An equivalent configuration approach for the moiré patterns appearing due to the reflecting surface in display system

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Abstract: A new moiré pattern appearing in the off-state of a display system with a reflecting surface under illumination of an external ambient light source was analyzed. The origin of the new moiré pattern was attributed to the moiré pattern which is formed on the reflecting surface by external light and plays as a new light source with intensity profile. Configuring an optically equivalent system with no reflecting surface layer was proposed in order to overcome the limitation of new simulation program, which was previously proved to be very efficient in computation time but unable to handle a non-sequential system containing a reflecting surface. It was verified that the new simulation algorithm combined with an equivalent configuration could provide an accurate and computation time-efficient analyses even for a system containing non-sequential stacked layer such as a reflecting surface.

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1. Introduction

A typical display system contains many optical layers including periodic unit structures which are intended to enhance the quality of display such as viewing angle, uniformity of brightness and color, and center brightness [1, 2]. The unit structure of each layer has similar pitch ranging from tens to hundred micrometers, and the pitch cannot be recognized by the human eye under normal viewing distance [1–4]. However, if there happen to be more than two stacked layers in the system, which is the usual case for actual display system, the moiré phenomenon always occurs. Since the moiré causes the degradation of the display image, it has become one of the main evaluation items in flat panel display (FPD) industry [5, 6]. Unfortunately, despite tremendous efforts for removing the moiré patterns in the display system comprised of the multiple optical layers, they cannot be removed completely.

Although complete removal of the moiré patterns may not be possible, the reduction of their amplitude and the control of their pitch can be attained by adjusting the pitch of each optical layer and changing the alignment angle. In 3D display field, many scientists and engineers have investigated to minimize the moiré effect by using analytic method [7–9]. In autostereoscopic display field, a good analytic method for finding the pitch of parallax barrier has been proposed by using the equivalent grating of liquid crystal display (LCD) and the special radial grating [10, 11]. The calculated results from analytic methods were shown to be in good agreement with measured ones as long as the intensity profiles transmitted through the all optical layers are similar [7–9]. But if the transmitted intensity profile from any of the stacked optical layers is distinctively different from others, the analytic method cannot be an accurate tool for the moiré effect. It is because of the facts that the biggest moiré pitch length does not always have the maximum visibility when the moiré patterns have various pitches, and that the relatively short pitch length of periodic moiré patterns made a new moiré pattern with longer pitch. To overcome these limitations of the analytic methods in the moiré pattern analysis, a bidirectional ray-tracing method has been adopted extensively because it provides the most accurate calculation of the complicated moiré pattern [12]. But the bidirectional ray-tracing method has a disadvantage of long computation time due to a massive calculation involved in it.

In our recent study, we proposed a new simulation algorithm (The program was named as “RaywizMOIRÉ”), which can greatly reduce the computation time while maintaining the accuracy [13, 14]. However, the new simulation method has a limitation in that it cannot model a non-sequential system directly, within which any reflecting surface is included. As described in our previous study, the new algorithm uses previous intensity profile to calculate intensity profile of current layer and it must start from a light source layer [14]. Therefore, the new simulation method could not handle a system containing any non-sequential stacked layer such as a reflecting surface.

In this study, we propose a simple way of overcoming such a demerit of RaywizMOIRÉ by postulating an equivalent system to which the actual system with a reflecting surface can be corresponded. The applicability and validity of the equivalent system were verified by comparing the results obtained from the RaywizMOIRÉ program combined with the equivalent system and those calculated for the actual system using the bidirectional ray-tracing method [12]. As a model system to be tested for these calculations, we chose OLED device which utilizes R, G and B color filter with a white emitting layer. The purpose of choosing this test system is twofold; 1) This system exhibits two types of moiré patterns which appear in on- and off-states of the panel layer, respectively. Therefore, it is of practical interest to investigate the cause the new moiré pattern appearing when the display is off-state. 2) The system is composed of the color filter layer and the white emitting layer (panel) together with a reflecting cathode metal surface which is positioned at a finite distance beneath the panel layer, and that the system is complicated enough to show the expandability of the proposed method [15, 16].

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2. Simulation method and verification systems

2.1 The influence of reflecting surface

The effect of the reflecting surface on the moiré pattern was examined by using the bidirectional ray-tracing method. The model test system is depicted in Fig. 1(a), and assumed to be composed of a panel layer with 211 µm (along x-axis) × 211 µm (along y-axis) pitch, a linear optical film layer with 432 µm pitch (along x-axis), and a reflecting surface under the panel layer at the distance of 0.5 mm. The panel layer can illuminate the system with Lambertian angular profile and an additional external light can illuminate the system simultaneously.

![Fig. 1. Schematic diagram of the simulation system (a), and the simulated moiré patterns for flux ratios of the panel to the external light source 1:0 (b), 0:1 (c), 1:1 (d), and 0.001:1 (e).](image)

We performed simulations for 4 cases of illumination conditions with different flux ratios of the panel to the external light source; 1) 1:0 (i.e., only panel source on without external light source), 2) 0:1 (i.e., panel source off with only external light source), 3) 1:1, 4) 0.001:1. The illuminating flux is assumed to be the sum of angular and spatial contribution. Figure 1(b) shows the moiré pattern obtained the panel source only. In this case, the moiré pattern is made by the pitch relations between the panel layer and the optical film layer without the influence of the surface of the reflecting layer. The simulated moiré pattern has fine pitch of 9.3 mm. The counter extreme case is when the panel light source is off and only external light source illuminates. This case will surely show the influence of the surface reflection layer,
and the simulation result is shown in Fig. 1(c). The simulated moiré pattern has 109.4 mm pitch, the partial disappearance of the fine pitch is observed. However, the fine pitch of 9.3 mm still persists in the relatively bright region, and the location of these pitches is the same as the previous case. Figures 1(d) and 1(e) show the results obtained for the flux ratios of the panel to the external light source 1: 1 and 0.001: 1, respectively. The output moiré pattern and intensity for the flux ratio of the panel to the external light source 1: 1 are almost the same as the case without external light source. With decreasing the intensity of the panel light source, the influence of the reflecting surface comes into play, and the moiré patterns from the reflecting surface and the pitch relations between the panel layer and the optical film layer are to be seen clearly. These results tell that, regardless of a reflecting surface, the main moiré pattern which originates from the interference between the panel and the optical film layer exists in the output moiré pattern. Furthermore, the new moiré pattern appearing due to the reflecting surface layer shows a large-pitched pattern due to the partial weakening of the main moiré pitch units. Also, the new moiré pattern from the reflecting surface is distinguishable only when the flux from the panel light source is substantially low. Naturally, in normal operating condition in which the flux of the external light is low when compared to the flux of the panel light source, the new moiré pattern due to reflecting surface cannot be seen.

2.2 The equivalent system

When the optical scientists or engineers make a simulation system to analyze the moiré phenomenon, if the system has any reflecting surface and have to include an external light, they would have some difficulties in getting data compare to the case of no reflecting surface. Because the ray direction is changed at reflecting surface, so eye receiver has to be located in the same direction of light source and has to be adjusted for proper acceptable angle.

When the panel source is off and an external light source is on, the equivalent system without the reflecting surface can be built by considering the propagating path of the rays in the original model system shown in Fig. 1(a). Figure 2(a) represents the original model system with ray path. Rays started from the external light source would form a spatial intensity profile of a moiré pattern after the passing through the P1 and P2 layer sequentially. These rays propagate distance \( l \), and make moiré pattern on the reflecting surface. After reflection, the rays having the intensity profile of the moiré pattern propagate again toward the P2 and P1 layer, and then meet the observer’s eye. In this respect, the reflecting surface is thought to be a new light source with spatial intensity profile in this system. The system can be then reconfigured into an equivalent one which has 4 sequential layers (P1, P2, P2’, and P1’) without reflecting surface as depicted in Fig. 2(b). It is noted that the distance from P2 to P2’ is set to be 2\( l \) which is double the distance between the P2 layer and the reflecting surface in the original model system. But it has to be mentioned that the mirror image in the equivalent system is not a simple structural mirror image. Rather, the equivalent system has to be interpreted from physical standpoint. The equivalent system describes an asymmetric structure because the gap distances between the inversely ordered layers will make new effective pitches.

In order to verify the equivalent system, we performed simulation using the bidirectional ray-tracing method for the equivalent system shown in Fig. 2(b). Figure 2(c) represents the simulated moiré pattern for the equivalent system, and the result obtained from the original system (shown in Fig. 1(c)) is redrawn in Fig. 2(d) for the sake of the comparison. The comparison between Fig. 2(c) and 2(d) clearly tells that the equivalent system can represents the original model system.
In general, an optical system with $n$ optical layers and a reflecting surface can be converted into an equivalent system. The exemplary schematics of the original system and the equivalent system are depicted in Fig. 3. The equivalent system is comprised of two sets of sequential layers; one set having the same order as the original system, and the other having an inverse order. Only the separation distance ($2G_{n,R}$) between the two sets becomes twice of the distance ($G_{n,R}$) between the $n^{th}$ layer and the reflecting surface. Using the same notation used in the previous study [14], the final spatial amplitude profile at the observation position is described as

$$I_{xy}(x_e, y_e) = \int \int \prod_{j=1}^{n} I_j(x, y) \times \exp \left\{ -\frac{1}{2} \left[ \left( \frac{x - x_e}{\sigma} \right)^2 + \left( \frac{y - y_e}{\sigma} \right)^2 \right] \right\} \frac{dxdy}{\sqrt{2\pi} \times \sigma \times \text{erf} \left( \sqrt{2} \right)} \quad (1)$$

Clearly, the difference between the above Eq. (1) and the Eq. (1) in the reference [14] is the occurrence of intensity factor due to mirror image-like structure. But it has to be mentioned that the mirror image in the equivalent system is not a simple structural mirror image. Rather, the equivalent system has to be interpreted from physical standpoint. The equivalent system describes an asymmetric structure because the gap distances between the inversely ordered layers will make new effective pitches.
Since the equivalent system was shown to work perfectly with the bidirectional ray-tracing program, next step is to verify if the equivalent system combined with the new RaywizMOIRÉ program would provide corresponding result as in the case of the bidirectional ray-tracing method. By applying the RaywizMOIRÉ program for the equivalent systems, we carried out a few additional simulations in which the distance between the P2 layer and the reflecting surface varied from 0.6 to 1.2 mm with 0.2 mm interval while keeping other parameters constant. The simulated moiré patterns are shown in the left column of Fig. 4, and those obtained by using the bidirectional ray-tracing method for the same equivalent systems are compared in the right column. Again, the panel light source was assumed to be off-state. It is noted that the moiré pitches change from 83.3 mm for 0.6 mm space to 41.7 mm for 1.2 mm space, which can be attributed to the change of the layer’s effective pitch due to distance change between the P2 layer and the reflecting surface. Clearly, the RaywizMOIRÉ program combined with the equivalent systems provide corresponding results with those obtained by using the bidirectional ray-tracing program for the same equivalent systems. Again, the image quality obtained by using the bidirectional ray-tracing method than that obtained by using the bidirectional ray-tracing method, which was attributed the ability to obtain the continuous intensity distribution of the image at the every point [14]. It would take a tremendous number of rays for the bidirectional ray-tracing method to obtain the same quality of result as the new method. Furthermore, it is worthy of mentioning the comparative results of computation time between these two simulation methods. Using the same computing hardware described in previous study [14], the average calculation time needed for the ray-tracing method was about 110.21 minutes for a given space distance, while that of the new RaywizMOIRÉ was merely 0.17 minutes. This means that the new RaywizMOIRÉ program can provide a solution about 648 times faster than the ray-tracing method.

Fig. 3. Scheme of system comprised with n number of layers with a reflecting layer (a), and equivalent system without reflecting layer (b).
3. Conclusion

In this paper, we proposed a more efficient simulation method of using an equivalent system for the analysis of the moiré pattern which appears from an optical system containing non-sequential stacked layer such as a reflecting surface. As a model system, we chose OLED device composed of the color filter layer and the white emitting layer (panel) together with a reflecting cathode metal surface, which display two types of moiré patterns appearing in on- and off-states of the panel layer. Firstly, by using the bidirectional ray-tracing method, we demonstrated the moiré pattern due to reflecting surface. From the results obtained by changing flux ratio of the display panel and external light power, we demonstrated the main reason of the off-state moiré pattern is the reflecting surface and the external light. In off-state, the moiré pattern formed on the reflecting surface by external light play a role of new light source with a spatial profile of intensity to the original configuration of the patterned layers. After this, we constructed an equivalent system to represent the model system with reflecting surface, and verified that the equivalent system could reproduce the exactly same moiré patterns as the model system. We provided the formality of the generalized equivalent configuration for an optical system with reflecting surface. Finally, by applying the equivalent system, we demonstrated the validity and the efficiency of the new RaywizMOIRÉ program when compared with the bidirectional ray-tracing method.

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