CHAPTER 5

CONCLUSION

5. CONCLUSION

Several new addressing techniques for displaying both general and restricted patterns have been **proposed, analysed and compared** with the conventional techniques in Chapter 3. The **merits** and **demerits** of these new techniques have also been discussed in the same Chapter. Practical **implementation** of these techniques and the **experimental verification of the results** have been covered in Chapter 4. A critical evaluation of these new techniques, their impact on the field of matrix addressing and scope for further work are discussed in this Chapter.

5.1. A CRITICAL EVALUATION

The new addressing techniques proposed in this thesis are classified into two categories as given below :

- The BAT, HAT, IHAT, IHAT-S3 and IHAT-S4 fall under the category of techniques for **displaying general patterns** ;
- The RPAT-NC and RPAT-PC fall under the category of techniques for **displaying restricted patterns** .

The performance of these techniques is critically evaluated in the following sections. It is clear from this evaluation that the new techniques reported in this Thesis for displaying general as well as restricted patterns provide better results in several areas, as compared to the conventional techniques.

5.1.1. Techniques for Displaying General Patterns

In the analysis of the ultimate limits for matrix addressing of rms responding LCDs displaying general patterns, Nehring and Kmetz (1979) have shown that the selection ratio cannot be improved significantly as compared to that of APT or IAPT. Hence the following objectives were set forth in the development of new addressing techniques :

- Reducing supply voltage requirements ;
- Obtaining good brightness uniformity of pixels ;
- Lowering of hardware complexity of drivers .

The level of success in each of these areas is summarized below :

- All the new addressing techniques reported in this Thesis require a lower supply voltage as compared to that of IAPT for well defined ranges of N .
- The brightness uniformity of the pixels is better in displays addressed using BAT, HAT, IHAT and IHAT-S4 than in IAPT.
- Only a partial success has been achieved in the reduction of the hardware complexity of the new addressing techniques. The BAT requires less hardware as compared to both IAPT and APT. The hardware complexity of HAT is comparable to that of APT and is slightly lower than that of IAPT. The hardware complexity of IHAT increases with l. Although the hardware complexity of IHAT-S3 and IHAT-S4 is higher than that of APT, it is lower than that of IHAT.

The selection ratio of the new addressing techniques is compared with that of APT (as well as IAPT) as given below :

- Lower in BAT ; this is not a serious problem since BAT is suitable only for small N.

- Lower in HAT; this technique is suitable only for SBE Displays.
- Same in IHAT.
- Lower in IHAT-S3 and IHAT-S4; a value close to that of APT is possible.

The selection ratios and the supply voltage requirements of these new techniques are compared with that of the conventional techniques in Fig.5.1 and Fig.5.2 respectively.

5.1.2 Techniques for Displaying Restricted Patterns

The main objective in the case of techniques for displaying restricted patterns was to develop new addressing techniques with a higher selection ratio than the conventional ones when the number of selected pixels in a column is greater than 1. The level of success achieved in this area is summarised below :-

- Both the RPAT-NC and RPAT-PC proposed in Chapter 3 are suitable for displaying more than one selected pixel per column.
- Both these techniques have a selection ratio independent of the matrix size.
- The selection ratio of these techniques however depends on the number of selected pixels (W) in each column.
- The selection ratio of RPAT-NC is higher than that of FMT (reviewed in Chapter 2) for all the values of W. The selection ratio is infinite when W = 1 as in the case of PCT and PRT (reviewed in Chapter 2).
- The selection ratio of RPAT-PC is higher than that of FMT, when

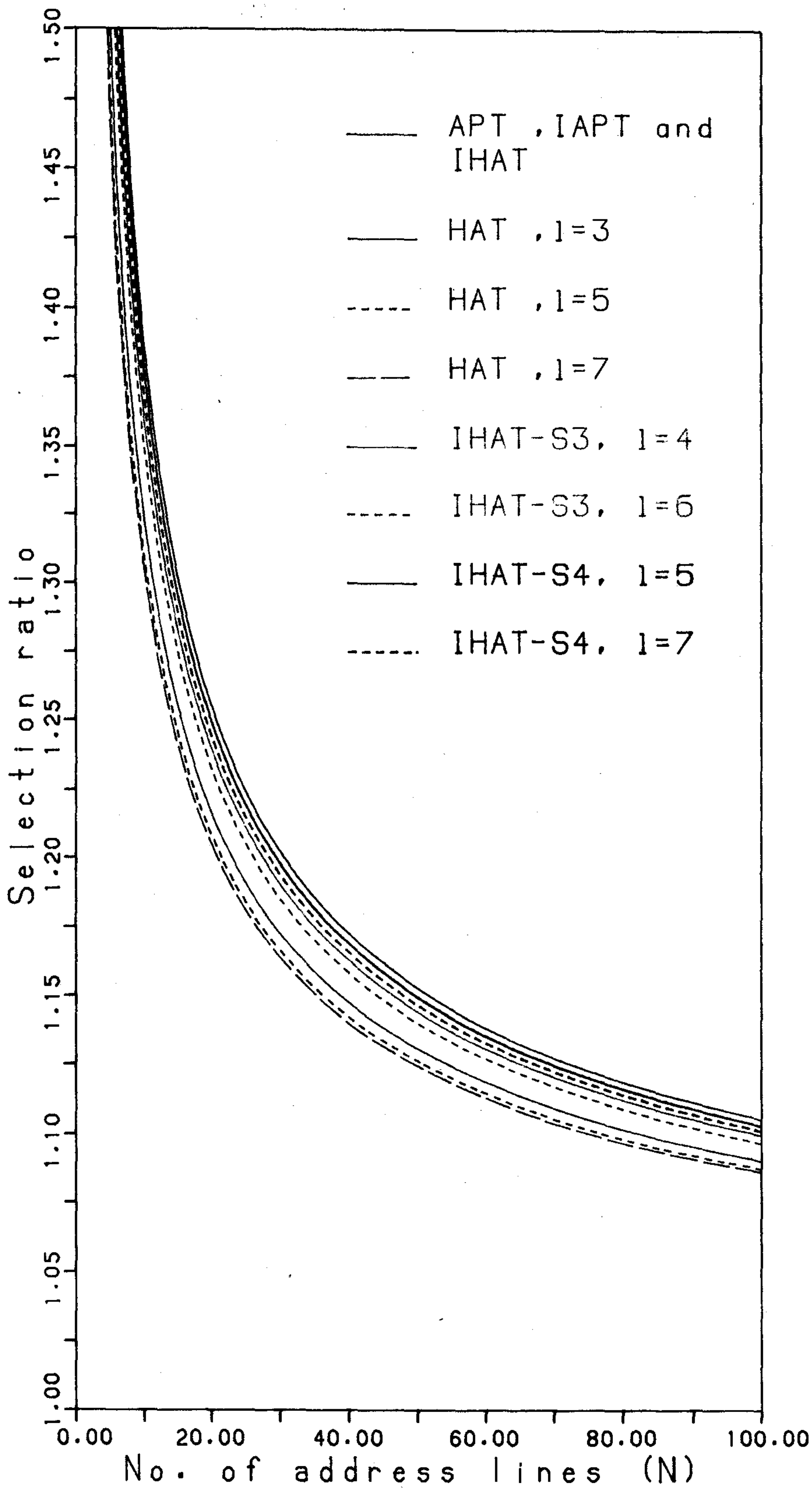

Fig. 5.1. A comparison of selection ratios of the new addressing techniques with that of APT .

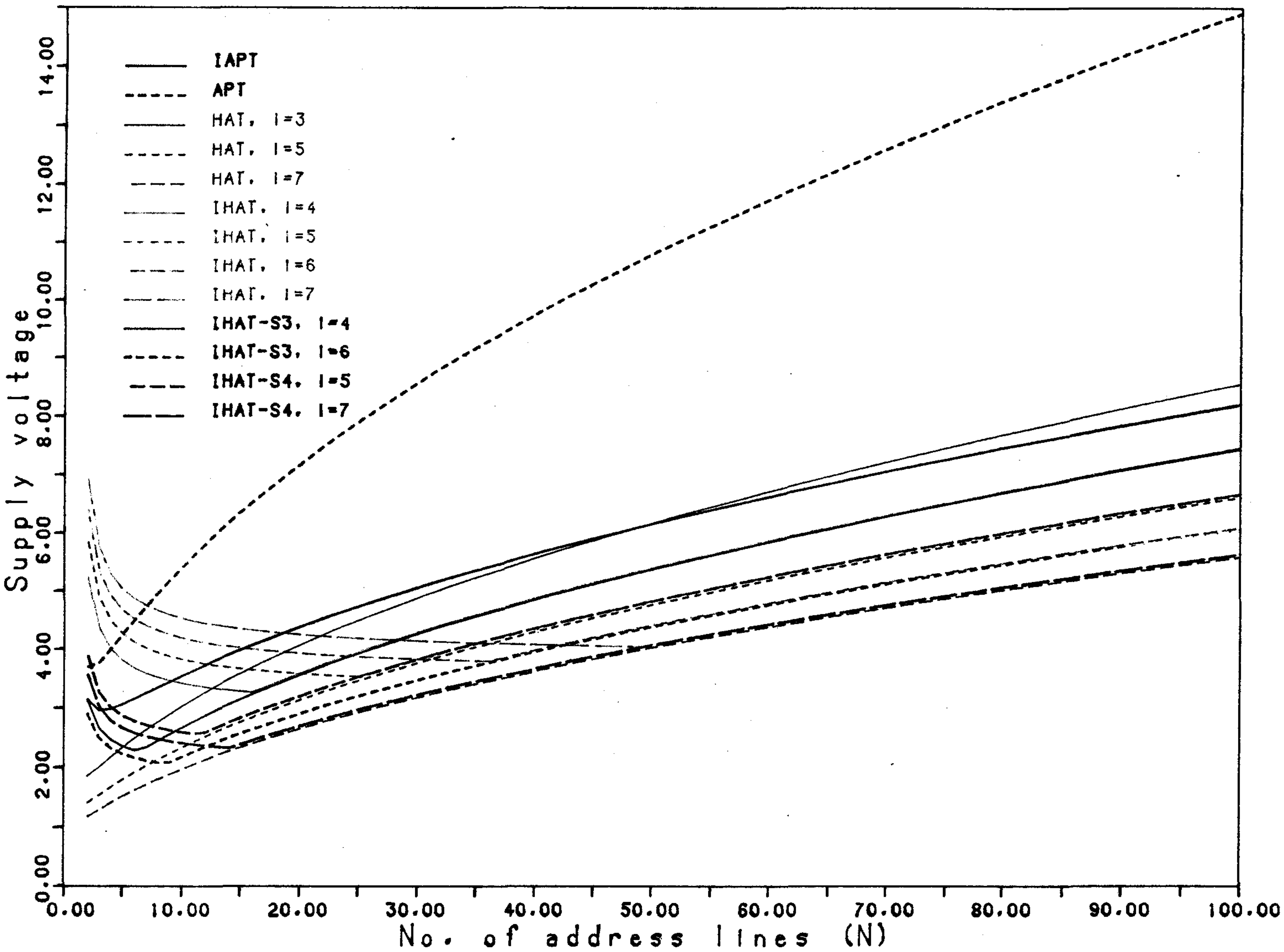

Fig. 5.2. A comparison of supply voltage requirements (normalized to V_{th}) of the new addressing techniques with those of APT and IAPT.

W is greater than 2. But the selection ratio of RPAT-PC is lower than that of RPAT-NC.

The selection ratios of RPATs are compared with that of FMT in Fig. 5.3.

5.2 IMPACT

The impact of the new addressing techniques reported in this Thesis on the field of matrix addressing of rms responding LCDs is as follows :

5.2.1. Techniques for Displaying General Patterns

The IHAT proposed in this Thesis is a **generalized form of** APT. The number of selected rows is a variable l in IHAT as compared to 1 in the case of APT. Even the other new techniques proposed in this thesis can be treated as special cases of IHAT as given below :

- BAT; when $l = N$ and the number of voltage levels in the column waveform (n_c) is restricted to 2 .
- HAT ; when l is odd and $n_c = 2$.
- IHAT-S3 ; when l is even and $n_c = 3$.
- IHAT-S4 ; when l is odd and $n_c = 4$.

The salient features of the new addressing techniques and the possible areas of applications are outlined below :

a) <u>BAT</u>

- The supply voltage requirement **decreases** with the increase in N; this is in contrast to IAPT wherein the supply voltage **increases** with N when N is greater than 3 .

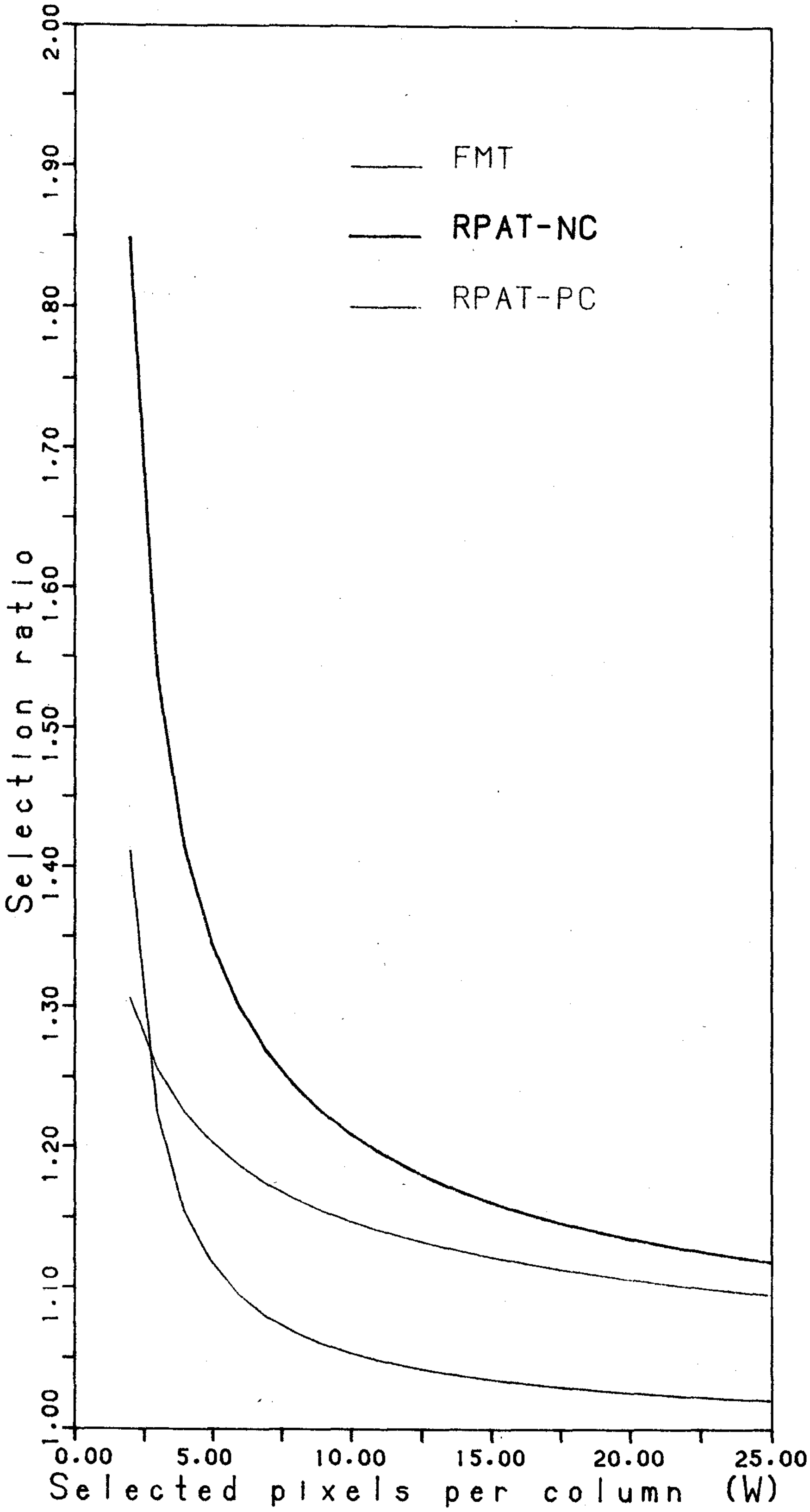

Fig. 5.3. A comparison of the selection ratios of the RPATs with FMT.

- The hardware complexity is low since only two voltage levels are required for both row and column addressing waveforms.

The BAT is well suited for applications like calculator displays (wherein a single row of alphanumeric information is to be displayed) because of the following advantages :

- The low supply voltage requirement makes it ideal for use in portable devices .
- The row and column drivers can easily be integrated into the calculator chip due to the binary nature of addressing waveforms.

The following drawbacks of BAT are not serious since N is small in this application :

- Lower selection ratio of BAT as compared to IAPT.
- Higher time intervals to complete a cycle as compared to IAPT.

b) HAT

- The HAT extends BAT for higher values of N ;
- It is an intermediate step between the BAT and IHAT.

HAT can be used for SBE displays for the following reasons :

- Low supply voltage requirement for limited values of N ;
- Good brightness uniformity of pixels ;

The lower selection ratio of HAT as compared to IAPT is not a serious problem here, considering the steep electro-optic characteristics of SBE Displays.

c) IHAT

- The supply voltage requirement is minimum for $N = l^2$;
- The supply voltage requirement of IHAT is considerably lower than that of IAPT for a wide range of N (few hundreds to few thousand lines) when l is greater than 3 ;
- The selection ratio is the same as that of IAPT .

IHAT is well suited for addressing matrix displays with a large number of address lines (N) as in the case of computer terminals based on both TNLCDs and SBE Displays for the following reasons : -

- Considerable reduction in the supply voltage requirement especially for large values of N. (Applications like portable lap-top computers) ;
- Good brightness uniformity of pixels ;
- No compromise in the selection ratio as compared to IAPT .

However the above advantages are obtained at the cost of the following factors :-

- Increase in the hardware complexity of column drivers ;
- Increase in the number of time intervals in a cycle; though the flicker can be eliminated by choosing a proper scanning sequence.

d) IHAT-S3

- Supply voltage requirement is minimum for N less than l^2 ;
- The supply voltage requirement is lower than that of IAPT for a wide range of N ;

- The hardware complexity is lower as compared to IHAT;
- This reduction is achieved without a significant sacrifice in the selection ratio and the low supply voltage requirement of IHAT ;
- Good brightness uniformity of pixels .

The IHAT-S3 is well suited for displaying matrix displays with a large number of address lines and when l is chosen to be even. This technique can be used for TNLCDs and SBE Displays in view of the advantages given above. However the number of time intervals to complete a cycle is same as that of IHAT.

e) IHAT-S4

The salient features and the applications of IHAT-S4 are the same as those of IHAT-S3. The IHAT-S4 is used when the value of l is chosen to be odd.

5.2.2. Techniques for Displaying Restricted Patterns

The RPAT-NC proposed in this thesis is a **generalized** form of PCT reviewed in Chapter 2. The number of selected pixels in a column (W) is a variable in RPAT-NC as compared to 1 in the case of PCT. The RPAT-NC reduces to PCT when $W = 1$. While the RPAT-NC results in a negative contrast mode (bright selected pixels against dark background pixels) in TNLCDs, the RPAT-PC proposed in this thesis results in a positive contrast mode with dark selected pixels against bright background pixels.

The salient features of these techniques are given below :-

- Selection ratio is independent of the matrix size and just depends on the number of selected pixels in each column.
- Suitable for displays wherein the number of selected pixels in each column is small as compared to the number of address lines in the matrix.
- Possibility of addition of dummy rows to allow for a variation in the number of selected pixels in each column.

The possible applications of these techniques are discussed below : -

a) RPAT-NC

This technique is well suited for LCDs based on Guest-Host effect since the resulting display has a positive contrast. However they can also be used for addressing TNLCDs, but this results in a negative contrast.

The possible applications are multitrace oscilloscopes and logic analyzers; wherein waveforms which are mostly single valued functions of time are to be displayed. Limited alphanumeric information in the form of legends can also be displayed in such applications as discussed in Chapter 3. This technique can also be used in applications like video games, wherein the number of selected pixels in each column is small as compared to the matrix size.

b) RPAT-PC

This technique is well suited for TNLCDs since the resulting display has a positive contrast although the selection ratio is lower than that of RPAT-NC. The possible applications are the same as those of RPAT-NC.

The supply voltage requirement of both RPAT-NC and RPAT-PC increases with N. This may be a limiting factor on the size of the matrix.

A new parameter, i.e., N_{eq} has been introduced (see, eqn. 2.20 and Appendix 6.c) and is used throughout this thesis. This parameter is well suited for comparing the selection ratio of the new addressing techniques (for displaying both general and restricted patterns) with the maximum selection ratio possible, i.e., the selection ratio of APT and IAPT.

In summary, this study on new addressing techniques for rms responding LCDs has led to a **better understanding** of the problem of matrix addressing. **Generalized addressing techniques** for displaying both general and restricted patterns **have been developed** as a result of this study. A number of new addressing techniques proposed in this thesis will **enhance** the use of rms responding LCDs in a wide range of applications. Availability of these techniques has increased the **choice** and **trade-off** possible in the selection of an addressing technique to suit a given application.

5.3 SCOPE FOR FURTHER STUDY

Stability analysis of the new addressing techniques, i.e., the effect of variations in the relative amplitudes of the voltage levels in the addressing waveforms on the selection ratio will be of practical interest.

In the case of displaying general patterns new addressing techniques with lower hardware complexity than the conventional technique is desirable. New addressing technique with lower supply voltage requirement is desirable in the case of displaying restricted patterns.

Although the electro-optic characteristics required for multiplexing and grey scale are in direct conflict as discussed earlier, new addressing techniques for displaying grey scale will enhance the use of rms responding LCDs.

The new addressing techniques proposed in this thesis have been used to address TNLCDs. Implementation of the same with SBE Displays will be of practical importance.

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APPENDIX 1

PHYSICAL PROPERTIES OF LIQUID CRYSTAL MATERIALS

The physical properties that are relevant to the display applications are discussed briefly in the following paragraphs.

a] Transition Temperatures

The temperature at which a liquid crystal material melts from solid phase into liquid crystalline phase is called the melting point. The clearing point is the temperature at which the liquid crystal material becomes an isotropic liquid. Both the melting and clearing points have well defined values for a single substance. In the case of mixtures, the transition does not necessarily take place at one temperature, but over a small range of temperatures. The melting and clearing points determine the useful range over which the display can operate satisfactorily. The melting point ranges from -30°C to 0°C and the clearing point ranges from 60°C to 120°C in the liquid crystal mixtures useful for displays.

b] Order Parameter

The molecular ordering in liquid crystals, represented by the director is time averaged at a macroscopic level. The order parameter is defined as,

$$S = \frac{1}{2}(\overline{3\cos^2\theta - 1}) \qquad (A1.1)$$

where θ is the instantaneous deviation of the long molecular axis from the preferred average direction and $\overline{\cos^2\theta}$ is the time average of $\cos^2\theta$. The value of S can range from 0.3 to 0.7 and it decreases with the increase in temperature.

c] Dielectric Anisotropy

The liquid crystal materials have two dielectric constants, one along the direction of the director ($\varepsilon_{\parallel}$) and the other perpendicular to the direction of the director ($\varepsilon_{\perp}$). The dielectric anisotropy ($\Delta\varepsilon$) is defined as the difference between the two dielectric constants, i.e.,

$$\Delta\varepsilon = (\varepsilon_{\parallel} - \varepsilon_{\perp}) \tag{A1.2}$$

The materials with positive dielectric anisotropy ($\varepsilon_{\parallel} > \varepsilon_{\perp}$) orient themselves with their long axes parallel to the external electric field, whereas those with negative dielectric anisotropy ($\varepsilon_{\parallel} < \varepsilon_{\perp}$) align themselves with the director perpendicular to the electric field as shown in Fig.A1.1. Typical value of dielectric anisotropy ranges from +15 to -5.

d] Dielectric Relaxation

In compounds with polar molecules, $\varepsilon_{\parallel}$ depends on the frequency of the applied field up to about 10 MHz while $\varepsilon_{\perp}$ is independent of the frequency in this range. The value of $\varepsilon_{\parallel}$ decreases with this increase in frequency and is known as dielectric relaxation. In some materials, the dielectric anisotropy changes its sign from a positive value to a negative value and the frequency at which $\varepsilon_{\parallel}$ is equal to $\varepsilon_{\perp}$ (i.e., $\Delta\varepsilon = 0$) is called as the cross-over frequency f_c (Fig.A1.2). The value of f_c ranges from a few KHz to a few MHz. The cross-over frequency is highly sensitive to temperature and typically it doubles for every 10°C rise in temperature. The change in sign of $\Delta\varepsilon$ has been exploited for addressing matrix displays leading to a two frequency addressing technique which is discussed in Section 2.4.1.

e] Optical Anisotropy

In a well-aligned nematic liquid crystal film, the optical axis coincides with the director. Light travelling parallel to the optical axis is subjected to one refractive index only, irrespective of the direction of the polarization of the incident beam since the distribution is circularly symmetric about the director. Light travelling perpendicular to the director, however, is subjected to two refractive indices, viz., $n_{\parallel}$ for the light with polarization vector parallel to the director, and $n_{\perp}$ for the light whose polarization vector is perpendicular to the director. This phenomenon is known as double refraction or birefringence.

The optical anisotropy Δn is defined as

$$\Delta n = (n_{\parallel} - n_{\perp}) \tag{A1.3}$$

Typical values of Δn range from 0.05 to 0.25. In the twisted nematic displays the contrast and viewing angle can be improved by a proper choice of the value of Δn.

f] Elastic Constants

There are three curvature elastic constants defined for a nematic liquid crystal. They are, splay (k_{11}), twist (k_{22}) and bend (k_{33}) elastic constants corresponding to the three possible distortions of the director configuration. This is shown in Fig.A1.3. Typical values for these elastic constants are of the order of 10^{-11} N. The magnitudes and the ratios of these elastic constants determine the exact nature of the electro-optic response of the liquid crystal materials. The electro-optic response is steeper with lower values of k_{33}/k_{11} in the case of twisted nematic effect, which is helpful in their matrix addressing.

g] Viscosity

Five viscosity coefficients are required to describe the flow properties of nematic liquid crystals. However, for practical applications, it is a common practice to measure the viscosity by using the standard techniques applicable to isotropic liquids. Typical values of the viscosity for liquid crystal materials range from a few to a few hundred mPas. The response time (switch **ON** and switch **OFF** times) of the liquid crystal material is proportional to viscosity and hence low viscosity mixtures are preferred for the displays. The viscosity increases with decrease in temperature, making the display appear sluggish at low temperatures. This limits the low temperature operation of the display.

h] Pitch

Cholesteric liquid crystals have a helical structure with either right handed or left-handed rotation. The pitch is defined as the distance required for the director to undergo one full rotation (360°), and it ranges from 0.5 mm to ∞ . If the wavelength of the incident light matches the pitch, then this light is selectively reflected back. Nematic materials doped with optically active materials also exhibit cholesteric structure. The pitch of such materials depends on the amount of doping and the temperature of operation. The latter dependence has been exploited in making temperature indicators. Liquid crystal materials used in super-twisted birefringence effect are doped with cholesteric materials to achieve a twist angle greater than 90° (typically 180° - 270°). Similar doping in twisted nematic displays avoid the reverse twist. Sometimes, the liquid crystal mixtures are doped with both right-handed and left-handed cholesterics to compensate for the variation of threshold voltage of the electro-optic response with temperature.

A key factor in achieving the best performance in a display lies in the choice of a suitable liquid crystal mixture for a given application. At present, nematic materials are being used in majority of applications, compared to smectics or cholesterics.

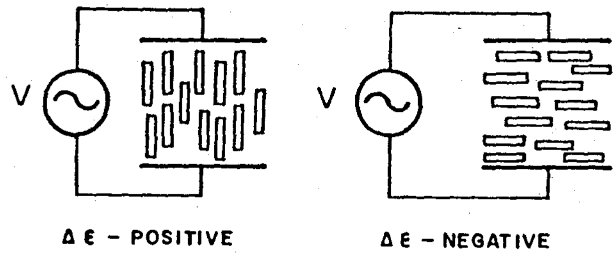

Fig. A1.1

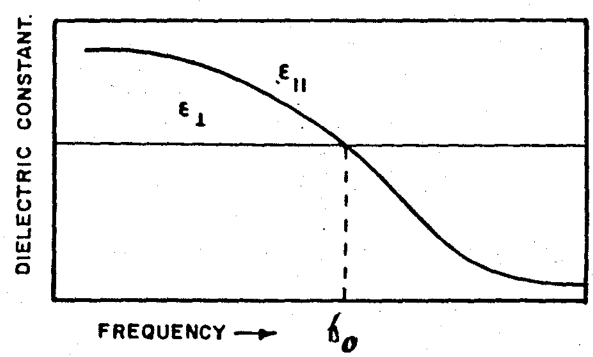

Fig. A1.2

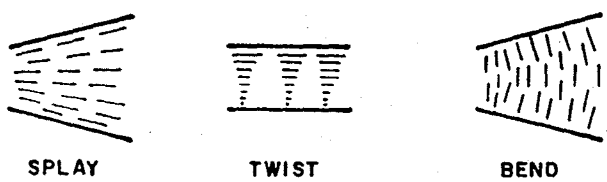

Fig. A1.3

APPENDIX 2

IMPORTANT PARAMETERS OF LCDs

Some important parameters of LCDs are briefly outlined below [19].

a] Threshold Voltage (V_{th})

The threshold voltage is the voltage **below** which further change in a defined optical characteristic is relatively small, i.e., the voltage at which the luminance has changed by 10% of the maximum change in luminance (V_{th} or V_{10}).

b] Saturation Voltage (V_{sat})

The saturation voltage is the voltage **above** which further change in a defined optical characteristic is relatively small, i.e., the voltage at which the luminance has changed by 90% of the maximum change in luminance (V_{sat} or V_{90}).

c] Sharpness Parameter (γ)

The sharpness parameter is defined as

$$\gamma = \frac{V_{50} - V_{10}}{V_{10}} \; 100 \, (\%) \qquad \text{(A2.1)}$$

where V_{50} is the voltage at which the luminance has changed by 50% of the maximum change in luminance.

d] Contrast ratio

The ratio of the luminance of a liquid crystal device in the bright state to that in the dark state under conditions of constant illumination.

e] Response times

The response times with reference to the excitation are shown in Fig. A2.1.

- **Delay time** (t_d) is the time interval between the initiation of an input pulse train and the luminance reaching its 10% as shown in the figure.
- **Rise time** (t_r) is the time interval during which the luminance is changing from its 10% -**ON** value to its 90% -**ON** value as shown in the figure.
- **Turn-on-time** (t_{on}) is the sum of t_d and t_r.
- **Turn-off delay time** ($t_{d(off)}$) is the time interval between the end of the input pulse train and the luminance reaching 90% -**ON** value. Usually it is negligible compared with the fall time.
- **Fall time** (t_f) is the time interval during which the luminance is changing from its 90% -**ON** value to its 10% -**ON** value as shown in the figure.
- **Turn-off time** (t_{off}) is the sum of $t_{d(off)}$ and t_f.

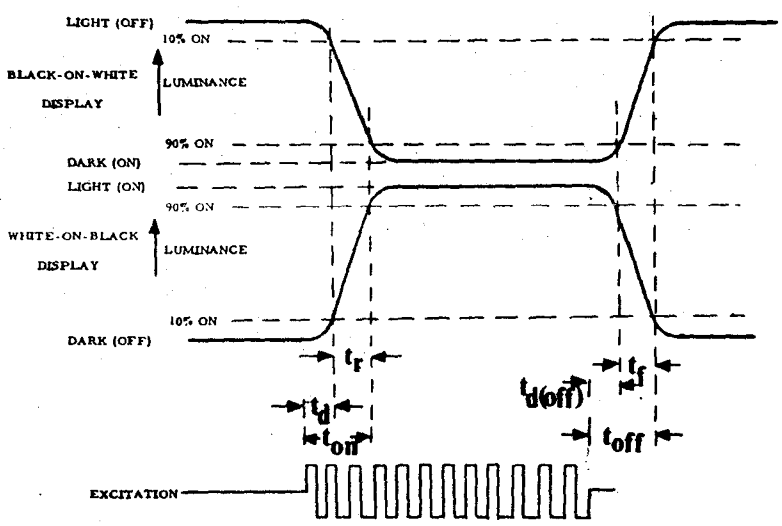

Fig.A2.1. Response times of LCDs

APPENDIX 3

SOME IDENTITIES IN IHAT ANALYSIS

3.a Proof of the identity $V_{(\ell-i)} = -V_i$ is given below :

The expression for V_i from eqn. (3.77) is as given below

$$V_i = \frac{(\ell - 2i)}{\ell} V_0 \tag{A3.1}$$

The following expression is obtained by substituting $(\ell - i)$ in place of i

$$V_{(\ell-i)} = \frac{(\ell-2(\ell-i))}{\ell} V_0 \tag{A3.2}$$

$$= \frac{-\ell + 2i}{\ell} V_0 \tag{A3.3}$$

$$V_{(\ell-i)} = -\frac{(\ell-2i)}{\ell} V_0 \tag{A3.4}$$

From eqn. (A3.1) it is clear that the RHS of the above equation is $-V_i$ .Hence,

$$V_{(\ell-i)} = -V_i \tag{A3.5}$$

3.b Proof of the following identity is given below :

$$\sum_{i=0}^{\ell} \frac{\ell!}{i!(\ell - i)!} = \sum_{i=0}^{\ell} \frac{(\ell-1)!\,(\ell-2i)^2}{i!\,(\ell-i)!} = 2^{\ell} \tag{A3.6}$$

Consider the term

$$\frac{\ell!}{i!(\ell - i)!} \tag{A3.7}$$

which is the standard binomial coefficient given below

$$\binom{n}{k} = \frac{n!}{k!\,(n-k)!} \tag{A3.8}$$

The binomial theorem can be used for deriving the various relations involving the binomial coefficients.

$$(1 + x)^n = \binom{n}{0}x^0 + \binom{n}{1}x^1 + \dots + \binom{n}{n}x^n \qquad (A3.9)$$

or
$$(1 + x)^n = \sum_{k=0}^{n} \binom{n}{k} x^k \qquad (A3.10)$$

Substituting $x = 1$ *in the above equation*

$$(1 + 1)^n = \sum_{k=0}^{n} \binom{n}{k} 1^k \qquad (A3.11)$$

Hence

$$\sum_{k=0}^{n} \binom{n}{k} = 2^n \qquad (A3.12)$$

i.e.,

$$\sum_{i=0}^{\ell} \frac{\ell!}{i!(\ell-i)!} = \sum_{i=0}^{\ell} \binom{\ell}{i} = 2^\ell \qquad (A3.13)$$

The following identities are useful in proving the second term in eqn. (A3.6) as equal to 2^ℓ:

a) $$\binom{n}{k} = \frac{n}{k}\binom{n-1}{k-1} \qquad (A3.14)$$

and

b) $$\sum k \binom{n}{k} = n\, 2^{n-1} \qquad (A3.15)$$

Consider

$$\binom{n}{k} = \frac{[n\,.\,(n-1)\,....(n-k+1)]\,[(n-k)\,......1]}{k\,![(n-k)\,......1]} \qquad (A3.16)$$

$$= \frac{n\,.\,(n-1).....\,(n-k+1)}{k\,!}$$

$$= \frac{n}{k}\,\frac{[(n-1)\,....\,(n-k+1)]\,[(n-k)(n-k-1)\,....\,1]}{(k-1)\,!\,(n-k)\,(n-k-1)\,....\,1} \qquad (A3.17)$$

$$= \frac{n}{k}\,\frac{(n-1).(n-2)\,....[(n-1)-(k-1)+1]\,.....\,1}{(k-1)\,!\;\,(n-k)\,(n-k-1)\,...\,1} \qquad (A3.18)$$

$$= \frac{n}{k}\,\frac{(n-1)\,!}{(k-1)\,!\,[(n-1)-(k-1)]!} = \frac{n}{k}\binom{n-1}{k-1} \qquad (A3.19)$$

Consider

$$\sum_{k=0} k\binom{n}{k} = \sum_{k} k\,\frac{n}{k}\binom{n-1}{k-1} = n\sum_{k}\binom{n-1}{k-1} \qquad (A3.20)$$

from equation (A4.7)

$$\sum k\binom{n}{k} = n\,2^{n-1} \qquad (A3.21)$$

Consider

$$\sum_{k=0}^{n}\frac{(n-1)\,!\,(n-2k)^2}{k\,!\,(n-k)\,!} = \sum_{k=0}^{n}\frac{(n-1)\,!\,[n^2-4nk+4k^2]}{k\,!\,(n-k)\,!} \qquad (A3.22)$$

$$= \sum_{k=0}^{n}\frac{(n-1)\,!\,n^2}{k!(n-k)\,!} - 4\sum_{k=0}^{n}\frac{(n-1)!\,nk}{k\,!(n-k)!} + 4\sum_{k=0}^{n}\frac{(n-1)!\,k^2}{k\,!(n-k)!} \qquad (A3.23)$$

$$= n\sum_{k=0}\frac{n\,!}{k!\,(n-k)!} - 4\sum_{k=0} k\,\frac{n\,!}{k\,!\,(n-k)!} + 4\sum_{k=0}\frac{k^2}{n}\;\frac{n\,!}{k!(n-k)!} \qquad (A3.24)$$

$$= n \sum_{k=0} \binom{n}{k} - 4 \sum_{k=0} k \binom{n}{k} + 4 \sum_{k=0} \frac{k^2}{n} \binom{n}{k} \qquad (A3.25)$$

$$= n\, 2^n - 4\, n\, 2^{n-1} + 4 \sum_{k=0} \frac{k^2}{n} \frac{n}{k} \binom{n-1}{k-1} \qquad (A3.26)$$

$$= n\, 2^n - 2n\, 2^n + 4 \sum_{k=0} k \binom{n-1}{k-1} \qquad (A3.27)$$

$$= - n\, 2^n + 4 \left[\sum (k-1) \binom{n-1}{k-1} + \sum \binom{n-1}{k-1} \right] \qquad (A3.28)$$

$$= - n\, 2^n + 4 \left((n-1)\, 2^{n-2} + 2^{n-1} \right) \qquad (A3.29)$$

$$= - n\, 2^n + (n-1)\, 2^n + 2.2^n \qquad (A3.30)$$

i.e.,

$$\sum_{k=0}^{n} \frac{(n-1)!\,(n-2k)^2}{k!\,(n-k)!} = 2^n \qquad (A3.31)$$

Hence,

$$\sum_{i=0}^{\ell} \frac{\ell!}{i!\,(\ell-i)!} \qquad \sum_{i=0}^{\ell} \frac{(\ell-1)!\,(\ell-2i)^2}{i!\,(\ell-i)!} = 2^{\ell} \qquad (A3.32)$$

3.c *Proof of the following identity is given below:*

$$\sum_{i=0}^{\ell} \frac{(A_i - B_i)^2}{A_i + B_i} = \frac{2^{\ell}}{\ell} \qquad (A3.33)$$

Substituting for A_i and B_i from eqn. (3.53) and (3.54) respectively in the LHS of the above expression,

$$\sum_{i=0}^{\ell} \frac{(A_i - B_i)^2}{A_i + B_i} = \frac{1}{\ell} \sum_{i=0}^{\ell} \frac{(\ell-1)!\,(\ell-2i)^2}{i!\,(\ell-i)!} \qquad (A3.34)$$

But,

$$\sum_{i=0}^{\ell} \frac{(\ell-1)!\,(\ell-2i)^2}{i!\,(\ell-i)!} = 2^{\ell} \qquad (A3.35)$$

Using eqn. (A3.31)

Hence

$$\sum_{i=0}^{\ell} \frac{(A_i - B_i)^2}{A_i + B_i} = \frac{2^{\ell}}{\ell} \qquad (A3.36)$$

APPENDIX 4

MAXIMIZATION OF SELECTION RATIO IN IHAT-S3

The derivation of the condition for a maximum selection ratio in IHAT-S3 is given here.

The selection ratio is maximum when the following ratio is maximized:

$$R^2 = (V_{ON}/V_{OFF})^2_{rms} = \frac{S_1 + S_2 + S_3 + S_4}{S_5 + S_6 + S_3 + S_4} \tag{A4.1}$$

This ratio is of the form

$$R^2 = \frac{f_1 + f_2}{f_1 - f_2} \tag{A4.2}$$

When the expressions for S_1 to S_6 given by eqns. (3.114) to (3.119) are substituted in eqn. (A4.1) where,

$$f_1 = 2^{\ell-1} V_r^2 + \frac{N}{\ell} \sum_{i=0}^{m} (A_i + B_i) V_m^2 \tag{A4.3}$$

and

$$f_2 = 2 \sum_{i=0}^{m} (A_i - B_i) V_r V_m \tag{A4.4}$$

The expression for f_1 and f_2 can be simplified by the following substitutions:

$$\sum_{i=0}^{m} (A_i + B_i) = \sum_{i=0}^{m} C_i = C_m^* \tag{A4.5}$$

Consider

$$B_{(i+1)} = \frac{(i+1)\,(\ell-1)}{(i+1)\,!\,(\ell - i + 1)} = \frac{(\ell-1)}{i\,!\,(\ell - i - 1)} = A_i \tag{A4.6}$$

Hence,

$$\sum_{i=0}^{m} (A_i - B_i) = A_m \tag{A4.7}$$

since

$$B_0 = 0 \tag{A4.8}$$

Thus,

$$f_1 = 2^{(l-1)} v_r^2 + \frac{N}{l} C_m^* \; v_m^2 \tag{A4.9}$$

and

$$f_2 = 2A_m v_r v_m \tag{A4.10}$$

The following relations which are similar to eqns. (3.61) and (3.62) must be satisfied for a maximum selection ratio

$$f_1 \, f'_{2v_r} = f'_{1v_r} \, f_2 \tag{A4.11}$$

and

$$f_1 \, f_{2v_m} = f'_{1v_m} \, f_2 \tag{A4.12}$$

where,

$$f'_{1v_r} = 2^l v_r \tag{A4.13}$$

$$f'_{1v_m} = 2 \frac{N}{l} C_m^* \, v_m \tag{A4.14}$$

$$f'_{2v_r} = 2A_m v_m \tag{A4.15}$$

and

$$f'_{2v_m} = 2A_m \, v_r \tag{A4.16}$$

The following equation is obtained by substituting for f_{1V_r} and f_{2V_r} in eqn. (A4.11)

$$f_1 \, 2A_m V_m = 2^{\ell} V_r f_2 \tag{A4.17}$$

or

$$\frac{f_1}{f_2} = \frac{2^{\ell} V_r}{2A_m V_m} \tag{A4.18}$$

Similarly the following equation is obtained by substituting for f'_{1V_m} and f'_{2V_m} in eqn. (A4.12)

$$\frac{f_1}{f_2} = \frac{N C^*_m V_m}{\ell A_m V_r} \tag{A4.19}$$

A relation between V_r and V_m is obtained by equating the right hand sides of eqns. (A4.18) and (A4.19)

$$\frac{f_1}{f_2} = \frac{2^{(\ell-1)} V_r}{A_m V_m} = \frac{N C^*_m V_m}{\ell A_m V_r} \tag{A4.20}$$

Hence

$$\frac{V_r^2}{V_m^2} = \frac{N C^*_m}{\ell 2^{(\ell-1)}} \tag{A4.21}$$

or

$$(V_r/V_m) = \pm (N C^*_m/\ell 2^{(\ell-1)})^{1/2} \tag{A4.22}$$

The expression (A4.2) is a maximum when the ratio given above is positive.

Substituting V_r *in equations (A4.9) and (A4.10)*

$$\delta_1 = 2\frac{N}{\ell} C^*_m \, v^2_m \qquad (A4.23)$$

and

$$\delta_2 = 2A_m (NC^*_m/\ell \, 2^{(\ell-1)}) \, v^2_m \qquad (A4.24)$$

The maximum selection ratio can be obtained by substituting for δ_1 *and* δ_2 *from eqns. (A4.23) and (A4.24) and is given by eqn. (3.122).*

APPENDIX 5

MAXIMIZATION OF SELECTION RATIO IN IHAT-S4

The derivation of the condition for a maximum selection ratio in IHAT-S4 is given here.

The selection ratio is maximum when the following ratio is maximized:

$$R^2 = (V_{ON}/V_{OFF})^2_{rms} = \frac{s_1 + s_2 + s_3}{s_4 + s_5 + s_3} \qquad \text{(A5.1)}$$

This ratio is of the form

$$R^2 = \frac{f_1 + f_2}{f_1 - f_2} \qquad \text{(A5.2)}$$

when the expressions for s_1 to s_5 given by equations (3.141) to (3.145) are substituted in eqn. (A5.1), where,

$$f_1 = V_r^2 \sum_{i=0}^{(\frac{l-1}{2})} (A_i+B_i) + \frac{N}{l}\left[V_{m1}^2 \sum_{i=0}^{m_1} (A_i+B_i) + V_{m2}^2 \sum_{i=m1+1}^{(\frac{l-1}{2})} (A_i+B_i)\right] \qquad \text{.....(A5.3)}$$

and

$$f_2 = 2V_r\left[V_{m1} \sum_{i=0}^{m1} (A_i - B_i) + V_{m2} \sum_{i=m1+1}^{(\frac{l-1}{2})} (A_i - B_i)\right] \qquad \text{(A5.4)}$$

The expressions for f_1 and f_2 can be simplified by the following substitutions

$$\sum_{i=0}^{(\frac{l-1}{2})} (A_i + B_i) = \sum_{i=0}^{(\frac{l-1}{2})} C_i = 2^{(l-1)}\text{ ; by using eqn. (3.5)} \qquad \text{(A5.5)}$$

$$\sum_{i=0}^{m1} (A_i + B_i) = \sum_{i=0}^{m1} C_i = D \qquad \text{(A5.6)}$$

$$\sum_{i=m1+1}^{(\frac{l-1}{2})} (A_i + B_i) = \sum_{i=m1+1}^{(\frac{l-1}{2})} C_i = E \tag{A5.7}$$

$$\sum_{i=0}^{m1} (A_i - B_i) = F \tag{A5.8}$$

and

$$\sum_{i=m1+1}^{(\frac{l-1}{2})} (A_i - B_i) = G \tag{A5.9}$$

Hence,

$$\sigma_1 = v_r^2\, 2^{(l-1)} + \frac{N}{l}(v_{m1}^2 D + v_{m2}^2 E) \tag{A5.10}$$

and

$$\sigma_2 = 2v_r\,[v_{m1} F + v_{m2} G] \tag{A5.11}$$

The following conditions must be satisfied in order to get the maximum selection ratio

$$\sigma_1\, \sigma'_{2v_r} = \sigma'_{1v_r}\, \sigma_2 \tag{A5.12}$$

$$\sigma_1\, \sigma'_{2v_{m1}} = \sigma'_{1v_{m1}}\, \sigma_2 \tag{A5.13}$$

and

$$\sigma_1\, \sigma_{2v_{m2}} = \sigma'_{1v_{m2}}\, \sigma_2 \tag{A5.14}$$

where,

$$\sigma'_{1v_r} = 2^l\, v_r \tag{A5.15}$$

$$\delta'_{1V_{m1}} = \frac{2ND}{\ell} V_{m1} \qquad (A5.16)$$

$$\delta'_{1V_{m2}} = \frac{2NE}{\ell} V_{m2} \qquad (5.17)$$

$$\delta'_{2V_r} = 2(F\, V_{m1} + G\, V_{m2}) \qquad (A5.18)$$

$$\delta'_{2V_{m1}} = 2FV_r \qquad (A5.19)$$

$$\delta'_{2V_{m2}} = 2GV_r \qquad (A5.20)$$

The following equations are obtained by substituting for δ_2, δ'_{1V_r} and δ'_{2V_r} in eqn. (A5.12)

$$\delta_1 2[FV_{m1} + GV_{m2}] = 2^{\ell} V_r 2V_r[FV_{m1} + GV_{m2}] \qquad (A5.21)$$

Hence,

$$\delta_1 = 2^{\ell} V_r^2 \qquad (A5.22)$$

The following equation is obtained by substituting for $\delta'_{1V_{m1}}$ and $\delta'_{2V_{m1}}$ in eqn. (A5.13)

$$\delta_1\, 2F\, V_r = \frac{2ND}{\ell} V_{m1}\, \delta_2 \qquad (A5.23)$$

or

$$\frac{\delta_1}{\delta_2} = \frac{NDV_{m1}}{\ell F V_r} \qquad (A5.24)$$

Similarly the following equation is obtained by substituting $\delta'_{1V_{m2}}$ and $\delta'_{2V_{m2}}$ in eqn. (A5.14)

$$\frac{\delta_1}{\delta_2} = \frac{N\, E\, V_{m2}}{\ell\, G\, V_r} \qquad (A5.25)$$

A relation between the column voltages V_{m1} and V_{m2} is obtained by equating eqns. (A5.24) and (A5.25) as given below.

$$\frac{\delta_1}{\delta_2} = \frac{N\,D\,V_{m1}}{\ell\,F\,V_r} = \frac{N\,E\,V_{m2}}{\ell\,G\,V_r} \qquad (A5.26)$$

or

$$V_{m2} = \frac{DG}{EF}\,V_{m1} \qquad (A5.27)$$

The following relation is obtained by using eqns. (A5.10) and (A5.21)

$$\delta_1 = 2^{(\ell-1)}V_r^2 + \frac{N}{\ell}(DV_{m1}^2 + EV_{m2}^2) = 2^{\ell}\,V_r^2 \qquad (A5.28)$$

or

$$2^{(\ell-1)}\,V_r^2 = \frac{N}{\ell}(DV_{m1}^2 + EV_{m2}^2) \qquad (A5.29)$$

Hence

$$\delta_1 = 2^{\ell}\,V_r^2 = 2\,\frac{N}{\ell}(DV_{m1}^2 + E\,V_{m2}^2) \qquad (A5.30)$$

An expression for V_r is obtained by substituting for V_{m2}^2 in the above equation using eqn. (A5.27)

$$V_r^2 = \frac{N}{2^{(\ell-1)}\,\ell}[D + E\,(\frac{DG}{EF})^2]\,V_{m1}^2 \qquad (A5.31)$$

or

$$V_r^2 = \frac{ND}{2^{(\ell-1)}\,\ell\,F}\;\frac{(EF^2 + DG^2)}{EF}\;V_{m1}^2 \qquad (A5.32)$$

Hence,

$$V_r = \pm \left(\frac{ND}{2^{l-1}\, lF} \right)^{1/2} \left(\frac{EF^2 + DG^2}{EF} \right)^{1/2} V_{m1} \qquad (A5.33)$$

The selection ratio is maximum when the positive root is considered.

The expression for δ_1 is obtained by substituting for V_r^2 from eqn. (A5.32),

$$\delta_1 = 2^l V_r^2 = \frac{2ND}{lF} \frac{(EF^2 + DG^2)}{EF} V_{m1} \qquad (A5.34)$$

The following expression for δ_2 is obtained by substituting for V_{m2} and V_r in eqn. (A5.11) using eqns. (A5.27) and (A5.33)

$$\delta_2 = 2 \frac{(EF^2 + DG^2)}{EF} \left(\frac{ND}{2^{(l-1)}\, lF} \right)^{1/2} \left(\frac{EF^2 + DG^2}{EF} \right)^{1/2} V_{m1}^2 \qquad (A5.35)$$

The maximum selection ratio can be obtained by substituting for δ_1 and δ_2 from (A5.34) and (A5.35) and is given by equation (3.152).

APPENDIX 6.a

Reproduction of a paper presented in the International Conference on Liquid Crystals, Bangalore, December 3-8, 1979.
Ref: Liquid Crystals, Proceedings of an International Conference held at Bangalore, Ed. S.Chandrasekhar, Heyden, pp. 499-503, 1980.

A CONVENIENT MULTIPLEXING SCHEME FOR ADDRESSING SMALL LIQUID CRYSTAL MATRIX DISPLAYS

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In this paper, a convenient method for multiplexing small liquid crystal matrix displays is presented. For a matrix of N rows, the method consists of addressing the rows with all possible combinations of a binary voltage scheme. For each of these 2^N combinations, a proper binary voltage is selected for each of the columns to get a majority-advantage compared to the picture pattern to be displayed. A mathematical analysis of this scheme is given. Though the contrast ratio with the present scheme is slightly less than that obtained with the conventional scheme it has the advantage of having a very large duty factor and of requiring only one power supply. The simplicity of the scheme is exploited to construct and operate a 16-segment alphanumeric display panel.

INTRODUCTION

For many low cost, high volume type of applications, it would be useful to have relatively cheap, multiplexed alphanumeric liquid crystal displays (LCDs). We have tried to develop such a display with simple circuitry.

THE MULTIPLEXING SCHEME

From the practical point of view, it is an extremely simple matter to generate a sequence of binary numbers using a counter. We have made use of this facility in developing an addressing scheme suitable for LCDs.

Consider a matrix with N rows. For reasons which will be obvious soon, let N be an odd number. If, as usual, 1 stands for 'high' and 0 for 'low' voltages (positive logic) a total of 2^N different signals (which are the possible N-bit binary numbers) can be applied to the N rows. With each of these possible voltage-patterns on the rows, we will apply such a voltage to a given column that the error with reference to the required pattern is minimised. This is illustrated in Fig.1 for a matrix with 5 rows. In general, if '1' is $+V_r$ and '0' is $-V_r$ on the rows, we can apply either $+V_c$ or $-V_c$ to the columns. Only the RMS voltage is relevant to the electro-optic response of the LCD and at any given time the squared voltage on any given element is $(V_r+V_c)^2$ or $(V_r-V_c)^2$. It is not necessary to consider all the 2^N possible binary numbers applied to the rows, since one half of them will be complementary to the other half (see fig.1). Let us assume that a given element in a given column should be 'ON'. The RMS voltage on that element can be calculated as follows: Let P be the number of times that the element has a squared voltage equal to $(V_r+V_c)^2$. In the remaining number of scans, viz.,

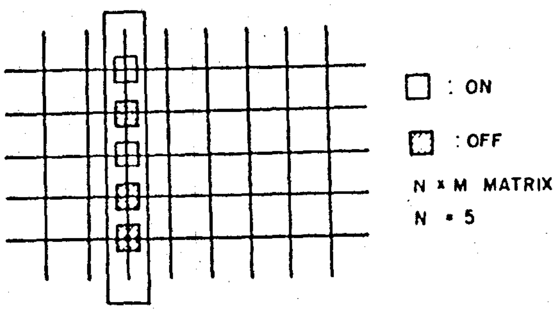
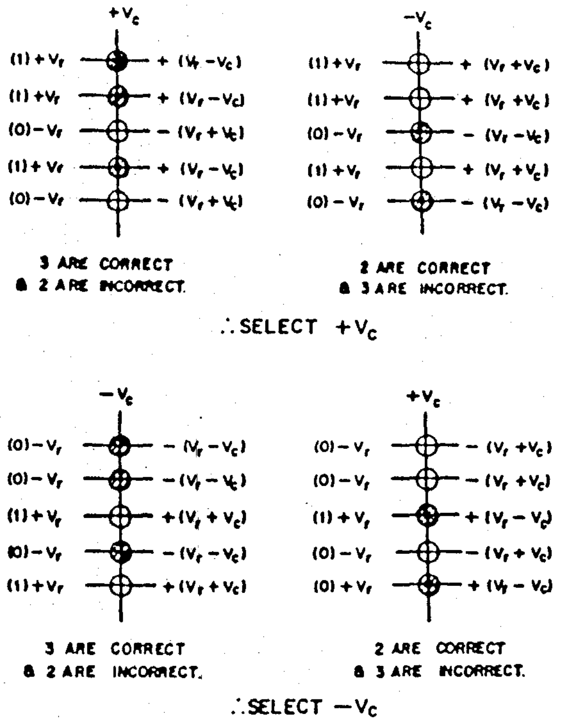


Figure 1.

(a) Schematic diagram of a matrix with 5 rows. The required picture-pattern of only one column is shown.



(b) Illustration of the scheme of selection of the row and column voltages used to reproduce the picture elements shown in Fig.1(a). In the upper section of the figure, the binary number defining the voltages applied to the rows is 11010. $+V_c$ is selected as the column voltage to minimise the errors. In the lower section of the figure, the rows get voltages corresponding to the binary number 00101 (i.e., complementary to 11010), with $-V_c$ selected for the column. Notice that in the complementary scan the polarities of the voltages on all the picture elements are reversed.

$(2^{N-1}-P)$ scans, that element will have a squared voltage equal to $(V_r-V_c)^2$. Only once during the 2^{N-1} scans, all the elements of the given column will have the correct voltages (i.e., 'ON' elements have $(V_r+V_c)^2$ and 'OFF' elements have $(V_r-V_c)^2$). There will be one mistake in N out of the 2^{N-1} scans. However, we want the given element to be 'ON'. So, in (N-1) scans the given element is 'ON' when the picture-pattern in the given column has one mistake. This can also be written as (N-1)!/1!(N-2)! which is the number of ways of selecting one out of (N-1) elements of the column.

In a similar manner, when there are two mistakes in the picture-pattern, excluding the cases where the given element has a mistake, the number of times it is 'ON' is (N-1)!/2!(N-3)!.

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We can continue this series till we reach the maximum possible error. By choice, this error cannot exceed (N-1)/2. The counting procedure is illustrated for N = 5 in figure 2.

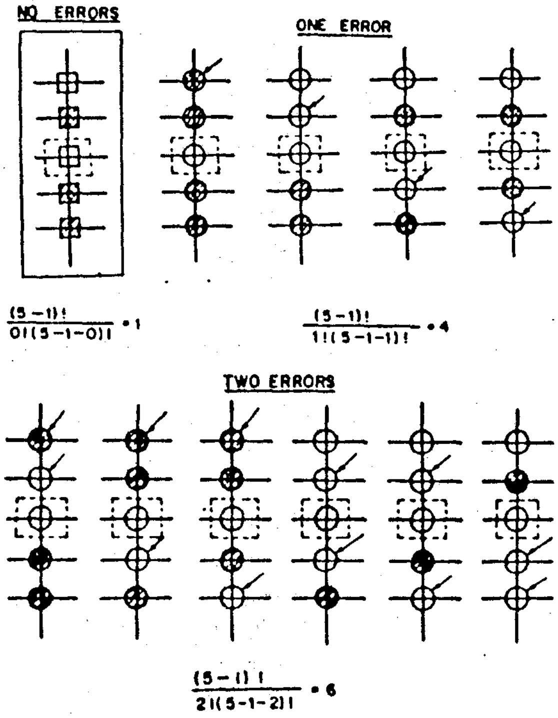


Figure 2.
Illustration of the method of counting the number P (as defined in the text) for a matrix with 5 rows. The central picture element (enclosed in a box with dashed lines) of the column shown in fig.1(a) is chosen for the purpose of calculating P. The arrows indicate errors compared to the pattern in fig.1(a).

Hence the total number of scans for which an 'ON' element has $(V_r+V_c)^2$ as the squared voltage is given by

$$P = \sum_{m=0}^{\frac{N-1}{2}} \frac{(N-1)!}{m!(N-1-m)!} \tag{1}$$

In the remaining $(2^{N-1}-P)$ scans, the element has $(V_r-V_c)^2$ as the squared voltage. Hence the RMS voltage on the 'ON' element is

$$V_{ON}(RMS) = \left[\frac{P(V_r+V_c)^2+(2^{N-1}-P)(V_r-V_c)^2}{2^{N-1}}\right]^{\frac{1}{2}} \tag{2}$$

In a similar manner,

$$V_{OFF}(RMS) = \left[\frac{P(V_r-V_c)^2+(2^{N-1}-P)(V_r+V_c)^2}{2^{N-1}}\right]^{\frac{1}{2}} \tag{3}$$

It can be easily shown that V_{ON}/V_{OFF} is optimised for $V_r = V_c$. Then

$$V_{ON}/V_{OFF} = \sqrt{P/(2^{N-1}-P)} \tag{4}$$

Let $V_r = V_c = V$. In fact we can chose '1' to be 'V' and '0' to be zero itself. Thus a single source of voltage is adequate to address the display. Further, when we scan through the complementary 2^{N-1} binary numbers, any given element will get an equal number of voltage pulses of opposite sign, so that a DC-free operation is automatically ensured (see also fig.1).

When N is even, it is clear that the choice of the voltage to be applied to the column electrode becomes ambiguous when N/2 mistakes occur for a given voltage-pattern on the row-electrodes. Covering both the possibilities is equivalent to scanning a matrix with (N+1) rows, i.e., eqn.(4) holds good with N replaced by N+1.

It is also clear that since a total of 2^N scans are needed to cover all possibilities, the number of scans rapidly increases with N. Hence this method of addressing is useful only for small matrices.

The optical contrast ratio depends on the RMS value of (V_{ON}/V_{OFF}). It is listed below for a few values of N and compared with the values for the conventional scanning method due to Alt and Pleshko[1].

RMS value of (V_{ON}/V_{OFF})

	Present method R_P	Alt and Pleshko R_{AP}	R_{AP}/R_P
N = 3	1.732	1.932	1.115
N = 5	1.483	1.618	1.091
N = 7	1.382	1.488	1.077
N = 9	1.324	1.414	1.068

Hence the Alt and Pleshko values are always higher than the ones got by the present method. However, as N increases the two values approach each other.

Nontheless, in view of the advantages of the new method, viz., (a) need for a single voltage source, and (b) DC-free operation, we have used it in addressing a 16-segment alphanumeric display. An additional advantage is that since, in the present method, an ON element is 'ON' most of the time (i.e., it has a relatively 'large' duty factor) a flicker-free operation is ensured even with relatively low scanning rates. (This may be compared with the duty factor of 1/N in the conventional method).

We very recently came across a paper by Clark et al[2] in which they appear to have considered a similar multiplexing technique. By using the results of a computer simulation analysis, they have conjectured that

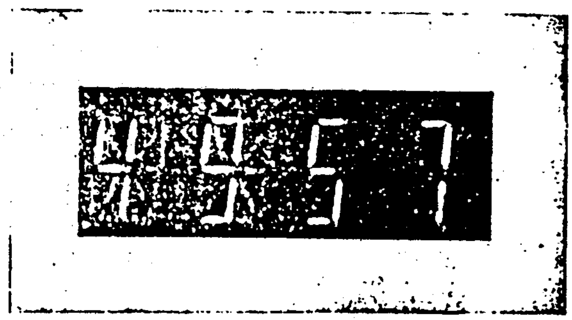
$$V_{ON}/V_{OFF} = \left[1+\left\{\frac{2^{2q-1}}{\binom{2q}{q}} - \frac{1}{2}\right\}^{-1}\right]^{\frac{1}{2}} \tag{5}$$

where q is an integer, N = 2q+1 and $\binom{2q}{q}$ denotes a binominal coefficient. By using binominal series, it can be easily shown that (4) reduces to (5). Thus our mathematical analysis confirms the conjecture by Clark et al.

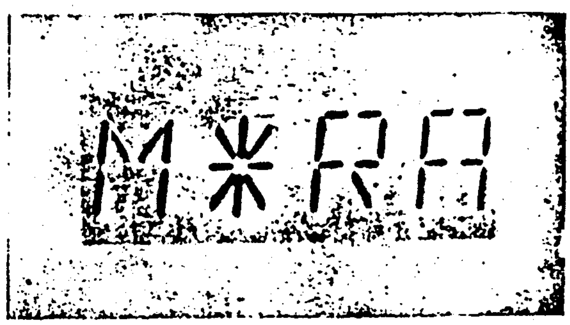
16-SEGMENT ALPHANUMERIC DISPLAY

We treat each character as a 4 × 4 matrix. The interconnections on the top and bottom plates are shown in figure 3.

Since we did not have a standard character generator IC for addressing such a display, a 1702EPROM was programmed to convert the ASCII code from a key board



a



b

Figure 5 Photographs of two alpha-numeric patterns of a TN display panel with (a) parallel polarizers and (b) perpendicular polarizers.

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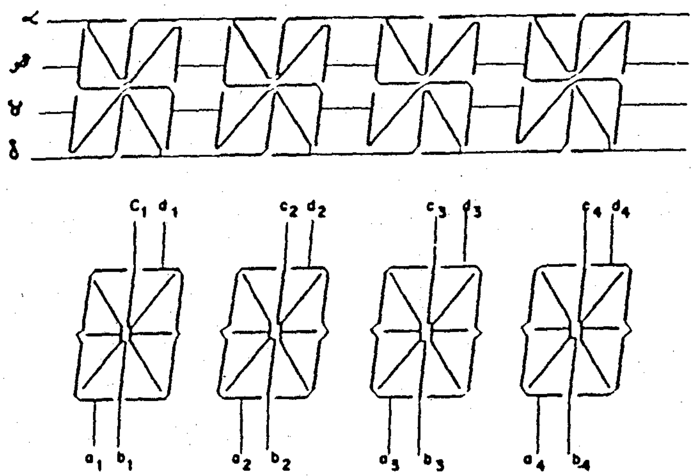

Figure 3.

The electrode patterns and the interconnections on the top and bottom plates of the display panel.

to the code necessary to address this display. The total memory required for 64 characters is $64 \times 4 \times 4 = 1024$ in the organisation 256×4. The block diagram of the system is given in figure 4. The logic circuitry required to produce the data for columns is simple and consists only of finding the number of coincidences of the column data with the addressing waveform and making a simple majority decision.

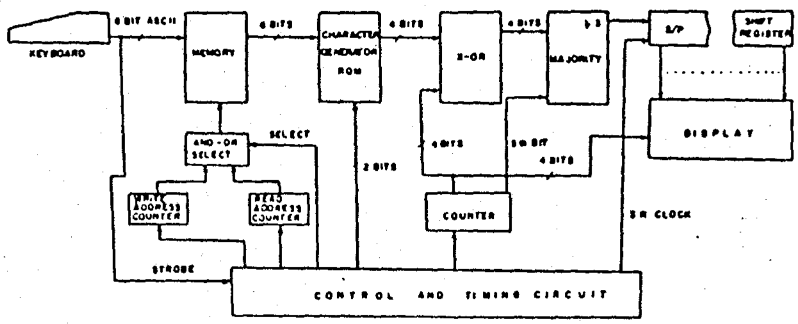

Figure 4.

Block diagram of the display system.

Photographs of some preliminary twisted nematic displays constructed on the basis of this scheme are shown in figure 5. We feel that if the display performance is optimized by a suitable choice of materials, this will be a convenient method of addressing the displays.

ACKNOWLEDGEMENT

We are indebted to Prof. S. Chandrasekhar for several useful discussions. Our thanks are also due to Mr. K. Subramanya and to Mr. H. Subramonyam for help in constructing the displays. This work was partially supported by the Indian Space Research Organization.

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APPENDIX 6.b

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NEW ADDRESSING TECHNIQUES FOR MULTIPLEXED LIQUID CRYSTAL DISPLAYS

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Abstract – A binary addressing technique (BAT) for multiplexing liquid crystal displays (LCDs) is described. It requires addressing waveforms with only two voltage levels, and leads to a naturally dc-free operation. The method is suitable only for small matrices ($N<9$). We propose a hybrid addressing technique (HAT) which combines the features of both BAT and the familiar Alt and Pleshko technique (APT). It is shown that HAT can be used for large matrices. The three techniques are compared.

I. INTRODUCTION

The Alt and Pleshko technique (APT)[1] is widely used in multiplexing liquid crystal displays (LCDs). An alternative technique which will be referred to as the binary addressing technique (BAT)[2] was proposed recently (see, also, Ref. 3). In this technique all the N rows to be multiplexed are selected simultaneously with voltage levels $\pm V_r$ corresponding to 1 or 0, so that the voltage pattern applied to the rows corresponds to an N digit binary number. This is compared with the binary pattern to be displayed in a given column and the column voltage is decided as $+V_c$ or $-V_c$ such that a majority of rows get a favorable voltage. Now, the row address pattern is changed to a new N-digit binary number and the process is continued until all the 2^N possible combinations are exhausted, and the cycle is then repeated. The principal merits of the technique are (a) it requires a single relatively low power supply and (b) a natural dc-free operation. To demonstrate this technique, we constructed a 16-segment alphanumeric display[2] which was treated as a 4×4 matrix. Since the binary addressing technique can be used only for an odd number of rows,[2] N was chosen to be 5. The details are given in Ref. 2 along with some photographs of the display, which had an acceptable contrast. However, BAT is not suitable if $N>9$ or 11, since the number of time intervals to complete a cycle takes a very high value.

In this paper, we will briefly review BAT and propose a combination of BAT and APT. It will be called the hybrid addressing technique (HAT) and can be used for relatively large values of N. In this technique the total N rows to be multiplexed are divided into N/n non-intersecting subsets, each consisting of n rows. At a given instant of time one of these subsets is subject to BAT while the rest of the rows are at ground potential. A cycle is complete when all the subsets are subjected to binary addressing. The features of the three techniques are compared in Table I.

II. THE BINARY ADDRESSING TECHNIQUE

In a multiplexed display with n rows, if the information to be displayed is bilevel (i.e., the segment is either ON or OFF), the pattern to be displayed in a column can be represented by $d_1, d_2, \ldots, d_n$; $d_i = 0$ or 1. In this addressing technique, the rows are applied with voltages corresponding to an n bit pattern $a_1, a_2, \ldots, a_n$; $a_i = 0$ or 1. A bit-by-bit comparison is made between the two patterns, and the number of anticoincidences (mismatches) is counted. Mathematically, we have to find s where

$$s = \sum_{i=1}^{n} a_i \oplus d_i$$

where $\oplus$ is an exclusive OR operation. The column voltage is decided by a majority decision, i.e., if $s>n/2$, the column voltage will correspond to 1, otherwise to 0. This reduces the number of errors in that column. Now, $a_1, a_2, \ldots, a_n$ is changed to a new binary pattern and the procedure is repeated. A cycle is complete when all the n-bit binary combinations are exhausted, i.e., after 2^n intervals. Since a majority decision is needed in this technique, n has to be odd.

The voltages across an element with different conditions during an interval are given in Table II.

Now it is required to calculate the number of times an element gets the correct voltage during one cycle. We will consider only 2^{n-1} intervals such that they are com-

TABLE I. Comparison of the features of the three techniques.

	APT	BAT	HAT
V_{ON}/V_{OFF}	High	Low	Intermediate
Address duty factor	$1/N$	$P/2^{n-1}$	$nP/2^{n-1}N$
V_r/V_c	$\sqrt{N}$	1	$\sqrt{N/n}$
Power supply voltage	High	Low	Intermediate
Number of voltage levels across an element	4	3	6
Number of intervals to complete a cycle	N	2^n	$2^n(N/n)$

TABLE II. Voltage across an element with different conditions during an interval.

Column	Row	
Logic level/voltage	logic level/voltage	
	$0/-V_c$	$1/+V_c$
$0/-V_r$	$-(V_r - V_c)$ OFF	$-(V_r + V_c)$ ON
$1/+V_r$	$+(V_r + V_c)$ ON	$+(V_r - V_c)$ OFF

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TABLE III. Values of P and V_{ON}/V_{OFF} for various values of n.

No. of rows multiplexed	P	V_{ON}/V_{OFF} BAT	APT
$n=3$	3	1.732	1.932
$n=5$	11	1.483	1.618
$n=7$	42	1.382	1.488
$n=9$	163	1.324	1.414

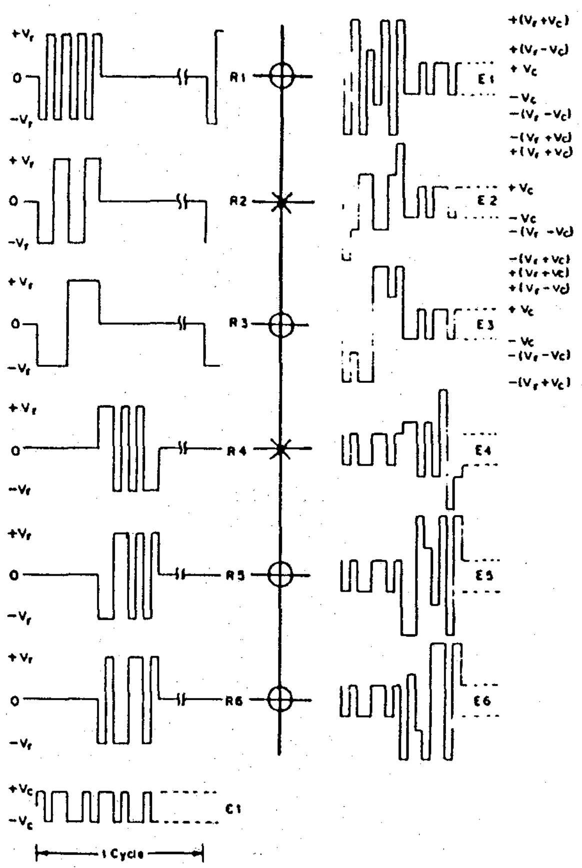

FIG. 1. Representative Waveforms for HAT R1-R6 are the waveforms applied to rows 1-6, respectively, and C1 is the waveform applied to a column. Note that R3-R1 are applied with the binary pattern sequence 000, 001, 010, 011, 100, 101, 110, and 111, whereas R6-R4 are applied with the binary pattern sequence 001, 101, 010, 011, 100, 111, 000, and 110. The sequence in which the 2^n combinations are applied to the rows does not alter the rms voltage across an element, but has an effect on the frequency spectrum of the waveform across the element.

plementary to the remaining 2^{n-1} intervals. As shown in Ref. (2), the number of times (say P) an element gets the correct voltage is given by

$$P=\sum_{m=0}^{\frac{n-1}{2}} \frac{(n-1)!}{m!(n-1-m)!}.$$

The expressions for V_{ON} and V_{OFF} can be written as follows:

$$V_{ON}=\left(\frac{2P(V_r+V_c)^2+2(2^{n-1}-P)(V_r-V_c)^2}{2^n}\right)^{1/2},$$

$$V_{OFF}=\left(\frac{2P(V_r-V_c)^2+2(2^{n-1}-P)(V_r+V_c)^2}{2^n}\right)^{1/2}.$$

The V_{ON}/V_{OFF} ratio is optimized for $V_r/V_c = 1$. Table III shows the values of P, and V_{ON}/V_{OFF} for various values of n.

III. THE HYBRID ADDRESSING TECHNIQUE

Here we use the binary addressing technique to address a subset consisting of n rows of the total N rows, while the rest of the $N-n$ rows are at ground potential. After completion of 2^n intervals, a different subset with n rows is scanned with BAT. The rows to be scanned by BAT can be represented by $ni+1$, $ni+2$, . . . $ni+n$, where i takes the values 0 to $[(N/n)-1]$.

Representative wave forms for the hybrid addressing technique are given in Fig. 1.

The rms voltage across the ON and OFF elements are given by

$$V_{ON}=\left(\frac{2P(V_r+V_c)^2+2(2^{n-1}-P)(V_r-V_c)^2+2^n[(N/n)-1]V_c^2}{2^n(N/n)}\right)^{1/2} \tag{1}$$

and

$$V_{OFF}=\left(\frac{2P(V_r-V_c)^2+2(2^{n-1}-P)(V_r+V_c)^2+2^n[(N/n)-1]V_c^2}{2^n(N/n)}\right)^{1/2}. \tag{2}$$

The V_{ON}/V_{OFF} ratio is optimized for $V_r/V_c = \sqrt{N/n}$. Substituting this into Eqs. (1) and (2), we get

$$V_{ON}=\left(\frac{2^n(N/n)+(N/n)^{1/2}(4P-2^n)}{2^{n-1}(N/n)}\right)^{1/2},$$

$$V_{OFF}=\left(\frac{2^n(N/n)-(N/n)^{1/2}(4P-2^n)}{2^{n-1}(N/n)}\right)^{1/2},$$

$$\frac{V_{ON}}{V_{OFF}}=\left(\frac{(N/n)^{1/2}2^n+(4P-2^n)}{(N/n)^{1/2}2^n-(4P-2^n)}\right)^{1/2}=\sqrt{K}. \tag{3}$$

Figure 2 gives a comparison of the V_{ON}/V_{OFF} ratio obtained for differeht values of N in both APT and HAT.

The supply voltage needed to address a multiplexed display using APT has been shown to be $(V_r + V_c)$ by Kawakami *et al.*[4] This can be achieved by the synthesis of suitable waveforms applied to both the rows and columns.

$$V_r+V_c=\frac{\sqrt{N}+1}{\sqrt{2[1-(1/\sqrt{N})]}}V_{th}, \tag{4}$$

where V_{th} is the threshold voltage of the liquid crystal. In

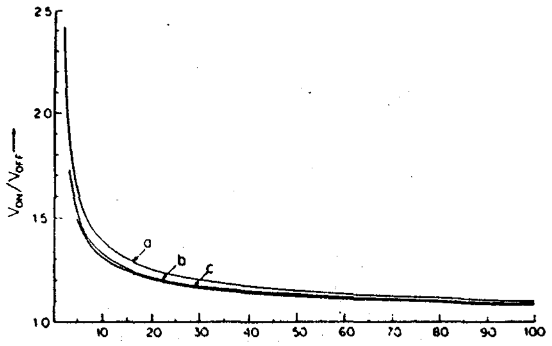

FIG. 2. Plot of V_{ON}/V_{OFF} vs. N for (a) ALT, Pleshko (b) HAT with n = 3, and (c) HAT technique with n = 5.

the case of HAT, it does not appear to be possible to rearrange the row and column address waveforms to reduce the power supply requirement to less than $2V_r$, which is given by the following expression:

$$2V_r = \left(\frac{2(N/n)}{1 - [(4P-2^n)/2^n\,(N/n)^{1/2}]} \right)^{1/2} V_{th}. \tag{5}$$

However, APT gives a higher contrast ratio than HAT. In order to make a proper comparison between the power supply requirements in the two cases, we reduce the V_{ON}/V_{OFF} ratio given by APT to the optimum value given by HAT, i.e.,

$$\left(\frac{V_{ON}}{V_{OFF}} \right)^2 = K = \frac{(x+1)^2 + (N-1)}{(x-1)^2 + (N-1)}, \tag{6}$$

where K is given by Eq. (3) and $x = V_r/V_c$ of APT which would give the same contrast ratio as HAT. This leads to the following expression for x:

$$x = \frac{(K+1) - [(K+1)^2 - (K-1)^2 N]^{1/2}}{(K-1)}.$$

Using this, we get the power supply voltage required for the degraded APT as

$$(V_r + V_c) = \left(\frac{N}{(x-1)^2 + (N-1)} \right)^{1/2} (x+1) V_{th}. \tag{7}$$

IV. RESULTS

The salient features of the three techniques are summarized in Table I. We give a comparison of the power supply requirements given by HAT [Eq. (4)] and the degraded APT [Eq. (7)] in Table IV for various values of N and n. If $n = N$, we recover BAT. As can be seen from Table I, the power supply requirement of HAT is lower than that of the degraded APT if n is large. For any n, the advantage decreases as N increases.

We constructed a twisted nematic (TN) cell to make an experimental comparison between the two techniques. The liquid crystal used had a threshold voltage V_{th} = 1.45 V and a steepness γ [$=(V_{50} - V_{10})/V_{10} \times 100$] = 17%. The percentage transmission as a function of the power supply voltage ($= V_r + V_c$) when the cell is addressed as if it is an ON and an OFF element of APT with N = 15 are shown in Fig. 3 as curves A and B, respectively. The same cell was addressed using HAT with n = 3 and N = 15. The corresponding percentage transmission coefficients as functions of the power supply voltage ($=2V_r$) are shown in Fig. 4.

In Fig. 5, we show the transmission curves for APT which is degraded to give the same V_{ON}/V_{OFF} as HAT with N = 15 and n = 5. These can be compared with the transmission curves for HAT shown in Fig. 6. It is clear that the power supply voltage required by HAT is lower than that for APT as expected from Table IV. The experimental values which are accurate to ~2% agree with the calculated values given in Table IV.

TABLE IV. Comparison of the power supply requirements given by HAT and the APT for various values of N and n.

N	n	Supply voltage of HAT $2V_r$ ($\times V_{th}$)	V_r/V_c of APT for same contrast as HAT	APT supply voltage $V_r + V_c$ ($\times V_{th}$)	$\frac{\text{V supply}_{HAT}}{\text{V supply}_{APT}} \times 100$
3	3	2.0 V	1.0	2.449 V	81.65
6	3	2.487 V	1.415	2.601 V	95.62
5	5	1.789 V	1.214	2.461 V	72.69
10	5	2.333 V	1.718	2.786 V	83.73
15	5	2.767 V	2.105	3.082 V	89.77
20	5	3.138 V	2.432	3.345 V	93.80
25	5	3.466 V	2.714	3.578 V	96.87
30	5	3.764 V	2.981	3.8 V	99.05
7	7	1.706 V	1.400	2.558 V	66.69
14	7	2.266 V	1.977	2.982 V	76.00
21	7	2.706 V	2.422	3.342 V	80.97
28	7	3.079 V	2.794	3.652 V	84.42
35	7	3.409 V	3.132	3.937 V	86.60

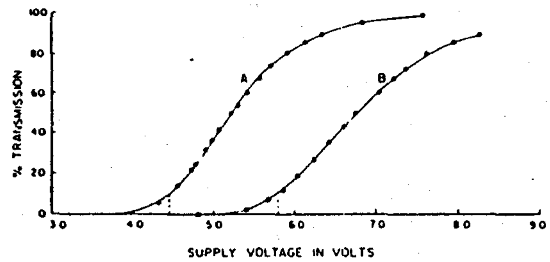

FIG. 3. Plot of transmission characteristics of a TN LC cell addressed by APT as modified in Ref. 4 for N = 15. A and B are the selected and nonselected elements, respectively.

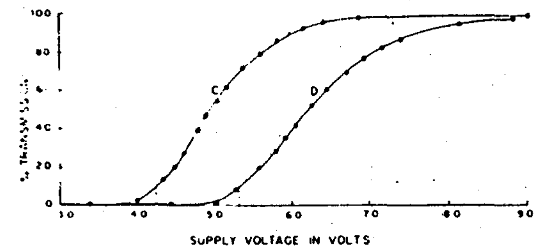

FIG. 4. Plot of transmission characteristics of a TN LC cell addressed by HAT with N = 15 and n = 3. C and D are selected and nonselected elements, respectively.

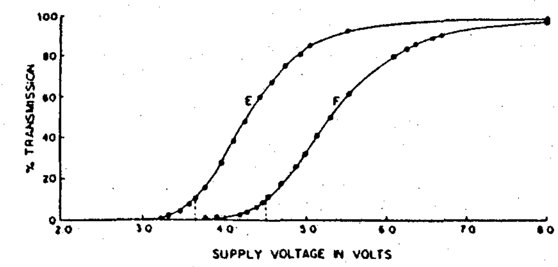

FIG. 5. Plot of transmission characteristics of a TN LC cell addressed by a degraded APT [see Eq. (7)] for $N = 15$ which has the same V_{ON}/V_{OFF} ratio as HAT with $N = 15$ and $n = 5$. E and F are selected and nonselected elements, respectively.

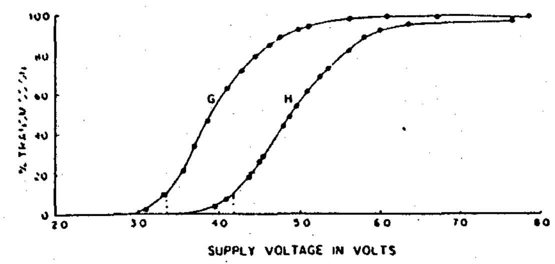

FIG. 6. Plot of transmission characteristics of a TN cell addressed by HAT with $N = 15$ and $n = 5$. G and H are selected and nonselected elements, respectively.

V. CONCLUSIONS

A binary addressing technique, which requires a single supply voltage has been described. It depends on scanning the N-row matrix, with the binary voltages corresponding to the 2^N possible N-digit binary numbers. It is useful for small matrices ($N<9$ or 11). A hybrid technique which combines BAT with APT in which the matrix is addressed line by line has been proposed to overcome this limitation. In many cases, this results in some reduction in the power supply requirement compared to the APT scheme. We have illustrated this point by studying the transmission characteristics of both the ON and OFF elements of a TN cell while being addressed by HAT and APT.

ACKNOWLEDGEMENT

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APPENDIX 6.c

Reproduction of a paper presented in SID International Symposium 1986.
Ref: SID Int. Symp. Dig. Tech. Papers., pp. 128-131.

8.3: An LCD for Multitrace Oscilloscopes

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Abstract

A liquid crystal oscilloscope display for multiple waveforms uses an addressing technique which exploits the restricted patterns in such displays to achieve a higher contrast ratio than conventional multiplexing. The selection ratio depends on the number of waveforms displayed but not on matrix size.

Introduction

Matrix displays for oscilloscopes and logic analyzers have to display multiple waveforms, which are mostly single valued functions of time. A large matrix (with 256 rows or more) is preferred so that the waveforms can be displayed without sacrificing finer details. The selection ratio obtained for a matrix with a large number of rows is low if the Alt and Pleshko line by line addressing technique (APT) is employed [1,2].

In order to achieve a high contrast ratio special techniques have been developed for oscilloscopes displaying single waveforms [3]. The N rows in the matrix are sequentially selected with low duty ratio (1/N) rectangular pulses of amplitude V. The column voltage is 0 volts for the 'ON' elements and a voltage V, (which is in-phase with the row select voltage) for the 'OFF' elements. Since the display has only one selected element ('OFF') per column, this technique achieves infinite selection ratio with 0 voltage across the 'OFF' elements which are points on the displayed waveform and $(2/N)^{1/2}.V$ across the background 'ON' elements.

In another technique, the correlation properties of pseudorandom binary sequences is used [4]. It is again possible to display a single waveform with infinite selection ratio.

Dual-traces have been displayed by using interleaved vertical electrodes, i.e., by using odd columns for one trace and even columns for the other. The horizontal resolution is sacrificed without any compromise in the selection ratio [5].

Alternatively, multitrace operation is possible if n waveforms are multiplexed in sequential frame periods. The selection ratio is $[n/(n-1)]^{1/2}$ without any compromise in horizontal resolution [5].

Theoretically, it has been shown by earlier workers [6,7] that a selection ratio higher than that of the APT can be obtained for restricted patterns. Further, the selection ratio is higher when most of the elements are 'ON' compared to the case when most of the elements are 'OFF', in a given column [6,7]. This theoretical conclusion has not been exploited for displaying multitraces in an oscilloscope.

In the present work we have developed an addressing technique for displaying multiple traces. It is important to note that the selection ratio depends only on the number of selected elements in a column (n = number of waveforms) and is independent of the total number of rows (N) in the matrix. This is in contrast to the results of Ref. 6 and 7, wherein the selection ratio is a function of both N and n.

Technique

Consider a matrix with N rows and M columns. Let the number of waveforms to be displayed be n. As discussed above, a better selection ratio is obtained when (N-n) elements are 'ON' and n are 'OFF' in a given column. This will result in a negative contrast for twisted nematic displays and a positive contrast when the guest-host mode is used.

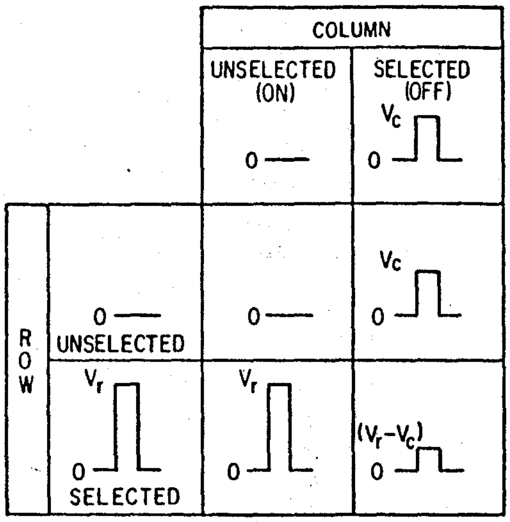

Fig: 1.a. D.C. Addressing of the Display.

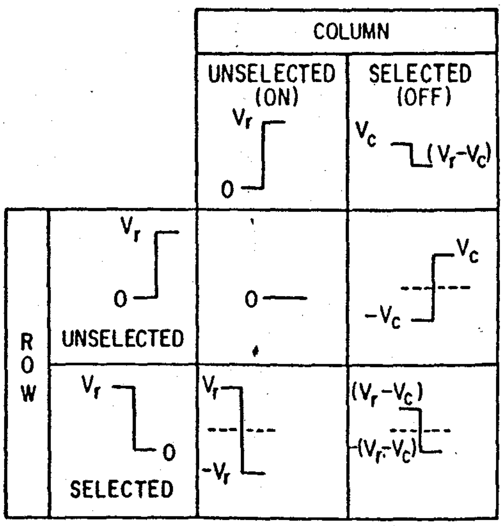

Fig: 1.b. A.C. Addressing of the Display.

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For the sake of clarity, we shall first discuss the dc addressing scheme (Fig. 1). The N rows in the matrix are selected one at a time with a row select voltage V_r while the unselected rows are grounded. The column (data) voltage is chosen to be 0 volts for an 'ON' element (background pixel) and a voltage V_c, which is in phase with the row select voltage, for an 'OFF' element (selcted pixel which is a point on the waveform). Since there are n waveforms to be displayed, any column in the matrix will get a voltage V_c for n time intervals and 0 volts in the rest of the (N-n) time intervals. The rms voltages across an element determines its state. The voltage across 'ON' and 'OFF' elements are given by

$$V_{ON(rms)} = [\frac{V_r^2+nV_c^2+(N-n-1)0}{N}]^{1/2} \quad (1)$$

$$V_{OFF(rms)} = [\frac{(V_r-V_c)^2+(n-1)V_c^2+(N-n)0}{N}]^{1/2} \quad (2)$$

The V_{ON}/V_{OFF} ratio is optimized for $V_r/V_c = n^{1/2}$, which is independent of the total number of rows (N) in the matrix. Substituting this in equations (1) and (2) we get

$$V_{ON} = [\frac{2n}{N}]^{1/2} V_c = [\frac{2}{N}]^{1/2} V_r \quad (3)$$

$$V_{OFF} = [\frac{2n-2\sqrt{n}}{N}]^{1/2} V_c = [\frac{2\sqrt{n}-2}{N\sqrt{n}}]^{1/2} V_r \quad (4)$$

The selection ratio V_{ON}/V_{OFF} is given by

$$R = \frac{V_{ON}}{V_{OFF}} = [\frac{2\sqrt{n}}{2\sqrt{n}-2}]^{1/2} = [\frac{\sqrt{n}}{\sqrt{n}-1}]^{1/2} \quad (5)$$

In order to compare this with the selection ratio obtained in APT the equation (5) is written in the form

$$R = \left[\frac{\sqrt{N_{eq}}+1}{\sqrt{N_{eq}}-1}\right]^{1/2} \quad (6)$$

where N_{eq} gives the number of rows to be multiplexed to obtain the same selection ratio

$$\frac{V_{ON}}{V_{OFF}} = \left[\frac{2\sqrt{n}}{2\sqrt{n}-2}\right]^{1/2} = \left[\frac{\sqrt{(2\sqrt{n}-1)^2}+1}{\sqrt{(2\sqrt{n}-1)^2}-1}\right]^{1/2} \quad (7)$$

Hence N_{eq} for this technique is $(2\sqrt{n}-1)^2$. Table 1 gives the selection ratio and N_{eq} against the number of waveforms to be displayed.

The supply voltage is determined by the amplitude V_r. The 'ON' elements can be biased to V_{s90}(90% of the saturation in the transmission characteristics).

$$V_{ON} = V_{s90} = [2/N]^{1/2} V_r \quad (8)$$

$$V_{supply} = V_r = [N/2]^{1/2} \cdot V_{s90} \quad (9)$$

The supply voltage increases with the matrix size and is independent of the number of waveforms displayed (n). In order to achieve a dc free operation the phase of the row and column waveforms are reversed as in Fig. 2.

Table 1

Comparison between the present technique and multitrace display by multiplexing the waveforms to be displayed frame by frame. N_{eq} gives the number of rows to be multiplexed if APT is used in order to achieve the same selection ratio.

n	Present technique		Multitrace by frame multiplexing of waveforms	
	Selection ratio $[\frac{\sqrt{n}}{\sqrt{n}-1}]^{1/2}$	N_{eq} $(2\sqrt{n}-1)^2$	Selection ratio $[\frac{n}{n-1}]^{1/2}$	N_{eq} $(2.n-1)^2$
1	∞	1.00	∞	1
2	1.848	3.34	1.414	9
3	1.538	6.07	1.225	25
4	1.414	9.00	1.155	49
5	1.345	12.05	1.118	81
6	1.300	15.20	1.095	121
7	1.268	18.41	1.080	169
8	1.244	21.68	1.069	225
9	1.225	25.00	1.060	289
16	1.155	49.00	1.033	961
25	1.118	81.00	1.020	2401

Discussion

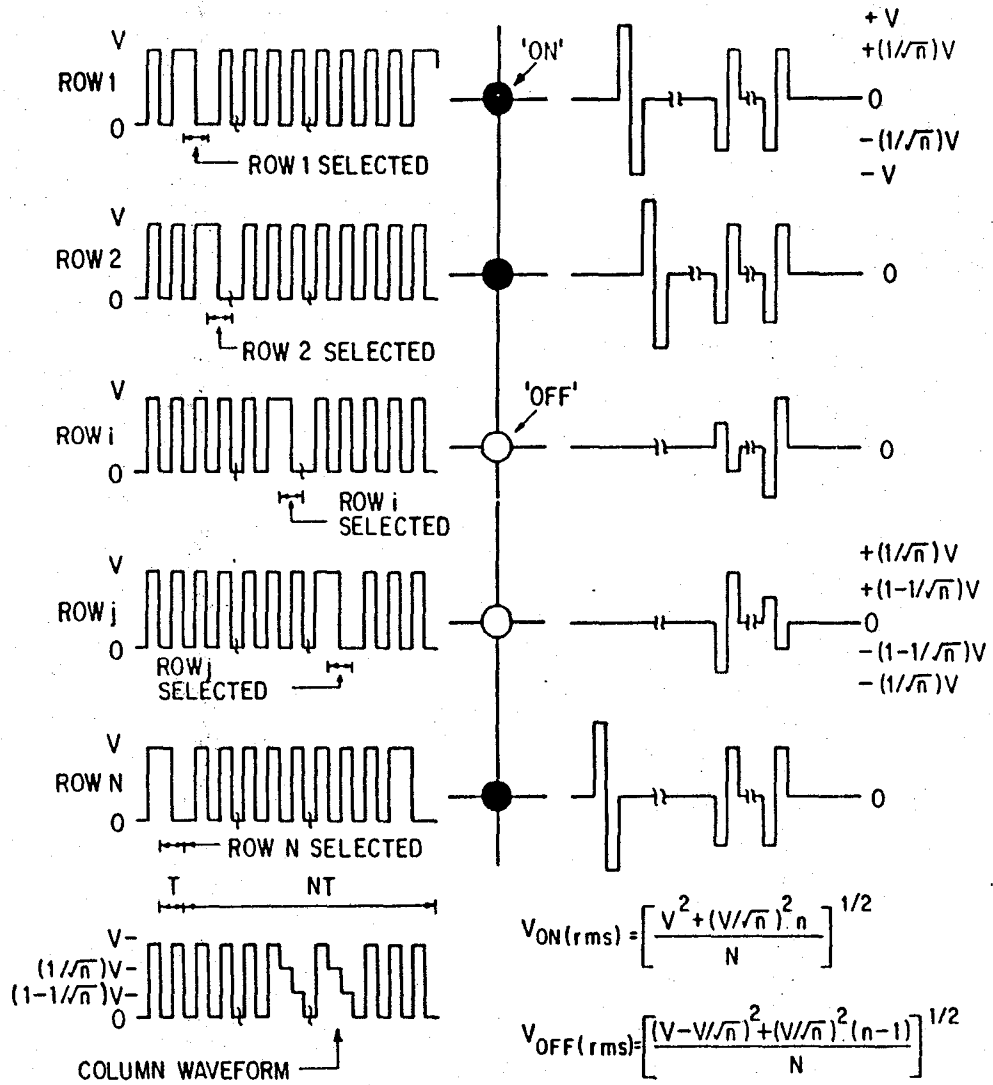
The selection ratio is independent of N, since the column voltage for the 'ON' elements is zero instead of a finite voltage. In practice n << N and hence there is no appreciable change in the selection ratio compared to the theoretical limits of techniques for restricted patterns discussed in Ref. 6 and 7. For single trace operation the technique achieves infinite selection ratio and the addressing waveforms are identical to those given in [3,5,8]. The addressing waveforms have been optimized, in the present technique for multitrace operation. As mentioned earlier the supply voltage for the present technique depends only on N.

It is preferable to add legends in oscilloscope displays. This can be done by including the legend at the top and its inverse video form at the bottom so that the number of elements selected in a column is constant. The number of selected elements in a column increases in this case and the selection ratio is lower compared to a display without legends.

The present technique can also be adopted for a case in which the number of selected elements is variable but always less than or equal to n (n << N). The number of selected elements can be adjusted to n for all the columns by adding n dummy rows to the addressing waveforms. The selection ratio will be $[\sqrt{n}/(\sqrt{n}-1)]^{1/2}$.

Results

The addressing technique discussed above has been implemented on a 64x64 matrix TN display. Photograph 1 shows four waveforms being displayed. The selection ratio in this case is $\sqrt{2}$(N_{eq} = 9). Photograph 2 shows a single waveform along with legends. The characters are formed by a 5x5 dot-matrix, with one row at top and bottom to separate the legends from the background. An additional 7 elements are selected in every column. The selection ratio is $[\sqrt{8}/(\sqrt{8}-1)]^{1/2}$, (i.e., N_{eq} = 22). The commercial mixture RO-TN 701 is used in the display and the supply voltage is 7V.



$$V_{ON(rms)} = \left[\frac{V^2 + (V/\sqrt{n})^2 n}{N}\right]^{1/2}$$

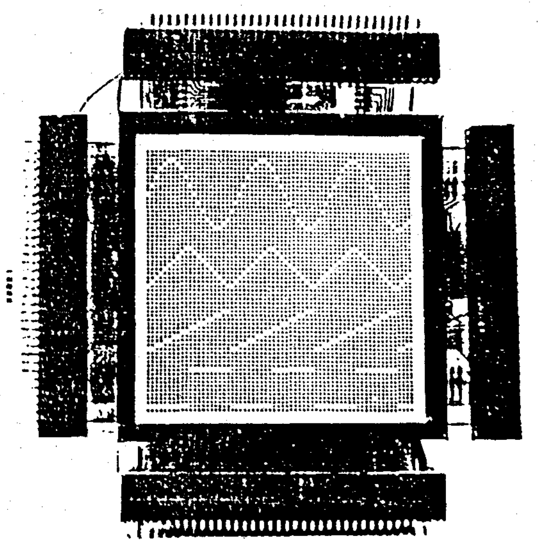
$$V_{OFF(rms)} = \left[\frac{(V - V/\sqrt{n})^2 + (V/\sqrt{n})^2 (n-1)}{N}\right]^{1/2}$$

$$V_{ON}/V_{OFF} = \left[\sqrt{n}/(\sqrt{n} - 1)\right]^{1/2}$$

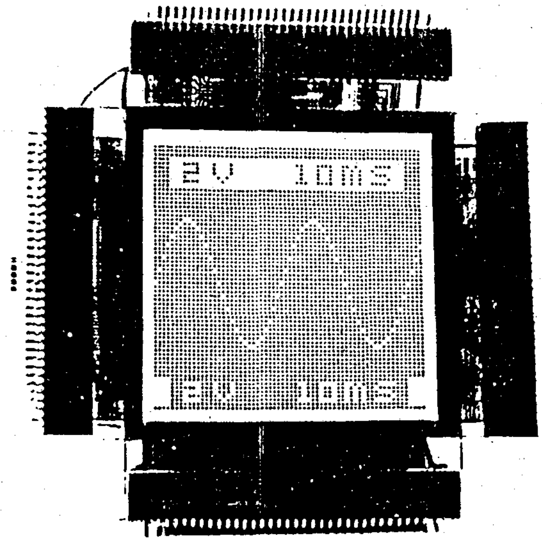
N - NUMBER OF ROWS IN THE MATRIX DISPLAY.
n - NUMBER OF ELEMENTS 'OFF' IN A COLUMN.

SUPPLY VOLTAGE $\Big| V_{ON} = V_{S90} = (N/2)^{1/2}$

Fig: 2 REPRESENTATIVE WAVEFORMS FOR ADDRESSING MULTITRACE OSCILLOSCOPE DISPLAY.



Photograph 1



Photograph 2

Impact

Since the selection ratio is higher than that of APT, a better contrast can be achieved. The selection ratio' is independent of the total number of rows in the matrix and hence displays with a large number of rows can be used increasing the Y resolution without sacrificing the contrast. Multiple waveforms with or without legends can be displayed. Typical applications are in multi-trace oscilloscopes and Logic Analyzers. This technique can also be adopted in applications wherein the number of selected elements is a variable with an upper bound n (n <<N), typical application being displays for video games.

The selection ratio achieved in the present technique is $[\sqrt{n}/(\sqrt{n}-1)]^{1/2}$ which is higher in comparison with the earlier technique of sequential frame multiplexing of waveforms proposed by Shanks et al for multitrace operation, (Ref. 5) which gives a selection ratio = $[n/n-1]^{1/2}$ (Table 1).

In Ref.2 a multitrace oscilloscope discussed has a 64 rows matrix LCD with 32 lines multiplexing. If a comparable mixture is used one can display 11 waveforms, using the present technique without any limitations on the matrix size. With L. C. mixtures currently available one can easily construct a display for 16 traces (N_{eq} = 49 lines) using the proposed technique.

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