Novel Color-Sequential Transflective Liquid Crystal Displays

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***Abstract*—A novel transflective liquid crystal display architecture and its system driving schemes are proposed. In the reflective mode, the ambient light is used to readout the displayed images. While in the transmissive mode, a color-sequential light emitting diode backlight is used to eliminate the color filters. Under such device configuration, several advantages such as increased brightness and maximized color saturation for both transmissive and reflective modes can be achieved.**

***Index Terms*—Color sequential imaging, liquid crystal display (LCD), reflective mode, transflective mode, transmissive mode.**

I. INTRODUCTION

TRANSFLECTIVE liquid crystal display (LCD) has been used widely for portable electronic applications because of its large dynamic range for ambient light. A transflective LCD can display images in transmissive mode and reflective mode, independently or simultaneously. Therefore, such a transflective LCD can be used under any ambient lighting circumstances. Because transflective LCDs can display images under a bright environment by reflective mode using ambient light, it reduces power consumption which is the key issue for mobile and portable applications. Also, transflective LCD provides good readability in low light ambient using its own backlight.

To realize the dual functions of reflective and transmissive displays, each color sub-pixel of a transflective LCD is divided into two regions: transmissive (T) and reflective (R) regions. Only the reflective region has a bumpy metal mirror for reflecting the incident light. The reflector partially implemented on the reflective region in the sub-pixel is called transflector [1] or an opening-on-metal transflector [2]. The transflector provides access to optimize the ratio of image brightness between transmissive and reflective modes by simply adjusting the areas of the reflective and transmissive regions. Therefore, we can develop an application oriented and optimized transflective LCD. However, this advantage could become disadvantage because the light efficiency of each transmissive and reflective mode is reduced.

To realize the bi-functional property of the system several technical challenges have to be overcome without raising manufacturing cost. Among the device performance factors, higher optical efficiency and better color reproduction for both T- and R-modes are most critical. Meanwhile, matching the electro-optical property between the T and R modes is another important issue for transflective LCDs.

The unequal electro-optical response, that is, the discrepancy between the voltage dependent transmittance and reflectance, originates from the phase retardation difference between the T and R modes. If the LC layer thicknesses on the T and R modes are equal, then the optical path length of the R-mode would be two times longer than that of the T-mode. As a result, the transmittance and reflectance of the LCD will be different. To solve this problem, several techniques have been developed. For example, the dual cell gap structure [3] employs different cell gaps for the T and R modes to compensate the phase difference. This is by far the most popular device structure for commercial transflective LCDs. However, fabrication of a dual cell gap structure is complicated. To avoid the fabrication difficulty, single cell gap is preferred. One approach is to use different LC modes (dual LC mode) for the T and R modes [4], [5]. However, realizing the dual LC mode in a device is more difficult than fabricating the dual cell gap. Another approach is to use two TFTs (thin film transistors) for each sub-pixel to independently control the transmissive and reflective modes. In this case, we can match the electro-optical responses of the transmissive and reflective modes very well by adjusting the driving voltages of each TFT. We call this the dual gamma driving method [6]. However, this method needs two times more data drivers than the conventional system and this method increases the system cost.

Unequal color reproduction is another technical issue of the transflective LCD which employs a single thickness color filter on the sub-pixel area. In the R region, the incident light passes through the color filter twice, while it passes only once in the transmissive region. Therefore, if we optimize the pigment density or color filter thickness for T-mode, then the color filter on the reflective region absorbs more light leading to a darker image than the transmissive one. To solve this problem, different thickness of color filters for reflective and transmissive modes has been suggested [7], [8]. This method also increases the fabrication complexity.

There exists an interesting imaging technology which improves the optical efficiency and color purity remarkably for the direct-view type transmissive LCD. The technology is called color sequential imaging method [9]–[11]. Color sequential imaging technology is already being widely used in projection displays especially for the single panel DLP (digital light processing) projection TVs [12], [13]. However, color break-up [14], [15] occurs when the response time of the imager is not fast enough. Color break-up is the tri-chromatic separation of the viewer's perception when our view-point moving speed is

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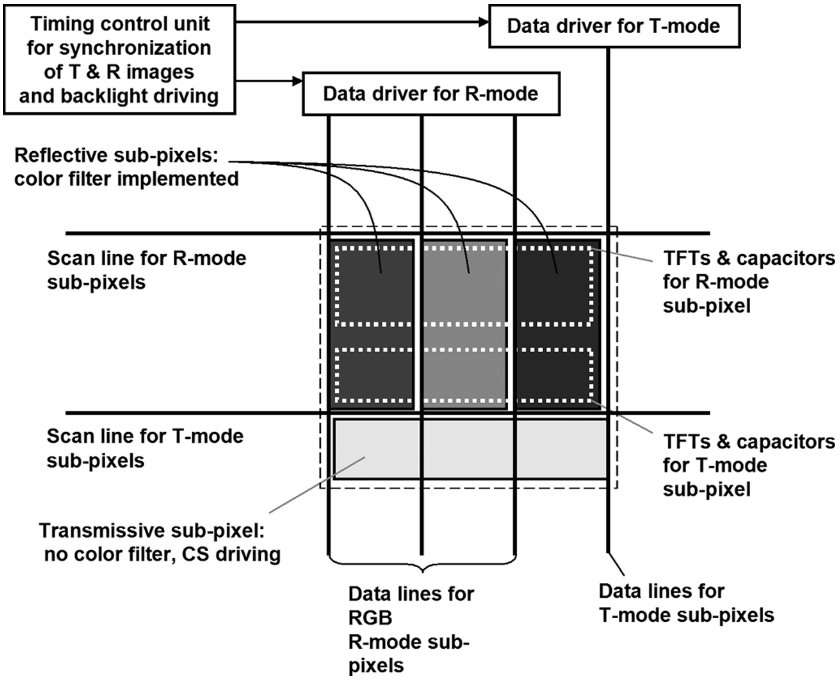

Fig. 1. Schematic of the new transflective LCD.

faster than the color sub-frame switching speed for following the moving object in the large-sized motion pictures. Basically color sequential imaging requires at least three times faster sub-frame refreshing rate than conventional standard video frame frequency to draw three primary color sub-frames sequentially. To solve the color break-up problem, one approach is to use a very fast sub-frame refreshing rate. Nowadays, many commercial DLP projection engines use very high sub-frame frequency rate, higher than 500 Hz, which is almost ten times faster than the standard video frame rate. However, some sensitive observers are still able to detect the color break. Since most of LCDs have a relatively slow response time, this approach is not amiable for large screen LCDs for HDTV applications. Another approach to solve the color break-up problem is to fix our view-point. We will meet this situation when we see a small size image. Therefore, the color sequential imaging is more suitable for small-sized LCDs. Together with the highly saturated color switchable light source, such as an LED (light emitting diode) backlight, the color sequential transmissive LCD has already been demonstrated to have brighter and better color images than other conventional small-sized transmissive LCDs for mobile devices [16].

In this paper, we suggest a new transflective LCD system architecture along with its operating methods using a color sequential imaging technique for small-sized LCDs for mobile/portable applications.

II. Device Design

Fig. 1 shows the schematic of our device configuration. Here, the dashed box represents one pixel unit. A unique feature of our new LCD, in comparison with the conventional transflective LCDs, is its pixel structure. Each pixel has four instead of three sub-pixels in other LCDs. Three of the sub-pixels with bumpy metal reflectors are for reflective modes and three different primary color filters for each sub-pixel, respectively. One sub-pixel is for transmissive mode without a color filter. Therefore, the color sequential imaging method is required to produce color images in the transmissive mode. For the color sequential imaging, our new device needs the color switchable backlight such as an LED backlight which is widely used in small sized LCDs for mobile phones. Each sub-pixel in our new device is driven by a single TFT which is independent from the TFTs of other sub-pixels in a pixel unit. All pixel electronic devices such as TFTs and storage capacitors, including those for transmissive sub-pixels, are located under the metal reflectors in the reflective region as shown in the figure as dotted boxes. Putting electronics under the metal electrodes is the same way as the conventional transflective LCDs to maximize the aperture ratio of the pixel. Reflective sub-pixels on a row are addressed by a scan line connected to a gate driver for the reflective mode, but transmissive sub-pixels are excited by another scan line connected to another gate driver for the transmissive mode. Just as the gate drivers, the data drivers for the transmissive and reflective modes are independent of each other. To synchronize the reflective image with the transmissive one, a timing control electronic circuit is required which also controls the timing of LED backlight's color switching.

III. Discussion

Because of the aforementioned structural characteristics, our new transflective LCD has following advantages:

1) The optical efficiency of both transmissive and reflective images is enhanced greatly. One pixel of the conventional transflective LCD is divided into six regions because each sub-pixel of the three primary color sub-pixels is divided into transmissive and reflective regions. However, in our

TABLE I
IMPACTS OF INCREASED APERTURE SIZE OF THE NEW LCD SYSTEM

Conventional transflective LCDs			New transflective LCD with Rr:Rg:Rb:T=1:1:1:1		Improvements	
R:T	Sub-pixel size (% for a pixel area)				R	T
	R	T	R	T		
6:4	100/3*0.6= 20%	100/3*0.4= 13.3%	25%	25%	25% ↑	88% ↑
5:5	100/3*0.5 16.7%	100/3*0.5= 16.7%			50% ↑	50% ↑

TABLE II
SYSTEM PARAMETER COMBINATION TABLE TO DESIGN THE SYSTEM DRIVING SCHEMES

Case	R-mode pixel electronics	T-mode pixel electronics	Backlight driving type	Dark sub-frame usage	Sub-frame scanning time	Required Response Speed of LC compared to conventional TFT LCDs	# of Data Lines	# of Scan Lines
#1	Single TFT	Single TFT	Color switching	YES (LC)	$1/6\times\tau_o$	6×	4/3×Nd	2×Ns
#2	Single TFT	Single TFT	Impulsive blinking	NO	$< 1/3\times\tau_o$	> 3×	4/3×Nd	2×Ns
#3	Single TFT	Frame buffer architecture	Color switching	NO	$1/3\times\tau_o$	3×	4/3×Nd	3×Ns
#4	Single TFT	Frame buffer architecture	Color switching	YES (LC+BLU)	$1/4\times\tau_o$	4×	4/3×Nd	3×Ns
#5	Frame buffer architecture	Frame buffer architecture	Color switching	NO	$1/3\times\tau_o$	3×	4/3×Nd	4×Ns

(τ_o: one frame scanning time, Ns: # of scan line in conventional TFT LCDs, Nd: # of data line in conventional TFT LCDs)

new device, one pixel is divided by only four sub-pixels because one transmissive sub-pixel shares the area for the three primary colors. Therefore, the aperture size of both transmissive and reflective regions increases, as shown in Table I, which also greatly increases the light efficiency. In addition, because the transmissive sub-pixel does not have a color filter which absorbs light and decreases optical efficiency of the transmissive mode, the light efficiency of the transmissive mode increases more noticeably.

2) We can easily optimize and maximize the color purity of both transmissive and reflective images without using the complicated color filter fabrication method, such as making different color filter thicknesses for the transmissive and reflective regions. We only need to optimize the color filter thickness for the reflective mode.
3) To obtain a single electro-optical response, we only need to control the driving voltages of the transmissive and reflective modes separately by data processing. Unlike the commercially employed dual-cell gap method, the fabrication process of this new approach is similar to that of single cell gap device. Thus, the fabrication yield should be higher and the manufacturing cost should be lower.

Some drawbacks are remaining. One drawback is the requirement of having 33% more data drivers which raises the cost of the final product. However, it is smaller than the case of the double TFT approach for conventional transflective LCDs which needs two times more data drivers. In addition, if we adopt the system-on-glass technology by using the low temperature poly-silicon process, no more cost-up issue remains. Another disadvantage is that our new system requires complex driving electronics. But it might be acceptable to today's well established ASIC design technologies.

For the synchronization of transmissive images with reflective images together with LED backlight color switching, several different driving schemes can be considered. In this paper, we use the system parameter combination table as shown in Table II. As a result, we suggest five different driving schemes which are appropriate to LCD's operation principle, line-at-a-time scanning.

Fig. 2 shows an example of the operation timing diagram of the system. The top graph is the timing diagram for reflective mode and the bottom graph shows the timing diagram for transmissive mode. Along the timing lines, which are shown as slanted lines of reflective mode, reflective sub-pixels are

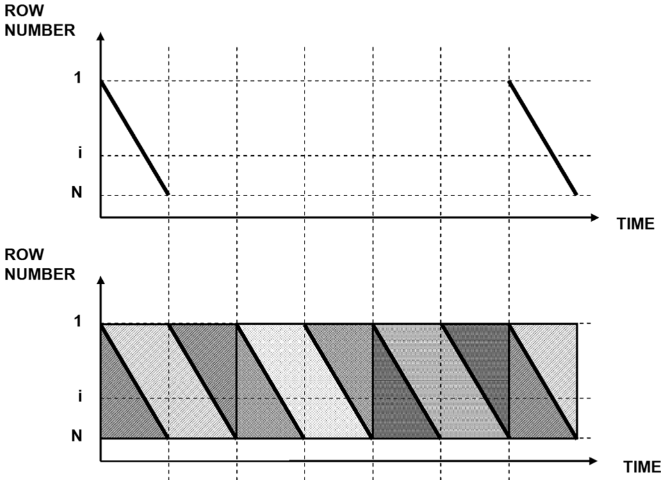

Fig. 2. System driving scheme using dark sub-frames in transmissive mode.

scanned by scan drivers and one frame of reflective image is drawn line by line. During one frame period, the transmissive sub-pixels are scanned six times. The first sub-frame scanning of the transmissive mode is synchronized with frame scanning of the reflective mode. To draw each primary color sub-frame image, the backlight switches its primary color at the time point when the scanning for primary color sub-frames—the first, third, and fifth sub-frames—start. As a result, the backlight is always turned on and only the illumination color is switched. Even numbered sub-frames among six sub-frames of the transmissive mode show black image on the whole LCD area by sending black image data to transmissive sub-pixels during the even numbered sub-frame scanning. This technique is a well known method for color sequential transmissive LCDs [17], [18] and is used to avoid the interference between two sequential color sub-frames. For example, if we do not use the black sub-frame, the latter half period of the last row imaging for a primary color overlaps with the first half period of the first row imaging for the next primary color. This is because the operation principle of an LCD is based on hold-type imaging and line-at-a-time scanning. Introducing the black sub-frame solves this problem easily. However, because of the black sub-frame, we lose half of the total light energy. To avoid this energy loss, a color scrolling light illumination technology can be considered which is used in some of the prototyped projection display systems. However, realizing a color scrolling backlight for direct view LCDs is challenging.

Another method is to use an impulsive type backlight. Fig. 3 shows the relationship between row scanning of the transmissive mode and the backlight flashing timing. This concept is also used in some recent high-end transmissive LCDs for improving motion picture quality. The backlight is activated between the time point when the last row of the transmissive sub-pixels are scanned at a sub-frame scanning and the time point when the first row of the transmissive sub-pixels are scanned at the next sub-frame scanning. This method allows slower scanning speed and LC response time than those of the aforementioned methods. One disadvantage is the requirement of driving the LED with a higher peak power in order to keep the same brightness for the transmissive image. In the previous case, the LC response time should be at least six times faster than conventional color sub-pixel based LCDs. However, in the case of the impulsive backlight based system, shorter backlight activation duration permits a slower LC switching speed.

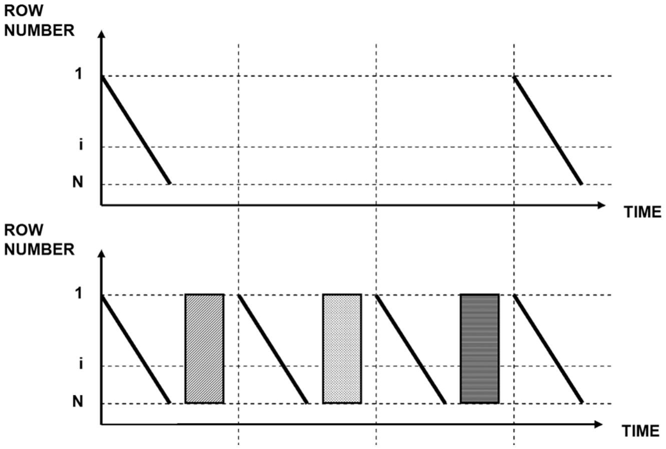

Fig. 3. System driving scheme using impulsive type backlight driving method.

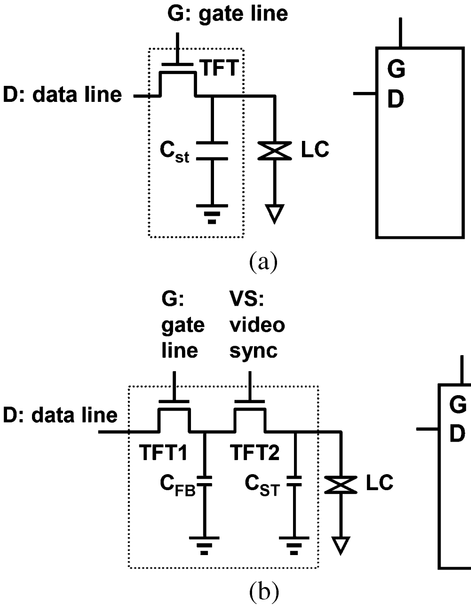

Fig. 4. Pixel electronic circuits: (a) conventional circuit for line-at-a-time scanning imaging method, and (b) frame buffer pixel circuit for frame by frame imaging method.

In the previous two methods, the employed pixel electronics is a single TFT-based electronics for both T and R-mode sub-pixels which is common pixel electronics for most of LCDs using line-at-a-time scanning driving scheme. However, there is another pixel electronics which helps to tolerate a slower LC response and higher power efficiency of backlighting which is called a frame buffer pixel circuit using more than two TFTs per sub-pixel [19].

Fig. 4 shows the difference between a conventional single TFT based pixel electronics and a frame buffer pixel circuit. In Fig. 4(a), one TFT is connected in parallel with a storage capacitor $(\mathrm{C_{ST}})$ and an electrode which applies the voltage to the liquid crystal layer (LC). To draw a line of image on a row of pixels in an LCD panel, the data driver sends the pixel data

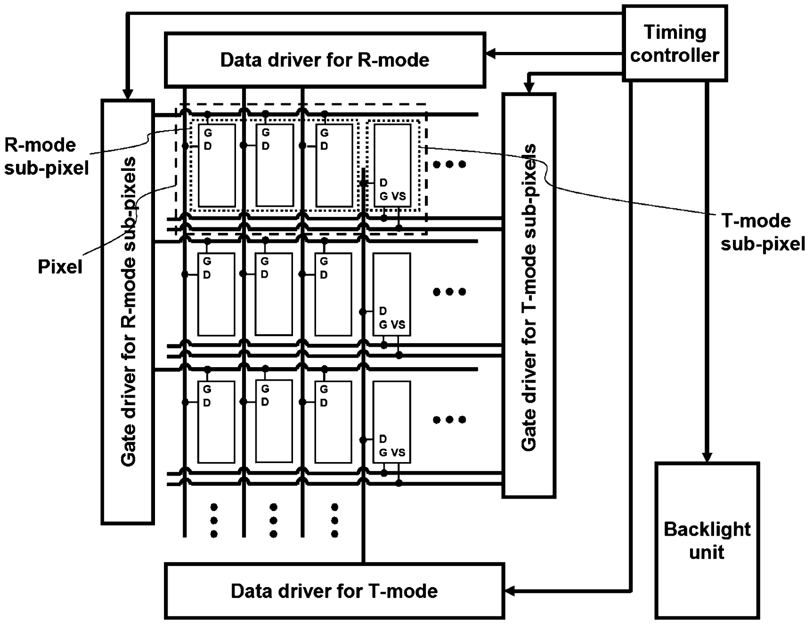

Fig. 5. Schematic of the system which uses the frame buffer pixel circuit only for the transmissive sub-pixels.

through data lines (D) of the sub-pixels on the same row and the gate driver triggers the TFTs by sending a signal through a gate line (G). Then data are transferred to the storage capacitors through TFTs and the stored data in the storage capacitors provide a voltage to the liquid crystal layer during one frame period. In the figure, the dotted box means a pixel electronic circuit and the right side square block is an equivalent circuit for the left side pixel electronic circuit.

Fig. 4(b) shows the basic concept of LCD driving based on frame buffer pixel circuit which has two TFTs in one sub-pixel. Each of these two TFTs has its own function: one function as a memory part to store the image data and the other as an imaging part to control the director orientation of the liquid crystal layer by using the data stored in the memory capacitor ($\mathrm{C_{FB}}$). In the figure, the data line (D) of the first TFT (TFT1) is connected to the data driver. The gate line (G) of the first TFT is connected to the gate driver. The drain of the first TFT is connected to the source of the second TFT (TFT2) which is also connected to the first storage capacitor. When the scan driver scans from the first row to the last row, image data are transferred to the first storage capacitor through the first TFT. The stored data in the first capacitor are not transferred to the liquid crystal layer immediately because the second TFT is not activated yet during the scanning time. Therefore, the combination of the first capacitor and the first TFT functions as a memory buffer. After scanning all rows, that is, after finishing writing one frame image data into the frame buffer, all second TFTs are activated simultaneously by triggering the gate lines VS. Consequently, the stored image data in the first capacitor ($\mathrm{C_{FB}}$) are transferred to the second capacitor ($\mathrm{C_{ST}}$) to control the liquid crystal layer. Because each sub-pixel has two gate input lines G and VS, two gate lines in each sub-pixel should be connected to the gate driver. This frame buffer pixel circuit based device architecture is used in some of liquid-crystal-on-silicon devices to realize single panel based optical engine for system cost-down. Because of several TFTs and storage capacitors in a sub-pixel, the frame buffer architecture reduces the aperture ratio if it is used for the transmissive LCDs. However, if it is used for the reflective LCDs or transflective LCDs, all pixel electronics can be hidden under the opaque metal reflector and no loss of aperture ratio arises.

By adopting the frame buffer architecture, we could design three more driving schemes which will benefit lowering the power consumption and relaxing the requirement of fast LC switching.

Fig. 5 shows the electronics schematic of the system which uses the frame buffer electronic circuit only for the transmissive sub-pixels. Because of the frame buffer concept, one more gate line from transmissive sub-pixels is connected to the gate driver for the transmissive mode and it increases the complexity of gate driver design. However, the effective aperture ratio of the display panel can be kept almost the same as that of the system, which does not use the frame buffer architecture, by adjusting the physical sub-pixel positions to locate all the gate lines and pixel electronics of the transmissive sub-pixel under the opaque metal reflectors of the reflective sub-pixels. In this system, we can design driving schemes with slower liquid crystal mode in comparison with aforementioned driving schemes based only on the line-at-a-time scanning technique in Figs. 2 and 3. In the case of the driving scheme using six sub-frames with dark sub-frame illustrated in Fig. 2, the response speed of liquid crystal should be at least six times faster than conventional LCDs. By using an impulsive type backlight in Fig. 3, we can relieve this strict requirement of liquid crystal switching speed. However, we still need to drive the liquid crystal faster than three times of the conventional LCDs because we have to secure the time for the duration of backlight illumination.

Fig. 6 shows the timing diagram of the device operation based on the frame buffer architecture. During one frame period, transmissive sub-pixels are scanned three times for three primary color sub-frames. The first scanning for the first primary color

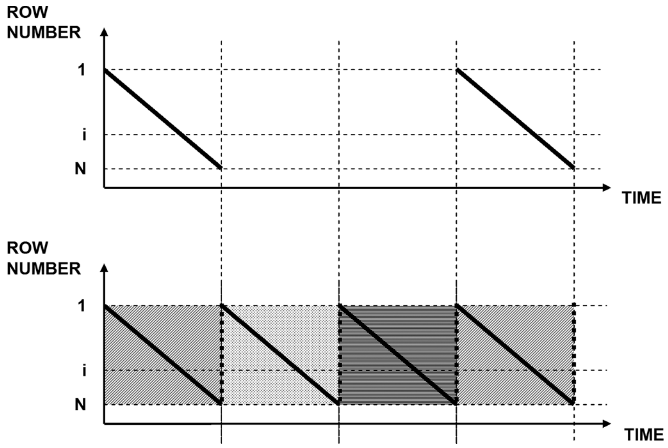

Fig. 6. System driving scheme using the frame buffer architecture only for the transmissive mode.

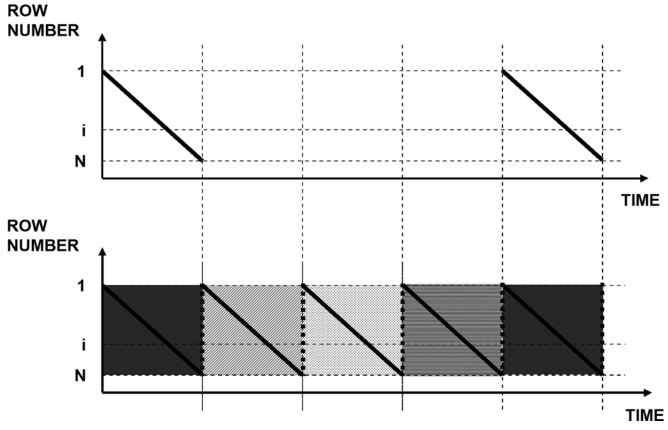

Fig. 7. System driving scheme using the frame buffer architecture only for the transmissive mode with dark sub-frames in the transmissive mode.

sub-frame is synchronized with the scanning of reflective mode for a frame. However, during the first scanning for the transmissive mode, image data are transferred into the frame buffer memory and they do not draw the image for the first primary color. After finishing the first scanning, image data stored in the frame buffer memory are transferred to the second capacitor [C_{ST} in Fig. 4(b)] through the second TFTs [TFT2 in Fig. 4(b)] by triggering the entire second gate lines [G in Fig. 4(b)] of the display panel at a time as shown in Fig. 6 as the leftmost vertical dotted line. As a result, the first primary color image on the whole area of the panel will be drawn at a time. In the same manner, the second and the third primary color images will be drawn. For this operation concept, the backlight only switches its color the same as the case in Fig. 2. However, different from the case in Fig. 2, there is no light loss here. One concern in this method is a mismatch of imaging timing between transmissive and reflective modes because of the different imaging mechanisms: the reflective mode draws the images line by line while the transmissive mode draws the images frame by frame. As a result, the last primary color sub-frame image of the transmissive mode is not matched to the reflective image. The psychological inconvenience of watching images based on this driving scheme should be studied further.

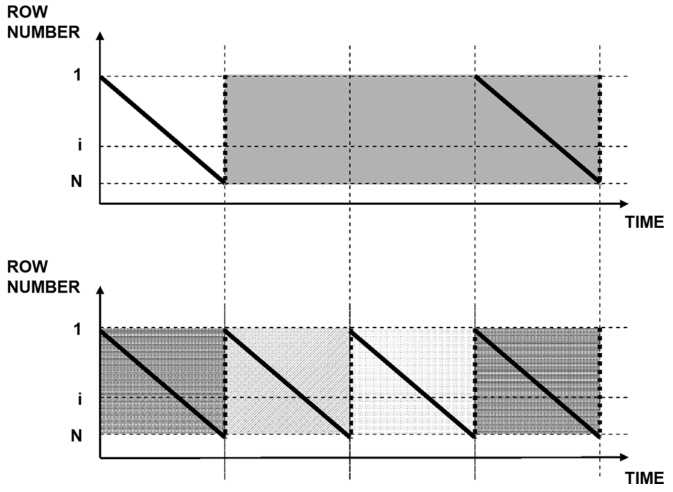

Fig. 8. System driving scheme using the frame buffer architecture for both transmissive and reflective modes.

To solve the mismatch image problem, we suggest a modified driving scheme as shown in Fig. 7. In this case, one frame period is divided by four sub-frames for the transmissive mode, instead of three in the previous method. Among four sub-frames, the last one is a dark sub-frame which can be realized by either turned-off backlight or dark image data signal. Using the dark sub-frame, all primary color sub-frames are well drawn during one frame of a reflective image is being shown. However, this method requires faster liquid crystal response than previous technique. Moreover, we lose about 25% light in comparison with the previous method.

The last method uses the frame buffer architecture for both reflective and transmissive modes. The reflective image is also drawn frame by frame as Fig. 8 shows. The time point of starting the first primary color image of the transmissive mode is synchronized with that of the frame image of the reflective mode. By using this method, the reflective images and the transmissive images are synchronized perfectly without brightness loss. In addition, the required LC response speed is only three times faster than a conventional LC.

IV. CONCLUSION

We have developed a new transflective LCD system using color sequential imaging for the transmissive mode. Considering several design parameters such as: 1) usage of dark sub-frame; 2) device operation mechanisms—line-at-a-time scanning and frame buffer architecture; and 3) the backlight driving method, we have suggested five different system driving schemes. Because our new system has several advantages in comparison with conventional transflective LCDs, we believe our new system will be promising for small-sized mobile display applications and hope that our design will be reduced to practice by LCD manufacturers.

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