Chapter 12. LCD Measurements

Both LC cell measurements to characterize the properties of the cell and LCD measurement to characterize the operation of the LCD are important and will be discussed here.

12.1 Refractometry

It is often necessary to measure the refractive index of the LC. We can use an Abbe refractometer. It makes use of TIR and index matching.

A beam of light is convergent on the interface. If the internal angle is larger than the critical angle, no light will be transmitted and a shadow is observed. Thus $\theta_c$ can be determined. From $\theta_c$ and the value of $n_p$, we can calculate $n$.

$$\sin \theta_c = \frac{n}{n_p}$$

Rutile prism is usually used because of its large refractive index (2.4).
12.2 Tilt angle measurement

Tilt angle (or pretilt angle) is needed to stabilize the twist deformation, to prevent reverse tilt, to prevent domain formation and other defects.

TN: 1-2°
STN: 4-8°

The pretilt angle is determined by (1) the PI material and (2) the process conditions such as curing temperature and rubbing strength. Therefore it is important to characterize the PI by measuring the pretilt angle for each process condition.

The pretilt angle can be measured by several methods. The most common is the crystal rotation method.

In order to make the crystal rotation method work properly, a special LC cell which is homogeneously aligned and which is reasonably thick (~30-50 µm) has to be used.

First, the plane of the LC director is determined by moving the cell between parallel polarizers. Then it is placed between cross polarizers with 45° as in a ECB geometry.
The transmitted light signal is measured as the LC cell is rotated. The angle between the cell and the light has to be determined accurately. The light beam is usually a HeNe laser beam.

The output is given by

$$T = \sin^2 \frac{\pi d \Delta n}{\lambda}$$
The offset angle and the tilt angle are related simply by the refraction relationship

\[ n_{LC} \sin \alpha = \sin \beta \]

where \( n_{LC} \) is either \( n_e \) or \( n_o \) depending on the polarization of the light used.
Have to worry about the refraction of the light beam inside the LC cell.

**12.3 Cell gap measurement**

The cell gap can also be measured using light interference. (Fabry-Perot effect)
For multiple reflection interference, it can be shown that the reflected signal is given by

$$\text{Refl} = \frac{4R \sin^2 \delta}{(1-R)^2 + 4R \sin^2 \delta}$$

$$\text{Trans} = \frac{(1-R)^2}{(1-R)^2 + 4R \sin^2 \delta}$$

where $R = \text{reflectance of a single surface}$ and

$$\delta = \frac{2\pi d}{\lambda \cos \theta}$$

and $d = \text{cell gap}$

**Proof:**

$$E_r = rE_o + (-r)t^2 e^{2j\delta} E_o + (-r)^2 t^2 e^{2j\delta} E_o + \ldots$$

$$= rE_o - r^2 e^{2j\delta} (1 - r^2 e^{2j\delta} + \ldots) E_o$$

$$= rE_o - \frac{r^2 e^{2j\delta}}{1 + r^2 e^{2j\delta}} E_o$$

where $r$ is the reflectivity of the $E$ field from the surface.

Therefore

$$R = \left| \frac{E_r}{E_o} \right|^2 = \left| r \right|^2 \left| \frac{1 - e^{2j\delta}}{1 + r^2 e^{2j\delta}} \right|^2$$
Hence
\[
\text{Refl} = \frac{4R \sin^2 \delta}{(1 - R)^2 + 4R \sin^2 \delta}
\]

where \( R = |r|^2 \) is the reflectance of the Poynting vector.

Similar multiple interference calculation applies to the transmission coefficient.

There are 2 kinds of equipment to make use of this effect to measure \( d \):

1. **Rotation method:** Just like crystal rotation to measure the tilt angle, \( \theta \) is rotated, \( \lambda \) is fixed, e.g. at the HeNe wavelength. This is cheaper but more cumbersome.

Typical result for a 6 \( \mu \)m empty glass cell with reflectance vs rotation angle:
(2) **Spectroscopic method:** the entire spectrum is measured as a function of $\lambda$. $\theta$ is fixed at 0. This is the best.

Typical reflection spectrum from such a measurement:

(d=5 $\mu$m)

Simulated results using standard formula:
* Note: the light interference method is only suitable for empty cells, where the interface between air and glass gives a reasonable R of ~4%. If the cell is filled with LC, R becomes very small since the refractive index of glass and LC are not too different. Therefore the method becomes inaccurate. Moreover, the presence of LC twist makes the interference method impossible.

We recently invented a method to measure the cell gap of filled LC cell with any twist angle. (patent pending)
12.4 Electro-optic curve

This is the same as the TVC. The measurement is straightforward.

![Electro-optic curve diagram]

The voltage source can be sinusoidal or square wave. Typical frequency is 100-500 Hz.

The transmitted signal is measured as a function of voltage. Typical example:

This measurement can be easily home-built. Commercial equipment is also available for such measurements. Two major suppliers: Autronic-Melchers and Otsuka.
12.5 Viewing angle measurement

The transmitted light is measured as a function of the viewing angles ($\theta$, $\phi$). The principle is simple but the equipment is difficult to make. Commercial equipment should be used. There are 2 approaches: (1) Rotate the LC cell. For example, DMS from Autronic-Melchers. (2) Use a special light collection optics to do the ($\theta$, $\phi$) measurement simultaneously – conoscopy.

This measurement is difficult to do with home-made machines. Commercial machines are necessary.

Typical results from a DMS machine:
13.1 Driving frequency

Voltage applied to the LC should be AC in order to avoid any charging effect. If there is any voltage imbalance, the residual ions in the LC will migrate to one of the electrodes and get stuck there. Eventually the LCD will cease to function if the accumulated charge is too high to shield the applied voltage.

The LC director responds to both DC and AC voltages. The reason is that the alignment of the LC director is through the dielectric (electrostatic) energy term:

\[ U = \frac{1}{2} \varepsilon |E|^2 \]

Therefore, only the RMS voltage is important. Both + and - voltages will align the LC director.

Square wave at V: RMS voltage = V
Sinusoidal wave at V: RMS voltage = 0.707V

Most LC drivers are based on digital electronics and square waves.

What should be the driving frequency?

The driving waveform has a lower and an upper frequency limit.
**Low frequency limit:** The lower frequency limit is determined by the charge migration time. Ionic charges can follow the voltage if the frequency is low. This leads to charge shielding effect and lowering of the voltage across the LC. Lower limit ~1 Hz.

Similar charge migration considerations leads to the requirement that the voltage across the LC cell should be balanced, i.e. perfect AC. Otherwise charge will accumulate on the PI and disable the display. Practice: voltage should balanced to 1mV.

**Image sticking (image retention):** if the voltage is applied to a particular pixel for too long, the image will stay there even if the voltage is turned off. This is due to charge retention as well.

**High frequency limit:** The high frequency limit is set by (1) LC molecular rotational response time and (2) circuit RC frequency response.

(1) **LC frequency response:**

The dielectric anisotropy disappears at high frequency because the LC molecules cannot rotate fast enough!
The upper frequency limit for rotational anisotropy is dependent on temperature. Example for a mixed LC below:

Fig. 2.47. Frequency dependence of the real and the imaginary parts of the complex permittivity for three different conditions of 7CB. (After Ref. 73.)

Fig. 2.46. Experimental results on frequency and temperature dependences of $\varepsilon_{\parallel}$ and $\varepsilon_{\perp}$ of a Roche mixture M1. Note that the crossover frequency increases exponentially with temperature. (After Ref. 70.)
(2) Circuit's RC response time:

The line resistance plus the LC cell is like a high pass (low cut) filter. If the frequency is too high, all the applied voltage will appear across the line resistor and not across the LC cell.

For example, if the pixel or segment is 5mm$^2$ in area, the capacitance is ~500 pF. If the ITO line resistance is 5 kΩ, the RC time constant is 2.5 µs. This sets the upper frequency limit to 400 kHz. For segment displays, this is no problem. However it is a big problem for high information content displays, which has to be driven at high frequencies. e.g. VGA (640x480) has a clock rate of 307 kHz. Therefore ITO line resistance has to be very low for such displays (both STN and AMLCD).

The other RC time constant comes from the R of the LC cell. That is usually much larger than the ITO resistance.

For TN LCD, the common AC frequency is 200Hz.

13.2 Direct Drive
Direct drive or static drive means each segment or symbol has its own applied voltage. There is no crosstalk or multiplexing.

However, for alphanumeric displays with many digits, time division multiplexing may have to be employed.

The ITO on the top and bottom glasses are etched into various patterns. The top electrode has N common electrodes for N alphanumerics. The bottom electrode has 7N segment electrodes plus possibly decimal places or colons.
The LCD voltage is determined by a logic exclusive OR gate (XOR)

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The common signal is usually the clock.

| com | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 1 |
| in  | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| out | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 0 |
| V   | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 |

This circuit always generates a ± LC voltage. This ± LC voltage ensures charge balance.

The common or clock frequency is usually 32 or 64 Hz.

Each segment has a similar XOR circuit. The driver looks like this:
For each digit, the encoder will send the appropriate segment signal to the corresponding XOR driver. For calculators, the encoder and the calculator can be integrated on the same chip.
Actual example of a direct drive clock display:

Figure 2. Example of a primitive 3 1/2 digit, direct drive LCD watch display popular in the early 1970s. A unipolar squarewave is constantly applied to the common backplane electrode and an identical signal is applied to off segment electrodes and a 180° phase shifted signal is applied to on segment electrodes.

This requires 20 connections. The number of connections can be reduced to 10 by multiplexing.

13.3 Passive matrix drive – segment displays

Direct drive is ultimately limited by the number of connectors needed. If there are N digits, there will be 8N+1 connectors (assuming all the common electrodes are connected and there is 1 decimal point for each digit). E.g. a 8 digit calculator will have 65 connections. Even for simple applications like digital
clocks, multiplexing is used nowadays. The technique is to employ **time division multiplexing (TDM)**.

Important point: there is no free lunch. Whenever multiplexing is used, there will be some degree of cross talk, i.e. one has to give up some contrast.

Suppose there are N rows and M columns. The rows are scanned line by line:

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Vs
```

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Vd

There are 2 kinds of passive matrix drives:

(1) Real physical matrix – dot matrix or **graphics displays**, 

(2) **Segment displays** (numerics) where the “matrix” is a mapping onto the segments.

For segment displays, there are 2 ways to multiplex. A simple straight-forward way is to drive the digits one by one by separating the common electrodes. So a N digit display is driven like a 8xN matrix and will have 8+N connectors. (8 segments and N commons).
The fancier way to divide up the common electrode into segments as well.

For example: a digit can be made from a $3 \times 3$ matrix as shown. So a $N$ digits display is driven like a $3 \times 3N$ matrix, or 3-way multiplex. Number of connectors is $3 + 3N$. Advantage over the previous scheme: lower MUX, or higher contrast.

![Diagram of a 3x3 matrix for a digit display]

Each digit is composed of a $3 \times 3$ matrix. The number of possible “pictures” = $2^9 = 512$ if it is a single digit display. We need only 11.

(Exercise: Find the combination of the voltages on the top and bottom segments to give all the digits)

The above arrangement is standard for a 1/3 duty cycle calculator type display.

The following is an actual 3 ½ digit clock display using the multiplexing scheme to reduce the number of connections:
The number of connections is reduced from 20 to 10.

There are 4 common signals, or 4-way multiplex or \( \frac{1}{4} \) duty. You can check that all possible numbers can be more than covered by a specific combination of the "row" and "column" voltages.

Why is 4-way used? It reduces the number of data segments. With 3-way multiplex, 13 connections are needed. With 4-way, we need only 10. (With direct drive, 24 connectors are needed.)

Another class of display is truly matrix driven with large N.

**13.4 Passive matrix displays - Alt and Pleshko law:**

For a general NxM matrix, the rows are scanned lin-by-line.
$V_s = \text{peak scanning voltage}$

These are called the row voltages, or address pulses, or $x_i(t)$. Period = $T$. Each scan pulse duration = $T/N$

Data pulse trains are applied to the columns. These are the column voltages or $y_j(t)$. Data pulses also have duration of $T/N$. There are $M$ data pulses in each data pulse train for each frame period.

$\frac{1}{2}$ biasing rule: if the $(i, j)$th pixel is supposed to be ON, then we put a voltage of $-V_d$ for that time frame. If it is OFF, we put $+V_d$ on it.

So the ON pixel will see the following pulse train:
If the pixel is supposed to be OFF, it will see:
The OFF pixel voltage pulse train looks exactly the same as that of the ON pixel except for the time frame of T/N that overlaps with the scan pulse. The ON pixel will see a voltage of \( V_s + V_d \), while the OFF pixel will see a voltage of \( V_s - V_d \). For the rest (N-1) time frames, the pulse trains are the same! This gives cross talk.

The RMS voltages over one period are given by:

\[
N V_{on}^2 = (V_s + V_d)^2 + (N-1)(\pm V_d)^2
\]

\[
N V_{off}^2 = (V_s - V_d)^2 + (N-1)(\pm V_d)^2
\]

Note that

\[
N(V_{on}^2 + V_{off}^2) = V_s^2 + NV_d^2
\]

The ratio of the RMS voltages between the ON and OFF pixels is therefore given by:

\[
\frac{V_{on}^2}{V_{off}^2} = \frac{(V_s + V_d)^2 + (N - 1)V_d^2}{(V_s - V_d)^2 + (N - 1)V_d^2} = \frac{(b + 1)^2 + N - 1}{(b - 1)^2 + N - 1}
\]

where \( b = \frac{V_s}{V_d} \) is called the bias ratio.

Also \( s = \frac{V_{on}}{V_{off}} \) is called the selection ratio.

(Note: some people refer to \( b+1 \) as the bias ratio for historical reasons. Traditionally, \( V_s = 2V_d \) is called the 1/3 biasing scheme. This 1/3 bias scheme fixes \( b \) and hence is not optimized.)
If we maximize $s$ by varying $b$, then it can easily be shown that:

$$N = \left(\frac{s^2 + 1}{s^2 - 1}\right)^2$$

or

$$s = \sqrt{N + 1}\sqrt{N - 1}$$

when

$$b = \sqrt{N}$$

This is called the Alt and Pleshko “Iron Law of Multiplexing”. If you want to multiplex $N$ rows together, then the maximum selection ratio is fixed. It cannot be increased at will!

Another way to express the Alt Pleshko Law is by noting that the steepness coefficient $p$ is given by

$$p = s - 1$$

Therefore

$$N = \left[\frac{(1 + p)^2 + 1}{(1 + p)^2 - 1}\right]^2$$

For $p<<1$, this expression reduces to

$$N \sim p^{-2}$$

Curve for Alt and Pleshko Law:
Important note: the selection ratio determine the contrast of the display! The RMS pixel voltages are either $V_{\text{on}}$ or $V_{\text{off}}$. There are no other possibilities!

**Nomenclature:** $V_{\text{on}}$ is also called the select voltage $V_s$.  
$V_{\text{off}} = V_{\text{ns}}$ (nonselect).

Recall that the transmission of a LCD is a function of the applied voltage,
Therefore large N => small s => poor contrast or large cross-talk.

If we want large N, we should have a steep TVC.

**Nomenclature**: N is called the MUX number, or the LCD has N-way multiplex, or has a duty cycle of 1/N.

Also from the Alt and Pleshko law, it can be shown easily that

\[
V_d = \frac{1}{2} \sqrt{V_{on}^2 + V_{off}^2}
\]

Therefore given N and V_{on} (or V_{off}) we can calculate all the voltages V_{s} and V_{d} needed to drive the display.

**Example**: A TN LCD has a duty cycle of 1/4. Then according to the above formulas, b=2 and s=1.73.
If the threshold voltage is 1.5V, then \( V_{\text{off}} = 1.5V \), so \( V_{\text{on}} = 2.60V \), \( V_d = 1.5V \) and \( V_s = 3V \). It can be seen that all the voltages scale as the threshold voltage.

For a high MUX STN display, the voltages required can be quite large.

**Example:** for \( N = 240 \), (dual scan VGA display), \( b = 15.49 \) and \( s = 1.067 \).

If the threshold voltage is 1.5V, then \( V_{\text{off}} = 1.5V \), so \( V_{\text{on}} = 1.60V \), \( V_d = 1.1V \) and \( V_s = 17.04V \).

For STN displays, the threshold is generally higher, so that the voltage requirement is higher as well.

Actually, the voltage required is 2x because of the need for frame inversion. In order for charge balance, the driving pixel voltage has to be reversed for each frame. This can be performed by adding \( V_s \) to both the scan signal and the data signal. So for the actual voltage required is 34V for the above example!

An alternative frame inversion scheme will reduce the maximum voltage required to 18.14V. See below.
As the voltage required gets higher, the cost of the driver becomes higher as well!

Examples of multiplex driving waveforms:

![Waveform Diagram]

Figure 7. On and off pixel waveforms of the optimized amplitude selection technique for LCD matrices of various sizes.
Here are examples of LCD drivers available commercially:

### LCD Driver Product Summary

#### Segmented LCD Driver for Low NIX Application

<table>
<thead>
<tr>
<th>Part Number</th>
<th>Description</th>
<th>System</th>
<th>Application Examples</th>
<th>Display Size (Examples)</th>
<th>Package</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCI4250603</td>
<td>4 MUX, Total 128 Segments, 240 x 64</td>
<td>Low MUX, General Purpose</td>
<td>Fax Machine, Pager, Digital Camera, Home Appliances</td>
<td>128 x 324</td>
<td>CPS, Uto, Dla</td>
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<tr>
<td>MCI426004</td>
<td>4 MUX, Total 128 Segments, 160 x 64</td>
<td>Low MUX, General Purpose</td>
<td>Fax Machine, Pager, Digital Camera, Home Appliances</td>
<td>128 x 324</td>
<td>CPS, Uto, Dla</td>
</tr>
</tbody>
</table>

#### DragonKali Series LCD Driver Kits with MC89HC08L10L11

<table>
<thead>
<tr>
<th>Part Number</th>
<th>Description</th>
<th>System</th>
<th>Application Examples</th>
<th>Display Size (Examples)</th>
<th>Package</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCI441111</td>
<td>DragonKali 1 - Simple Driver, 32400 MUX, 128 Segments</td>
<td>Display: Pager, Organizers, Games</td>
<td>128 x 324</td>
<td>DRS, ISOPack</td>
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<tr>
<td>MCI441112</td>
<td>DragonKali 2 Basic Driver, 146 MUX, 80 Segments</td>
<td>Display: Pager, Organizers, Games</td>
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<td>MCI441113</td>
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<td>Display: Pager, Organizers, Games</td>
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<td>MCI441115</td>
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<td>MCI441118</td>
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#### TFT LCD Driver Accepts RGB Signal Inputs

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<thead>
<tr>
<th>Part Number</th>
<th>Description</th>
<th>System</th>
<th>Application Examples</th>
<th>Display Size (Examples)</th>
<th>Footage</th>
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<tbody>
<tr>
<td>MCI43120</td>
<td>TFT LCD Face (Points) Driver, 128 Row Outputs</td>
<td>Active LCD</td>
<td>Portable TV, Projector</td>
<td>400 x 340, 240 x 400</td>
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</tr>
<tr>
<td>MCI431204</td>
<td>TFT LCD Face (Points) Driver, 128 Column Outputs</td>
<td>Active LCD</td>
<td>Portable TV, Projector</td>
<td>400 x 340, 240 x 400</td>
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#### MC14153X Series LCD Driver with Common, Segments, Annunciations “All-In-One” Chip

<table>
<thead>
<tr>
<th>Part Number</th>
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<th>Display Size (Examples)</th>
<th>Package</th>
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<td>17 Cam, 109 Seg, 3 Annunciations</td>
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<td>TAB, ISO, 50, Gold Bump Dia</td>
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<td>General: MCU, 6500, 68K Embedded Architecture</td>
<td>Mobile Communication Devices, Phone, Callers, PHS</td>
<td>125 x 17, 103 x 23</td>
<td>TAB, ISO, 50, Gold Bump Dia</td>
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</table>
Frame inversion:

For charge balance, it is necessary to reverse the pixel voltages. Common method is to reverse the voltage every frame. Other method includes reversing the voltage every line, or several times within a frame.

Simple method: just reverse $V_s$ and $V_d$ for every alternate frame. However, in order to keep the voltages positive, add $V_s$ to both the scan and data signals. However this will double the
voltage required to $2V_s$. Alternative: use $V_d$ and $V_s$ bias for alternate frames as shown:

![Diagram showing normal and reversed polarity for row, column, and pixel voltages.](image)

**Figure 17.** Reversal of the row and column drive polarities on alternate frames eliminates any net dc component across the pixel (left) but doubles voltage requirement of row driver from $S$ to $2S$. However by additionally offsetting (biasing) both row and column voltages by $D$ in the normal frame and by $S$ in the reversed frame (right), the identical dc-free pixel waveform can be obtained while significantly reducing the voltage requirement for the row driver to $S+D$.

The maximum voltage required will be $V_s+V_d$. For the above example, it will be 18.1V which is much easier to do.
Sometimes it is necessary to apply the bias several times within a frame:

![Waveform Diagram](image)

**Figure 9.** Row, column and pixel waveforms for a 240 row display where, to reduce image-dependent crosstalk, DF switching occurs every 27 lines instead of only once per frame as shown in Fig. 8. These waveforms are more representative of a practical, operating display.

The above examples are under \( \frac{1}{2} \) biasing. It is possible to use \( \frac{1}{3} \) biasing or other kinds of biasing as well. They are all inferior to the above scheme of having \( \pm V_d \) on the columns (data lines).

For example, the \( \frac{1}{3} \) biasing scheme: the address lines are as shown:
The address voltage is $V_o$ if it is on and $1/3V_o$ if it is off. The data voltage is $2/3V_o$ if it is off, and 0 if it is on.

Therefore the select pixels voltage is

$$NV_{on}^2 = V_o^2 + (N-1)(1/3V_o)^2$$

and the nonselect voltage is

$$NV_{off}^2 = N(1/3V_o)^2$$

The selection ratio is therefore

$$s = \sqrt{1 + \frac{8}{N}}$$

For example, $N = 100 \rightarrow s = 1.039$

Using the Alt and Pleshko Law for $\frac{1}{2}$ bias, $s = 1.1055$, which is much better.

Summary: you cannot do better than the Alt Pleshko Law.
13.5 Active addressing (multi-line addressing)

When the number of lines in a graphics display becomes too large, it is impractical to use passive matrix drives. The LC has to be slow and the display in general is poor in quality.

There are 2 methods to overcome this problem: (1) active addressing. (2) active matrix driving.

Active addressing actually does not change the selection ratio requirement of the LCD. It only makes the speed of the LCD faster. It also improves the contrast ratio as well by increasing the average brightness of the on-state.
Principle of AA:

The usual passive matrix driving is line-by-line. The selection voltage only appears 1/N duty cycle. It is possible to design a set of scan voltages such that the average selection voltage is the same but it is spread out more evenly over the entire frame. This is also called multi-line addressing (MLA). MLA is becoming popular for improving the quality of STN displays, especially high MUX (480, 600 lines for VGA and SVGA displays).

Orthogonal functions:

The line-by-line scanning of N lines is equivalent to a diagonal NxN matrix:

\[
\begin{bmatrix}
1 & 0 & . & 0 & 0 \\
0 & 1 & . & 0 & 0 \\
. & . & . & . & . \\
0 & 0 & . & 1 & 0 \\
0 & 0 & . & 0 & 1 \\
\end{bmatrix}
\]

The row functions \(F_i(t_k) = (00100...)_xF\) are orthogonal in the sense that \(F_i \circ F_j = 0\).

We can scan the N lines by another set of orthogonal functions. For example, the **Walsh functions**. A 4x4 case is like:

+ + + +
+ + - -
+ - + -
+ - - +
It is like Yin Yang!

The matrix formed by the N Walsh functions is called a **Hadamard matrix**.

In the AA scheme, we apply scanning voltages $F_i(t_k)$ to the rows. $F_i(t_k)$ is given by the Walsh function with a peak voltage of $V_s$. Note that the scan voltage is now both $+V_s$ and $-V_s$. The time slot $t_k$ stands for the N rows.

The idea of AA is that we can now calculate what column voltages should be applied to the columns, given the known picture $M_{ij}$ we want to display. In the passive matrix addressing scheme, the column voltages are also calculated after knowing $M_{ij}$. But the $F_i(t_k)$ are much simpler.

Now if the elements of $M_{ij}$ is taken as $+$ if it is ON and $-$ if it is OFF, then the data lines (column voltages) should be

$$G_j(t_k) = \gamma \sum_{i=1}^{N} F_i(t_k) M_{i,j}$$

for some constant $\gamma$. Note that $F_i(t_k)$ can be represented by a NxN matrix and $M_{ij}$ is a NxM matrix. So $G_j(t_k)$ is also a NxM matrix.

The RMS voltage on the pixel is then given by

$$\langle u_{i,j}^2 \rangle = \sqrt{\frac{1}{T} \int_0^T [F_i(t_k) - G_j(t_k)]^2 dt}$$
where T is the period. Now the set of functions $F_i(t_k)$ should be orthogonal, i.e.

$$\frac{1}{\sqrt{T}} \sqrt{\int_0^T F_i(t)F_j(t)dt} = F\delta_{i,j}$$

It can then be seen that

$$\langle u_{i,j}^2 \rangle = F\sqrt{1 - 2\gamma M_{i,j} + N\gamma^2}$$

Therefore the ratio of the select and nonselect voltages or the selection ratio

$$s = \frac{V_s}{V_{ns}} = \sqrt{\frac{1 - 2\gamma + N\gamma^2}{1 + 2\gamma + N\gamma^2}}$$

Now we can optimize $s$ by varying $\gamma$. Simple differentiation shows that the maximum $s$ is given by

$$s = \sqrt{\frac{\sqrt{N} + 1}{\sqrt{N} - 1}}$$

when $\gamma = -\frac{1}{\sqrt{N}}$

This is the same Alt and Pleshko iron rule! (Exercise: Check that the column voltage $G$ is the same as the conventional passive matrix case if $F_i$ are given by the diagonal matrix, i.e. line by line scanning).

So there is no gain in the multiplex number of the selection ratio using the AA driving scheme. What is gained is that the pixel
voltages are now spread out more evenly so that a fast LC can be used. The brightness will also improve. In ordinary PMLCD the LC has to be slow in order for sufficient averaging of the pixel voltage to give the RMS value.

In the above calculations, we used a binary $F_i$. It is possible to use a 3-level $F_i$. Many orthogonal functions can be used.

**Maximum voltage:** Two important disadvantages of AA scheme compared to the conventional passive matrix scheme is the need to calculate $G_j$ and the higher voltages needed. Now

$$G_j(t_k) = -\frac{1}{\sqrt{N}} \sum_{i=1}^{N} F_i(t_k) M_{i,j}$$

So the maximum possible column voltage is $\pm \sqrt{N} F$. This is much higher than the conventional case where the bias ratio

$$b = \frac{V_s}{V_d} = \frac{F}{G} = \sqrt{N}$$

For example, if $N = 240$, previous calculation shows that $V_s = 17V$ and $V_d = 1.1V$. Here $G_{\text{max}} = 264V$ if $F = 17V$. This is a very high voltage! Some statistical calculations: It can be shown that

$$G_j(t_k) = \frac{F}{\sqrt{N}} \left(2D_j(t_k) - N\right)$$

where $D_j$ is the number of times the $j$th column of $M_{i,j}$ is on. It is easy to see that $0 < D_j < N$. Hence $G_j$ varies from 0 to $\pm \sqrt{N} F$. Using the law of large numbers, the distribution of $D$, $f(D_j)$, is a Gaussian function with an average value of $D_j = N/2$ and a standard deviation of

$$\sqrt{\langle (D_j - N/2)^2 \rangle} = \frac{1}{\sqrt{N}}.$$
So there are chances that the addressing will fail if the voltage required is too large, and the picture will not be displayed. Given any voltage for the driver, it is possible to calculate the chances that the AA scheme will fail to show the picture.

**Multiline addressing:**

MLA is used to overcome the disadvantages of AA. In MLA, only $L$-lines are AA together, where $L<N$. If $L$ is small enough, the calculation complexity for $G$ and the high voltage requirement can be much reduced. Actually AA and MLA were independently proposed in 1992. Both are implementations of the IHAT (Improved hybrid addressing technique) proposed by Ruckmongathan in 1988.

If $K=N/L$, there will be $K$ blocks or selection intervals as shown:

![Diagram](image)

*Figure 20.* Example of tri-level Multiple Line Addressing row function matrix built up by repeating smaller $L\times K$ Hadamard units down the diagonal and distributing the $K$ selection intervals over the frame period by rearranging the order of the matrix columns.

An example of a $N=256$ display showing the actual pixel voltages for MLA with different $L$: 
L=256 means the entire picture is multiplex by AA.
L=32 means there are 8 subblocks for scanning.
L=4 means 64 subblocks.
L=1 is equivalent to conventional passive matrix line-by-line scanning.

Comparison of conventional and MLA drivers:
Advantages of MLA:
1. A fast LC can be used, video rate is no problem.
2. The brightness and contrast are generally higher than conventional STN.

Cost:
1. MLA requires more processing power. Driver chips using 4-line to 8-line MLA are now available commercially. Seiko-Epson sells one for 4-line MLA. Optrex/Asahi sells one for 7-line MLA. MLA is also called MLS (multi-line selection).

**Comparison of data processing for conventional and MLA:**

**Conventional:**

![Diagram of conventional data processing]

**MLA scanning:**
13.6 Grayscales

There are several ways to get grayscales in a display:

1. **Amplitude control.** From the TVC it can be seen that the transmission of the LCD depends on the selection voltage. Therefore one can get grayscale by modulating the selection voltage. This is done for AMLCD, but difficult for STN.

2. **Frame rate control.** Each frame can consist of \(2^N\) subframes. One can turn the subframes ON and OFF to provide a grayscale.

   FRC requires the display driver to have very high speed.

3. **Frame duration control.** This similar to frame rate control, except that the duration of the frame is changed.
4. Spatial modulation. Each pixel is divided into $2^N$ subpixels. The pixels are turned ON or OFF in order to show grayscale. This requires real estate on the display.

e.g.

Typically, 8 bit grayscale is needed for a good display. So there are 256 gray levels. With colors, there will be $256^3$ or 16.7 million combinations.