Design and Analysis of Color Separation Grating by Using Fresnel Diffraction Theory

Chien-Hung Chen* and Hoang-Yan Lin
Graduate Institute of Electro-Optical Engineering and Department of Electrical Engineering, National Taiwan University, Taipei 10617, Taiwan, Republic of China
Phone:(886)2-23635251-351, E-mail: r93941071@ntu.edu.tw

Abstract
We use the color separation grating (CSG) to split colored light into the sub-pixel of LCD to enhance the optical efficiency as compared with that of using color filter. Based on the Fresenl diffraction theory, the theoretical optical efficiency can reach 66-81%, ranging almost from 2 to 2.5 times of that using color filters.

1. Introduction
In LCD, the color filters pass the light of corresponding spectrum and absorb the other two bands so that they decrease the optical efficiency to 33% in LCD.

In order to increase the efficiency, one can separate the RGB lights spatially and direct them into the corresponding sub pixels. One way introduced by Dammann [1] is to use a new diffraction device that can separate and direct different wavelengths of light into different diffraction orders and hence into corresponding sub-pixels. The Dammann grating was designed to have a common phase profile such that mod 2π phase for each wavelength diffract it to the designed order. This new structure realizes a device that can separate green, blue and red lights into 0, +1 and -1 orders, respectively. Under far field approximation, the diffraction efficiency can be calculated from the Fraunhofer diffraction theory for each wavelength. The efficiency of the +1 and -1 order is about 75% in this paper [1],[2].

Layet [3] use the Dammann grating in LCD to replace the color filter to increase the optical efficiency. For example as shown in Figure 1, the green CSG under the green sub-pixel pass green light and diffract the red and blue lights into the red and blue sub pixel, respectively. Since lights are not absorbed but diffracted to the corresponding sub-pixels, they can be used very efficiently. From the grating equation, Layet [3] showed that the period of CSG can be decided from the pixel size of LCD and distance between CSG and pixel.

However, both of the above papers [1],[3] showed the light efficiency but not the light distribution. In this paper, we use the scalar theory to simulate the light distribution as well as analyze the efficiency when the CSG is used in LCD panel.

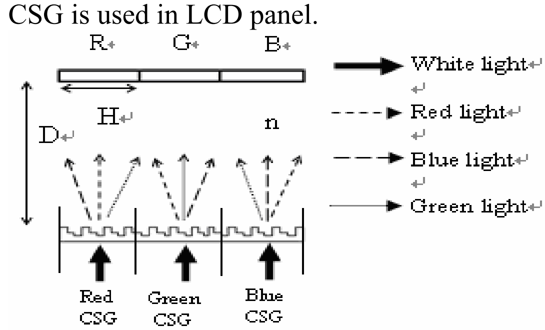

Figure 1. The configuration of using CSG's in the LCD system for light enhancement.

2. Results
As we know that if it is observed at the far field, the relation between the diffraction efficiency and wavelengths can be got by Fourier transform based on Frauhofer diffraction theory. The power efficiency obeys the following equation [1].

$$a_q(\lambda) = \left| \sum_{k=0}^{k=N} \int_{\xi_k}^{\xi_{k+1}} \exp[-i\varphi_k(\lambda)] \exp[2\pi i q \xi] d\xi \right|^2 \quad (1)$$

First of all, we change the number of steps, the width, and the height of the multiple-step structure to see their influences on the efficiency as shown in Figure 2. In Figure 2a. the number of the steps increases, the efficiency is higher and the FWHM (full-width of half-maximum) of the spectrum is narrower. Moreover, it is noted that the peaks of the +1 and -1 order are closer to the 0 order. In Figure 2b. the height of the step is increased, the FWHM is getting narrower, but the efficiency is not changed. Usually, the widths of the steps are the same, but if we make the widths unequal, the efficiency is decreased and the peak of the +1, -1 order will be shifted a little as in Figure 2c. Therefore, by controlling these three parameters, we can find a diffraction spectrum with optimized efficiencies at three RGB wavelengths. The simulation results based on Fraunhofer diffraction theory for an ideally infinite long grating are shown in Figure 3. Ideally the peak diffraction efficiency of the Green CSG, which is designed to have green spectrum at the 0 order, can reach 91%. Similarly, the peak diffraction efficiencies of the Red CSG and Blue CSG are both 81%.

a.
b.
c.
d.

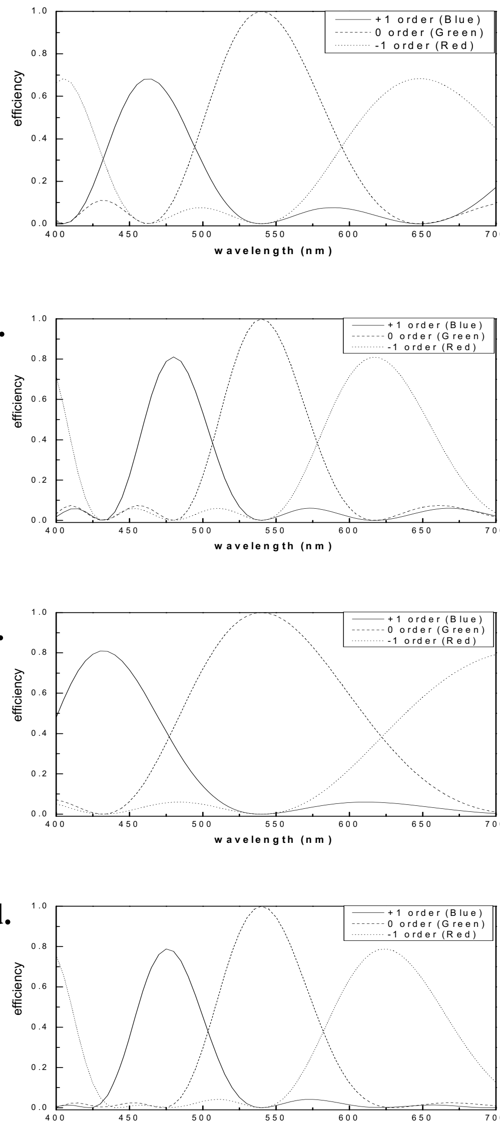

Figure 2. Wavelengthes vs. Efficiency. Number of steps N, height of steps V for a. N=2, V=2; b. N=3, V=2; c. N=3, V=1; d. N=3, V=2, and width is unequal.

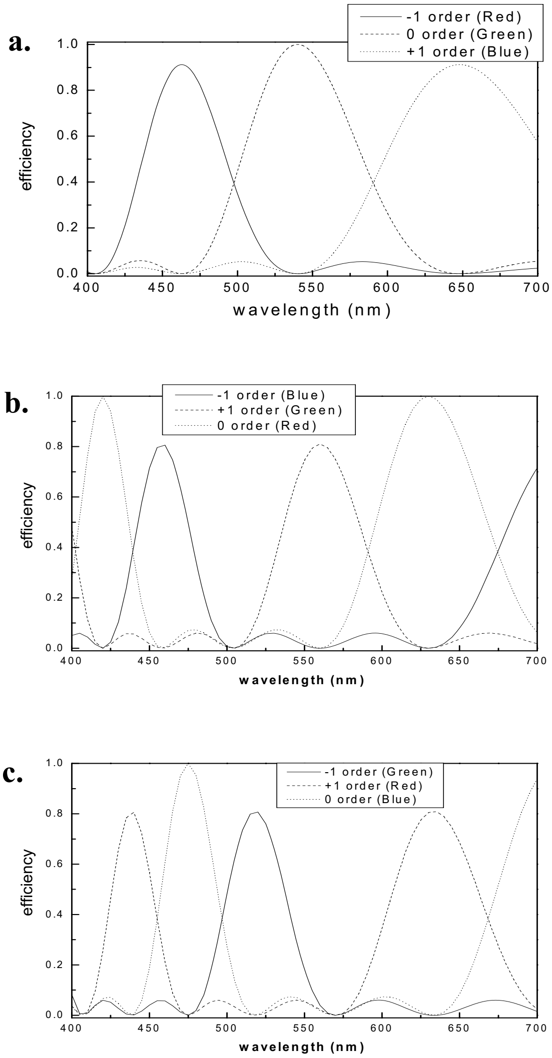

Figure 3. Light efficiency spectrum based on the Fraunhofer diffraction theory for a. Green CSG; b. Red CSG; c. Blue CSG.

After deciding the parameters above, we have to find the period of the grating. For example, we assume that H=80 μm, D=1 mm and n=1.46, which are the sub-pixel width, glass thickness and the refractive index of the glass as shown in Figure 1. Assume the composed wavelengths of the incident light are three discrete ones: λ_b = 460 nm, λ_g = 540 nm, λ_r = 650 nm. For the Green CSG, the diffracted angles of blue and red lights should satisfy the geometrical relationship $\theta_g = \tan^{-1}(H/D)$. From the grating equation, $n \sin\theta_m = m\lambda / p$ where n, λ, p, m, θ_m are the refractive index, wavelength, period, diffraction order and diffraction angle, the blue or red lights can be designed to be diffracted to the $m = \pm 1$ orders. Let $\theta_m = \theta_g$, the periods for blue and red lights can be calculated as 3.95 μm and 5.58 μm and Layet [3] chose the average 4.76 μm as the implemented period. The performance will undoubtedly be affected by this decision and be deviated from those in Figure 3. We show the periods of the Red and Blue CSG for various D value in Table 1.

Unit: μm	Red CSG	Green CSG	Blue CSG
1mm	4.29	4.76	5.11
2mm	8.56	9.51	10.19
3mm	12.84	14.26	15.28
4mm	17.12	19.01	20.38

Table 1. The periods of the RGB gratings while the distance D is 1, 2, 3, and 4mm as shown in Figure 1.

Next, we want to discuss the distribution of the RGB light when the light passing through a practical device. The distance between CSG's and sub-pixels is not sufficiently large as compared with the sub-pixel size. It is more appropriate to use the Fresnel diffraction theory as the following formulation.

$$v(x_0, y_0) \sim e^{j\frac{k}{2z}(x_0^2+y_0^2)} F\{v'(x_1, y_1) e^{j\frac{k}{2z}(x_1^2+y_1^2)}\} \qquad (2)$$

Where $v(x_0, y_0)$ is the field on the screen , and $v'(x_1, y_1)$ is the phase of the CSG.

By using the same parameters above, the simulated results are shown in Figure 4. For Green CSG, it is found that the blue and especially the red light are not passed through the corresponding sub-pixels completely. Moreover, the other two CSG have such a problem, too. It will affect the efficiency since there is a finite open aperture rate ranging from 30% to 70% for practical LCD panels. The TFT and black matrix will block parts of the diffracted light and hence reduce the efficiency. This will also cause cross-talks between different sub-pixels, however cross-talks can be eliminated by using color filters.

Both the transmission efficiencies and cross-talks can be improved by using microlenses to focus the colored lights into the sub-pixels. When the lenses are added after the grating, the focusing of the microlenses will introduce an additional quadratic phase term in the Frensel diffraction integral (2).

$$v(x_0, y_0) \sim e^{j\frac{k}{2z}(x_0^2+y_0^2)} F\{v(x_1, y_1) e^{j\frac{k}{2}(\frac{1}{z}-\frac{1}{f})(x_1^2+y_1^2)}\} \qquad (3)$$

Where f is the focal length of the microlens

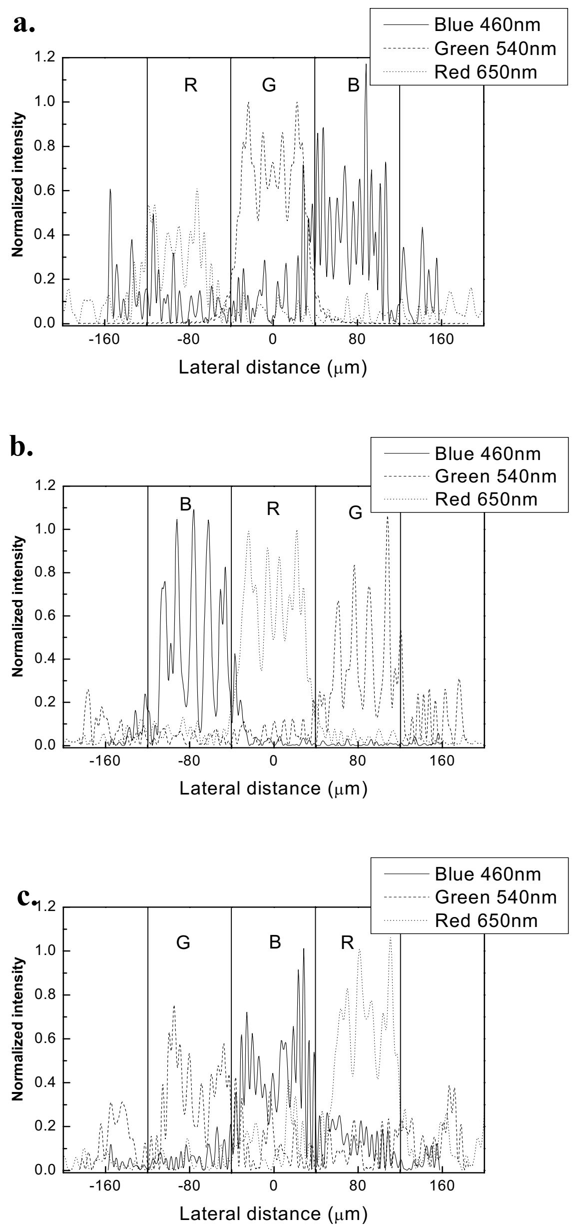

Figure 4. Relative diffraction pattern based on the Fresnel diffraction theory for a. Green CSG; b. Red CSG; c. Blue CSG.

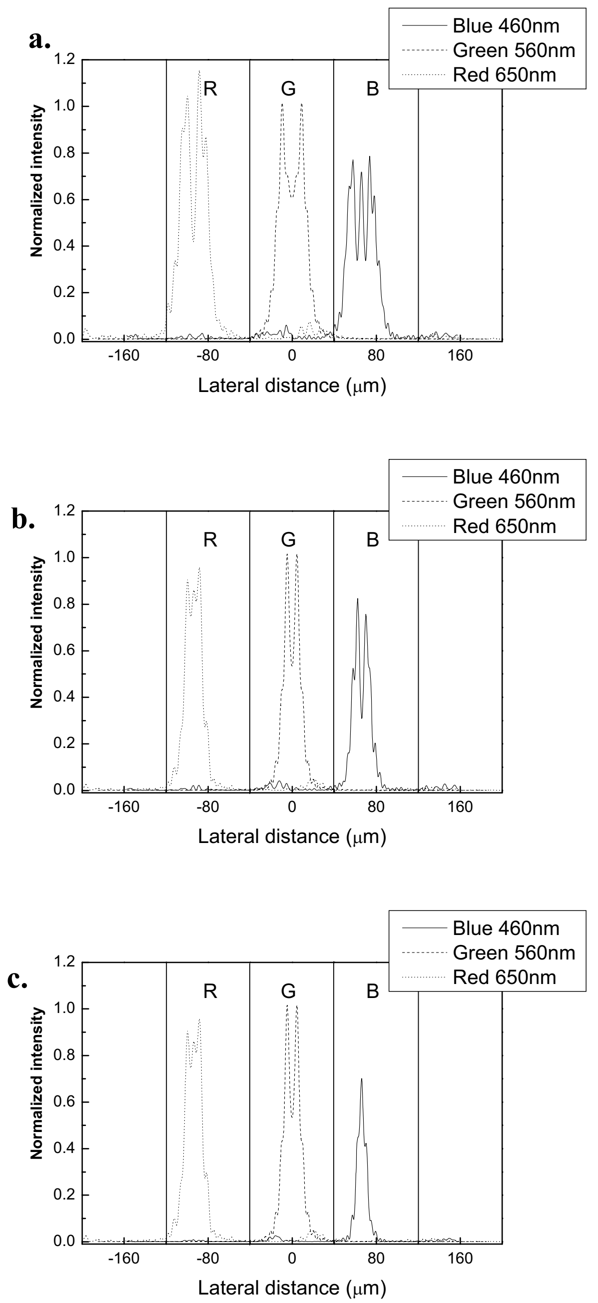

Figure 5. Relative diffraction pattern based on the Fresnel diffraction theory when microlens is used for a. f=2mm; b. f=1.5mm; c. f=1.25mm.

Take Green CSG for example, as the focal length is decreased, the spot size is decreased and the crosstalk can be eliminated as shown in Figure 5. Especially, when the focal length is decreased to be the exact distance between the grating and the sub-pixels, the equation (3) will be reduced to (4), the performance will turns out to be the same as that predicted from the Fraunhofer theory, and the results are shown in Figure 6.

$$v(x_0, y_0) \sim e^{j\frac{k}{2f}(x_0^2+y_0^2)} F\{v(x_1, y_1)\} \qquad (4)$$

Therefore, we can get the minimum spot of the color-separated light, if the focal length of the lens is equal to the thickness of the glass.

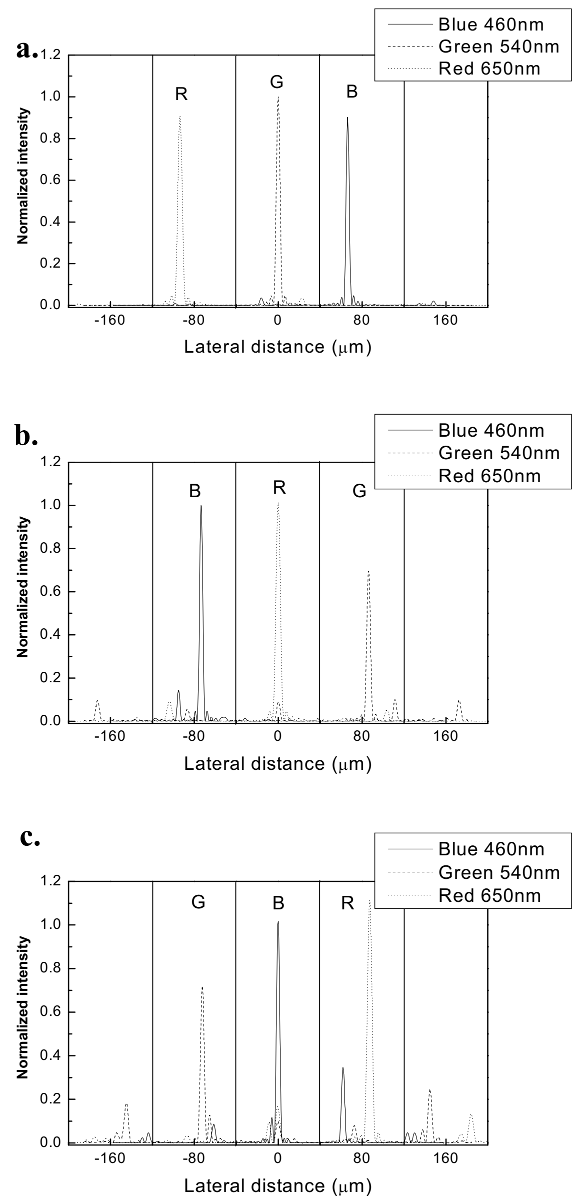

Figure 6. Light distribution by adding a microlens of which focal length is 1mm for a. Green CSG; b. Red CSG; c. Blue CSG.

Finally, we simulate for the Red, Green, and Blue CSG's as shown in Figure 1 and then sum up the transmission light from each sub-pixel. Assume that equal intensity of RGB lights entering the CSG. The Green beam passes through the Green CSG completely, so we take it as the reference for normalization. As shown in Table 2, we can conclude that the transmission efficiencies for R, G, B sub-pixels are 81%, 66%, and 78%, which are ranging almost from 2 to 2.5 times of those for using color filters.

wavelength	650nm	540nm	460nm
RCSG	0.83	0.57	0.81
GCSG	0.91	1	0.912
BCSG	0.69	0.42	0.61
AVG.	0.81	0.663	0.7773

Table 2. The respective and average efficiencies of the CSGs.

3. Conclusion

To realize CSGs for practical LCDs, we have built an accurate model of the CSG's based on the Fresnel diffraction theory. It can be used to estimate the diffraction efficiency by calculating from the field distribution. Fresnel diffraction pattern shows efficiency reduction and cross-talk between sub-pixels. Both of the drawbacks can be improved by using microlenses. We have simulated and analyzed the effect of CSG's used in a practical LCD. The theoretical optical efficiency can reach 66-81%, ranging almost from 2 to 2.5 times of those for using color filters.

4. References

[1] H. Dammann,, Applied Optics, **Vol. 17**, p. 2237 (1978).

[2] Rich Hicks, Wes Haistead, and Thomas Gunn Sanders, Proc. of SPIE, **Vol. 3057**, p. 200 (1997).

[3] Ben Layet, Iain G. Cormack, and Mohammad R. Taghizadeh,, Applied Optics, **Vol. 38**, p. 7193 (1999).