De-Mura Taking the Gamma Inconstancy into Account

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Abstract

The demura technology is used to augment product uniformity in the display industry. It makes sampling in the luminance space and makes effect in the gray space. We learned the relationship between luminance space and gray space. Based on the learning, we proposed the demura method taking gamma inconstancy into account. The experiment shows the proposed method outperforms the constant gamma version demura.

Author Keywords

Demura; Non-Uniformity Compensation; Gamma; OLED.

1. Introduction

In the display industry, the manufacturers suffer from the phenomenon that the luminance or color output of the product pixels are not uniform to each other. The non-uniformity is called mura in the industry. In the manufacturing practice, the mura would result in a low yield of acceptable products, rejection of expensive components, or costly rework(1).

The display non-uniformity is caused by the driving or material variation(2). It's impractical or too expensive to prevent non-uniformity at the first step of manufacture. The manufacturers have been taking measures to reduce product loss and to augment product performance. Firstly, at the designing phase, the designers adopt delicate compensation circuits on the designing to suppress the variation among pixels(3). Secondly, several measures are taken to try to find the defective products as early as possible, to prevent further investments in them. To make early rejection of defective products, the manufacturers put the automated optical inspection (AOI) devices on several nodes of the production line. Thirdly, the industry does not discard all products with any defects. When dealing with a slightly defective product, the demura process is adopted to augment the display performance of the product, while the panel's physical status is not touched.

The demura process augments the display performance by modifying the input digital signal based on the panel's physical status, which is encoded and saved to the memory of the display module. The demura technology takes effect as shown in Figure 1.

In the manufacturing phase, the demura process is composed of two parts. The objective of the first part is to make a sampling of the panel's pre-compensation display performance. In this part, the panel is made to show some certain patterns. Generally, an area array camera is employed on each pattern to capture its performance. Then, the captured images are processed to make corresponding feature maps, pixels of which are one-to-one corresponded to pixels of the display panel. In the second part, the compensation value of each pixel is calculated from previous feature maps, then encoded and saved to the memory component of the display module. There are mainly two kinds of approaches to making compensation calculations. Some researchers employ the methods, that make compensation calculations by assuming a gray-luminance relationship or fitting the gray-luminance relationship, then, calculating the compensation based on the gray-luminance relationship(4–6). In the meantime, some other researchers try to calculate the compensation by machine learning(2). Then, the compensation value is encoded in the way the demura circuit is designed and saved to the memory component of the display module.

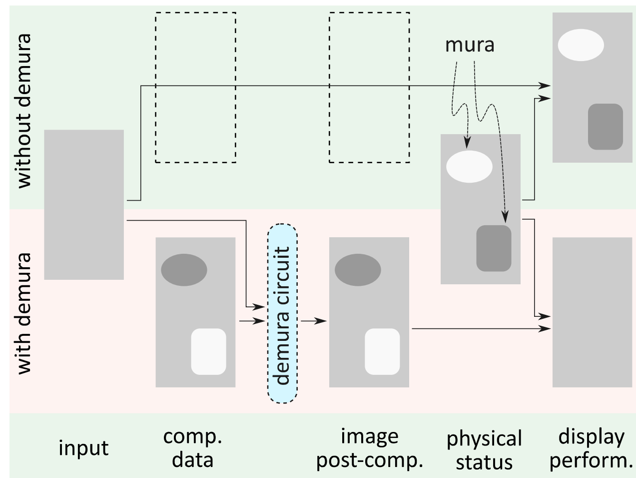

Figure 1. The Principle of Demura

In the post-manufacturing status, the demura compensation happens on the module's driver integrated circuit (IC). Conventionally. In the driver IC, the image signal comes from the host and flows through the demura circuit, where the digital image signal is modified to be adaptive to the panel's physical status so that the display would show both color and brightness consistently. Then, the modified signal is sent to the gamma circuit to convert the digital signal to an analog signal, which controls the pixel's brightness.

In this paper, we focus the compensation calculation on the manufacturing phase. We learned the relationship between digital gray count and the display luminance of the display module. We found that the gray-luminance relationship varies among grays, colors, and pixels. Based on the study, we proposed the method of demura compensation calculation taking the gamma inconstancy into account. Finally, we made an experiment on practical OLED modules. The experiment shows the proposed method augments the performance of the display module significantly and outperforms the constant gamma version demura. As the demura technology processes the red, green, and blue channels separately, we did not strictly distinguish the terms of sub-pixel and pixel in this paper.

2. Gray-Luminance Inspection

The non-uniformity or mura of the display module is the unevenness among the luminance of pixels. Conventionally, an area array camera is adopted to make sampling of the display performance. The picture produced by the camera tells the luminance of display pixels, as shown in Figure 2. However, the demura architecture asks for modifying the digital gray count to make the luminance of each pixel uniform to each other. Bridging the gap between the luminance space and the digital gray space is

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essential in determining the quantity of digital gray count to be subtracted from or added to the input.

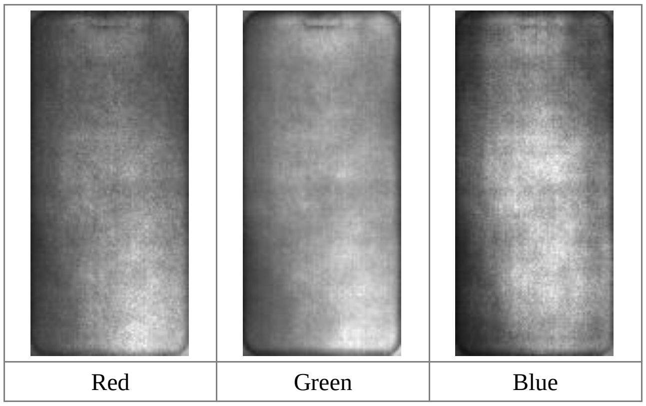

Figure 2. The Initial Display Performance

The theoretical gray-luminance relationship fits a gamma function Equation 1, which is used to determine the target luminance of the key patterns of gamma tuning. Hence, the gamma parameter could be used to represent the gray-luminance relationship. Usually, the gamma parameter is set to 2.2 in practice (7). However, the gamma parameter varies among grays, colors, and pixels. The gamma tuning process only adjusts the chromaticity and luminance of the center spot of white patterns, shown in Figure 3. So, the chromaticity and luminance of red, green, and blue patterns are guaranteed by no more than the physical character of the display module and the lighting property of corresponding white patterns. Consequently, the gamma parameter varies among red, green, and blue channels. The gamma tuning only measures and adjusts the lighting property of the center spot as a whole. The variation among pixels is not taken into consideration. Hence, it is not guaranteed that the gamma parameter be unified among pixels. Furthermore, the variation of the gamma parameter is also found among grays.

$$lv = lv_{base} \cdot \left(\frac{gray}{gray_{base}}\right)^{gamma} \quad (1)$$

Where lv and $gray$ are the luminance and the digital gray count of the pattern of given gray respectively, lv_{base} and $gray_{base}$ are the luminance and the digital gray count of the basis pattern respectively and $gamma$ is the gamma exponent parameter.

To demonstrate the variation of the gray-luminance relation, the experiment is made on a practical OLED module. We measured the pixels' luminance of red, green, and blue patterns on several digital gray counts (16, 32, 64, 128, 192, 255) as key grays, by adopting the factional pixel measurement method, which retrieves the luminance of each display pixel(1). As there are six key grays, they divide the gray axis into seven sections. We take the middle five sections into consideration. Speaking of each section, there are two key grays and corresponding luminance. Its gamma parameter is retrieved by feeding the grays and luminance to Equation 1 and solving the equation. Finally, we use the gamma parameter to show the variation of gray-luminance relation among grays, colors, and pixels.

2.1. Gray-Luminance Among Grays

Taking a practical OLED module as an example, its luminance and gamma parameters of the key grays are plotted in Figure 4. The figure shows the gamma parameter varies from 1.5 to 2.8. As a result, it's inadequate to share the gamma exponent parameter among grays. To show the inadequateness more clearly and directly, the inferred luminance, which is also shown in Figure 4, of all grays from the gamma function of each section. It's easy to find that there is an ignorable gap between the inferred luminance and the actual luminance of the same gray. Understanding it in another way, given a certain target luminance, the gap between the expected grays inferred from alternative sections is ignorable. Furthermore, it also shows that the gap between luminance increases, as the corresponding gray goes far from the key grays. As a result, the compensation calculation in the demura process should not share the gamma parameter among grays.

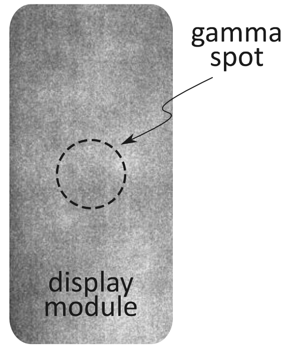

Figure 3. Gamma Spot

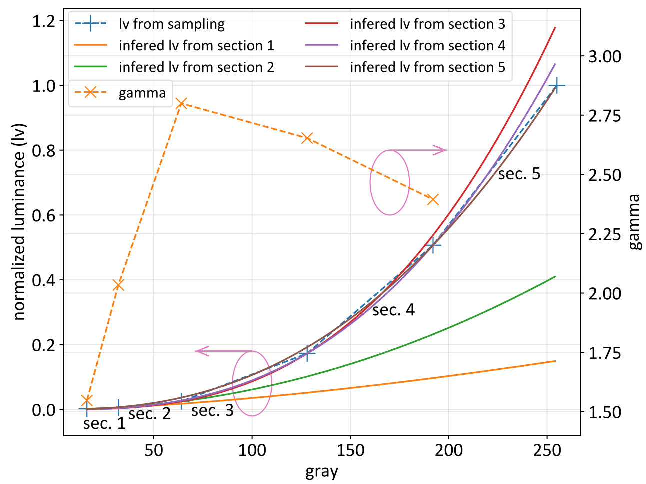

Figure 4. Gray-Luminance Among Grays

2.2. Gray-Luminance Among Colors

The consistency of the gray-luminance relation among R/G/B channels is also investigated. Similar to the investigation of the gray-luminance among grays, we plot the gamma parameter of key grays of R/G/B channels separately in Figure 5. Additionally, the maximum gamma deviation among colors is also shown in the figure. The figure shows the gamma parameters of R/G/B channels on an arbitrary key gray vary to each other. Moreover, the variation becomes more severe as the digital gray descends. The maximum gamma deviation between colors reaches about 1.0 at gray 16. As a result, sharing the gamma exponent parameter among R/G/B channels is also inadequate in the demura process.

2.3. Gray-Luminance Among Pixels

The gamma parameter of each pixel is produced by solving the gamma function by feeding the sampling data. Taking the green pattern of gray 32 as an example, Figure 6 shows the gamma parameter distribution on the display module. The figure shows the gamma parameters vary from pixel to pixel. It roughly falls in the range of about 1.0 to about 2.2. The deviation of the gamma reaches as much as 1.2, which will have a substantial negative impact on the demura performance. So, the demura compensation calculation should be processed pixel by pixel, without sharing the gamma parameter.

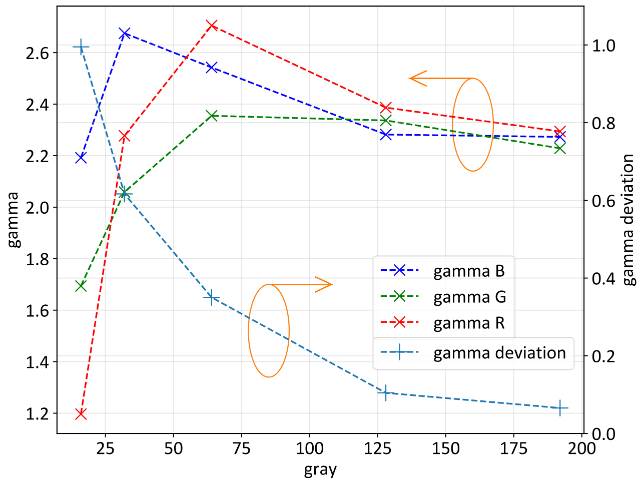

Figure 5. Gray-Luminance Among Colors

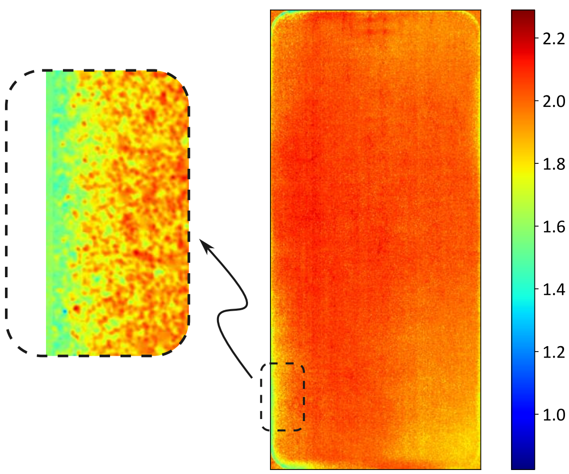

Figure 6. Gamma Distribution

3. Method To Calculate Compensation

Based on previous study, the proposed method follows the assumption that the gray-luminance fits the gamma function. Additionally, it takes the inconstancy of gamma into consideration. The proposed method processes the colors and the pixels separately, calculating their compensation value depending on their gamma value. Furthermore, depending on the module's initial status, the compensation value of one pixel may need to be produced from alternative gray sections.

3.1. One-Section Demura

To bridge the gap between the gamma assumption and the truth, the proposed method makes sampling of the gray pattern, to which the compensation is applied, and at least one more pattern with a near digital gray count. Then, the digital gray counts and the luminance of each pixel are passed to Equation 1 to get the pixel-wise gamma parameter.

The methodology of calculating the compensation is finding the digital gray count for each pixel to make its luminance equal to the target, as shown in Figure 7. Since the luminance of the center spot of the module is tuned in the gamma process, the proposed method uses the average pixel luminance of the center spot of the module as the target luminance for all pixels, when calculating the compensation of the gray ($gray0$) pattern. Then, the gamma parameter of each pixel is calculated by Equation 1. Finally, for each pixel, the target luminance, sampled gray, sampled luminance, and gamma parameter are passed to Equation 1 to solve the digital gray count ($gray1$), on which the pixel's luminance is equal to the target luminance. At this point, it's apparent that the compensation (delta gray) is the difference between $gray1$ and $gray0$.

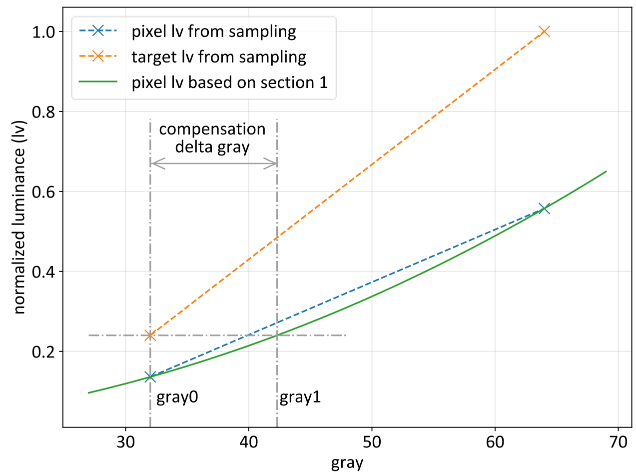

Figure 7. Compensation of a Pixel

3.2. Two-Section Demura

Moreover, in some scenarios, where the compensation value is large enough to exceed some certain threshold, the demura performance may not reach the expected criteria. It depends on the initial status of the module. In these scenarios, the gray-luminance relation inferred from one-section sampling, where the sampling is made on two gray patterns, will have a nonnegligible gap with the actual one.

To deal with this, in the proposed method, one more sampling is made on an additional gray pattern, making sure the compensated gray would not exceed the digital gray count of the pattern. Similar to one-section demura, the compensated gray is calculated from the second and the third samples, the second section. If the compensated gray falls between the second and the third sampling gray, this compensated gray is treated as the true compensated gray. Then, the compensation is produced in the same way as the one-section version.

Figure 8 shows the compensation methodology of the two-section demura. As shown in Figure 8, the target luminance of gray 32 is 0.108. Taking the first two key grays, the first gray section, as the basis, the compensated gray is 100.1. On the other hand, taking the second gray section as the basis, the compensated gray is 77.6. It's apparent, from the figure, the compensated gray from the second gray section will be closer to the truth.

Making a step further, if making more samplings on other gray patterns, by applying the same approach, the compensation will be more accurately fitting the truth, and the compensation performance will be better. But it's impractical to make sampling on a lot of patterns for its time expense. It's a tradeoff between the performance and the investment. In our experience, one-section demura is enough in most scenarios. The need for two-section demura only happens in several conditions.

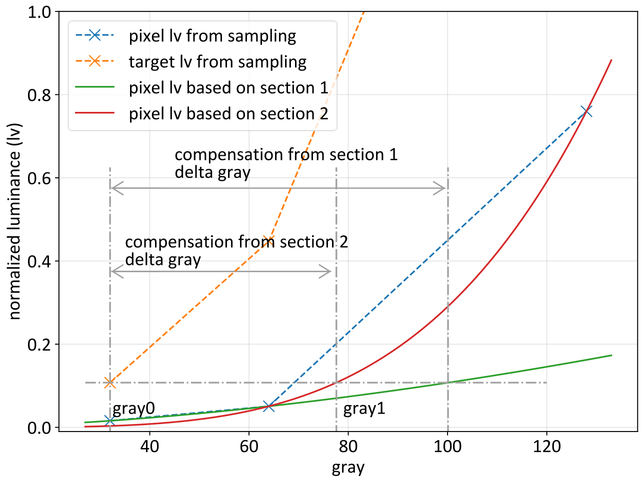

Figure 8. Compensation of a Pixel with Two Gray Sections

4. Experiment and Result

To demonstrate the performance of the proposed method, we made an experiment on practical OLED modules. In the experiment, the OLED modules showed similar performance augmentation.

We take one module as an example to illustrate the experiment details. In the experiment, we make sampling on R/G/B channels separately. The sampling result, the initial display status, of the module is shown in row 1 of Figure 9. It's shown in the figure that the display uniformity is unacceptable. Especially, the left part of the blue channel is much darker than its center part. Based on the sampling result, we calculated the compensation of the pattern with the method of constant gamma, the method of one-section demura, and the method of two-section demura separately. Then, we applied the compensation to the module and made sampling of the performances of these methods by adopting the same way as previous. The performances of the proposed method are shown in row 2 to row 4 of Figure 9.

In Figure 9, we can see the method of constant gamma caused severe overcompensation on the blue channel. Apart from this, the compensation performances of one-section demura and two-section demura outperform the method of constant gamma. In the meantime, the performance of the two-section demura is slightly better than the one-section demura. Moreover, some overcompensation is still observed in the fringe region of the module in the performance of one-section demura. The insufficiency of the one-section demura results from the poor initial status of the module. In a word, the proposed method outperforms the constant gamma demura and makes an outstanding performance.

5. Conclusion

In this paper, we provided a general introduction to the demura process of manufacturing and the mechanism of demura compensation. Then, we exposed and analyzed the key joint to make demura compensation. The analysis shows the gray-luminance relationship is not consistent among grays, colors, and pixels. Based on the study, we proposed the method for making demura compensation taking the gamma inconstancy into account. Finally, we test the proposed method on a practical OLED module. The experiment shows the proposed method makes an outstanding performance.

	Red	Green	Blue
Gray 32			
The display performance of constant gamma demura			
The display performance of one-section demura			
The display performance of two-section demura			

Figure 9. Experience Data

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