High efficient Transflective TFT-LCD by tRGB-rW Sub-Pixel Rendering

***L. Lin*, B. J. Liang**
The Graduate Institute of Electrical and Communications Engineering & Department of Electrical Engineering, Feng Chia University, Seatwen, Taichung, Taiwan 40724, R.O.C.

C. M. Huang, H. C. Lin and Y. N. Chen
Wintek Corporation, No. 10, Chien-Kuo Road, TEPZ Tantzu, Taichung, 427, Taiwan, R.O.C.

Tel: 886-4-25318899 Ext.7736 ; E-mail: lin-lin@wintek.com.tw

Abstract
The total light efficiencies of the novel 1.9" transflective tRGB-t/rW and tRGB-rW TFT LCDs are calculated and they are implemented by the traditional 7-mask a-Si processing. Then, the two vehicles are turned on with the appropriate Sub-Pixel Rendering White (SPRW) algorithms, so they can exhibit the extra luminance without the original visual resolution loss. Their outstanding optical properties are approved by measuring the contrast ratio (C.R.) and the NTSC ratio. Because they utilize the light resource very effectively and efficiently, they are very suitable for the dark indoor and the bright outdoor environments.

1. Introduction
As 3G communications are becoming ubiquitous, the seamless perusing environments including very dark midnight or very bright noontide are strongly demanded. Among diverse advanced displays, the transmissive LCDs exhibit the excellent performance especially in the gloomy circumstance. Their innate optical properties like high contrast ratio and vivid color saturation are satisfactory for this kind of situations due to applying the back light. Simple structures and no patent issues are their additional advantages. However, while the bright sunlight is exposing on the surface of transmissive LCDs, the glare light rays wash out the penetrating luminance from the back light. The heavy power consumption originated from back light is the other serious issue. The substitutive solutions are expected to solve these problems by the reflective LCDs. When the environment is brighter, the legibility is better. The reflective LCDs do not need the backlight anymore, so the power consumptions are reduced very significantly. On the contrary, their color saturation and C.R. are inferior to transmissive LCDs. Because they fail the visibility under the dark ambient light sources and they lead to the request for the front light modules. However, the particle pollution of front light modules is hard to control in the mass production line, so that the yield rate is deprived finally. The expensive front light guide is the other issue as well.

The transflective (T/R or t/r) LCDs are the trade-off solutions for both respects due to the low power consumption, the reasonable visibility and the easy manufacture and so on. Therefore, the T/R LCDs are very popular in the current marketing. The remarkable T/R displays are nothing more than single cell gap structures and dual gap structures. About the single cell gap structures, the conventional T/R types are adopted with the reflectors attached to the rear side of transmissive single cell gap structures. On account of the different phase retardations existing in the T mode and the R mode, they are difficult to optimize the electro-optical (EO) features for both modes at the same time. Lee's "Hybrid-Aligned"[1] tried to overcome the discrepant EO properties. But its alignment processing is unlike the traditional processing, when in the mass-production stage. It would be complicated to control the uniformity of multi-alignments in the single pixel. The other creation of Lee is the "Periodically Patterned Electrode" [2]. Lee applied the induced voltage on the patterned floating reflector which is anticipated to generate the different phase retardations for the T mode and the R mode separately. Although the method is a simple way to achieve the EO discrepancy, the band gap between the two modes would cause the optical leakage. Taiwan ITRI published the "single-cell double gamma method" [3]. Its aperture ratio does not be scarified, if the extra TFT is placed beneath the reflectors. Whereas the scheme is required two data lines to control the different modes of TFTs, the application is limited to LTPS panel. On the side, dual cell gap structures are the other options to carry out the trnasflective function. S. J. Roosendaal's "patterned retardation film" [4], Narutaki's "High efficient transflective TFT" [5] and Fujimori's "High Transmissive Advanced TFT LCD" [6] belong to the dual-cell gap designs. These structures are the easiest ways to maintain the same total phase retardation in the T mode and the R mode. Roosendaal required extra inner thin retardation coating processes. The inner retardation was approved to have an excellent performance in the paper [4], but the reproduction of the past mass-production equipments is hard to finish. Narutaki and Fujimori resolved the misalignment in the taper between T region and R region. They also decreased the different color saturation between the T mode and the R mode. Even though it was easy to realize the prototypes to become commercial products, the reflectance was low in the paper [6]. In order to further enhance the reflectance and maintain the reasonable transmittance of T/R LCDs, two novel structures tRGB-r/tW and tRGB-rW panels are developed. They use with the effective white pixels [7] to enhance the light utilities and revise the previous SPR algorithm [8] to maintain the original visual resolution without loss. Consequently, they are approved not only to have an amazing reflectance, but also to provide the simple processing without any penalty.

2. TFT Array Designs

The sub-pixel dimensions of the two novel tRGB-t/rW and tRGB-rW panels are built as the same 57*228 um^2, which can be divided into the suitable aperture ratio for T region and R region. The white sub-pixel unit is constructed by connecting all the reflective region of every RGB sub-pixels to the t/rW sub-pixel (transflective type of white sub-pixel) or to the rW sub-pixel (reflective type of white sub-pixel). And then, the white sub-pixel unit is controlled by the original signal of the t/rW sub-pixel or the rW sub-pixel. They are shown as Fig. 1 and Fig. 2.

And then, the light efficiency [9] of the two novel T/R panels is compared to the other traditional t/rRGB panel and t/rRGBW panel, the two novel T/R panels are calculated to have the optimal light efficiency. They are shown as Table 1. Based on the results, they are implemented by the 7-mask a-Si processes. They are shown as Fig 3.

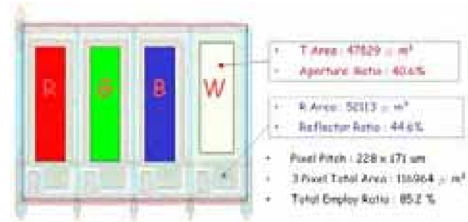

Fig. 1: Mechanism & A.R. of tRGB-t/rW LCD

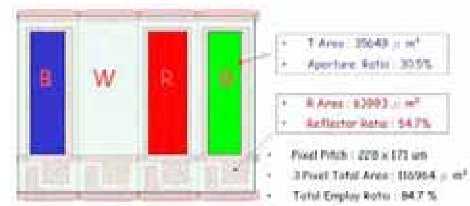

Fig. 2: Mechanism & A.R. of tRGB-rW LCD

1.9" TFT LCM Vision Resolution = 176 * 220 dots

	t/r RGB		t/r RGBW				tRGB-rW(W- digging)			tRGB-rW(W- w/o digging)	
	T mode	R mode	T mode		R mode		T mode		R mode	T mode	R mode
	tRGB	rRGB	tW	tRGB	rW	rRGB	tW	tRGB	rW	tRGB	rW
Polarizer * 2	38%	38%	38%	38%	38%	38%	38%	38%	38%	38%	38%
Aperture Ratio	40.80%	47.70%	10.20%	30.60%	11.94%	35.81%	10.16%	30.48%	44.55%	30.50%	54.70%
Liquid Crystal	96%	96%	96%	96%	96%	96%	96%	96%	96%	96%	96%
Color Filter (d_R=0.5 * d_T)	37%	37%	100%	37%	100%	37%	100%	37%	100%	37%	100%
Reflector	None	93%	None	None	93%	93%	None	None	93%	None	93%
DEBEF	130%	None	130%	130%	None	None	130%	130%	None	130%	None
Light Efficiency	7.16%	5.99%	4.84%	5.37%	4.05%	4.50%	4.82%	5.35%	15.11%	5.35%	18.56%
Total Light Efficiency	13.15%		18.75%				25.28%			23.91%	

Table 1: Light Utilization ratio Comparison under different types of transflective TFT-LCD

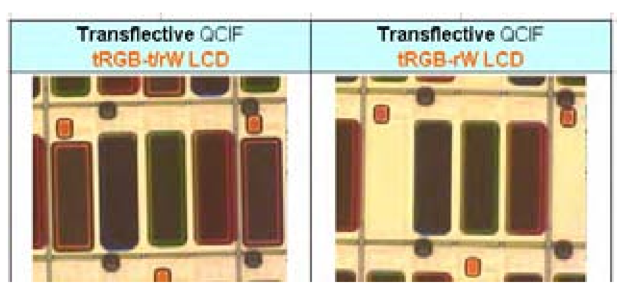

Fig. 3: Photos of tRGB-t/r(r)W LCDs

3. Electro-Optical Designs

The dual cell gap and the parallel alignment are applied to these two novel panels. For the purpose of no color dispersion effect, effective wide band of λ/4 retardation film is attached to front side and rear side. According to Yoon's papers [10] [11], the effective wide band of λ/4 retardation film can be composed of λ/4 retardation film and λ/2 retardation film, hence the two panels utilize the combinative λ/4 retardation film. Their assemblies of optical films are shown as Fig. 4.

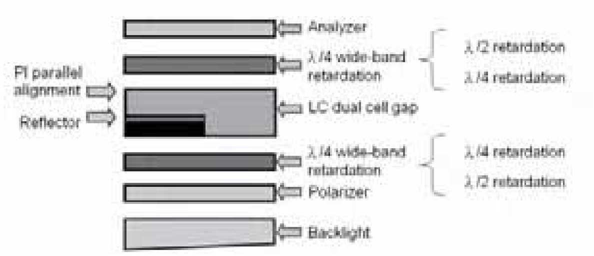

Fig. 4: Optical structures of tRGB-t/r(r)W panels

Because the t/rW sub-pixel and the rW sub-pixel are fully covered by the reflective region of one pixel (one pixel consists of four sub-pixels), the C_{LC} of white sub-pixel might be different from original C_{LC} of t/rRGB panel or t/rRGBW panel. From the table 2, the C_{LC} of white sub-pixel is larger than the C_{LC} of every red, green or blue sub-pixel. So the C_{total} of white sub-pixel becomes to larger. Based on this fact, it is worth to evaluate the charge ability depended on the same charged period. When the cell is filled with 4V liquid crystal, the pixels of tR, tG and tB are able to be charged to 3.9999V, the pixel of t/rW is able to be charged to 3.9997V and the pixel of rW is able to be charged to 3.9989V. Therefore, the charge capability is approved to have no any sacrifice whether the C_{total} is increased by these special designs, or not.

Elements	tR, tG, tB	t/rW	rW
C_{ST} [Farad]	2.27×10^{-13}	2.27×10^{-13}	2.27×10^{-13}
C_{LC} [Farad]	6.06×10^{-14}	2.51×10^{-13}	3.38×10^{-13}
C_{ST}/C_{LC} Ratio	3.749	0.908	0.672
V_p (Simulation)	3.9999 V	3.9997 V	3.9989 V

Table 2: Charged capabilities evaluation

4. tRGB-rW SPR algorithms

In order to enhance the light efficiency, it is the good way to employ the white pixel. Not only the transmittance is improved, but also the reflectance is raised. Nevertheless, the original t/rRGB coordination data arrangements (as Fig. 5) are required to modify and to be tRGB-rW coordination data arrangements (as Fig. 6). Some sub-pixel of R, G or B sub-pixels is indeed to substitute to W pixel. The modification may induce the distortions to the original t/rRGB data information. So the unique tRGB-rW SPR algorithms are very important to keep the original visual resolution without loss.

Equations (1) ~ (6) are expressed the energy sharing method. The algorithms are tried to share the energy of the truncate sub-pixel to the same color of neighboring four sub-pixels. This method is able to maintain the maximum information and to enhance the luminance by the white sub-pixel. After the analysis, the algorithms can save the 75% information content with only 25% information content loss for every sub-pixel. However, the 25% information content loss can be transferred to 50% luminance increasing. It means that subtract the 25% RGB sub-pixel luminance deprivation from the 75% white sub-pixel luminance profit and the luminance gain has 50% increasing.

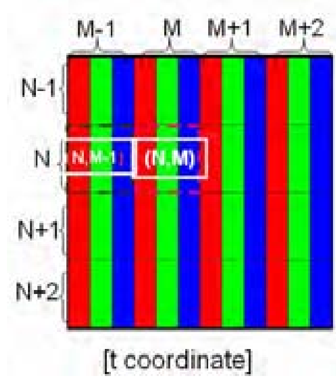

Fig. 5: t/rRGB coordination data arrangements

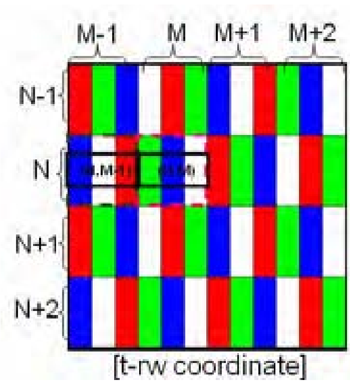

Fig. 6: tRGB-rW coordination data arrangements

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(a.) For the "white balance effect", there are different directional spread sharing factors (k_S) are necessary to set as below:

$$kp = kq = kr = k_{SR} + k_{SL} + k_{SU} + k_{SD} \ldots\ldots(1)$$

(b.) For the 100% maximum brightness condition:

Assumed

$$100\% = kp + k_{SL} = kr + k_{SR} = kq + k_{SU} + k_{SD} \ldots(2)$$

So let

$$k_{SL} = k_{SR} = x \ldots\ldots(3)$$

$$kp = kq = kr = y \ldots\ldots(4)$$

, then

$$(1) \,\&\, (3) \rightarrow y = 2x + k_{SU} + k_{SD} \ldots\ldots(5)$$

$$(2) \,\&\, (4) \rightarrow x = k_{SU} + k_{SD} \ldots\ldots(6)$$

$$(2), (5) \,\&\, (6) \rightarrow 100\% = y + x = 4x$$

$$x = 25\%, y = 75\%$$

(c.)The balanced energy distribution in horizontal direction:

$k_{SL} = 25\%$, $k_{SR} = 25\%$

(d.)The balanced energy distribution in vertical direction:

$k_{SU} = 12.5\%$, $k_{SD} = 12.5\%$

The kp, kq and kr stand for the preserved original energy percentage. The k_S parameter is the definition of the sharing coefficient. The k_{SU}, k_{SD}, k_{SL} and k_{SR} stand for the upper, lower, left and right spread sharing energy percentage, respectively. The x and y are the transitional coefficients.

5. Results

Full cover W sub-pixel promotes the light efficiency very effectively. The calculating light utilization ratios of tRGB-t/rW panel and tRGB-rW panel are 25.28% and 23.91%, respectively, which are greater than that of 13.15% of traditional t/rRGB panel and that of 18.76% of traditional t/rRGBW panel. Furthermore, because there have no gap regions existing between the sub-pixel and the sub-pixel, their valid aperture ratios are able to upgrade to 85.2% for tRGB-t/rW and 84.7% for tRGB-rW, respectively. Hence, the outstanding physical EO properties can be achieved. The transmittance and the NTSC ratio (based on 1931CIE) are measured about 8.72% and 44.22% for tRGB-t/rW, and about 7.04% and 40.81% for tRGB-rW, respectively. On the other hand, their reflectances can be raised to the novel results about 8.09% for tRGB-t/rW and about 10.86% for tRGB-rW, respectively. The reflective C.R. of the tRGB-t/rW panel and tRGB-rW panel are increased to 12.00:1 and 14.54:1, respectively. These remarkable results (as Table 3) did not use with any beam steering bumps.

The panels are also tested whether if they are capable of exhibiting color saturations when the two novel structures are exposed under 65,000cd/m^2 simulated ambient light source and the backlight is illuminated by 5,000cd/m^2 simultaneously. The other conditions are that the testing point angle of instrument PR650 is avoided to measure the area where the glare rays are strongly. And the distance from the instrument PR650 to the integrating spheres is set to 60cm. Eventually, the reflective C.R. of tRGB-t/rW panel and tRGB-rW panel related to the standard white are measured about 13.35:1 and 18.45, respectively. They are greater than the reflective C.R. of Narutaki's traditional t/rRGB type panel [5] which is 10:1 under 65,000cd/m^2 ambient light shining. The NTSC ratio (based on 1931CIE) and the reflective C.R. of tRGB-t/rW panel and tRGB-rW panel related to the standard white are measured about 5.47% and 6.41%, respectively.

Due to the non-stripe color filter arrangements, the SPR algorithms are necessary to keep a low loss MTF. For the novel tRGB-rW SPR algorithms, the various directional spread sharing factors (k_S) are applied. Under these combinations of k_{SR}=25%, k_{SL}=25%, k_{SU}=12.5% and k_{SD}=12.5%, which can retain the optimal white balance, optimal brightness and also preserving the maximum signal to noise ratio because of the truncated sub-pixel.

Reflective Mode : (BL OFF)	tRGB-t/rW 1.9" TFT-LCD 176 x 220 pixels (with DBEF) BL : White LED [illegible]	tRGB-rW 1.9" TFT-LCD 176 x 220 pixels (with DBEF) BL : White LED [illegible]
Contrast Ratio	12.00	14.54
Diffused Reflectance		
Driven White	8.09%	10.86%
Driven Black	[illegible]	[illegible]
Transmissive Mode : (BL ON)		
Contrast Ratio	127	99
Mean Luminance	419 cd/m^2	330 cd/m^2
Diffused Transmittance		
Driven White	8.72%	7.04%
Driven Black	0.07%	0.07%
NTSC Color Reproduction Ratio		
1931 CIE x,y coordinate	44.22%	40.81%

Table 3: Optical measurement Data

6. Conclusions

The super high reflectance and the reasonable transmittance are implemented by the novel 1.9" transflective tRGB-t/rW and tRGB-rW TFT LCDs. The physical photos are shown on the Fig. 7. However, the two samples have little misalignments between CF and array. Whether if the reason makes the reflective NTSC ratios coming out or there really exist the colorful light penetrated from the panels, which are required to be examined. The reflective image can only display the black and white gray color. "What kinds of applications can access the B/W gray color in the R mode?" is an interesting investigation later. For the "*fine* text letters" applications, they are asked to decrease the *color fringe error* [12] in the T mode. Some various assemblies of the directional spread sharing factors can enhance the texture performances, so that the adaptive "k_S" parameters are the next important researches. The "sharpen filters" is the advanced scheme which is expected to diminish the blurring texture, too. The same $C_{total}(C_{ST}+C_{LC})$ is demanded to get the same *feed through voltage*($\triangle V_P$) in order to reduce the flicker degree. Hence, the same C_{total} will be designed to improve the glimmer image. Ultimately, the optical performance can be much improved by the different optical film structures, the different LC modes and with the beam steering reflectors. Above issues will be the good reforming courses in the near future.

Fig. 7: tRGB-rW T mode (B/L on) and R mode(B/L Off).

7. Acknowledgements

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8. References

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