Pseudo-random arranged color filter array for controlling moiré patterns in display

Yangui Zhou, Hang Fan, Sengzhong An, Juntao Li, Jiahui Wang, Jianying Zhou, and Yikun Liu*

State Key Laboratory of Optoelectronic Materials and Technology, Sun Yat-sen University, Guangzhou 510275, China
SYSU-CMU Shunde international Joint Research Institute, Shunde 528300, China

*liuyk6@mail.sysu.edu.cn

Abstract: Optical display quality can be degraded by the appearance of moiré pattern occurring in a display system consisting of a basic matrix superimposed with a functional structured optical layer. We propose in this paper a novel pseudo-random arranged color filter array with the table number arranged with an optimal design scenario. We show that the moiré pattern can be significantly reduced with the introduction of the special color filter array. The idea is tested with an experiment that gives rise to a substantially reduced moiré pattern in a display system. It is believed that the novel functional optical structures have significant impact to complex structured display system in general and to the autostereoscopic and integrated display systems in particular.

©2015 Optical Society of America

OCIS codes: (330.0330) Vision, color, and visual optics; (330.1720) Color vision; (070.0070) Fourier optics and signal processing.

References and links

1. I. Amidror, *The Theory of the Moiré Phenomenon*, (Springer, 2000), Ch. 1.
2. W. X. Zhao, Q. H. Wang, A. H. Wang, and D. H. Li, “Autostereoscopic display based on two-layer lenticular lenses,” Opt. Lett. 35(24), 4127–4129 (2010).
3. N. A. Dodgson, “Autostereoscopic 3D displays,” Computer 38(8), 31–36 (2005).
4. V. Saveljev and S. K. Kim, “Simulation and measurement of moiré patterns at finite distance,” Opt. Express 20(3), 2163–2177 (2012).
5. S. J. Byun, S. Y. Byun, J. Lee, W. M. Kim, H. P. Kim, M. Y. Jeon, and T. S. Lee, “An efficient simulation and analysis method of moiré patterns in display systems,” Opt. Express 22(3), 3128–3136 (2014).
6. B. Masters, “Three-dimensional microscopic tomographic imaging of the cataract in a human lens in vivo,” Opt. Express 3(9), 332–338 (1998).
7. L. Kong, G. Jin, and T. Wang, “Analysis of Moiré minimization in autostereoscopic parallax displays,” Opt. Express 21(22), 26068–26079 (2013).
8. V. V. Saveljev, J. Y. Son, B. Javidi, S. K. Kim, and D. S. Kim, “Moiré minimization condition in three-dimensional image displays,” J. Disp. Technol. 1(2), 347–353 (2005).
9. V. V. Saveljev, J. Y. Son, J. H. Chun, and K. D. Kwack, “About a Moiré-less condition for non-square grids,” J. Disp. Technol. 4(3), 332–339 (2008).
10. Y. Kim, G. Park, J.-H. Jung, J. Kim, and B. Lee, “Color moiré pattern simulation and analysis in three-dimensional integral imaging for finding the moiré-reduced tilted angle of a lens array,” Appl. Opt. 48(11), 2178–2187 (2009).
11. L. Kong, G. Jin, T. Wang, S. Cai, X. Zhong, and K. Xu, “Parameter design of a parallax barrier based on the color moiré patterns in autostereoscopic display,” Appl. Opt. 50(34), H153–H158 (2011).
12. H. Kakeya, S. Sawada, Y. Ueda, and T. Kurokawa, “Integral volumetric imaging with dual layer fly-eye lenses,” Opt. Express 20(3), 1963–1968 (2012).
13. S. T. Hodgkin, M. J. Irwin, P. C. Hewett, and S. J. Warren, “The UKIRT wide field camera ZYJHK photometric system: calibration from 2MASS,” Mon. Not. R. Astron. Soc. 394(2), 675–692 (2009).
14. J. Wang, H. Liang, H. Fan, Y. Zhou, P. Krebs, J. Su, Y. Deng, and J. Zhou, “High-quality autostereoscopic display with spatial and sequential hybrid control,” Appl. Opt. 52(35), 8549–8553 (2013).
15. L. Condat, “Color filter array design using random patterns with blue noise chromatic spectra,” Image Vis. Comput. 28(8), 1196–1202 (2010).
16. Y. Zhou, P. Krebs, H. Fan, H. Liang, J. Su, J. Wang, and J. Zhou, “Quantitative measurement and control of optical moiré pattern in an autostereoscopic liquid crystal display system,” Appl. Opt. 54(6), 1521–1527 (2015).
17. H. Liang, S. An, J. Wang, Y. Zhou, H. Fan, P. Krebs, and J. Zhou, “Optimizing time-multiplexing auto-stereoscopic displays with a genetic algorithm,” J. Disp. Technol. 10(8), 695–699 (2014).
1. Introduction

Moiré fringe is produced when repetitive even non-periodic structures (such as grids, screens or gratings) are superposed or viewed against each other [1]. Present day display technology is getting increasingly sophisticated as functional optical layers are commonly employed on the top of an active or passive display unit. For example, in order to achieve glass-free, or autostereoscopic display, a periodical lenticular lens structure is employed on top of an LCD display unit to divert different pixel images to the different eyes of an observer [2, 3]. As the periodic pixel unit and the lenticular structure has similar dimension, the period of the moiré pattern would be in several millimeter to centimeter scale. As a result, the moiré pattern becomes very pronounced so that the viewing experience is substantially spoiled [4, 5]. There are now a number of techniques to reduce the undesirable moiré pattern, and the most common technique is using the optical layer that is slanted to the original display unit [6–9]. However, the slanting angle is around 10 degrees or more [10, 11], and the display effect can be substantially degraded with the slanted optical layer. Furthermore, new display technologies, such as integrated optics [12], field camera [13], etc., adopt additional optical layers to realize new display functionality. Hence control of the moiré pattern is scientifically curious and technologically important.

Our previous work showed that the moiré pattern is caused by the superimposition of several non-optimized gratings [14]. Color filter array with random structure, on the other hand, was used to reducing demosaicking noise in optical system [15]. For a display unit, the control of the visibility of the moiré pattern is vital to high-quality display. In this work, we propose a novel RGB pixel arrangement for color filter (CF) array for the elimination of the moiré pattern. Ideally, the basic unit of a CF should be random. In reality in display the appearing probability of each RGB color should be equal in each pixel. This arrangement is in analog to the so called pseudo-random arrangement. The simulation and experimental results described below show that the moiré pattern can be highly reduced by pseudo-random optimal CF array.

2. Optimization method

Fig. 1. (a) The structure of LCD panel consists of a trio-color filter; (b) The scheme of 1-fold binary grating that represent red color in (a); (c) equivalent binary grating corresponding to one color shown in (b) is shown as a transmittance function (c).

Each pixel of LCD panels can be consisting of three colors (Red, Green and Blue, RGB), as shown in Fig. 1(a). Here a stripe-type RGB color filter array is considered. According to [16], monochromatic contribution to moiré pattern is analyzed first, and trio-color generated moiré pattern is obtained by combining their contributions to form the polychrome one. The color
filter can then be simulated as 1-fold binary grating (denoted as Grating 1) for each color of R, G, B, as shown in Fig. 1(b). When processing such simulation, only the position of one color is assumed transmitting and the positions of other colors are assumed opaque for the input light field. The opening ratio of the equivalent binary grating of color filter is \( \tau_1 / T_1 = 1 / 3 \). The normalized transmittance function of Grating 1 \( t_1(x) \) is shown in Fig. 1(c), with it normalized to the input light intensity. For an ordinary RGB color filter, the transmittance function of each color labeled as \( t_{1,p}(x) \) (\( p = 1, 2, 3 \)) can be expressed as following:

\[
t_{1,1}(x) = \begin{cases} 
1 & nT_i \leq x < nT_i + \frac{1}{3}T_i \\
0 & nT_i + \frac{1}{3}T_i \leq x < (n+1)T_i 
\end{cases} \quad (1)
\]

\[
t_{1,2}(x) = \begin{cases} 
1 & nT_i + \frac{1}{3}T_i \leq x < nT_i + \frac{2}{3}T_i \\
0 & nT_i + \frac{2}{3}T_i \leq x < (n+1)T_i 
\end{cases} \quad (2)
\]

\[
t_{1,3}(x) = \begin{cases} 
0 & nT_i \leq x < nT_i + \frac{2}{3}T_i \\
1 & nT_i + \frac{2}{3}T_i \leq x < (n+1)T_i 
\end{cases} \quad (3)
\]

Where the subscript “\( p \)” represents the sub pixel position in one pixel unit, and \( n \) refers to the order number of pixel.

For the sake of simplicity, we assume another binary grating with opening ratio \( \tau_2 / T_2 \) superposing with the color filter array. Its period is \( T_2 \) and its transmittance function can be expressed by \( t_2(x) \):

\[
t_2(x) = \begin{cases} 
1 & nT_2 \leq x < nT_2 + \tau_2 \\
0 & nT_2 + \tau_2 \leq x < (n+1)T_2 
\end{cases} \quad (4)
\]

When the two gratings are superimposed, the transmittance of the resulting image \( t(x) \) is given by the product of \( t_1(x) \) and \( t_2(x) \):

\[
t(x) = t_1(x) \cdot t_2(x) \quad (5)
\]

Essentially, the intensity of colorful moiré pattern changes periodically. It is obvious that the \( t(x) \) describes binary grating, i.e., only two values of 0 and 1 for transmitting values from the Eq. (1)-(5). The visibility of moiré pattern depends on the angular or lateral resolving ability of an observer. To interpolate the contrast variation, an average intensity \( s_i \) of moiré pattern is introduced as:

\[
s_i(x) = \frac{1}{\eta T_i} \int_{x-\eta T_i/2}^{x+\eta T_i/2} t(x') dx' \quad (6)
\]

Where \( i \) represents the different color (\( i = R, G, \) and \( B \)), and \( \eta \) (1, 2, 3…) describes the number of periods of grating 1 that are considered to calculate \( s_i \), and \( s_i \) is the average intensity of each color (R, G, and B) with the length of \( \eta T_i \).

The contrast of the color moiré \( m_i \) is given by:
To eliminate the moiré pattern, the arrangement of the sub pixel column should be optimized to get the smallest \( m_i \). Assumed that it contains the same color in one sub pixel column. Generally, for each pixel column of the color filter, there are six kinds of arrangements: RGB, RBG, GRB, GBR, BRG and BGR. The position of the sub pixel column in pixel \( n \) is labeled as R \((n)\), G \((n)\) and B \((n)\). As shown in Fig. 2, in pixel \( n \), when the R sub pixel column is at the position 1, then labeled R \((n)\) = 1. If the R sub pixel is at the position 2, R \((n)\) = 2, etc. For example, the sub pixel arrangement RGB results in R \((n)\) = 1, G \((n)\) = 2 and B \((n)\) = 3, while a BRG one is labeled in R \((n)\) = 2, G \((n)\) = 3 and B \((n)\) = 1. With this notation, intensity and the contrast of each color moiré can be calculated by Eq. (1)-(7).

Equation \((p)\) \((p = 1, 2, 3)\) describe the transmittance function of each color in ordinary RGB arrangement situation. If we rearrange the sequence of RGB in one pixel column, the transmittance function of different color will exchange according to the position notation above. When color \( i \) is at position \( p \) in pixel \( n \), the transmittance function of color \( i \) is calculated by equation \((p)\) among Eq. (1)-(3). For example, the red color is at position 2 of the 50th pixel column, and then the transmittance function of the red color here is calculated by Eq. (2).

In the simulation, enumeration algorithm [17] is introduced to find the smallest \( m_i \) among all the sub pixel column arrangements.

First of all, the whole possible arrangements of sub pixel column are enumerated. For each arrangement, the product of \( t_1(x) \) and \( t_2(x) \) is calculated by Eq. (1)-(5) where \( t_1(x) \) is determined by its position notation mentioned above. After the calculation of \( t(x) \), the \( s_i(x) \) is computed with Eq. (6) by substituting different value of \( \eta \). Then the contrast of moiré is obtained by Eq. (7). Finally, we search in the whole \( m_i \) value to find the smallest value corresponding to the optimized sub pixel column arrangement.

3. Simulation result

In the simulation in line with a newly developed back-directional autostereoscopic display system with a LCD and a linear Fresnel lens array [18], the pitch of the color filter \( T_1 \) is selected as 0.26 mm, and the pitch of the binary grating \( T_2 \) is 0.5 mm. The opening ratio of binary grating \( \tau_2/T_2 \) is approximate to 0.8 [16]. The display visibility, according to [19], is determined by the lateral resolution of the observer. For widely used retina display technology, the pixel size should be smaller than the retina resolution so that several pixels are grouped to be visualized by the observer. In our case, a value of \( \eta = 4 \) is adopted for the simulation, although any other value between 2 to 5 is producing similar result.

To demonstrate the validity of the optimization method, 100 pixels of color filter is taken into calculation, and the program is operated with Matlab. Parts of the optimum position (first 20 sub pixel columns) are shown in Table 1.
Table 1. Optimum randomized sub pixel position (first 20 pixels are shown here)

| R | 1 | 2 | 1 | 1 | 1 | 2 | 1 | 1 | 3 | 3 | 1 | 3 | 1 | 1 | 3 | 2 | 1 | 3 | 1 | 1 | 3 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| G | 2 | 1 | 2 | 2 | 1 | 2 | 3 | 1 | 1 | 2 | 3 | 2 | 1 | 3 | 3 | 1 | 3 | 2 | 2 | 1 | 2 |
| B | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 3 | 3 | 2 | 1 | 1 | 2 | 2 | 1 | 2 | 1 | 2 | 2 |

According to Table 1 the optimum arrangement of pixels can be simulated. The intensity of moiré pattern of each RGB color can be calculated by using Eq. (6) and shown in Fig. 3.

Fig. 3. Optimum arrangement of sub pixel (here first 20 pixels is schemed).

For spatial domain, the average intensity \( s \) distribution for each color in the generated moiré pattern is shown in Figs. 4(a), 4(c) and 4(e). The average intensity of a conventional pixel arrangement can be approximated as a cosine mode. With the optimum re-arrangement, the average intensity of each color moiré results in pseudo-random distribution. In one period, the optimum RGB arrangement disrupts the continuous vibration of the original one and makes one peak of the original one spreading out as several peaks and valleys. Besides, the vibration amplitude of the moiré pattern of the optimum arrangement is much smaller than the original one. As shown in Figs. 4(a), 4(c) and 4(e), the peak to peak value of the fluctuation for red sub pixels and green sub pixels decline from the original 50% to 20%, and the blue sub pixels decline below 25%.

The Fourier transform of the optimal structure for each color are also calculated. Because of the visual acuity of human eyes, only the low spatial frequency (below 35 cycles / mm) part of moiré pattern is sensitive to the eyes [20]. As shown in Figs. 4(b), 4(d) and 4(f), each frequency component in the ordinary RGB arrangement spectrum is decomposed into many smaller components, which spread over the region around the location of the original ones. It is easily seen that the spatial frequency components of the optimum arrangement is smaller and many more than the ordinary ones. It is well known that if there is a well-defined phase relationship between the frequency components of several functions, when the frequency components are summed (inverse Fourier transform), a clear pattern will be resulted. However, the optimization process has the effect of randomizing the phase values of these components; therefore a pattern with very low contrast is resulted in the space domain. Benefited from the quasi-period and the contrast \( m \) decline, the moiré pattern is hardly detected by human eyes. In other words, the optimum sub pixel arrangement can prominently eliminate the moiré pattern effect.
Fig. 4. Average intensity $s_i$ of the ordinary RGB arranged color filter and the optimum arranged one. The dot line represents the ordinary one, and the solid line shows the optimum one. (a) the average intensity of red sub pixel; (b) the Fourier transform of red moiré; (c) $s_i$ of green sub pixel; (d) Fourier spectrum of green one; (e) $s_i$ of blue sub pixel; (f) Fourier spectrum of blue one.

In the simulation, the binary grating is superposed with the ordinary RGB arrangement CF and the optimum arrangement CF displaying a white image. The red, green and blue color moirés can be simulated independently according to the data shown in Figs. 4(a), 4(c) and 4(e). Then the three color components are composed together to form the final visual effect of superposing of the binary grating and the CF. The results of the superposition of binary grating and the ordinary RGB arrangement CF are shown in Fig. 5(a). Because of the periodicity of the RGB color moirés, the composing image results in colorful moiré pattern. While the results of the superposition of the same binary grating and the optimum arrangement CF is shown in Fig. 5(b). After the intensity of each color moiré broken by the re-arrangement, the image of each color moiré is no longer vibrating as cosine mode. And the composing image results in a white one, which means the colorful moiré pattern is eliminated by the optimum arrangement.
4. Experiment

For ease of verify, the experiment data of the superposing binary grating and the simulation sub pixel arrangement is scaled up 10 times. In other words, the pitch of pixel is chosen as $T_1' = 10T_1 = 2.6 \text{ mm}$, and the pitch of the binary grating is $T_2' = 10T_2 = 5 \text{ mm}$. The pixels are displayed at the LCD, and the binary grating is printed on a transparent plastic film of 0.1 mm thickness by the printer “HP LaserJet M2727nf” with 600 dpi. The gratings are shown in Fig. 6.

First of all, binary grating is superposed with the ordinary RGB arrangement one, the visual effect is shown in Fig. 7. As shown in Fig. 7, the ordinary RGB arrangement results in obvious moiré effect, and the period of the moiré pattern is about 7 mm.
The visual effect of the superposition of binary grating and the optimum sub pixel arrangement is shown in Fig. 8. For the purpose of comparison, the right part of the figure is the original image without superposition. As shown in Fig. 8, the moiré pattern has been reduced, and the left part of the image is almost the same with the right part. This means that the experiment results match the simulation well. In recent experiment the CF array was fabricated by printing to prove the simulation result, the scale of pixel was about 10 times larger than the real CF array size. In future the CF array with real size can be fabricated by photolithography, which can be applied in the real LCD unit.

Fig. 8. The visual effect of the superposition of binary grating and the optimum RGB arrangement. Left part covers superposition (corresponding to the left part from the yellow dash line in Fig. 6(c)), and the right part is the original image without superposition.
5. Conclusion

In this work, the arrangement of RGB sub pixel position is optimized to eliminate the moiré pattern. The optimum structure is analogous to the concept of pseudo-random arrangement. The numerical simulation shows that after optimum arrangement, the contrast of each color moiré declines beyond 50%; and the Fourier spectrum shows that the frequency components of moiré are spread out around the original ones. Furthermore, the phase of moiré pattern is randomized resulting in weakened moiré effect evidently. Finally, a pilot experiment was launched by using color printing, and results were well match with the simulation result. We believe that this method and results could be the design guideline of display system containing several periodic optical components to eliminate moiré effect.

Acknowledgment

This work is supported by the National Basic Research Program of China (2012CB921904) and by the Chinese National Natural Science Foundation (11534017, 61505265), Pilot Project of SYSU-CMU Shunde International Joint Research Institute (20150101), and Guangdong Provincial Scientific Research Starting Foundation for Doctors (2015A030310388).