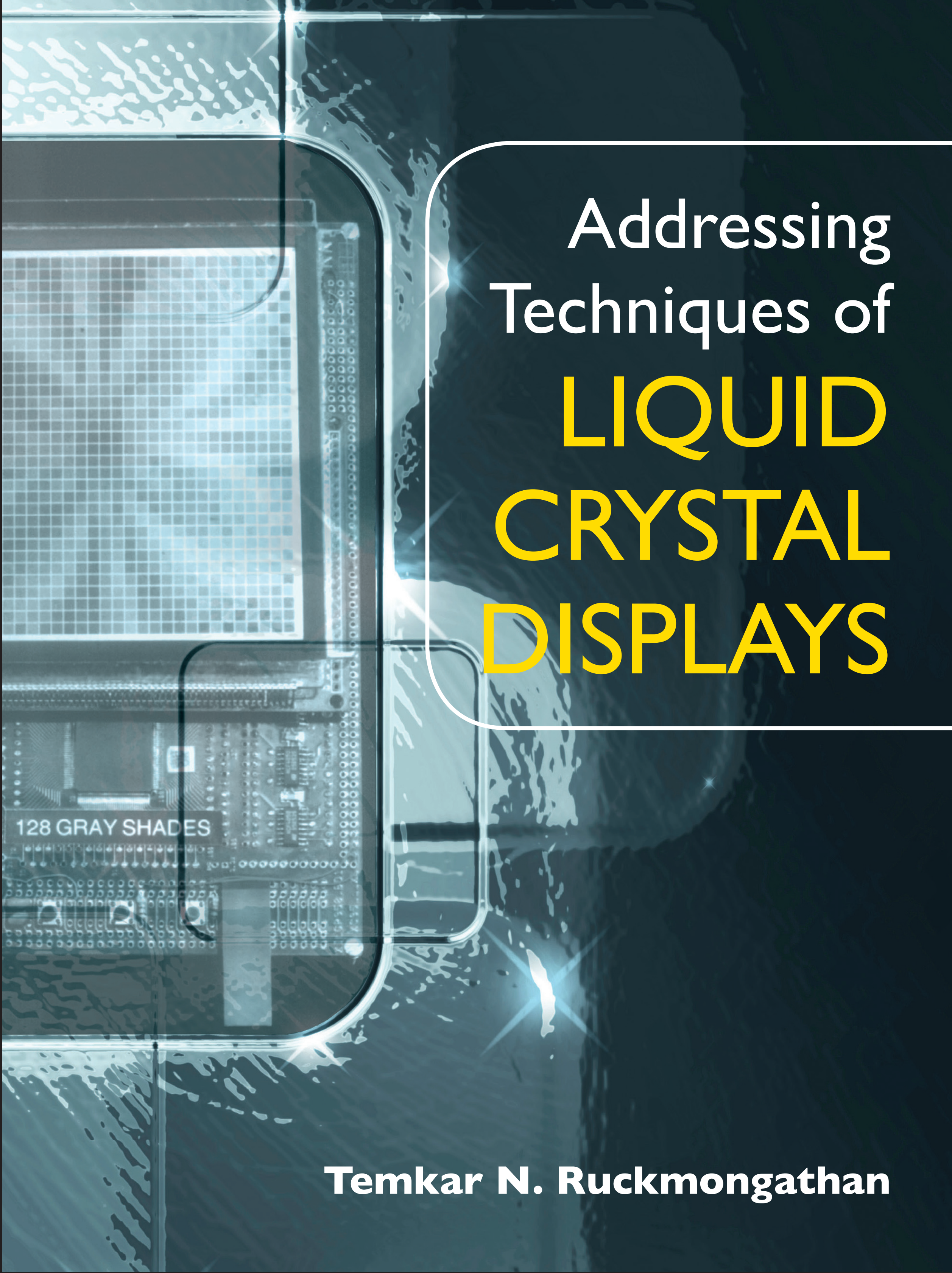

Addressing Techniques of LIQUID CRYSTAL DISPLAYS

Temkar N. Ruckmongathan

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ADDRESSING TECHNIQUES OF LIQUID CRYSTAL DISPLAYS

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Dedicated to my wife Nagamani R and my brother Loknath Rao T N

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Series Editor's Foreword

When flat panel displays first began to appear in products, they did so in areas where their flatness and relative thinness made those products at all possible to produce. They were the enabling technologies for the laptop computer and for many portable instruments, so their performance properties and their cost were of somewhat secondary importance. So slow optical response, slow address rates, low contrast, narrow viewing angles, lack of more than two colours and (for electroluminescent and LED displays) relatively high power consumption were properties which the manufacturers of products, if grudgingly, had to accept.

When flat panels began to make inroads into markets which had been the exclusive preserve of the CRT, the situation was very different because although flat panels, specifically LCDs, had the undoubted advantage of low power consumption, in order to dislodge the CRT from its dominant position, they also had to compete by providing video performance, long lifetime, full colour and, most importantly for the manufacturers, competitive cost.

It is this background of entry into two very different areas of the market that influenced the nature of LCD development from the late 1970s. At first, passive matrix LCDs – the primary subject of this book – successfully led the development effort. Active matrices of TFT switches, integrated on to the rear glass substrates of LCDs could not then be made with sufficiently high yield and low cost even to begin to compete effectively with the CRT in computer and TV displays. This situation persisted until the last decade of the 20th century. Therefore the heyday of the passive matrix LCD was in the 1980s and early 1990s.

Written by a globally acknowledged leader in the field, this book describes with great clarity and in great detail the many sophisticated methods by which liquid crystal displays may be driven and it contains content which has not previously been published. It focusses on passive matrix LCDs, and although market share of passive matrix LCDs is in slow decline, there is at present a sizeable market of the order of $1B US in technical, medical, appliance and other displays, some of which are battery powered. Although these displays do not require the ultimate performance in terms of power, speed or colour, in order to preserve their market share they must achieve the best possible performance by optimising specific display characteristics for a particular application and that is why these driving methods are important.

Although the displays discussed are predominantly passive matrix LCDs, some of the addressing techniques are also applicable to AMLCDs and to other display technologies which between them occupy by far the largest part of the display market. Bit slice and multi-bit slice addressing can be used in projection and backlit displays with bistable or fast responding optical transducers, which use fast switching light diode or laser backlight or projection sources, to reduce backlight power consumption without compromising image quality. Furthermore, nibble slice addressing can be used to drive state of the art AMLCDs with simple drivers that can apply only 16 voltage levels and yet achieve 256 greyscales and simultaneously suppress motion blur.

This book provides all the technical information a display engineer will need to decide which of the methods described here to use to best drive a particular display for a particular application. Because the concepts of wavelet-based addressing, successive approximation, cross pairing of select and data voltage to increase the number of greyscales with a small number of select and data voltages, micro-pulse width modulation, etc., are applicable not only to passive matrix LCDs but also to other display technologies, this book will also be an invaluable text for first and higher degree students.

Anthony Lowe
Braishfield, UK, 2014

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First of all, I would like to thank the teachers of the Municipal High School, Ootacamund, faculty members of the PSG College of Technology and Polytechnic, Coimbatore, and the Indian Institute of Science, Bangalore, who were instrumental in shaping me as an engineer.

I joined the Raman Research Institute, Bangalore, in 1978 with a strong urge to do research. I would like to acknowledge the freedom I was given to explore problems that were of my interest at the Raman Research Institute. During the 1980s, I needed to fabricate liquid crystal displays before I could explore the ways and means of addressing them. I would like to acknowledge the support of Majeed S. A., Subramanya K. and Subramonyam H. who had helped me to fabricate liquid crystal displays and the prototypes in the laboratory. I would like to thank Shashidhara A. R. as well as a large number of students for the design and development of prototypes to demonstrate the new addressing techniques during the last decade. I would also like to acknowledge the supportive role of staff in the library and administrative sections of the Raman Research Institute in procuring books, materials, components and equipments that were essential to fabricate liquid crystal displays in the laboratory.

I would like to thank a long list of friends and colleagues at Philips in the Netherlands, the Asahi Glass Research Center in Japan and the University of Chalmers in Sweden during my short stints in these organizations that helped me to benchmark myself.

Finally, I would like to thank the Society for Information Display for being a platform for free flow of information. Most of all, I would like to thank the series editor Anthony C. Lowe, copy editor Patricia Bateson and the whole team of John Wiley & Sons, Ltd for their support towards transforming my flow of thoughts into a book.

Temkar N. Ruckmongathan

1

Introduction

The main objective of this book is to present methods to drive a liquid crystal display (LCD). Chapter 2 is devoted to introducing the device itself. Starting with the basics of matrix addressing, the chapter prepares the reader by introducing fonts and formats, liquid crystals and some electro-optic effects. It is by no means complete and the goal is to give a flavour of electro-optic effects and display devices that need to be addressed using the knowledge gained from this book. Addressing techniques are reviewed in Chapter 3, starting with a discussion of the need for nonlinear elements for matrix addressing, the cross-talk in a matrix LCD and the need for direct current (DC) free waveforms across pixels in an LCD. Chapter 3 also provides a historical perspective of methods to drive an LCD and points out some problems and limitations of matrix addressing.

Addressing techniques presented in this book are broadly classified into three major divisions. Chapters 4 to 12 are devoted to multiline addressing, Chapters 13 to 17 discuss methods to display grey shades and Chapters 18 to 20 introduce methods to drive displays with short response times.

Chapter 4 introduces the binary addressing technique, which departs from the conventional approach of selecting one address line at a time. The binary addressing technique is based on Rademacher functions, an orthogonal function. Chapter 5 introduces orthogonal functions and the role of orthogonal functions in multiplexing and matrix addressing. The active addressing technique, a direct application of compact orthogonal functions, like Walsh functions and Hadamard matrices to select all rows in a matrix LCD, is presented in Chapter 6. Active addressing can multiplex a large number of address lines but demands a large number of voltages in the addressing waveforms and a new architecture that integrates frame buffer memory with column signal generator. Hybrid addressing techniques are presented in Chapters 7 to 12. The improved hybrid addressing technique presented in Chapter 8 is the first multiline addressing to overcome all the limitations of the binary addressing technique. It is the most general method used to drive the matrix LCD and all other addressing techniques can be viewed as a special case of the improved hybrid addressing technique. The sequency addressing technique presented in Chapter 11 is also a hybrid addressing technique that uses compact orthogonal functions to select a few address lines. Selecting all rows simultaneously is useful in restricted pattern addressing as described in Chapter 12.

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Chapter 13 provides a review of methods to display grey scales. The number of voltage data waveforms is proportional to the number of grey shades in the case of amplitude modulation presented in Chapter 14. Amplitude modulation serves as a reference to compare other grey scale methods but it is too complex to implement along with multiline addressing. On the other hand, the successive approximation method discussed in Chapter 15 needs simple drivers and the number of time intervals is proportional to the logarithm of the number of grey scales. The successive approximation method does not increase the driver circuit in combination with line-by-line as well as multiline addressing. The cross-pairing method of Chapter 16 takes less time intervals to display grey scales as compared to the successive approximation method and is easy to implement in combination with line-by-line addressing. The cross-pairing method is difficult to implement with multiline addressing. Line-by-line and multiline versions of wavelet-based addressing techniques are introduced in Chapter 17.

Bit slice addressing, multibit slice addressing and micro pulse width modulation are discussed in Chapters 18 to 20 respectively. Micro pulse width modulation is especially useful in reducing power consumption of backlight without sacrificing image quality when displays have a short response time in the range of 100 μs. Bit slice addressing as well as micro pulse width modulation are useful to display grey scales with fast bistable displays like the digital micro mirror device and ferroelectric LCD.

Chapter 21 compares all the addressing techniques to help a designer choose an appropriate addressing technique for an application. Chapter 22 focuses on reducing power dissipation in drivers whereas Chapter 23 illustrates methods to save power consumption of backlights in an LCD. Chapter 24 is devoted to describe drivers for the LCD. Methods to combine passive and active matrix addressing and a few suggestions to cope with the ever increasing demand on resolution and size of matrix displays are presented in Chapter 25.

Most of the effort in this book has been directed towards providing information that cannot be found in other books on addressing liquid crystal displays. An in-depth analysis of hybrid addressing makes no assumptions (not even the orthogonal nature of Rademacher functions) and cannot be found elsewhere. The book is full of tables, figures and examples of benefit to those who would like to skip the analysis.

2

Liquid Crystal Displays

2.1 Matrix Displays

A display is an important interface between man and machine. The picture element (pixel) (Lyon, 2006) is the smallest element in a display. Pixels are tightly packed into a two-dimensional (2D) array that resembles a matrix, a rectangular array of pixels arranged in row and columns. A display consists of a large number of pixels – a few hundred to a few million pixels depending on the gadget that incorporates the display device. Information on a display device depends on the collective state of the pixels and some degree of correlation exists between neighbouring pixels. However, the pixel is the smallest element that can be driven to a state without affecting the state of other pixels. A pixel in a colour display consists of three or four subpixels that are driven independently of each other and the collective state of subpixels is the state of a pixel that determines the colour and intensity of the pixel. Each pixel in a display has at least two terminals that are useful to activate the pixel (i.e. drive the pixel).

Numeric displays in watches, calculators, multimeters, thermometers, weighing machines, etc., have a small number of pixels and in these displays each pixel is connected to a driver so that the pixel can be switched ‘ON’ or ‘OFF’ depending on the number to be displayed. However, such direct driving of pixels is not practical when the number of pixels is large. For example, consider a display with pixels arranged in 480 rows and 640 columns. It is a standard display format that is referred to as a vector graphics array (VGA). The number of drivers is large if each of all the 30 700 pixels in a monochromatic VGA display has to be driven with dedicated individual drivers for each pixel.

If the number of connections from the drivers to the pixels is large it is not practical to have so many wires connecting the pixels and drivers. The number of connections and the number of drivers increase linearly with the number of pixels and the number of drivers and interconnections is multiplied by a factor of three in a colour display. For example, a low resolution colour graphics array (CGA) format demands 240 rows of colour pixels with 320 pixels in each row. Each colour pixel consists of three pixels of a primary colour (red, green and blue) and therefore a display will have about 0.23 million (230 400) pixels. An equal number of connections is necessary if each pixel is connected to a driver. The number of connections is too large and it is not practical to drive the pixels directly when the number

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of pixels in a display is large, as in graphic displays that are used to display images. A group of pixels can share a driver to reduce the number of connections between pixels and the corresponding drivers.

A common lead that connects a number of pixels to a driver is referred to as an address line and it reduces the number of drivers as well as the number of connections to the display. A matrix display is a two-dimensional array of pixels and one lead of each pixel in a row is connected to a row address line and similarly the second lead of each pixel in a column is connected to a column address line. Each pixel in a matrix display is uniquely identified with a row address line and a column address line. A drastic reduction in the number of drivers is achieved with this approach in a matrix display. Drivers of one set of address lines, for example row drivers, are used to select all pixels in a row. Hence, the address line that is used to select all pixels connected to an address line is also referred to as a scanning electrode. Drivers that are used to control the state of pixels in a selected address line are referred to as data drivers. Matrix displays with a larger number of columns as compared to the number of rows are popular. It is advantageous to scan the matrix display with a lower number of address lines. Hence, drivers that are used to scan the display are usually referred to as row drivers and the data drivers are referred to as column drivers.

However, we can also select all pixels in a column with a column driver and the row drivers can be employed simultaneously to drive all pixels in the selected column. The number of drivers reduces to 1120 (480 + 640) for a monochromatic VGA display as compared to 307 200 (480 × 640) drivers if each pixel in the display is driven with a dedicated driver. Similarly, the number of drivers and interconnections reduces to 1680 (240 row drivers and 1440 data drivers) in a CGA display. Hence, each pixel in a matrix display can be driven with a small number of address lines as compared to direct driving of each pixel. It is similar to a random access memory (RAM) wherein a large number of memory cells are addressed with a smaller number of decoded address lines. A random access memory has a much lower number of address lines as compared to the matrix display because rows and columns are coded as binary numbers and each row or a column is selected using its address, which is a binary number. Such a reduction is feasible in RAM because just one or a few bits (e.g. a byte or a nibble) are accessed at a time. A display device has to display all pixels simultaneously at a high frame rate and therefore pixel-by-pixel addressing is not feasible in most displays.

In summary, a matrix display with N rows and M columns can address a maximum of $(N \times M)$ pixels with $(N + M)$ drivers. The number of connections to the display is a minimum when the number of rows is equal to the number of columns. In other words, the number of connections to the display is a minimum when the number of address lines is an integer that is equal to or close to the square root of the number of pixels. For example, if the number of pixels is 1000 then the square root of 1000 is about 31.6. The number of connections to the display is a minimum when the pixels are arranged and interconnected to form a 32 × 32 matrix. A further reduction in the number of drivers and interconnections can be achieved by using an unconventional interconnection scheme. For example, x address lines can address $x(x - 1)$ polarity-dependent pixels in, for example, a light emitting diode (LED) (Gillessen *et al.*, 1981). In the case of an LCD, $x(x - 1)/2$ pixels can be addressed if the number of pixels is small (Kmetz, 1982). Multilevel addressing is feasible by stacking a few displays in front of each other to reduce the number of drivers. Pixels in each of these panels are addressed by electrical means and optical means of addressing is used in the third dimension to combine the results of addressing the individual panels in the stack (Sherr, 1972).

2.2 Display Fonts and Formats

The quality of images reproduced on a display depends on the number of pixels per unit distance and the viewing distance, that is the distance between the display and the eyes in addition to the original quality of the image. A display has to reproduce an image without any degradation in quality as compared to the original image. A person with normal vision can resolve two points that subtend an angle of 1 minute of arc at the eye (Hartidge, 1922). This translates to a minimum of 12 pixels/mm when a display is viewed at a distance of 250 mm. The display in some mobile phones has such a high resolution (~300 pixels per inch). Such a high density of pixels is not easy to achieve in some display technologies. For example, each pixel in a plasma display panel (PDP) is isolated from its neighbouring pixels and therefore it is not feasible to fabricate a PDP with a high pixel density due to various process-related factors.

Displays with a high density of pixels may be too expensive for some applications. For example, we need a cluster of about 900 pixels to display an alphanumeric character or a symbol in order to achieve the high resolution of a printed text. The cost of the display, drive electronics and the associated circuits is proportional to the size of the display and the resolution. It is not necessary to have a large number of pixels in numeric and alphanumeric displays. We can use some standard fonts to reduce the number of pixels and consequently the number of drivers, cost, reliability, etc. (Sherr, 1979). A seven segment font is a standard font that is used to display numbers in calculators, instrument panels, thermometers, etc. At least 14 to 16 segments are necessary to display alphabets in addition to numerals. A dot matrix font with 5 rows and 3 columns (5 × 3 dot matrix font) of pixels is also useful to display numbers. A dot matrix of 7 rows and 5 columns (7 × 5 dot matrix font) or a larger matrix size is used to display alphanumeric information. Several fonts that are useful to display alphanumeric information are listed in Table 2.1; however, some of these fonts are no longer popular.

Fonts are designed to reduce the number of pixels and sometimes malfunction or failure of a segment or pixel can lead to reading errors. For example, in a seven segment display; three segments are activated when the numeral seven is displayed. If the top horizontal segment of the seven segments is not activated due to a fault (either due to a failure of the corresponding

Table 2.1 Fonts and formats for numbers and alphabets (alphanumeric fonts)

No.	Fonts	Number of segments or elements	Format	Application	Comments
1	Seven segments	7 segments and a numeric dot	Tilted to right	Calculators/ digital watches	Numbers and a few symbols
2	Star burst pattern	13 to 16 segments	Tilted to right	Programmable calculators	Alphabets and numbers
3	Dot matrix	3 × 5, 5 × 5, 7 × 5, 9 ×7	Tilted to right in some cases	Programmable and simple hand-held devices	3 × 5 for numbers Others for alphabets and numbers

driver or a snapped interconnection between a driver and a segment), such a fault related to the segment may go unnoticed because the number will be interpreted as 1, whereas a fault related to the same segment will be noticed if the number 8 is displayed. A similar failure in a sixteen segment font may lead to the alphabet R being read as P. Hence, failure of even one segment can lead to an erroneous reading and interpretation of data in segmented displays.

Hence, a fault condition that leads to failure of pixels is not acceptable in segmented and dot matrix fonts that are used to display alphanumeric characters. On the other hand, a fault related to a pixel in a dot matrix font will not lead to an erroneous reading because of the redundancy of pixels in dot matrix fonts. A wrongly activated pixel is relatively more prominent and gets noticed easily as compared to an OFF pixel in the dot matrix font. The state-of-the-art displays in many applications have millions of pixels and it is not necessary to use fonts with a small number of pixels in such graphic displays. For example, most mobile phones have a matrix display with a large number of pixels to display images. Fonts with a large number of pixels are used to display alphabets and numbers on these displays.

Electrode patterns on the top and bottom glass plates are used to form pixels in a liquid crystal display, which is described in the next section. Electrode patterns on the glass substrates are designed such that the electrode pattern in the top and bottom glass plates of the LCD intersect at the pixel and not anywhere else in the active area of the LCD. The shape of the pixel is determined by the area of intersection of the two electrode patterns; it allows some flexibility to shape the fonts. Symbols like kHz, mV, Ω, etc., can be incorporated in the LCD with a high resolution. Pixels in the LCD are interconnected to form a matrix display when the number of pixels is large, as shown in Figures 2.1 to 2.3. A dashboard display shown in Figure 2.1 has pixels of different shapes ranging from symbols (S1 to S10), pointers (K1 to K23), segments (X1 to X9, T1 to T8, F1 to F5) and dot matrix font (a 3 × 5 dot matrix for the numeric display). The electrode patterns on two substrates of the LCD are shown in Figures 2.2 and 2.3. Electrode patterns on the two substrates of the LCD interconnect the pixels of varying shape and size to form a matrix display, as shown in Figure 2.4. The electrode patterns on the

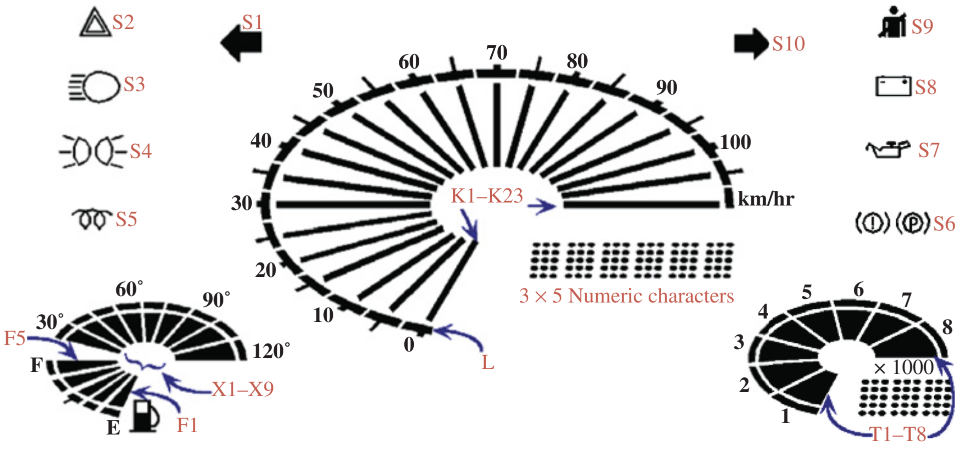

Figure 2.1 A dashboard display for an automobile, which is a collection of several displays of varying size and format.

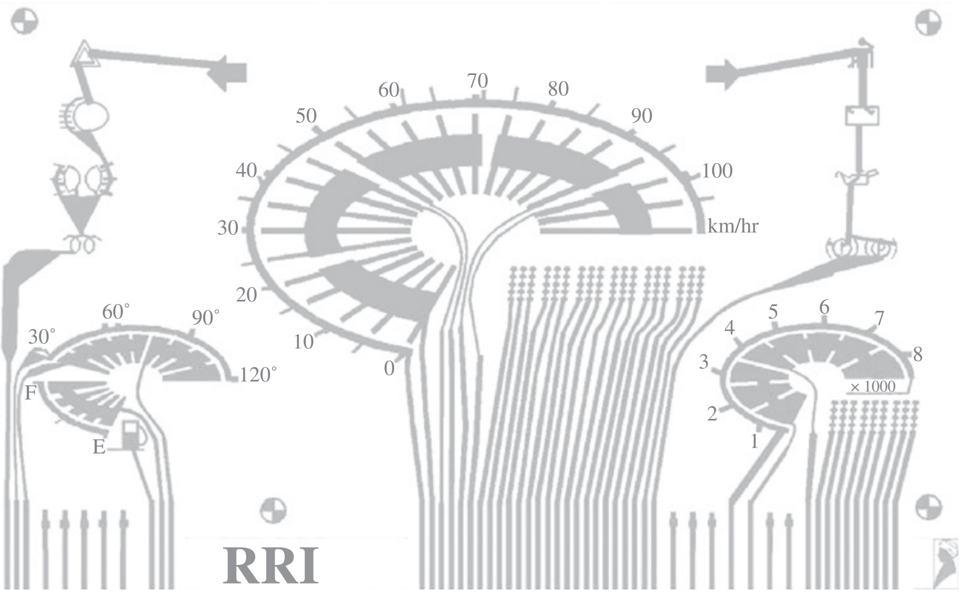

Figure 2.2 Electrode pattern of segments and pixels and their interconnection to form data electrodes of a matrix display on a glass substrate of the LCD shown in Figure 2.1.

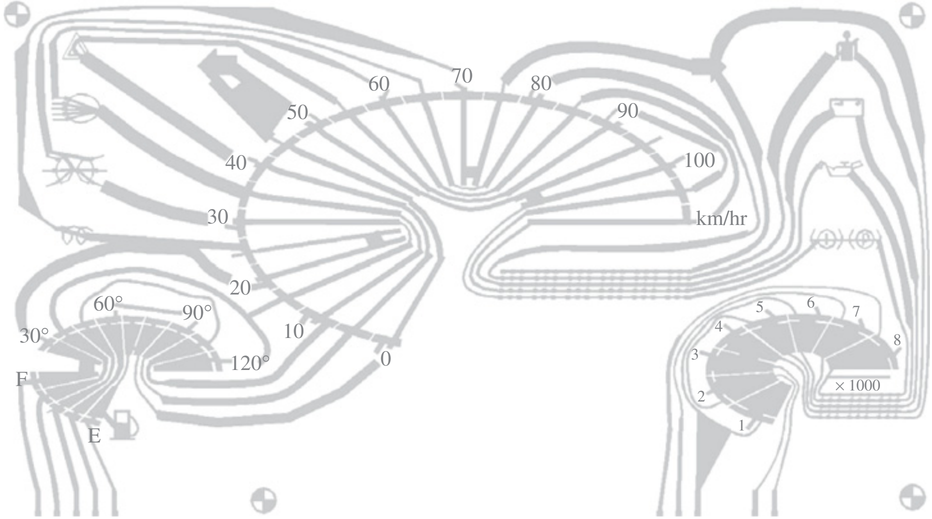

Figure 2.3 Electrode pattern of segments and pixels and their interconnection to form scanning electrodes on a glass substrate of the LCD shown in Figure 2.1.

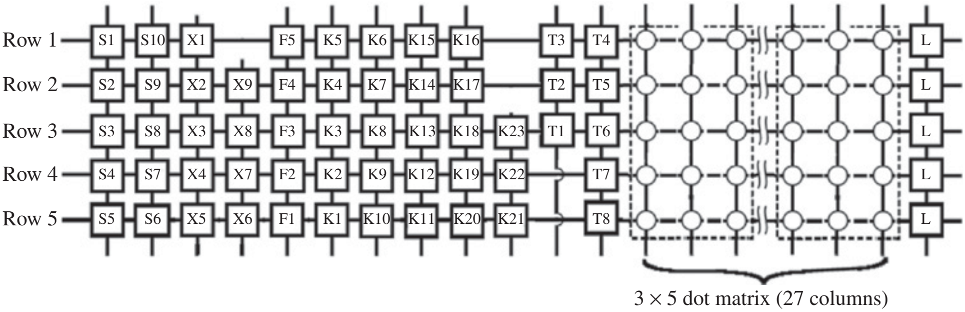

Figure 2.4 Interconnection of pixels in the display shown in Figure 2.1 to form a matrix display of 5 rows and 40 columns.

glass plates form the pixels as well as the address lines. Photograph of the display is shown in Figure 2.5.

2.3 Liquid Crystals

Friedrich Reinitzer, an Austrian botanist, found in the year 1888 that ‘cholesteryl benzoate’ has two distinct melting points (Reinitzer, 1888; Shanks, 1982). Many organic materials melt from the solid state to form a turbid liquid and on further heating undergo a second transition and melt to form a clear ‘isotropic liquid’. Such materials exhibit some properties of crystalline materials and also some properties of liquid when they are in an intermediate state between the

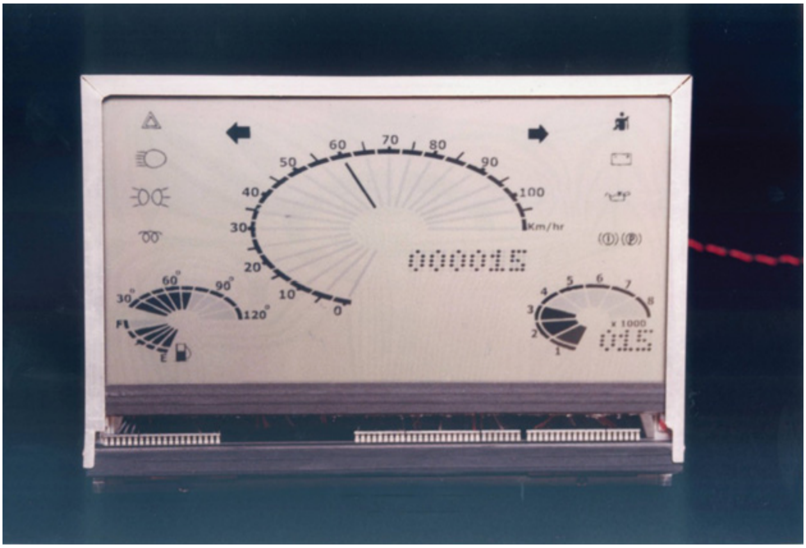

Figure 2.5 Photograph of the dashboard display.

solid and the isotropic liquid state. Hence, this intermediate phase is called the liquid crystalline phase and materials exhibiting such phases are called liquid crystals and also mesomorphic substances or mesomorphs. Liquid crystals are broadly classified either as thermotropic liquid crystals or lyotropic liquid crystals. Liquid crystalline phases are obtained by heating or cooling thermotropic liquid crystals. Lyotropic materials exhibit a liquid crystalline phase when they are dissolved in an appropriate solvent. Thermotropic liquid crystals are used in liquid crystal displays. Liquid crystal molecules have shape anisotropy and most of the liquid crystals used in displays are rod-like molecules that are elongated in a certain direction. Such liquid crystal molecules exhibit an orientation order in the liquid crystalline phase. The average direction of orientation of liquid crystal molecules in a small volume of liquid crystal is represented by a unit vector (of arbitrary sign); this unit vector is referred to as the director. Nematic liquid crystals are the simplest and most widely used in an LCD. Rod-like molecules of nematic liquid crystals are approximately parallel to one another and therefore have an orientation order, but the molecules do not have positional order. Cholesteric liquid crystals also exhibit orientation order. The director of a cholesteric material rotates continuously about a helical axis due to the presence of one or more chiral centres within the molecules. A cholesteric liquid crystal has a characteristic pitch; a nematic liquid crystal can also be visualized as a cholesteric liquid crystal with an infinite pitch. Smectic liquid crystals are more like solids because they have a one-dimensional positional order in addition to the orientation order, due to the presence of one or more chiral centres within the molecules. Smectic liquid crystals are further classified as smectic-A to smectic-H, depending on the order within and between layers. Smetic-C* is of special interest as such crystals are used in a ferroelectric LCD. Columnar liquid crystals have a two-dimensional positional order wherein molecules are closely packed into flexible columnar structures; that is the disc-like molecules are piled on each other to form the columns.

2.4 Physical Properties of Liquid Crystals

Physical properties of liquid crystals depend on the molecular structure of liquid crystals as well as the ordering of molecules. Many physical properties of liquid crystals are anisotropic. Macroscopic properties of liquid crystals are measured as principle components in a direction parallel to the director and perpendicular to the director. Some important physical properties are discussed in this section.

The temperature at which a liquid crystal melts from the solid state to the liquid crystalline phase is called the melting point. Similarly, the temperature corresponding to the transition from the liquid crystalline state to an isotropic liquid is called the clearing point. These two temperatures are important for the liquid crystal display (LCD) because these temperatures determine the operating range of the LCD. Most liquid crystal mixtures that are used in an LCD have a melting point below 0 °C and a clearing point above 60 °C.

Dielectric anisotropy is another parameter that is important for the operating mode and operating voltage of an LCD. Dielectric anisotropy ($\Delta\varepsilon$) is the difference between the dielectric constant that is measured parallel to the director and the dielectric constant that is measured perpendicular to the director ($\Delta\varepsilon = \varepsilon_{\text{parallel}} - \varepsilon_{\text{perpendicular}}$). Liquid crystal materials with a positive dielectric anisotropy orient their long axis of molecules to be parallel to the direction of the external electric field and materials with a negative dielectric anisotropy orient their long axis of the molecules to be perpendicular to the direction of the electric field.

The dielectric constant $\varepsilon_{\text{parallel}}$ depends on the frequency of the electric field that is applied to the liquid crystal cell in compounds with polar molecules whereas $\varepsilon_{\text{perpendicular}}$ is independent of the frequency from DC to 10 MHz. A decrease of $\varepsilon_{\text{parallel}}$ with frequency is called a dielectric relaxation. In some materials $\Delta\varepsilon$ can change sign from a positive value at low frequencies to a negative value at high frequencies. The frequency at which the $\Delta\varepsilon$ is zero is called the crossover frequency. Dual frequency addressing relies on the frequency dependency of the dielectric constant to drive the LCD. The crossover frequency is highly sensitive to temperature and therefore limits the potential of two-frequency addressing to drive the LCD.

In a well-aligned nematic liquid crystal layer, the optic axis coincides with the director and therefore a ray of light travelling parallel to the optic axis encounters one refractive index that is independent of polarization of the incident light because the distribution has circular symmetry around the director. Light travelling perpendicular to the director is subjected to two refractive indices: n_{parallel} for light with its polarization vector parallel to the director and $n_{\text{perpendicular}}$ for light with its polarization vector perpendicular to the director. This phenomenon is called birefringence or double refraction. Optical anisotropy is defined as $\Delta n = (n_{\text{parallel}} - n_{\text{perpendicular}})$.

Liquid crystals have three curvature elastic constants, viz. splay (k_{11}), twist (k_{22}) and bend (k_{33}), corresponding to three possible distortions in the director configuration. An electro-optic response of the LCD depends on these elastic constants. For example, the ratio (k_{11}/k_{33}) determines the steepness of the electro-optic response in a twisted nematic LCD. The response times of the LCD depend on the viscosity of the liquid crystal; low viscosity mixtures are preferred for a fast response of the LCD.

The pitch of a cholesteric liquid crystal is defined as the distance between the director in two planes that are separated by a 360° rotation of the director.

2.5 Basics of Electro-optic Effects with Liquid Crystals

Many physical properties of liquid crystals depend on the orientation of the molecules because they have shape anisotropy and are sensitive to relatively weak stimuli. Therefore, an electric field, magnetic field or thermal energy can be used to induce optical effects in liquid crystals by reorienting the molecules to achieve change in absorption, reflection or scattering of light. Display devices demand liquid mixtures with appropriate electrical, optical, elastic and thermal properties, including a stable phase over a wide temperature range and operating conditions. Small external stimuli can induce a large change in the orientation of liquid crystal molecules and modulate the external light. Some advantages of an LCD are low voltage operation, a flexible format, flat panel construction and a wide range of size. A reflective LCD consumes low power to operate and has good legibility even under high ambient light. An LCD consists of a thin layer (a few micrometres) of a liquid crystal mixture sandwiched between two glass plates. Most LCDs need a uniformly aligned liquid crystal cell. Molecular alignment in an LCD is achieved by preparing the inner surfaces of the cell. The orientation of molecules may be parallel to the inner surface of the glass substrate, which is referred to as planar or homogeneous alignment. In some LCDs, the molecules are oriented to be perpendicular to the inner surface of glass substrates, which is referred to as perpendicular or homeotropic alignment. The molecules may also be aligned to subtend an angle to the surface of the glass substrates, which is referred to as tilted alignment. Planar alignment is obtained by coating the surface of a substrate with a layer of polyimide, curing the polyimide to form a rigid coating and buffing the cured polyimide surface in one direction with a roller covered with nylon, cloth or velvet material. Perpendicular alignment is obtained by chemical treatment of the surface. Photopolymerization is preferred to achieve surface alignment of liquid crystal molecules because it is a clean process as compared to the buffing process, which leaves traces of the material from the buffing material. Photopolymerization has the additional advantage of the ability to control the tilt angle at the surface of the substrate. Some important steps involved in manufacturing liquid crystal display are as follows: (a) coating substrates (glass or plastic) with transparent and electrically conducting material like indium tin oxide; (b) patterning the conducting layer either by photolithography or by selective printing to form pixels and electrodes for interconnection; (c) treating the surface of the substrates to align the molecules; (d) spreading the spacer particles on a substrate to control the display cell thickness; (e) assembling substrates with a sealant to form a display; (f) injecting liquid crystal mixture in to the display cell (nowadays a drop-fill method is preferred to avoid wastage of the liquid crystal mixture, where a measured quantity of the liquid crystal mixture is dispensed on to one of the substrates and the other substrate with a pre-cured sealant is brought together and the cell sealed once the liquid crystal mixture is spread uniformly between the two substrates); (g) fixing the polarizers on the outer surfaces of the cell; (h) connecting the electrodes on the display cell to the display drivers (interconnection); (i) attaching the backlight assembly to the cell; (j) connecting the assembled LCD to the controller; and (k) testing the LCD module.

2.6 Twisted Nematic Effect

The twisted nematic (TN) effect (Schadt and Helfrich, 1971; Schadt, 2009) was the most widely used effect in an LCD during the 1970s until the end of the last century. A TN-LCD cell consists of a thin layer of nematic liquid crystal (NLC) mixture with a positive dielectric anisotropy sandwiched between two substrates that are treated for parallel alignment. The cell is assembled such that the molecular alignments at the inner surfaces of the cell are perpendicular to each other. Liquid crystal molecules that are confined in the cell form a 90° twisted structure as dictated by the alignment at the surfaces of the TN cell. The twisted structure of liquid crystal molecules acts like a waveguide and rotates the plane of polarization of light incident on it by 90°; that is the incident light follows the molecular rotation inside the cell. Hence, a linearly polarized light that is incident on the cell will emerge linearly polarized in the orthogonal direction if the plane of polarization of the incident light is parallel or perpendicular to the director at the surface of the cell and the product of the optical anisotropy (Δn) and the pitch (P) is high compared to the wavelength of the incident light. Here, P is four times the thickness of the cell because only a 90° twist is allowed in the cell due to a small cell gap of a few micrometres. A TN-LCD cell in an unexcited state without application of an electric field rotates the plane of the polarization of incident light by 90°. Hence, the cell appears dark when the TN cell is viewed by sliding it between two parallel polarizers with the polarizing axis parallel or perpendicular to the cell. The TN-LCD cell will be transparent, when it is viewed by holding it between two polarizers that are perpendicular to each other and the polarizing axis of the polarizers are parallel or perpendicular to the director at the surfaces of the cell. The 90° twist of molecules in the cell is lost when a sufficiently strong electric field is applied to the cell (ON). Hence, the cell excited cell will appear transparent between two parallel polarizers and dark between two perpendicular polarizers. The change in transmission light in the unexcited and excited states is exploited to achieve a contrast in the TN-LCD. Just one optical mode is excited in the TN-LCD because the polarizers are either parallel or perpendicular to the director at the surface of the cell. TN-LCDs require a low power to operate; ($\sim$1 μW/cm^2) because they modulate the incident light and do not emit light. A voltage in the range of 2–5 V is adequate to excite the ON pixels. The TN-LCD can be either a transmissive type display with the light source at the back and the observer in front of the display or a reflective type display with the light source and the observer in front of the display by using a polarizer with a reflector at the back of the LCD. Most displays are of a trans-reflective type with a trans-reflector at the back so that the display is legible under dark and bright environments. The TN-LCD can be operated in either a positive contrast mode with dark symbols against a bright background or a negative contrast mode with bright symbols against a dark background by fixing the top and bottom polarizers to be parallel to each other. A positive contrast mode is preferred in a reflective type of display, whereas a negative contrast mode is preferred in a transmissive type of display. The TN-LCD responds equally well to both positive and negative voltages. However, the life of the display will be reduced due to irreversible electrochemical reactions if the LCD is driven with a DC field. Hence, LCDs are normally driven with an AC field. The TN-LCD is slow to respond to the electric field and the response time can range from a few milliseconds to a few tens of milliseconds. The electro-optic response is determined by the root-mean-square (RMS) voltage when the period of addressing waveforms is small as compared to the response times. The electro-optic response is described by (a) the threshold voltage (V_{th}), (b) the saturation voltage (V_{sat}), the sharpness parameter (γ) and the response times, as shown in Figure 2.6.

The threshold voltage (V_{th}) decreases with an increase in temperature (typically –5 to –20 mV/°C). V_{th} is also a function of the viewing angle and decreases with an increase in the viewing angle from the normal of the LCD. The sharpness parameter is a measure of the steepness of the electro-optic response and gives an idea of the number of lines that can be multiplexed by using the liquid crystal mixture. A value close to 1 is preferred for γ to be useful in an LCD with a large matrix size. Both V_{th} and γ depend mainly on the NLC mixture used in the display. The response time depends on the NLC mixture, the display cell thickness

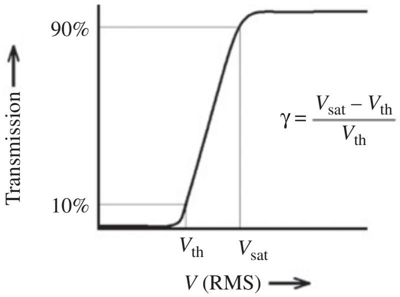

Figure 2.6 Electro-optic response of the LCD.