High-efficiency spatial color separation method based on fractional Talbot effect

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Based on fractional Talbot effect, Talbot grating is adopted to realize spatial color separation with high light efficiency. For red and green colors, a two-step Talbot grating is optimized and the light efficiency reaches over 95%. The two-step Talbot grating is fabricated and tested. Experimental results show that the Talbot grating indeed has the good ability of spatial color separation.

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Color liquid crystal display (LCD) is widely used in many multimedia products. Wavelength-selective filters are generally used to realize color display. Each color pixel is composed of three sub-pixels which are filtered to pass red (R), green (G), and blue (B) light, respectively. Obviously at least 2/3 of the light is absorbed by color filters, which results in low light efficiency of color LCD.

Color sequential method[1−3], which realizes color separation of R, G, and B light in time domain, can increase the light efficiency without the use of color filters. This method has the advantages of high resolution and less use of drive integrated circuit (IC). However, high-speed liquid crystal mode is necessary in this method because one image is constructed with sequential change of three primary color sub-images, otherwise color breakup occurs[4].

To avoid the strict requirement of liquid crystal, color separation can also be realized in spatial domain and then the light efficiency will be increased under the hardware condition of LCD nowadays with the use of color filters. Color separation grating (CSG)[5] based on far-field diffraction has been proposed to increase the light efficiency of LCD[6], but the period of the designed CSG is rather smaller than the size of sub-pixel, which leads to fabrication difficulty and decrease of light efficiency.

To increase the period and light efficiency, and considering the practical thickness of LCD, Talbot grating which realizes beam-splitting in near field based on fractional Talbot effect[7−9] has been proposed to realize spatial color separation[10,11]. When the RGB wavelengths are chosen as $\lambda_{\rm b}$=0.45 μm, $\lambda_{\rm g}$=0.54 μm, and $\lambda_{\rm r}$=0.63 μm, respectively, one three-step Talbot grating and one four-step Talbot grating can be optimized to realize spatial color separation with 85% and 89% light efficiencies, respectively. However, it is rather difficult to fabricate the optimized three-step and four-step Talbot gratings because the deepest step height is larger than 3.75 μm[11].

Therefore, a two-step Talbot grating having small step height is designed and fabricated to realize color separation of red and green light. To simplify the experimental measurement, the wavelength of red and green light are chosen as 0.6328 and 0.532 μm, respectively. The substrate of the Talbot grating is K9 glass, the refractive index is n=1.51630, and the dispersion is ignored.

If phases of two-step Talbot grating are φ_1 and φ_2 respectively, the period of the grating is d, then the transmittance function of the Talbot grating is

$$t(x_0) = \left[\mathrm{rect}\left(\frac{x_0+d/4}{d/2}\right)\exp(\mathrm{i}\varphi_1) + \mathrm{rect}\left(\frac{x_0-d/4}{d/2}\right)\exp(\mathrm{i}\varphi_2)\right] * \frac{1}{d}\mathrm{comb}\left(\frac{x_0}{d}\right), \quad (1)$$

where $*$, rect, and comb take place of convolution, rectangular function, and comb function, respectively.

Equation (1) can be rewritten as Fourier series:

$$t(x_0) = \sum_{l=-\infty}^{+\infty} c_l \exp(\mathrm{i}2\pi x_0 l/d), \quad (2)$$

where $c_l = \frac{1}{2}[\exp(\mathrm{i}\phi_1)\exp(\mathrm{i}\pi l/2) + \exp(\mathrm{i}\phi_2)\exp(-\mathrm{i}\pi l/2)] \cdot \mathrm{sinc}(\frac{l}{2})$, and $\mathrm{sinc}\,(x) = \dfrac{\sin(\pi x)}{\pi x}$.

When an ideal plane wave is incident, based on the angular spectrum theory, the field on the output plane at a distance z behind the grating is

$$u(x,z) = \sum_{l=-\infty}^{+\infty} c_l \exp(-\mathrm{i}2\pi l^2 z/Z_{\rm t})\exp(\mathrm{i}2\pi x l/d), \quad (3)$$

where $Z_{\rm t}=2d^2/\lambda$ is the Talbot self-imaging distance.

When φ_1=0 and $\varphi_2=3\pi/2$, the beam-splitting of 2:0 could be realized at the position of $z=NZ_{\rm t}/2-Z_{\rm t}/4$, herein the light intensity in one period can be written as

$$I(x,z) = 2\mathrm{rect}\left(\frac{x-(-1)^N d\big/4}{d/2}\right), \quad (4)$$

where N is an integer.

The position of the color separation plane is chosen as $(3+1/4)Z_{\rm tr}$, which is very close to $(2+3/4)Z_{\rm tg}$, here $Z_{\rm tr}$ and $Z_{\rm tg}$ represent the Talbot self-imaging distances with

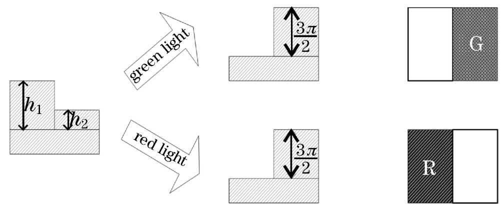

Fig. 1. Structure of the Talbot grating in one period and the color separation of red and green light.

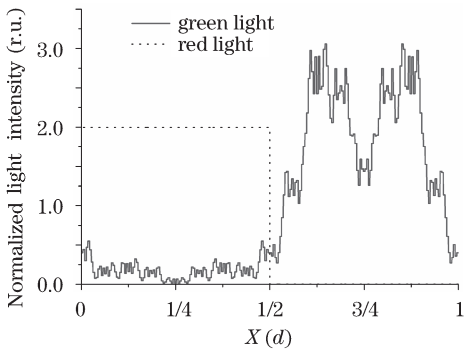

Fig. 2. Result of the color separation in one period using Talbot grating for red and green light.

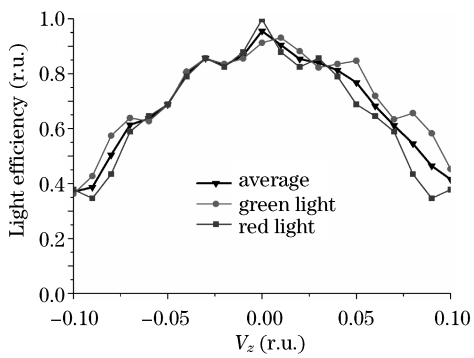

Fig. 3. Relationship between the light efficiency and the movement of the color separation plane.

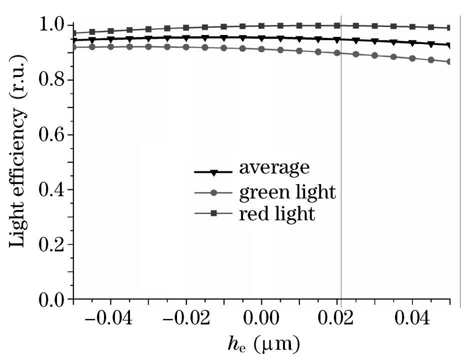

Fig. 4. Change of light efficiency with the change of step height.

incident red and green light, respectively. The structure of the two-step Talbot grating is shown in Fig. 1 after phase modulo 2π.

After optimization, h_1=0.29 μm when h_2 is supposed to be 0 μm. The final distributions of the color separation are shown in Fig. 2. All of red light is located in the corresponding desired zone and a little part of green light leaks out to the red zone, so the color filters should be placed at the color separation plane, and then the color purity of sub-pixels and the reproductive color range are maintained. The light efficiency reaches over 95%, and here the light efficiency is defined as

$$\eta = \left(I_{\mathrm{r},[0,d/2]}/I_{\mathrm{r},[0,d]} + I_{\mathrm{g},[d/2,d]}/I_{\mathrm{g},[0,d]}\right)/2, \qquad (5)$$

where $I_{\mathrm{r},[0,d/2]}$ and $I_{\mathrm{r},[0,d]}$ are the red light intensities within the intervals $[0,d/2]$ and $[0,d]$, respectively, and $I_{\mathrm{g},[d/2,d]}$, $I_{\mathrm{g},[0,d]}$ are the green light intensities within the intervals $[d/2, d]$ and $[0,d]$, respectively, on the output plane.

The color separation effect of the Talbot grating as a function of the relative displacement along the Z axis (optical axis) is analyzed, as shown in Fig. 3. Here the horizontal axis represents the relative movement of the color separation plane, i.e., $V_z = \frac{Z_{\mathrm{des}}-z}{Z_{\mathrm{des}}}$, and z, Z_{des} represent the distances of the practical and designed color separation plane, respectively. As shown in Fig. 3, the light efficiency is larger than 70% when V_z is within the interval $[-0.05, 0.06]$.

The light efficiency under the influence of the steps error is also analyzed. As shown in Fig. 4, h_{e} represents the error of the step height (h_1-h_2). The light efficiency remains above 90% for the step height changing over a range of $\pm$50 nm.

The period of the grating is chosen as d=50 μm and then the position z of the color separation plane is 25.68 mm. After fabrication, the local profile of the two-step Talbot grating, measured by a profilometer (Ambios XP-1), is shown in Fig. 5, where the step height is 0.24 μm and the period of the grating is 54.4 μm. The schematic of experimental setup is shown in Fig. 6. The combination of red and green beams were expanded by an objective lens and filtered by a pinhole, then the light collimated by a collimating lens was normally incident to the two-step Talbot grating and the optical field behind the grating was recorded by a charge-coupled device (CCD).

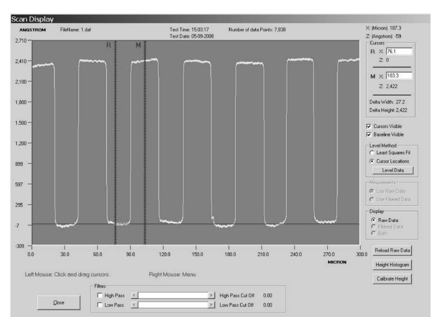

Fig. 5. Step height and period of the two-step Talbot grating.

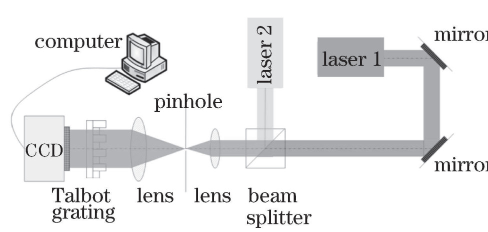

Fig. 6. Schematic of experimental setup.

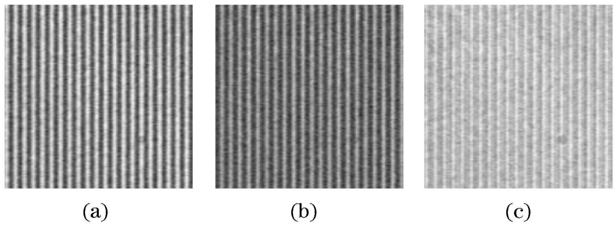

Fig. 7. Experimental results of the two-step Talbot grating. (a) Only red light incident to the grating, (b) only green light incident to the grating, (c) red and green light simultaneously incident to the grating.

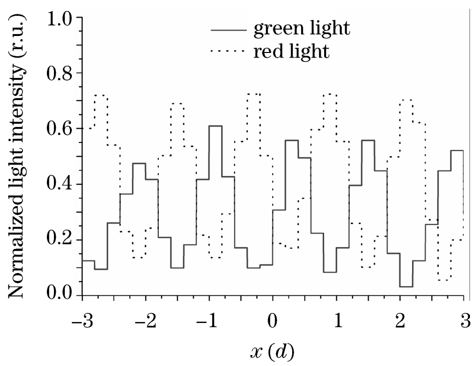

Fig. 8. Color separation performance of the two-step Talbot grating (one-dimensional distribution).

When the two-step Talbot grating is illuminated by red or green light alone, one part of the gray image is recorded by the CCD, as shown in Figs. 7(a) and (b), respectively. When the two-step Talbot grating is illuminated by red and green light together, the same part of the gray image recorded by CCD is shown in Fig. 7(c).

The one-dimensional intensity distributions of Figs. 7(a) and (b) are shown together in Fig. 8. With the bad experiment conditions, which include the step height error of 17%, the color separation plane not being at the ideal position, and the existence of the background noise, the subsequent analysis indicates that the light efficiencies of red and green light are 75% and 76% with the two-step Talbot grating, respectively. Thus the average light efficiency is larger than 75%, while the light efficiency is only 50% with color filters.

In conclusion, based on the fractional Talbot effect, Talbot grating can be used to realize spatial color separation with high light efficiency. Limited by the fabricating technique, a two-step Talbot grating with a small step height for spatial color separation of red and green light is fabricated and tested. Experimental results show the validity of the Talbot grating used for spatial color separation with high light efficiency. Moreover, the Talbot grating for color separation has large tolerance to the position error of the color separation plane and the height error of the steps. Compared with the CSG adopted in Ref. [6], Talbot grating has the advantages of larger period and higher light efficiency and is a better way to realize spatial color separation in LCD.

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