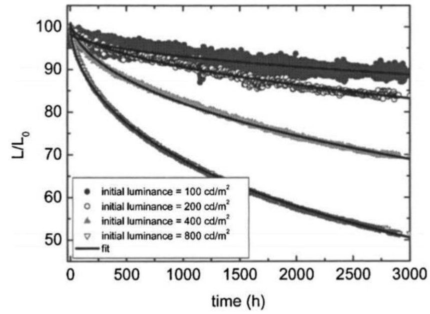

FIGURE 1. Luminance decay curves measured at various initial luminance [9].

A. LUMINANCE DEGRADATION MODEL

Since OLED lifetime is defined as the consumed time of the initial luminance decreased by half, the key to improve the OLED lifetime is to reduce the luminance degradation rate or compensate luminance. Fig. 1 [9] is the normalized luminance decay curve of an OLED display from 0 to 3000 hours with initial luminance 800, 400, 200, and 100 cd/m^2. It is evident that the OLED luminance gradually decreases with time and the decrease rate is proportional to the initial luminance. The coulomb aging model has deviations compared to the actual decay in case of high luminance, while the SED model can accurately fit the luminance decay curve of OLED in the whole range of luminance [9], [18]. Therefore, after comparing the two typical luminance decay models, the SED model is chosen to fit luminance decay curve:

$$L(t) = L_0 \exp\left(-(t/\tau)^{\beta}\right), \tag{1}$$

$$L_0^n t_{1/2} = C, \tag{2}$$

where L_0 is the initial luminance of OLED, t is the display time, $t_{1/2}$ is the time when luminance decays to half of the initial luminance, τ is the coefficient which is related to the initial luminance, and β is related to the material and manufacturing processes of the OLED sample. The parameters C and n are constants for a certain OLED sample, where the accelerated factor n reflects the decay rate.

B. CALCULATION OF LUMINANCE DEGRADATION

The OLED luminance degradation model is expressed by (1) and (2). Moreover, the luminance degradation can be calculated using this model when the OLED is driven by a constant current. The luminance degradation degree α is usually defined as $L(t)/L_0$. The OLED lifetime $t_{1/2}$ can be

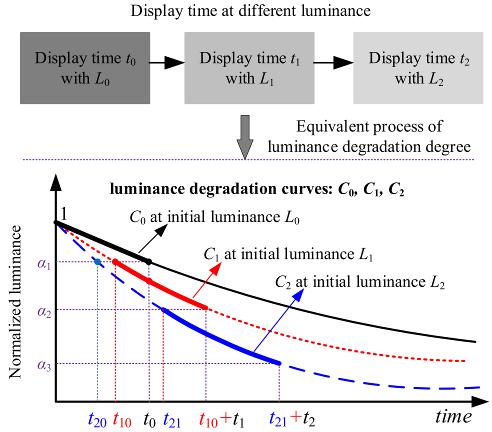

FIGURE 2. The principle of equivalent lifetime method for dynamic images.

obtained when the luminance decays to half of initial luminance, i.e., $L(t) = L_0/2$. The relationship between τ and L_0 shown in (3) is deduced from (1) and $t_{1/2}$:

$$\tau = C/\left(L_0^n(\ln 2)^{1/\beta}\right), \tag{3}$$

Therefore, the luminance degradation can be described as follows:

$$L(t) = L_0 \exp\left(-\left(tL_0^n(\ln 2)^{1/\beta}/C\right)^\beta\right), \tag{4}$$

Using (4), the luminance degradation degree α is given as follows:

$$\alpha = \exp\left(-\left(tL_0^n/K\right)^\beta\right), \tag{5}$$

where K as a constant is equal to $C/(\ln 2)^{1/\beta}$.

C. EQUIVALENT LIFETIME METHOD

According to (5), for any two initial luminance values L_0 and L_x, to achieve the same degradation degree α, the display time and initial luminance should meet the relationship given as follows:

$$t_0L_0^n = t_xL_x^n, \tag{6}$$

where t_0 and t_x are the display times of initial luminance values L_0 and L_x, respectively.

As shown in Fig. 2, the same degradation degree α_1 can be achieved by initial luminance L_0 for displaying t_0, L_1 for displaying t_{10}, or L_2 for displaying t_{20} if $t_0L_0^n = t_{10}L_1^n = t_{20}L_2n$. For the dynamic image display, we suppose that the initial luminance $L_0 < L_1 < L_2$ are all normalized and the corresponding specific luminance decay curves are C_0, C_1, and C_2, respectively. The display times for initial luminance values L_0, L_1, and L_2 are t_0, t_1, and t_2, respectively, and the corresponding degradation degrees are α_1, α_2, and α_3, respectively. Using (5) and (6), we get the following

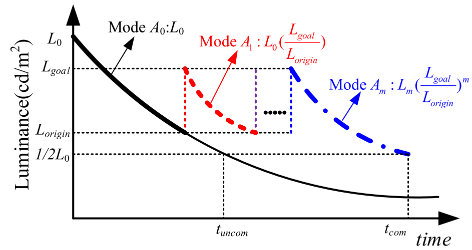

FIGURE 3. The principle of luminance compensation.

expression of α_3:

$$\begin{aligned}\alpha_3 &= \exp\left(-\left((t_{21}+t_2)L_2^n/K\right)^\beta\right)\\ &= \exp\left(-\left(\left((t_{10}+t_1)L_1^n + t_2L_2^n\right)/K\right)^\beta\right)\\ &= \exp\left(-\left(\left(t_0L_0^n + t_1L_1^n + t_2L_2^n\right)/K\right)^\beta\right),\end{aligned} \tag{7}$$

When the dynamic image serials contain h images corresponding initial luminance values $L_0, L_1, \ldots, L_h$ and display times t_0, $t_1, \ldots, t_h$, the final degradation degree α can be expressed by (8):

$$\alpha(T) = \exp\left(-\left(\left(t_1L_1^n + \cdots\cdots + t_hL_h^n\right)/K\right)^\beta\right), \tag{8}$$

III. OPTIMIZATION OF LUMINANCE COMPENSATION

A. COMPENSATION METHOD

To improve the OLED lifetime, luminance compensation is implemented by adjusting the drive voltage V_{gs} (drive voltage converted from image signal through source driver) and drive current successively when the luminance drops to a certain threshold. The luminance compensation principle is shown in Fig. 3. In this figure, the parameter m indicates the compensation iteration while t_{uncom} and t_{com} are lifetime without and with compensation, respectively. The compensation goal value L_{goal} and compensation origin value L_{origin} are the same for any compensation modes $A_0, A_1, A_2, \ldots A_m$.

The initial luminance is proportional to the drive current. In the compensation mode A_0, the initial luminance L_m is expressed as L_0. When the luminance drops to L_{origin} along the degradation curve, the compensation mode changes from A_0 to A_1. Then, in the compensation mode A_1, the initial luminance L_m is expressed as L_1 and the luminance decays along the curve, while initial luminance value L_1 is equal to $L_0(L_{goal}/L_{origin})$. The compensation mode will change from A_1 to A_2 when the luminance drops to L_{origin} again. Further, the initial luminance L_m has the value $L_0(L_{goal}/L_{origin})^m$ in the compensation mode A_m. Therefore, the luminance compensation is a dynamic process, and the lifetime of OLED after m compensation iterations can be deduced based on (6) and (8) as follows:

$$t_{1/2} = \left(k/\left(\beta L_0^n\right)\right) \times \left(\ln\left(\frac{L_0}{L_{origin}}\right) + \cdots + \frac{\ln\left(\frac{L_{goal}}{L_{origin}}\right)}{\left(\frac{L_{goal}}{L_{origin}}\right)^{(m-2)n}} + \frac{\ln\left(\frac{2L_{goal}}{L_0}\right)}{\left(\frac{L_{goal}}{L_{origin}}\right)^{mn}}\right), \tag{9}$$

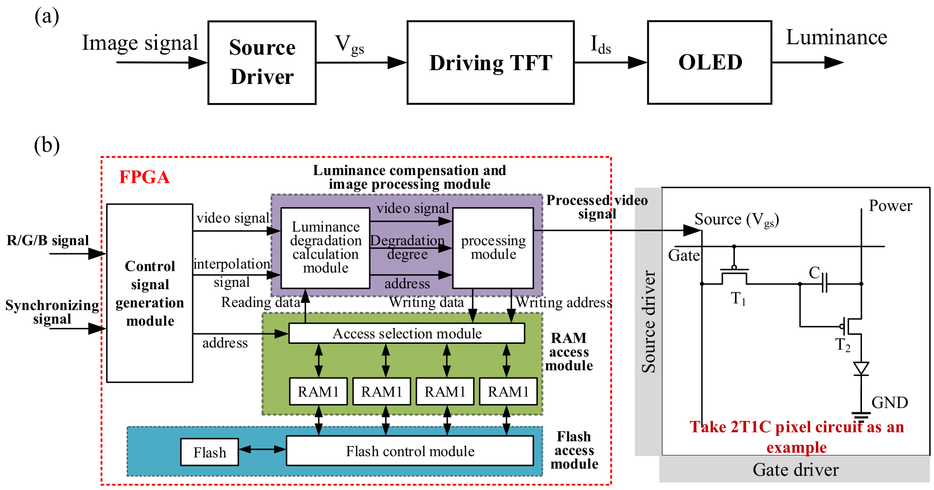

FIGURE 4. **The (a) process and (b) system diagram of luminance compensation implementation.**

where n, K and β are constants for a certain OLED sample with initial luminance L_0, which is similar to it in (5). The compensated lifetime $t_{1/2}$ depends on parameters L_{goal}, L_{origin}, and m. In order to obtain a longer lifetime $t_{1/2}$, L_{goal}, L_{origin}, and m should be optimized to obtain the balance among lifetime, image quality, and hardware resource, etc.

In addition, the system diagram of luminance compensation implementation is indicated in Fig. 4. The OLED luminance compensation process is shown in Fig. 4(a). The external image signal is converted into V_{gs} signal by the source driver. The V_{gs} voltage determines the source current I_{ds} flowing through the driving TFT. Compensation for OLED luminance degradation can be implemented from adjusting V_{gs} voltage. Figure 4(b) represents the system diagram of luminance compensation applied in real active matrix OLED. Here, an example of 2T1C pixel circuit is given to illustrate how the luminance compensation method is applied to active matrix OLED. To the real active matrix OLED displays, firstly, R/G/B and synchronizing signals are inputted into control signals generation module in FPGA. Then, the video and interpolation signals are sent to the luminance compensation and image processing module, and the luminance degradation is calculated according to the previous calculated luminance degradation data stored in RAM, video and interpolation signals. Finally, according to the degradation status, the compensation mode is built and the video signal is compensated. The corresponding V_{gs} is sent to the OLED driver circuits to compensate the luminance degradation. Meanwhile, new degradation degree is stored in RAM. Due to the newest luminance degradation is calculated by superimposing the accumulated degradation with the new degradation, the degradation and corresponding address data is stored in Flash to avoid the data loss when the power is off.

B. LIFETIME COMPENSATION OPTIMIZATION

The purpose of lifetime compensation optimization is to extend the lifetime sufficiently with a lower cost. Among the three parameters L_{goal}, L_{origin}, and m, L_{origin} is mainly determined by display uniformity while m and L_{goal} are mainly limited by IC driver ability and characteristics of the OLED. Specifically, the optimized values of these parameters should create a balance among the resources, real-time implementation and significant lifetime extension.

For a certain OLED sample with IC driver bonded, the luminance corresponding to the maximum drive current L_{max} is a constant. In theory, the initial luminance $L_0(L_{goal}/L_{origin})^m$ after m compensation iterations becomes

$$L_{\max} = L_0\left(L_{goal}/L_{origin}\right)^m, \tag{10}$$

where L_0 is a constant, and m is inversely proportional to L_{goal} under the fixed L_{origin}.

For the different luminance compensation modes shown in Fig. 3, the compensation iteration can be obtained using (5). By substituting (5) into (8), the luminance degradation α can be expressed as in (11). The luminance cannot be compensated if degradation degree α is lower than the worst threshold α_{limit} because OLED is seriously damaged due to exciton quenching and stability of radical cations and anions.

$$\alpha = \exp\left(-\left(\left(\ln\left(\frac{L_0}{L_{origin}}\right)\right)^{1/\beta} + \cdots + \left(\frac{L_{goal}}{L_{origin}}\right)^{(m-1)n} \times \left(\left(\ln\left(\frac{L_0 \times L_{goal}^m}{L_{origin}^{m+1}}\right)\right)^{1/\beta} - \left(\ln\left(\frac{L_0 \times L_{goal}^{m-1}}{L_{origin}^m}\right)\right)^{1/\beta}\right)\right)\right) = \alpha_{\lim it}, \tag{11}$$

Based on the principle of luminance compensation mentioned above, the parameters m, L_{origin}, and L_{goal} can be optimized according to the flow chart shown in Fig. 5. Primarily, different parameters are initialized. The L_{origin} is set according to the threshold of luminance uniformity. For example, if the luminance uniformity of the OLED panel is 0.85, the L_{origin} is $0.85L_0$. The value of $tL_0{}^n$ in (5) after m compensations is expressed as $tL^n(m)$, which is used to calculate the luminance degradation α after m^{th} compensations.

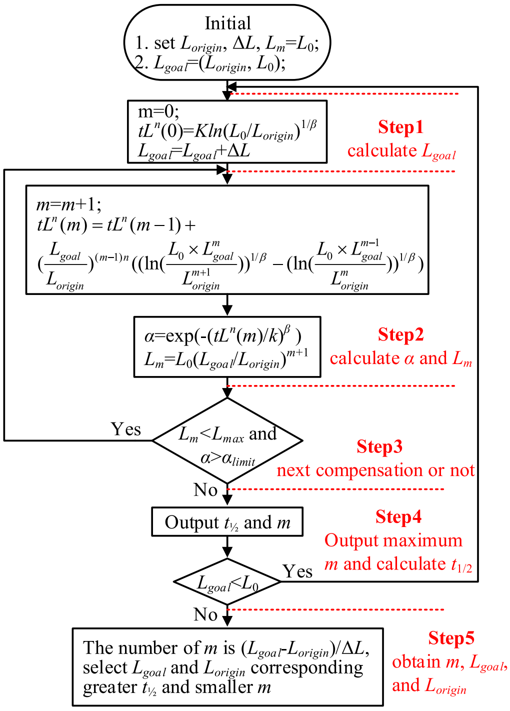

FIGURE 5. Flow chart of the luminance compensation optimization.

The initial value of $tL^n(m)$ is $tL^n(0)$ and initial luminance L_m is L_0 when compensation iteration $m = 0$. The L_{goal} changes from L_{origin} to L_0 with a fixed step $\Delta\ L$, where L_{origin} is initialized to a fixed value. After setting the initial parameters, we obtain the maximum m corresponding to each L_{goal} iteratively and finally select the optimal L_{goal} and L_{origin}. The flow chart shown in Fig. 5 can be used to calculate m and L_{goal} for different L_{origin}. For each L_{origin}, the steps are as follows:

Step 1: Calculating L_{goal}, i.e., $L_{goal} = L_{goal} + \Delta L$.

Step 2: Keeping L_{goal} unchanged, calculating α and initial luminance L_m after m^{th} compensations using (11).

Step 3: According to the limiting conditions $L_m < L_{max}$ and $\alpha > \alpha_{limit}$, we can determine whether the next compensation should be carried out or not. Step 2 is carried out for the next compensation, otherwise, Step 4 will be carried out.

Step 4: The maximum m corresponding to the values of L_{goal} and L_{origin} can be obtained when $L_m = L_{max}$ or $\alpha = \alpha_{limi}$, and $t_{1/2}$ corresponding to the values of m, L_{goal}, and L_{origin} can then be calculated using (9). The number of maximum m is $(L_{goal} - L_{origin})/\Delta L$ corresponding to L_{goal} and L_{origin}. Subsequently, when $L_{goal} = L_0$, Step 1, i.e., $L_{goal} = L_{goal} + \Delta L$ is no longer carried out and Step 5 will be carried out instead.

Step 5: According to the values of m and $t_{1/2}$, we can obtain the optimal L_{goal} and L_{origin}. A larger m will increase the cost due to more hardware resources and more complex algorithm. Therefore, we can optimize L_{goal} and L_{origin} to obtain longer lifetime $t_{1/2}$ with suitable m.

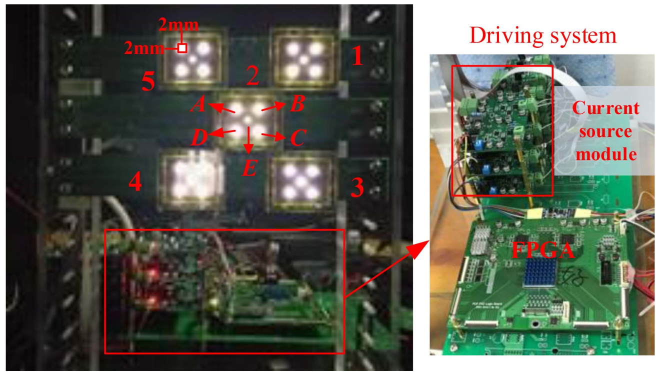

FIGURE 6. OLED cells and verification system.

TABLE 1. Constant and variable currents of the OLED samples (Unit: mA).

Sample	A	B	C	D	E
1	1.17	1.24	1.34	1.46	0-1.72
2	1.17	1.24	1.34	1.67	0-1.72
3	1.17	1.24	1.34	1.65	1.17-1.65

IV. RESULTS AND DISCUSSION

A. LUMINANCE COMPENSATION SYSTEM

The proposed luminance compensation and optimization method was implemented using several OLED macro cell samples shown in Fig. 6. The verification system consists of five OLED samples, which contain a total of twenty-five light-emitting cells. The size of the OLED cells is 2×2 mm^2. In our experiment, we choose typical OLED samples 1, 2, and 3 for analysis since OLED samples 4 and 5 are broken due to the circuit problem. Each OLED sample has 5 light-emitting cells marked as A, B, C, D, and E. The cells A to D are driven with constant current while E is driven with variable current. Both variable currents and constant currents are set according to the actual luminance of OLED panel. The variable drive current is controlled by the IEC (International Electrotechnical Commission) standard video. The specific current values are listed in Table 1. The steps to verify equivalent lifetime and luminance compensation methods are described in the following.

(1) Determination of parameters: Measuring and fitting luminance decay curves with constant current, and calculating the parameters of SED model.

(2) Verification of equivalent lifetime: Measuring the luminance degradation of OLED samples driven with variable currents. According to the display contents and display time, we compare the measured luminance degradation with the estimated results calculated by equivalent lifetime method.

(3) Optimization of luminance compensation: According to the estimated luminance degradation, luminance compensation is performed by increasing the drive current. After analyzing the display uniformity, driver IC ability, and resources usage, we simulate the optimization results with $L_{origin} = 0.75L_0$, $0.85L_0$, and $0.95L_0$.

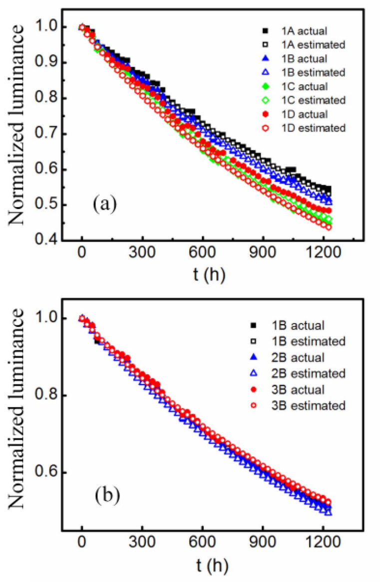

FIGURE 7. Actual and estimated luminance degradation of (a) cells *A*, *B*, *C*, and *D* of OLED sample 1 with constant current and (b) cells *B* of OLED sample 1, 2, and 3 with constant current.

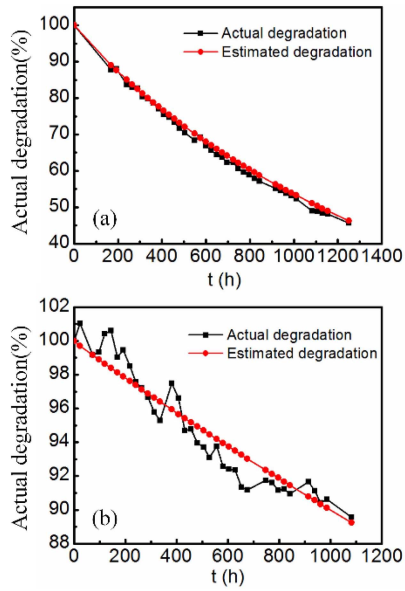

FIGURE 8. Actual and estimated luminance degradation of (a) four kinds of variable current and (b) IEC standard video.

(4) Comparison of simulation and measured results: According to the simulation results, the optimal compensation parameters $L_{origin} = 0.75L_0$ and $L_{goal} = 0.83L_0$ are obtained. Furthermore, we compare the luminance compensation curves of simulation and measurement obtained by using the optimal compensation parameters.

B. EQUIVALENT LIFETIME VERIFICATION

In our experiments, we measured the luminance degradation of OLED samples driven with constant current and fitted more than twelve luminance decay curves using the SED model. The average relative error of these fitting curves is about 1.08%. The relative error is caused by cell E because cell E is driven with variable currents, which results in a propagation of luminance fluctuations and affects cells A to D during luminance measurement. The fitting error has less influence on luminance compensation, which can be ignored. Based on the fitted luminance decay curves, the parameters β, n, and K of SED model can be determined. In our experiment, the parameter β is 0.958, the accelerated factors n of OLED samples 1, 2, and 3 are 1.649, 2.362, and 1.984, respectively, corresponding constants K of samples 1 to 3 are 6.98×10^9, 4.3×10^{12}, and 1.69×10^{11}, respectively. The luminance degradation of different OLED sample can be estimated by (5) with the corresponding parameters.

Fig. 7 shows the actual and estimated luminance degradation with constant current. Fig. 7 (a) shows the luminance degradation curves of cells A to D of OLED sample 1. Fig. 7 (b) shows the luminance degradation curves of cell B of OLED samples 1, 2, and 3. It can be observed that the estimated luminance decay curves match the corresponding actual luminance decay curves closely with the constant drive current. The average relative error of estimated luminance degradation with constant current is 1.9%, which is small enough to cause less effect on luminance compensation. The luminance degradation can be estimated accurately by (5) with constant current.

Fig. 8 shows the actual and estimated luminance degradation values with variable current. There are two cases for the variable current tests. Case 1: Cell E of OLED sample 3 is driven with four kinds of currents, which are 1.17, 1.24, 1.34, and 1.65 mA. Case 2: Cells E of OLED sample 1 and 2 are driven with variable currents corresponding IEC standard video. Based on the equivalent lifetime equation given in (8), the luminance degradation of dynamic image can be estimated. Fig. 8 (a) and (b) are the actual and estimated luminance degradation of case 1 and case 2, respectively. It can be seen that the luminance degradation in case 1 can be estimated accurately. Luminance decay curves in case 2 have some fluctuations. The distances between cell E and cells A to D are 14 mm. The measured luminance of cell E is affected by cells A to D due to the light diffusion. The maximum relative error of estimated luminance degradation with variable currents is 2.2%, which cause about 2% change of lifetime extension and can be tolerated in our experiment.

C. OPTIMIZATION COMPENSATION RESULTS

According to the principle of luminance compensation optimization mentioned in Section III, the results of luminance compensation optimization are not affected by the initial luminance because the initial luminance can be canceled out. In our experiment, we simulate the optimization of L_{origin}, L_{goal}, and m with an initial luminance of 5000 nits. We suppose that the displayed image quality is acceptable if the luminance uniformity of display device is larger than

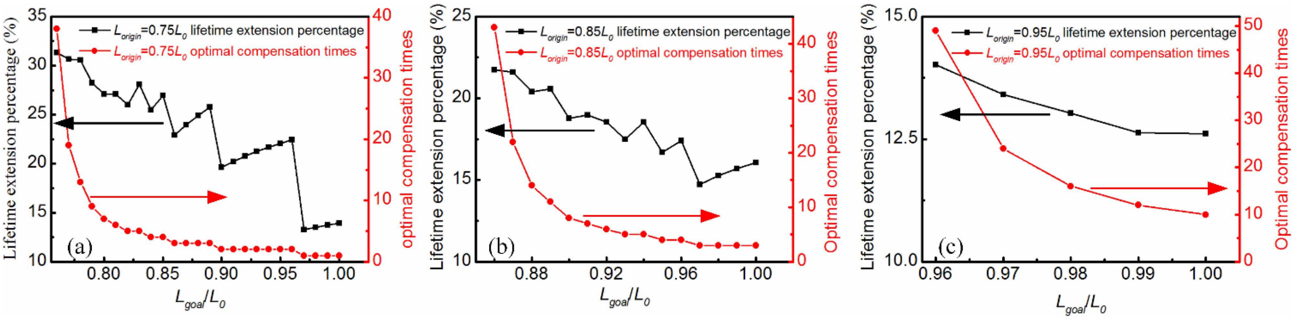

FIGURE 9. The relationship of compensation iterations m, compensation goal L_{goal} and lifetime extension when (a) L_{origin} is $0.75L_0$ and (b) L_{origin} is $0.85L_0$ and (c) L_{origin} is $0.95L_0$.

75%. The maximum drive current of driver IC is usually three times of the initial current/initial luminance. Therefore, we set three values of L_{origin} as $0.75L_0$, $0.85L_0$, and $0.95L_0$, and $L_{max} = 3L_0$. The step ΔL and the worse degradation degree α_{limit} are $0.01L_0$ and 30%, respectively.

Fig. 9 shows the relationship of compensation iterations m, compensation goal L_{goal}, and lifetime extension when L_{origin} is $0.75L_0$, $0.85L_0$, and $0.95L_0$. We can get the following conclusions:

(1) Both compensation iteration m and lifetime extension are inversely proportional to L_{goal}.

(2) When L_{origin} is $0.75L_0$ and $0.85L_0$, m keeps the same for a number of adjacent L_{goal} under the limited driver IC ability.

(3) With increase of L_{goal}, the lifetime will increase for the fixed m, while decrease with decrease of m. Therefore, the lifetime extension curves show fluctuations.

(4) When L_{origin} is $0.95L_0$, the lifetime extension reduces with increasing L_{goal} and decreasing m. Lifetime extension curve does not have any fluctuations because the compensation iteration m for adjacent increasing L_{goal} values shows a monotonically decreasing trend.

(5) The larger L_{goal} and m, the longer of lifetime extension.

As L_{goal} is a discrete value, we can individually analyze the influence of L_{origin}, L_{goal}, and m on lifetime extension.

The iteration m can affect resource usage and compensation result. The lifetime cannot be extended remarkably if compensation times m is smaller. However, larger m means more hardware resources and more complex algorithm because luminance will be compensated too many times. In addition, the iteration times m is limited due to the limited IC driver ability and the worst luminance degradation α_{limit}. The iteration m between 3 to 7 can get better balance between resource usage and compensation result. Based on simulation results, if the lifetime extension is almost same with different iteration m, the smallest m is the best chance. Therefore, when $L_{origin} = 0.75L_0$ and $L_{origin} = 0.85L_0$, longer lifetime extension can be achieved with a relatively smaller m and larger L_{goal} due to the fluctuations of lifetime extension curves. When $L_{origin} = 0.75L_0$, the iteration times m is larger than 10 when $L_{goal} < 0.79L_0$, otherwise, the lifetime extension is longest when $m = 5$ and $L_{goal} = 0.83L_0$.

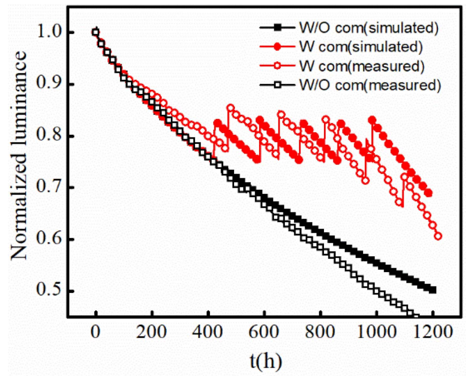

FIGURE 10. The comparison of luminance compensation of simulations and measurements when $L_{origin} = 0.75L_0$, $L_{goal} = 0.83L_0$.

According to the above analysis, the optimal compensation parameters $m = 5$, $L_{origin} = 0.75L_0$, and $L_{goal} = 0.83L_0$ are chosen which can increase the lifetime by 28%.

According to the simulation results, three OLED samples are chosen to verify the luminance compensation method with the optimal compensation parameters $m = 5$, $L_{origin} = 0.75L_0$, and $L_{goal} = 0.83L_0$. In Fig. 10, the red lines with filled circular markers and hollow circular markers represent luminance decay curves of compensation of simulations and measurements, respectively. The black lines with solid square markers and hollow square markers represent luminance decay curves without compensation of simulations and measurements, respectively. It can be seen that the luminance compensation results of simulations and measurements are consistent. However, there are a few deviations because of the following reasons: Firstly, we assumed the same parameters among OLED macro cells in our experiment while there is some inevitable difference between the parameter values. The assumption may cause some difference of compensate start time between simulations and measurements. Secondly, due to the driving voltage limitation of the driver IC, the relationship between current and luminance deviates from linearity with the increase of current. It will affect the luminance compensation that can be noticed in the Fig. 10, where the normalized luminance could not be maintained between 0.75-0.83 as shown by the hollow

TABLE 2. Performance of the proposed method compared with that of the prior works.

Index	[3]	[12]	[22]	This work
Driving method	Analog	Analog	Digital	Analog
Pixel circuit	4T0.5C	5T1C	3T1C	No limit
Detection circuit or not	yes	yes	no	no
Initial luminance(cd/m^2)	--	70	350	1500
Test time(hour)	250	3000	40	1000
Normalized luminance	0.750	0.928	R: 0.997 G: 0.960 B: 0.926	0.830

circular markers. However, both the simulation and measurement results indicated that the proposed equivalent lifetime method can effectively extend the lifetime. The measurement results show that the lifetime can be extended to 32.64% when L_{origin} and L_{goal} are $0.75L_0$ and $0.83L_0$, respectively, which is even longer than it of simulation results.

The performance of the proposed compensation method is compare with that of the prior works is shown in Table 2. Luminance compensation method in this work has no specific limitation on the pixel circuit and it can be used for the basic 2T1C pixel circuit. No additional sensors are required to predict luminance degradation. To accelerate the test process of luminance compensation, the initial luminance is set to 1500 cd/m^2 in our work. The luminance decays faster than it used in normal display. In addition, considering the hardware conditions, display performance, and lifetime extension of OLED, the parameters of luminance compensation is optimized.

V. CONCLUSION

Based on the measured luminance decay curves, we proposed an equivalent lifetime method to calculate the luminance degradation of dynamic images. The estimated luminance degradation derived from the equivalent lifetime equation agrees with the actual luminance degradation with variable drive current. Subsequently, with the calculated equivalent lifetime, the luminance is compensated with the method of increasing the driving voltage. Three key parameters m, L_{goal}, and L_{origin} are optimized to obtain a better lifetime extension under IC driver capability and OLED characteristics. Experimental results showed that the average relative error of estimated luminance degradation is 1.9% when the OLEDs are driven by a constant current. As for dynamic degradation estimation, such as the IEC standard video, the relative error is approximately 2.2%. The relative error is small enough to have very less influence on luminance compensation. Therefore, the equivalent lifetime method can accurately estimate the luminance degradation of actual dynamic display. In addition, the parameter L_{origin} is limited by luminance uniformity, and the maximum compensation iteration m of each L_{goal} can be obtained when $L_m < L_{max}$ and $\alpha > \alpha_{limit}$. The measured OLED lifetime was prolonged to 32.64% with parameters $m = 5$, $L_{origin}/L_0 = 0.75$, and $L_{goal}/L_0 = 0.83$, respectively.

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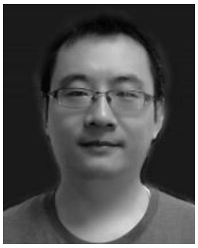

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