

**EXAMPLE 4.3** Brightness of an LED

We take an LED with a chip diameter of 0.2 mm which is viewed from a distance of 1 m. It emits at a wavelength of 550 nm and has an external quantum efficiency of 0.1%. We further assume that the emission is isotropic and that the diode is operated at 50 mA. We must first decide whether the diode acts as a point or as an extended source at the eye. The emitting area subtends an angle  $\theta$  where

$$\tan \frac{\theta}{2} = \frac{2 \times 10^{-4}}{2 \times 1} = 10^{-4}$$

whence  $\theta < 1$  minute of arc, and the LED acts as a point source.

The total radiant power output  $W$  is given by

$$\begin{aligned} W &= hf/\lambda \times \text{quantum efficiency} \times \text{photon emission rate} \\ &= \frac{hc}{550 \times 10^{-9}} \times (0.001) \times \frac{(50 \times 10^{-3})}{e} \end{aligned}$$

Therefore  $W = 1.13 \times 10^{-6}$  watts.

Using Fig. 1.24, we take an average luminosity at 550 nm of 600 lm  $W^{-1}$ , hence the luminous flux from the source is  $1.13 \times 10^{-6} \times 600$ , that is  $6.8 \times 10^{-7}$  lm. Isotropic emission means the flux is uniformly distributed over the solid angle  $2\pi$ , and so the luminous intensity at normal incidence is  $6.8 \times 10^{-7}/2\pi = 1.1 \times 10^{-7}$  candela.

Another brightness unit sometimes encountered is the foot-Lambert (ft L). This is obtained by dividing the total luminous flux (in lumens) by the area of the device in square feet. This definition assumes a Lambertian emission pattern. To convert nits or candelas  $m^{-2}$  into foot-Lamberts (for a Lambertian surface) we multiply by the factor 0.292 (this factor may be derived from eq. 4.22a).

The brightness level required of a display will depend on the ambient lighting conditions. In a dimly lit room, a brightness of about 10 nits may suffice, whilst in a well-lit environment about 1000 nits may be needed, although the difference between the display on and off brightnesses also plays an important role. A more thorough discussion is given in ref. 4.9.

#### **4.9** Liquid crystal displays

We turn now to the most important of the 'passive' types of display (and indeed the only one of this type we shall mention), namely liquid crystal displays (LCDs). These have come into prominence in the last few years mainly as display elements for digital watches and pocket calculators. Here one of the prime requisites is for low power consumption, particularly so for the digital watch because of the necessarily low capacity of the power source. LCDs consume the least power of all common display devices because no light generation is required. This, as we have seen in the LED, for example (Table 4.2), is a very inefficient process; at best the efficiency is only some 10%. There are two basic types of LCD avail-

able. These are (a) reflective, which requires front illumination, and (b) transmissive, which requires rear illumination. Most reflective types utilize ambient light for illumination with provision for secondary illumination via a small incandescent lamp or LED if ambient levels become too low. At the heart of all LCD devices is a cell formed between two glass plates, each with a conductive coating. The cell has a thickness of about 10  $\mu\text{m}$  (sometimes less) and is filled with a liquid crystal material.

The liquid crystal state is a phase of matter which is exhibited by a large number of organic materials over a restricted temperature range. At the lower end of the temperature range, the material becomes a crystalline solid, whilst at the upper end it changes into a clear liquid. Within this range it has a milky yellowish appearance and combines some of the optical properties of solids with the fluidity of liquids. A major characteristic of all liquid crystal compounds is the rod-like shape of their molecules. When they are in the liquid crystal phase, these molecules can take up certain orientations relative both to each other and to the liquid crystal surface. It is usual to describe this orientation in terms of a *director*, that is a unit vector pointing along the time-averaged preferred orientation of the molecules in any small volume.

There are three basic types of ordering in liquid crystals, which are termed *nematic*, *cholesteric* and *smectic*. Only the first two of these are of importance in display devices at present and are illustrated in Fig. 4.23. In nematic ordering, the molecules (or, rather, the directors) are aligned parallel to each other, but apart from remaining parallel the molecules are free to move relative to each other so that the phase has liquid properties. A nematic liquid crystal molecule usually consists of two benzene rings linked with a central group. A typical example is 4-methoxybenzylidene-4-butylniline (MBBA), which has the chemical formula  $\text{CH}_3\text{O}-\text{C}_6\text{H}_4-\text{CH}=\text{N}-\text{C}_6\text{H}_4-\text{C}_4\text{H}_9$ . MBBA shows liquid crystal behaviour over the temperature range 20°C to 47°C. For more general details concerning liquid crystal materials the reader is referred to ref. 4.10.

In the cholesteric phase (Fig. 4.23b) we may regard the material as being made up from a large number of planes each having a nematic-like structure, but with each plane showing a progressive change in the director direction from the one below. The director directions thus display a helical twist through the material. The distance between planes having the same director direction is called the *pitch*,  $p$ . Cholesteric liquid crystals exhibit some interesting colour effects. If, for example, light of wavelength  $\lambda$  is incident normally on the director planes, then strong Bragg reflection will occur when  $p = n\lambda$  ( $n$  an integer), but not otherwise. Thus if white light is shone onto a cholesteric liquid crystal, it can appear strongly coloured. Furthermore, the pitch is usually temperature dependent, so that the colour of the reflected light will also be temperature dependent. Obviously this can form the basis of a thermometer. Most liquid displays, however, are of the so-called twisted nematic type, and we shall spend the rest of this section discussing them.

When a nematic liquid crystal material comes into contact with a solid surface, the directors often become aligned either perpendicular to the surface (*homeotropic* ordering) or parallel to the surface (*homogeneous* ordering). These two forms can be produced by suitable treatment of the surface. In the case of homogeneous ordering, this can often be achieved by rubbing the surface once or twice along a particular direction with a soft fabric (e.g. cotton) before it comes into contact with the liquid crystal material. The liquid crystal directors then take up an orientation parallel to the direction of rubbing.

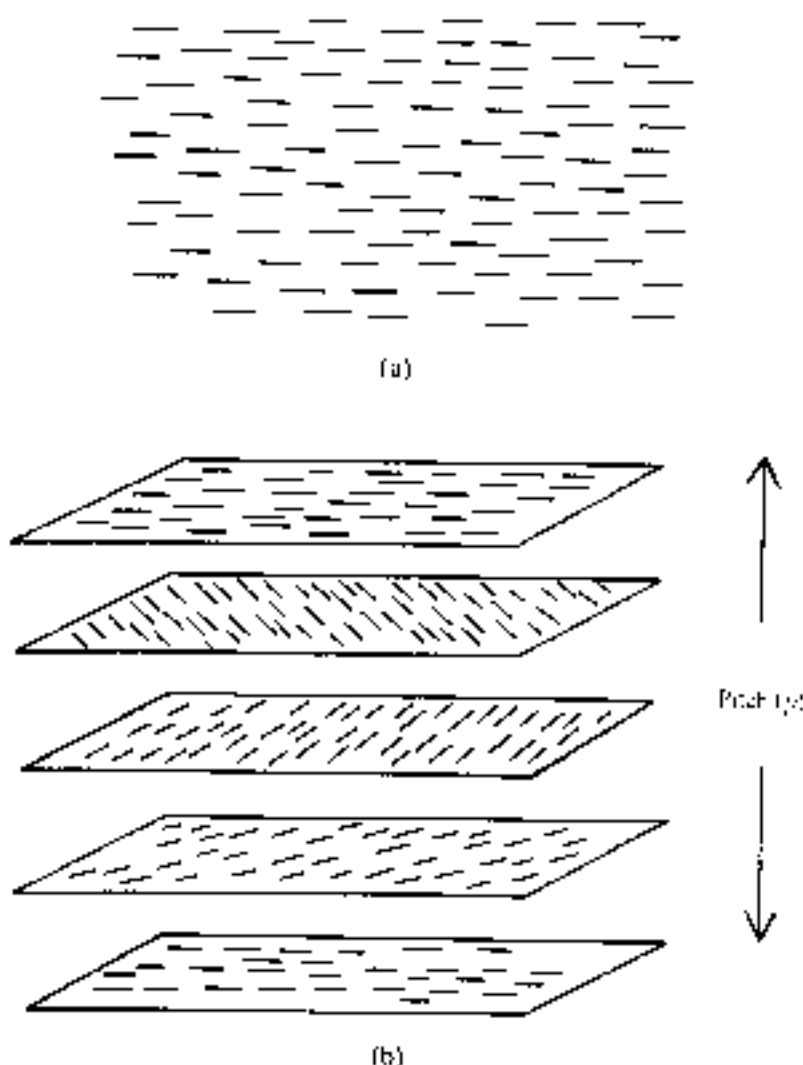


FIG. 4.23 (a) Nematic ordering and (b) smectic ordering. (a) The dashes all line up parallel to each other. In (b) a large number of planes of nematic order are formed where the dashes rotate as we move along a direction perpendicular to the planes.

One of the most important electrical characteristics of liquid crystal materials is that they show different dielectric constants  $\epsilon_{\parallel}$  and  $\epsilon_{\perp}$  depending on whether the external field is parallel to, or perpendicular to, the molecular axis. If  $\epsilon_{\parallel} > \epsilon_{\perp}$  we refer to it as a *positive* material. The application of an external electric field to a positive material will tend to make the molecules lie along the electric field, since this will tend to minimize their energy. We see that there is thus a possibility of changing the homogeneous type of ordering into a homeotropic type by the application of a field which is perpendicular to the surface (assuming a positive material!). This transition is found to take place above a critical field ( $E_c$ ) and is illustrated in Fig. 4.24.

The most common liquid crystal display uses a 'twisted nematic' cell. In this, the opposite walls of the cell are treated to produce a homogeneous arrangement in which the molecular alignment directions at the walls are at right angles to each other. Thus the molecules

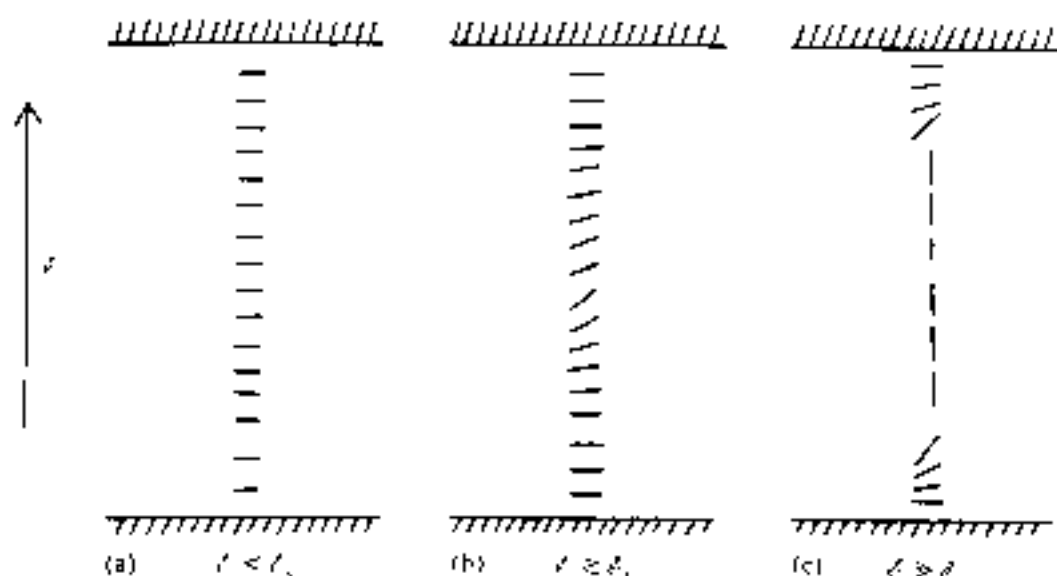


FIG. 4.24 Behavior of molecules in an initially homogeneously oriented liquid crystal material as an increasing electric field of magnitude  $E$  is applied in a direction perpendicular to the liquid crystal-solid interface. If  $E$  is less than a critical value ( $E_c$ ) the ordering is not affected (a). If  $E \approx E_c$ , the molecules furthest away from the interface begin to align along the field direction (b). If  $E \gg E_c$ , then most of the molecules are aligned along the field direction (c).

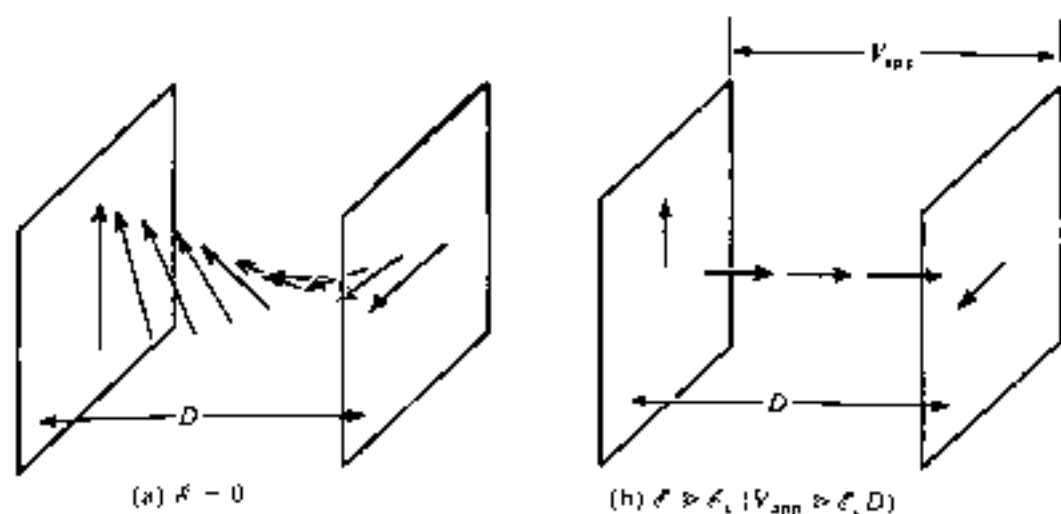


FIG. 4.25 Behavior of the molecules in a liquid crystal cell of thickness  $D$  with (a) no applied voltage ( $E = 0$ ) and (b) with a voltage applied such that  $E \gg E_c$ . In the former the molecules undergo a  $90^\circ$  rotation across the cell; in the latter they are mostly oriented with their axes parallel to the applied field.

undergo a  $90^\circ$  rotation across the cell as shown in Fig. 4.25(a). When a beam of polarized light is incident on the cell the strong optical anisotropy of the liquid causes the polarization to undergo a  $90^\circ$  rotation. With a strong enough electric field across the cell, however (i.e.  $E \gg E_c$ ), the molecular alignments will become as shown in Fig. 4.25(b) and in this state the molecular alignments will have no effect on an incident polarized light beam.

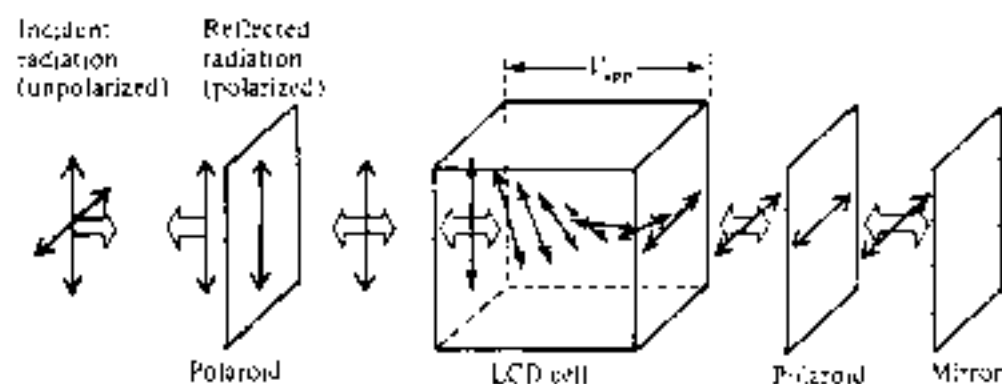


FIG. 4.26 Illustration of the action of an LCD in reflective mode.

In operation, the cell is sandwiched between two pieces of polaroid whose polarizing directions correspond to the director ordering direction of the particular cell surfaces they are next to. In the reflective mode a reflector is placed behind the back sheet of polaroid. Figure 4.26 shows the arrangement and traces the behaviour of a polarized beam as it traverses the system. With no applied voltage, the incident light is first polarized, then has its polarization direction rotated by  $90^\circ$  as it traverses the cell, then passes through the second polarizer and is then reflected back along its path where the same process is repeated. With no field applied, therefore, the device reflects incident radiation and appears bright. When a field is applied the direction of polarization of light traversing the cell is not rotated and hence cannot pass through the second polarizer. Little light will then be reflected from the device and it will appear dark.

The amount of light reflected from an LCD as a function of applied voltage is shown schematically in Fig. 4.27. The reflectance, initially constant, falls rapidly beyond a critical

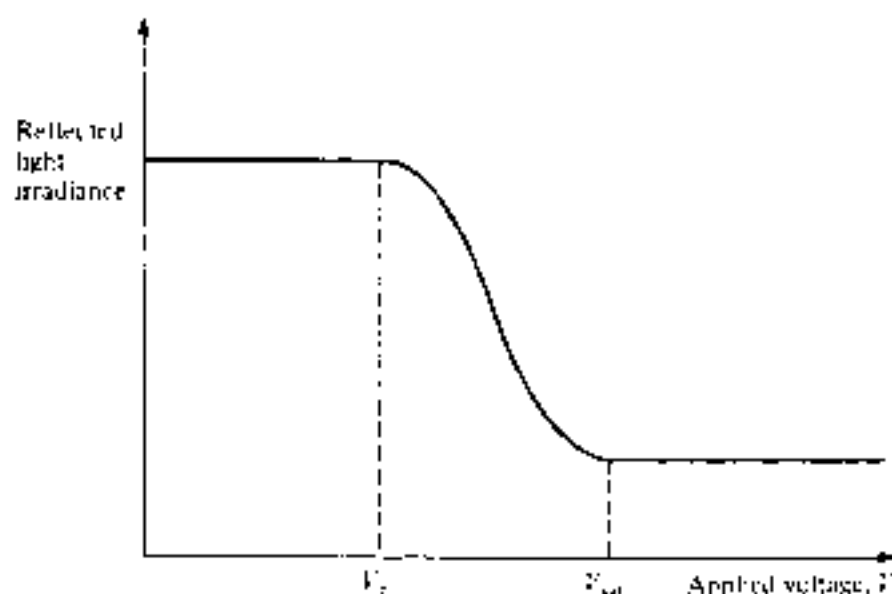


FIG. 4.27 Amount of light reflected from a liquid crystal display as a function of applied voltage  $V$ . The reflected irradiance remains constant up to the critical voltage  $V_c$ , then falls with increasing voltage until it again becomes constant beyond  $V_{sat}$ .

cal voltage  $V_{\text{th}} (= \lambda/D)$ ;  $D$  = cell thickness) and again becomes constant beyond a voltage  $V_{\text{th}}$ . A typical value for  $V_{\text{th}}$  is 3 V. D.C. operation tends to shorten the operating lifetime of the device owing to electromechanical reactions taking place, and hence a.c. waveforms are invariably used. The cell responds to the r.m.s. value of the voltage waveform. A square waveform which has a frequency of between 25 Hz and 1 kHz is often used.

Transistor LCD displays do not have the reflector, and must be provided with rear illumination, but otherwise they operate in a very similar fashion to the reflective displays. Colour displays are possible by incorporating a colour filter. The use of polarizers in the twisted nematic cell substantially reduces the maximum amount of light that can be reflected from it (see Problem 4.7). In addition, the angle of viewing is found to be restricted to about  $\pm 45^\circ$ . A greater image contrast over a wider range of viewing angles can be obtained by increasing the angle of twist to  $270^\circ$  to give the so-called 'super-twist' display. The light reflection curve shows a much more rapid switch from on to off states (i.e. the corresponding  $V_{\text{th}}$  and  $V_{\text{off}}$  values are much closer together than for the  $90^\circ$  twist curve (Fig. 4.27)). A disadvantage of this is that the switching times are longer than for the  $90^\circ$  twist and the cell width has to be reduced to compensate.

#### 4.10 Numeric displays

We turn now to the problem of combining our individual display elements into some pattern capable of conveying more information than just a simple 'on' or 'off' situation. There is no doubt that for medium area, high resolution displays there is as yet no ready alternative to CRTs. These do, however, have the obvious disadvantages of a small display area to volume ratio, of requiring a high voltage supply and of being sensitive to adverse environmental conditions (e.g. stray magnetic fields).

Displays that require only a small number of basic elements are easily catered for by using LED, liquid crystal or plasma display elements. One of the simplest display formats commonly used to form the numbers 0 to 9 consists of seven bar segments and is illustrated in Fig. 4.28(a). Each bar might itself consist of several discrete display elements depending

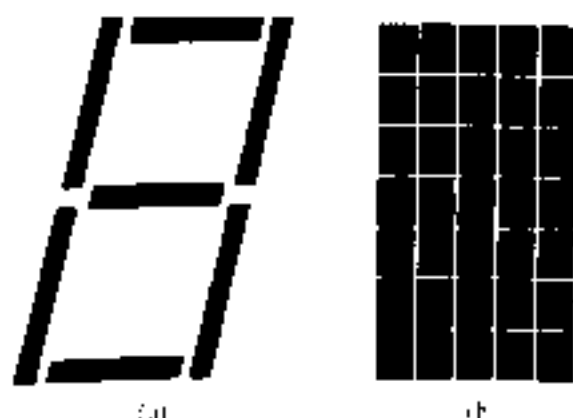


FIG. 4.28 Two numeric display formats to illustrate the seven-segment display used to form the numbers from 0 to 9; the  $6 \times 5$  matrix display can be used for more complex characters.