Bit Slice Addressing of Fast Switching Bi-Stable Displays and Multi-Bit Slice Addressing of Active Matrix Liquid Crystal Displays

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***Abstract*—Bit slice addressing (BSA) is useful to display grayscales in fast switchable bi-stable displays and active matrix liquid crystal displays (AMLCD). The display is used as a dynamic mask and intensity of light source that illuminates the display is controlled to be proportional to the bit-weight of the bit that was used to refresh the display. A viewing angle characteristic that is independent of grayscales, color purity of images, reduction of motion blur, wide voltage margin to switch the state of pixels, option to reduce power consumption of backlight and low hardware complexity of data drivers are some of the advantages of BSA. Multi-BSA is also proposed to drive the state-of-the-art active-matrix LCDs.**

***Index Terms*—Addressing, bi-stable displays, digital micro mirror device (DMD), light modulators, liquid crystal displays (LCDs), matrix displays.**

I. Introduction

LIQUID CRYSTAL display (LCD) has replaced cathode ray tube (CRT) in many applications; but, CRT has left behind some challenges. None of the flat panel displays (FPDs) have the simple addressing method of CRT; i.e., the x-y deflection and z-modulation for intensity control. Pixels in FPDs are arranged and interconnected to form a 2-D array of pixels and therefore FPDs have as many drivers as the number of rows and columns of the matrix of pixels. An LCD has as many digital to analog converters (DACs) in column drivers as the number of columns in the matrix display to control intensity of pixels; whereas just three DACs are adequate in CRT to control the intensity of red, green and blue pixels. Is it possible to have a simple mechanism which is similar to z-modulation of CRT to control intensity of pixels in flat panel displays? Bit Slice Addressing (BSA) [1] can control the intensity of pixels in non-emissive displays by controlling the intensity of light source that illuminates the display and therefore BSA has the elegance and simplicity of z-modulation in CRT. BSA relies on bi-stable displays as well as light sources that can be switched at 1000 Hz or more and the persistence of vision to control intensity of pixels in non emissive bi-stable displays. A fast responding bi-stable display or a light modulator is used as a dynamic mask to display the bit frames sequentially and intensity of backlight is controlled to be proportional to the bit-weight of the data-bit that was used to refresh the display. BSA replaces the complex DACs (8–10 bits) in data drivers with simple level shifters that are equivalent to 1-bit DACs. BSA can drive ferroelectric LCD, a passive matrix type bi-stable display and blue phase LCD with active matrix backplane. IPS (in-plane switching) or VAN (vertically aligned nematic) mode with response times of a few milliseconds are used in the state of the art active matrix LCDs. A multi-bit slice addressing (MBSA) method is also proposed to drive the main stream AMLCDs with response times of a few milliseconds.

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II. Principle of Bit Slice Addressing

Bit slice addressing (BSA) is based on binary representation of numbers. Intensity of pixels that is represented in binary number system can be interpreted as summation of a finite numbers of intensity values. If I is the intensity of a pixel; then

$$\mathrm{I} = \sum_{i=0}^{g-1} b_i \cdot 2^i. \tag{1}$$

Here, b_i is the bit-weight of the bit-i. For example, 256 intensity values (0–255) can be obtained by adding some of the numbers in the set $128, 64, 32, 16, 8, 4, 2, 1$, that are the bit weight (2^{i}) of the eight bits b_7 to b_0. A non-emissive bi-stable display like ferroelectric LCD or an active matrix LCD is used as a dynamic mask to display one bit of the intensity value of pixels that is represented as a binary number. This bilevel image is referred to as *bit frame* and the pixels are driven either to ON state, if the bit is logic-1 and OFF state, if the bit is logic-0. Bit frames are displayed sequentially by using one bit at a time and the intensity of backlight is controlled to be proportional to the weight of the bit used to refresh the display. Bit frames of all bits are displayed sequentially at a fast rate to avoid flicker and it will be perceived as the original image due to persistence of vision. Intensity of backlight for the bit frame of the most significant bit (MSB) is 128 times the intensity of backlight for the bit frame of the least significant bit (LSB), as shown in Fig. 1. The duty cycle is $(\mathrm{T_{ON}}/(\mathrm{T_{ON}} + \mathrm{T_{OFF}}))$ and the frame frequency of bit frames has to be at least 'g' times the frame frequency of images. Wherein 'g' is the number of bits used to represent the intensity of pixel. $\mathrm{T_{OFF}}$, the time taken to refresh the display is determined by the response times of the display and the speed of data transfer from the controller to the drivers an additional time $\mathrm{T_{ON}}$ is necessary to display the image that was updated with backlight OFF. For example, intensity that is coded with 8 bits will need a display that is capable of displaying images at least at 1600 bit frames; to display images at 100 Hz, if 50% duty cycle is assumed for the intensity modulation of backlight.

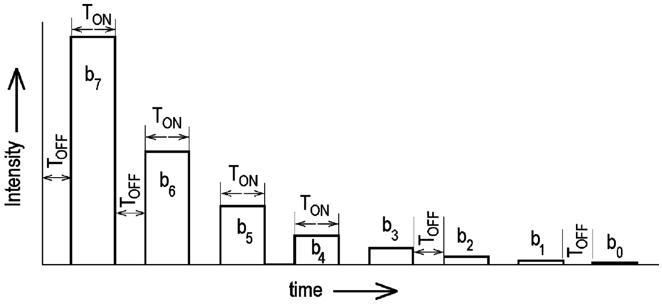

Fig. 1. Intensity modulations of backlight in bit slice addressing. Display is refreshed during $\mathrm{T_{OFF}}$ with bit-b_i of intensity of pixels and the backlight is turned ON during $\mathrm{T_{ON}}$ and the intensity of backlight is set to be proportional to the bit weight (2^i) of the bit.

The maximum bit frame frequency that is necessary to implement bit slice addressing can be reduced if there is a overlap of refresh time $(\mathrm{T_{OFF}})$ and display time $(\mathrm{T_{ON}})$ and this can be achieved by having a few nonoverlapping clusters of pixels and if each of these clusters are illuminated with independent backlights [2] as described in the next section.

III. BSA OF LCD

Let us consider an LCD with response times short enough to display bit frames at 1000 Hz. Pixels in the LCD can be grouped into several large horizontal clusters of pixels. For example, clusters A to D, as shown in Fig. 2, wherein each cluster has pixels from $(N/4)$ non-overlapping rows out of the total N rows of Display. At a given instant of time, backlight to one of the cluster is switched OFF so that the pixels in that cluster are driven to ON or OFF state depending on one of the bit of intensity values of pixels. Backlight is switched ON after scanning the $N/4$,rows in that cluster and the intensity of backlight is controlled to be proportional to the bit weight of the bit that was used to refresh the cluster. For example, if pixels in cluster-A are refreshed at time $\mathrm{T_1}$ using the most significant bit (MSB) of each color (R, G, and B) with its backlight switched OFF; then the backlight intensity is set to the maximum intensity during $\mathrm{T_2}$, $\mathrm{T_3}$, and $\mathrm{T_4}$. Pixels in $N/4$ rows of cluster-B are refreshed with another bit for example, the next significant bit of the image with backlight OFF during $\mathrm{T_2}$ and the backlight intensity is set to 50% of the maximum intensity during the following 3-time intervals, i.e., $\mathrm{T_3}$ to $\mathrm{T_5}$. Pixels in cluster-C are refreshed by using 3rd significant bit by switching OFF its backlight during the time interval $\mathrm{T_3}$ and intensity backlight to cluster-C is controlled to be 25% of the maximum during $\mathrm{T_4}$ to $\mathrm{T_6}$. Backlight to cluster-D is switched OFF during the time interval $\mathrm{T_4}$ and pixels in that cluster are scanned by using the fourth significant bit of the image. Backlight intensity of cluster-D is set to 12.5% during the subsequent 3-time intervals that follows, i.e. $\mathrm{T_5}$ to $\mathrm{T_7}$. This process is continued till the least significant bit; i.e., the durations $\mathrm{T_5}$ to $\mathrm{T_8}$ can be utilized to refresh cluster-A to cluster-D with 5th to 8th significant bits of grayscale in the same manner as $\mathrm{T_1}$ to $\mathrm{T_4}$ but for the fact that the intensity of backlight is controlled to be 6.25%, 3.13%, 1.56%, and 0.78%, respectively, for the least significant nibble. As one can observe the intensity of backlight is reduced by 50% for each successive bit starting with the maximum intensity for the MSB. All pixels

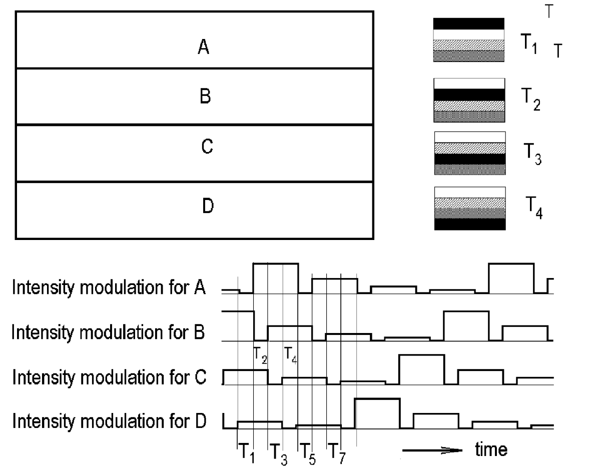

Fig. 2. Bit slice addressing of LCD by refreshing one of the clusters (A, B, C and D) with backlight OFF and displaying rest of the clusters by turning ON the backlight to other clusters.

in the display will be refreshed after 32 time intervals i.e., period of 8-bit frames and the backlight has a duty cycle of 3/4 as compared to period of 16 bit frames that will be necessary assuming a equal $\mathrm{T_{ON}}$ and $\mathrm{T_{OFF}}$ periods in the scheme herein the backlights to all pixels is switched OFF during refreshing as discussed in Section II.

IV. ADVANTAGES OF BSA

Bi-stable displays can be used to display grayscales when they are driven with bit slice addressing because BSA uses just one bit at a time to refresh the display. Simple data drivers that can apply any one of two voltages (equivalent to 1-bit A/D) to turn pixels ON/OFF are adequate to display grayscales if bit slice addressing is used to drive fast responding LCD. Voltage margin to drive pixels to ON and OFF are large in LCD as shown in Fig. 3. Hence, drive voltages need not be controlled down to a few millivolts (mV) with 8–10 bit A/D converters as in the case of conventional AMLCDs. Therefore, displays driven with bit-slice addressing need not have metallization of address lines to reduce drop in voltage in the data line from one end of the matrix display to the other end. Viewing angle characteristics of the LCD driven with BSA will be relatively independent of grayscale because pixels are either turned ON or OFF and therefore light transmission through the cell has small deviation in transmission even with large changes in voltage across pixel because the pixels are operated in the threshold and saturation regions of the electro-optic response as illustrated in Fig. 4. Consequently, color purity of images will also be better because viewing angle characteristics of R, G, and B pixels are almost independent of intensity of color pixels. Gamma correction is not necessary because LCD is used as a light shutter in BSA. and nonlinear characteristics of LCD does not influence the device operation because pixels are either turned ON or OFF. In the state-of-the-art AMLCD, the alternate fields are blanked to reduce motion blur. Intensity of backlight is less than 1% of the maximum intensity in BSA. Intensity profile of the backlight (Fig. 1) is similar to the decay of intensity of pixels in CRT and it will be useful to minimize the motion blur in AMLCD [2] without introducing alternate blank fields. Considering that the state-of-the-art LCDs have response time below 5 ms; demand

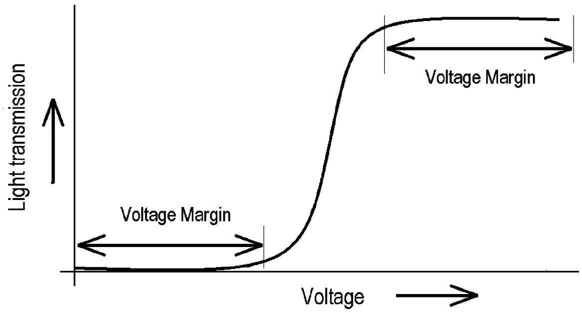

Fig. 3. Large voltage margins when pixels are driven to either ON or OFF states.

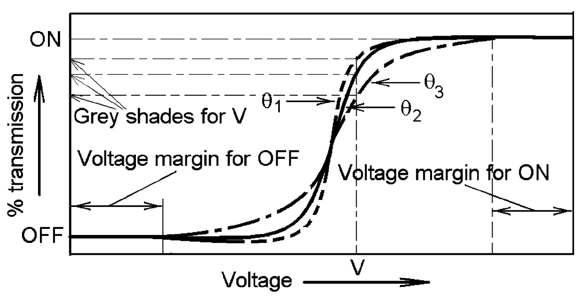

Fig. 4. Variation of light transmission with viewing angle is small when pixels are driven to ON and OFF states.

Fig. 5. Image of Girl.

of shorter response times is a major drawback of BSA. The technique may exhibit some visual perception related problems due to sequential projection of bit frames and color that can only be found experimentally with the development of LCDs with short response times.

V. Backlight Power

Analysis of 16 color images and 28 grayscale images; i.e., 608 bit frames led to the following results. Percentage of OFF pixels in bit frames of the two MSBs has a wider range as compared to the rest of the six bits. It is not surprising because 75% of the maximum intensity value is contained in the two MSBs. Percentage of OFF pixels ranged from 40% to 60% in bit frames of next six LSBs. For example, the percentage of OFF pixels in bit planes of the three images (Girl, Lena, and Pepper) shown

Fig. 6. Image of Lena.

Fig. 7. Image of Pepper.

in Figs. 5–7 is shown in Table I. Light incident on OFF pixels does not reach the eye and therefore it is not useful. Backlight power can be saved if backlight is switched OFF to these pixels. It is feasible only when large cluster of pixels are OFF. Such large clusters are present mostly in bit frames of a few MSBs as shown Figs. 8–12. The OFF pixels in bit frames of LSBs are scattered and therefore they are not useful for saving power in addition to the fact that the power consumption of the backlight for LSBs is small. Monochrome images of the three primary colors of the image Barbara are shown in Fig. 8. Bit plane image of MSB (bit-8) and bit-7 of primary colors of the image Barbara in Figs. 9 and 10, respectively. Similarly, the bit-plane images of the bit-8 and bit-7 of primary colors are shown in Figs. 11 and 12, respectively. Number of OFF pixels in bit planes of MSB and the next significant bit (bit-7) depends on the brightness of the original image as evident from the Table I. MSB bit of the image of Barbara has more OFF pixels (more than 87% as shown in Table) because its brightness is less as compared to the image of Lena. Number of OFF pixels in bit plane of Lena is less (just 20% for the color red, 69% for green and 78% for blue). In LCDs power can be saved by switching OFF light selectively; it is more practical when large sized clusters are OFF. Bit plane images of a few most significant bits have large clusters of OFF pixels and backlight power can be saved

TABLE I
STATISTICS OF BITS OF SOME IMAGES, THE NUMBER OF OFF PIXELS IN EACH BIT FRAME

Image	Bit 7	Bit 6	Bit 5	Bit 4	Bit 3	Bit 2	Bit 1	Bit 0
Girl-R	87	60	44	48	50	47	46	59
Girl-G	92	76	57	61	53	54	55	58
Girl-B	94	79	61	64	56	50	47	53
Lena-R	20	26	53	50	49	50	50	49
Lena-G	69	52	57	49	50	50	51	49
Lena-B	78	30	51	48	49	50	50	50
Pepper-R	32	50	51	51	50	50	51	51
Pepper- G	50	66	53	53	54	54	53	53
Pepper- B	91	58	53	59	54	53	53	53

R = red; G = green; and B = blue

Fig. 8. Monochrome images of red, green, and blue in the image of Girl.

Fig. 9. Most significant bits of the primary colors of the image Girl.

Fig. 10. Bit plane images of bit-7 of primary colors of the image Girl.

by selectively switching OFF the backlight to large clusters of OFF pixels. Saving in backlight power diminishes rapidly as we move from MSB to LSB because intensity of reduces by 50% for each successive bits and also because large clusters of pixels in same state is more common in bit plane images of most significant bits than in bit plane images of least significant bit. There are several schemes to save power by switching OFF backlight to large clusters of pixels but it is out of the scope of this paper. However, the potential to save power can be easily seen from Fig. 13. Fifty-six clusters out of 256 clusters have all pixels OFF and therefore about 20% of backlight power can be saved if each of these clusters is illuminated with independent backlights. Pulse width modulation for the two MSBs (bit-8 and bit-7) is useful to form large clusters and thereby reduce power consumption of the backlight. Dynamic range of backlight intensity is also reduced with this approach as shown in Fig. 14. About 20%–40% reduction in backlight power can be achieved by switching OFF backlight selectively to clusters of 256 pixels depending on the image. It is possible to achieve reduction in power consumption of backlight even when displaying static images with good brightness and high contrast.

Fig. 11. Bit plane images of MSB of primary colors of the image Lena.

Fig. 12. Bit plane images of bit-7 of red, green, and blue colors of the image Lena.

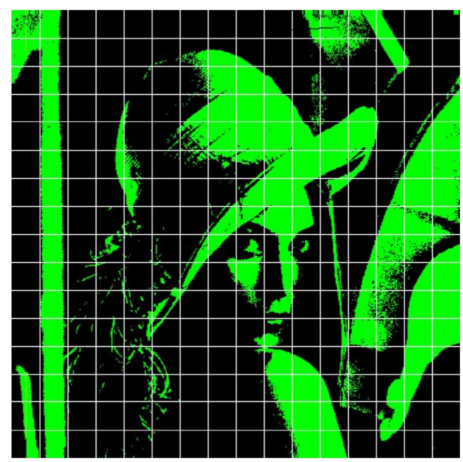

Fig. 13. Bit plane image of MSB of green color of the image Lena.

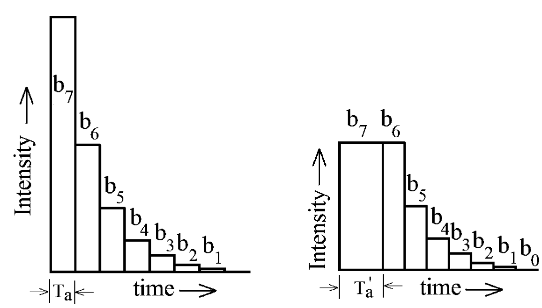

Fig. 14. Pulse width modulation of the two most significant bits is useful to reduce power consumption and also to reduce the dynamic range of the backlight.

VI. MULTI-BIT SLICE ADDRESSING OF AMLCD

Multi-bit slice addressing is a compromise solution that has at least some of the advantages of bit-slice when the response

Fig. 15. Image to be displayed during first time interval of pulse width modulation of bit-8 and bit-7 (see right side on Fig. 14) of image Lena.

Fig. 16. Image to be displayed during the second interval of pulse width modulation of bit-8 and bit-7 of green image of Lena.

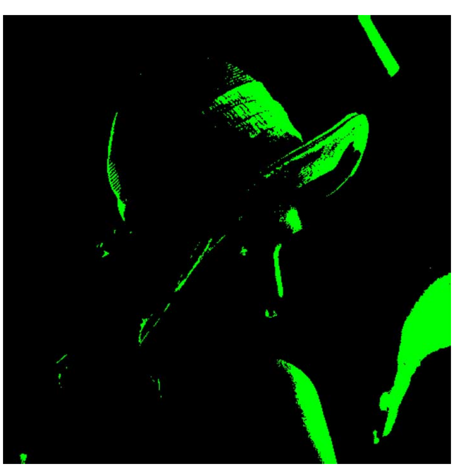

Fig. 17. Image corresponding to the third interval of pulse width modulation of bit-8 and bit-7 of green image of Lena.

times of LCD is not fast enough for bit-slice addressing. Four bits are called nibble and a technique to drive the AMLCD with a nibble at a time is described next.

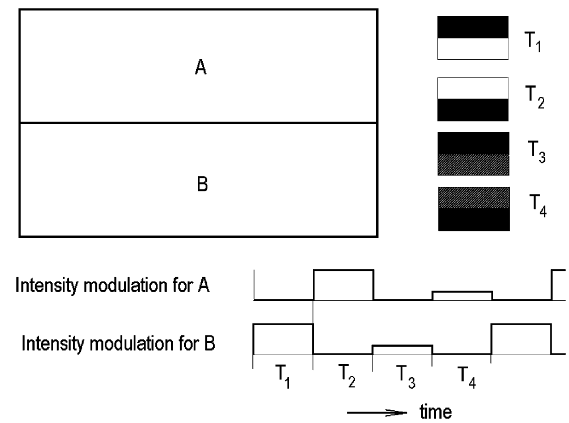

Fig. 18. Nibble Slice Addressing (NSA) of AMLCD and intensity control of backlight.

A. Nibble Slice Addressing (NSA)of AMLCD

Pixels LCD can be split into two large clusters of pixels each of them illuminated by an independent backlight source and intensity control. The expression for intensity of pixel is $\sum_{i=0}^{g-1} b_i \cdot 2^i$, wherein b_i is either 0 or 1 and it is directly used in BSA. This expression can be rewritten for the nibble-slice addressing of AMLCD as shown in (1).

$$\text{Intensity} = 2^4 \sum_{i=4}^{7} b_i \cdot 2^{(i-4)} + \sum_{i=0}^{3} b_i \cdot 2^i. \qquad (2)$$

Backlight to the cluster-A (consisting of pixels in $N/2$ rows) is switched OFF and pixels in this cluster are refreshed with the 4-most significant bits of grayscales as the data during the time interval T_1, Intensity of backlight for the cluster-A is set to the maximum during the time interval T_2 because the most significant nibble was used to refresh the cluster-A during T_1. Pixels in N/2 rows of the cluster-B are refreshed during T_2 with the least significant nibble of grayscale with its backlight switched OFF. Intensity of backlight is set to (1/16) of the maximum intensity during T_3 for the cluster-B while the pixels in cluster-A are refreshed with the least significant nibble of the grayscale data with its backlight switched OFF. Pixels in cluster-B are refreshed with most significant nibble with its backlight switched OFF during T_4 and the intensity of backlight to cluster-A is set to (1/16) of the maximum intensity as shown in Fig. 18. LCD can also be refreshed with the following scanning sequence: most significant nibble (MSN) for cluster-A, MSN for cluster-B, least significant nibble (LSN) for cluster-A followed by LSN for cluster-B and the intensity of backlight is controlled accordingly. Time taken to refresh the AMLCD with nibble slice addressing is equal to duration of frames in the conventional AMLCD. If blanking of alternate frames to suppress motion blur [2] in the state of art AMLCD is taken into consideration, then the display refresh rate of NSA is same as the conventional AMLCD and the response time of 2–5 ms is sufficient for nibble-slice addressing (NSA) of AMLCD. Hardware complexity of data drivers is reduced by 50% as compared to the conventional data drivers of AMLCD because 4-bit analog to digital converters (A/D) can be used in the data drivers in place of the 8-bit A/D converters that are employed for displaying 256 grayscales. If the response time of AMLCD is further reduced; then one can consider driving the panel by using

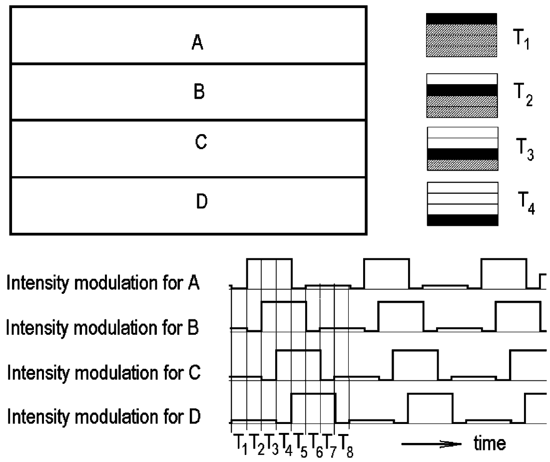

Fig. 19. Nibble Slice Addressing of AMLCD with four clusters of pixels and intensity profile of backlight.

3-bit (8-grayscales) and 2-bit (4-grayscals) in each multi-bit frame. Nibble addressing can also be implemented by splitting the pixels in LCD to form 4 clusters as described here. Pixels in N/4 rows of cluster-A are refreshed with the MSN of grayscale during T_1 and the backlight is switch ON with maximum intensity during T_2 to T_4. Similarly, pixels in the other three clusters are refreshed with backlight OFF during the time intervals T_2, T_3 and T_4, respectively, and the backlight of the respective clusters are set to the maximum intensity during 3-subsequent time intervals; i.e. during T_3–T_5 for the cluster-B, T_4–T_6 for the cluster-C and T_5–T_7 for the Cluster-D. Pixels in Cluster-A to Cluster-D are refreshed by switching OFF the backlight during T_5, T_6, T_7 and T_8, respectively and the backlight is switched ON with the intensity set at 1/16 of the maximum intensity during T_6–T_8, T_7–T_9, T_8–T_{10} and T_9–T_{11} for the clusters A, B, C, and D, respectively. This process is repeated continuously with backlight intensity profile, as shown in Fig. 19, and the frame rate depends on the response times of AMLCD. Maximum intensity of the backlight is lower in case of four clusters as compared to that of two clusters because the duty cycle of the backlight is 75% as compared to 50% duty cycle in case of two clusters. Data drivers that are capable of applying one of sixteen voltages is adequate for displaying grayscales in AMLCD that is driven by nibble slice addressing (NSA).

B. Dual Bit Slice Addressing of AMLCD

Intensity of pixels can be rewritten as shown in the following expression for dual bit slice addressing of AMLCD.

$$\mathrm{I}=2^6\sum_{i=2}^{3}b_i\cdot 2^{(i-6)}+2^4\sum_{i=0}^{1}b_i\cdot 2^{(i-4)}+2^2\sum_{i=2}^{3}b_i\cdot 2^{(i-2)}+\sum_{i=0}^{1}b_i\cdot 2^{i} \quad (3)$$

Pixels in N/4 rows of clusters A-D are sequentially refreshed with two bits of grayscale at a time by switching OFF during T_1, T_2, T_3 and T_4 respectively. Intensity of backlight is set to the maximum if most significant two bits are used to refresh the cluster and the backlight is ON with a duty cycle of 75% because backlight is switched ON during three time intervals following the refresh period. A frame in the conventional sense consists of 16 time intervals because it takes 4 bit frames it displays 256 grayscales.

C. Multi-BSA With Duty Cycle

If the time taken to refresh the display is small as compared to the frame time then it is not necessary to divide the pixels into large clusters of pixels. For example if the number of rows is small or if the carrier mobility of thin film transistor in AMLCD is high, then the time taken to refresh the display will be short as compared to the frame time. Then the backlight for the whole LCD can be switched OFF during refresh time of pixels with bit(s) and the backlight can be switched ON at the end of each refresh.

VII. Conclusion

Multi-bit slice addressing (MBSA) also relies on fast responding devices like LED as backlight source for addressing AMLCD. However, viewing angle characteristics will no longer be independent of grayscales with MBSA and therefore color purity of images will not be as good as BSA if MBSA is employed. Response times will also depend on grayscales to some extent in MBSA. Nibble slice addressing is feasible with the state of the art AMLCDs. Some of the advantages of bit slice addressing, viz., low hardware complexity of data drivers, reduction of motion blur, low power consumption of backlight can be retained with multi-bit slice addressing. Backlight power can be saved with techniques proposed by Shigara *et al.* [3] and Pierre de Greef [4]. Digital micro mirror device (DMD) can also be driven with bit slice addressing because the pixels can switched in about 20 μs.

Acknowledgment

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Prof. Ruckmongathan is a member of Society for Information Display.