

Polymer dispersed liquid crystal (PDLC) films

Devices constructed from thin polymer films with randomly dispersed liquid crystal droplets (PDLC films) are reviewed. PDLC films have already been researched in some detail and materials in the form of tough flexible films are available commercially. The materials used in their manufacture are available in commercial quantities and can be processed by standard film-forming techniques rendering large-area, environmentally robust displays and light shutters easy and inexpensive to manufacture. Single-piece light valves of up to 3 m² are relatively common. PDLC shutters do not require polarisers, so that light loss through the cell in the clear state is reduced. The article describes the operating principle of PDLC films and discusses their electro-optic properties with emphasis on their influence on device performance. Finally, an assessment of present and future applications of this technology is presented.

by G. Spruce and R. D. Pringle

1 Introduction

Thin polymer films comprising liquid crystal (LC) microdroplets dispersed in a matrix are promising materials for a variety of light control and electro-optic applications. In these films the fabrication problems inherent in twist cells (such as surface alignment, cell filling and sealing) are not encountered. In addition, PDLC shutters (in contrast to other liquid crystal light shutters such as twisted nematic [TN], π -cell or supertwist cells) do not require polarisers. This simplifies design, reduces cost and can increase device lifetime in high-temperature, high-humidity conditions where polarisers often degrade or peel off. The absence of polarisers substantially reduces light loss through the cell in the clear state (polarisers usually block over 50% of the incident light in TN cells). PDLC films are for this reason particularly suited to light projection applications. The

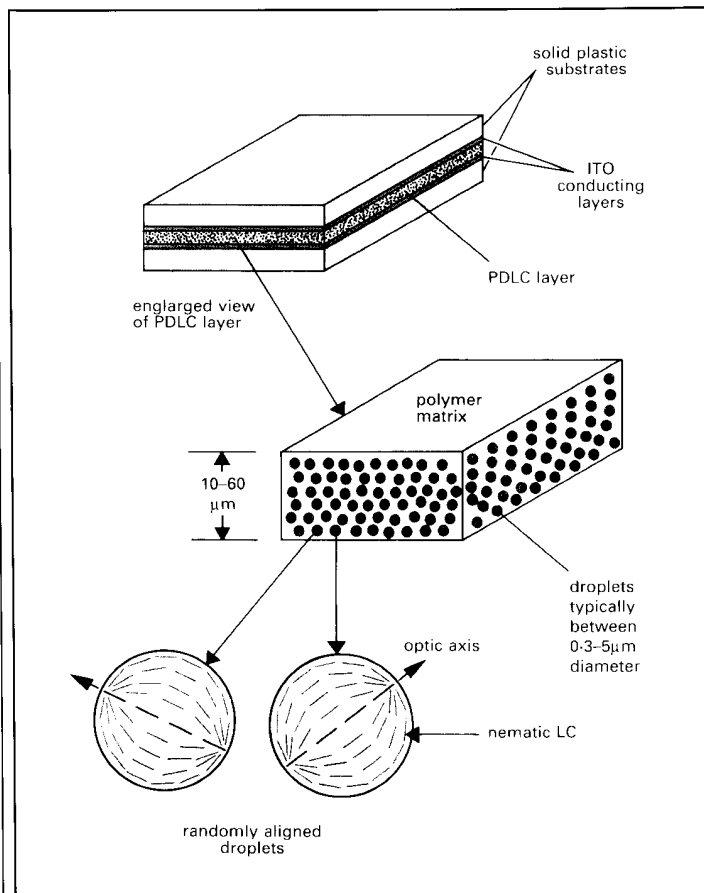
improved transmission characteristics of these films also, alternatively, permit lower-power backlighting to be used which in itself is an attractive feature for any display intended for portable computer or television applications. These devices are generally capable of a much faster response than a TN display utilising the same liquid crystal and submillisecond response times have been reported.

The operation of these polymer film devices is based on the ability of the birefringent LC droplets to either scatter or transmit incident light, depending on the relationship between the refractive indices of the component materials. The films fall into two major classes: encapsulated liquid crystals^{1,2} (often referred to as nematic curvilinear aligned phase [NCAP] films) and polymer-dispersed liquid crystal (PDLC) films.³⁻⁷ A typical film structure is shown schematically in Fig. 1. The

distinction between NCAP and PDLC films lies in their method of preparation. Both classes of film, however, have the same operating principle and very similar electro-optic characteristics and thus, for convenience, are treated together in this article and generally referred to as PDLC films. The optoelectronic response of these devices depends on the film structure, which is in turn determined by the constituent materials and the film formation process used.

2 Operating principle

These films switch between a highly scattering translucent state in which images are blocked and a very clear transparent state (see Fig. 2). These states correspond, respectively, to a nearly random alignment and to a nearly perfect alignment of the LC in the cavities. The LC molecules within each droplet, in the off-state, adopt the configuration which minimises the droplet free energy for the boundary conditions determined by interactions at the droplet-polymer interface. In the off-state, the LC molecules usually adopt a bipolar configuration^{8,9} in which the nematic director is tangential to the droplet wall, the director field possesses cylindrical symmetry, and there are two point disclinations at opposite sides of the droplet. The axis of cylindrical symmetry (bipolar axis) is the optic axis of the droplet. The rod-like LC molecules within the cavities are birefringent, i.e. they have more than one index of refraction: two equal 'ordinary' indices, n_o , along two normal axes to the director axis, and one 'extraordinary' index, n_e , along the director axis. The birefringence, Δn , is defined as $n_e - n_o$, and is typically between +0.12 and +0.25 for the LC materials used in these films. Therefore, light polarised along the droplet optic axis sees a refractive



1 Structure of a PDLC film

index close to n_o , whereas light polarised normal to the droplet optic axis sees an index close to n_e . The optic axes of all the droplets are randomly aligned in the off-state and incoming light propagating normal to the film encounters a range of refractive indices between n_e and n_o . All of these refractive indices cannot be equal to the refractive index, n_p , of the polymer matrix and thus the light is scattered by the droplets. For a film of sufficient thickness (10–60 μm) with droplet diameters somewhere in the range 0.1–10 μm and for droplet concentrations of up to 50% by volume, the light undergoes many scattering events before emerging from the film. This multiple scattering produces the translucent off-state, shown schematically in Fig. 3a.

An applied electric field interacts with the LC via the dielectric torque to reorientate the molecular configuration within each droplet. PDLC films usually utilise a nematic LC of positive dielectric

anisotropy (i.e. $\epsilon_{para} > \epsilon_{per}$, where ϵ_{para} and ϵ_{per} are the dielectric permittivities parallel and perpendicular, respectively, to the long molecular axis), and so the LC molecules attempt to align with their long axes along the applied field direction. For a sufficiently strong field, the axes of nearly all the molecules point along the field direction and each droplet presents a refractive index close to n_o to the incoming light. The polymer refractive index, n_p , is usually chosen to be close to n_o and thus light entering the powered film sees very little change in refractive index in crossing the polymer/nematic interfaces and is transmitted without refraction. The powered film, therefore, is highly transparent to normally incident light (see Fig. 3b).

PDLC films are driven by AC voltages since LC devices can undergo serious electrochemical degradation with long-term exposure to DC voltages. The nematic LC droplets respond to the

RMS value of the applied field. Film switching voltages (typically 30 to 70 V_{RMS}) are relatively high, but can be readily produced with BIFET (bipolar – FET) drivers. The on-time response of these devices is typically between 1 and 10 ms for an applied field of the order of 1–2 $V/\mu\text{m}$. The decay response of these films, unlike conventional LC devices, is not limited by the thickness of the electro-optic layer, but is governed by the size and shape of the droplets. Submillisecond relaxation times are possible (albeit at some cost in drive voltage) for films possessing droplets of submicron diameter or high shape anisotropy,^{10,11} but turn-off times in the region of 1–10 ms are more typical. This is quite rapid in comparison to conventional nematic devices, whose decay response is usually in the 20–100 ms range. It is noteworthy that elongated droplets possess a greater deformation energy for the nematic in the field-aligned state than near spherical droplets and hence possess a stronger restoring force on removal of the field, which increases the field required to orientate the droplets and decreases the decay time, respectively.

3 Film formation

NCAP films are formed by emulsifying the nematic LC with an aqueous phase containing the encapsulating medium. The continuous aqueous phase can either contain a water soluble polymer (e.g. polyvinylalcohol)² or can be a colloidal suspension of a water insoluble polymer (latex emulsion).^{1,2} The emulsion is usually spread onto an indium-tin-oxide (ITO) coated polyester substrate and allowed to dry. The evaporation of the carrier fluid (e.g. water) leaves a continuous transparent polymer matrix containing LC droplets. The droplets in the dried film are similar in size and shape to those in the original emulsion. The size distribution of the LC droplets in the emulsion is controlled by the fluid agitation process used to form the emulsion. Droplets in NCAP films typically possess a mean volume diameter in the range of 1 to 5 μm .² These films are completed by either depositing an electrode layer on to the film or adding a second electrode-coated solid substrate to form a sandwich structure.

In contrast to NCAP films, PDLC films are formed from a



2 Application of an electric field switches the film between a highly scattering translucent state and a very clear transparent state (Courtesy of Polytronix Inc., Richardson, Texas)

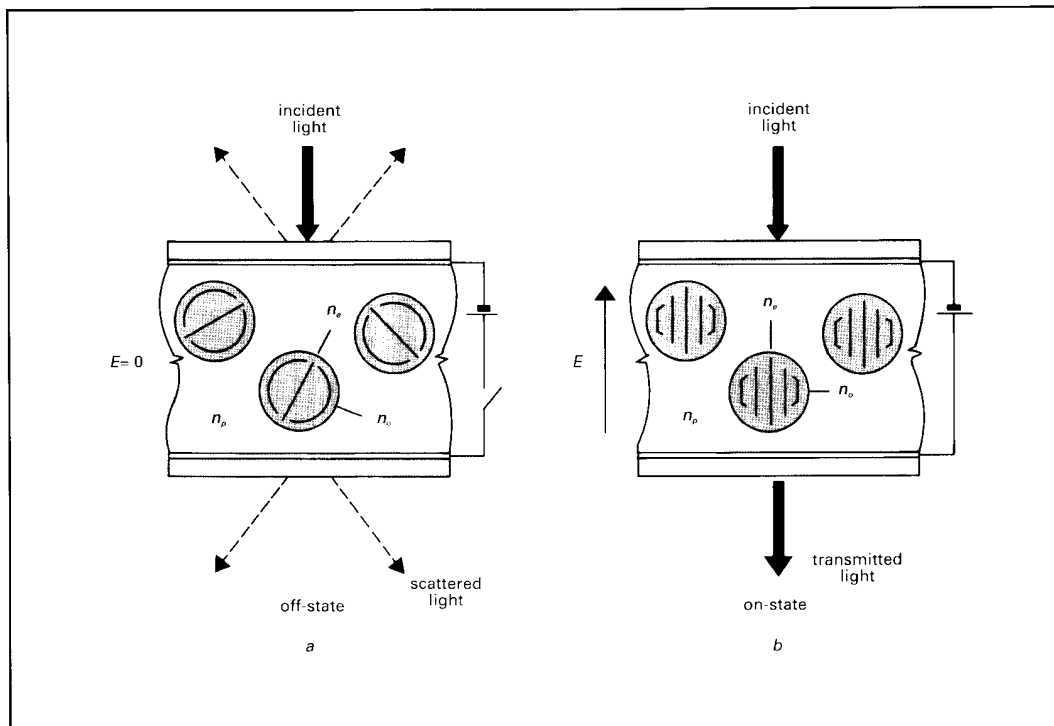
homogenous, isotropic solution of the LC material in either the polymer matrix material or its precursors. Droplets are formed spontaneously by a phase separation process which occurs during film formation. The phase separation process can be induced by polymerisation, temperature, or a combination of solvent and temperature. Phase separation processes will not be discussed here since they are described in detail elsewhere.^{3-5,7,9,12} The use of phase separation processes allows

the droplet size to be made relatively uniform and to be preselected to be of the order of the wavelength of light at which the scattering efficiency is maximised. Droplet sizes are, therefore, usually preselected to be between 0.3 and 3 μm in diameter for display applications.¹³

4 The electro-optic response curve and multiplexing capability

Images are displayed on PDLC films (as with conventional LC

devices) by photolithographically defining patterns in electrodes deposited on the film surface and selectively energising various segments to form, for instance, alphanumeric character displays. Such segments are often directly driven but when separate connections to each display element are not possible multiplexing or matrix addressing (time sharing) of the display elements is necessary. These segmented electrodes are usually connected in orthogonal rows and



3 PDLC light shutter illustrating (a) the opaque scattering state and (b) the field-induced transparent state

columns to produce display elements at the intersections. The rows of the matrix are scanned sequentially in time and appropriate voltages applied, in parallel, to the columns such that the display element at the intersection is on or off. Each segment responds to the RMS voltage across it and thus, if the voltage at the intersection is above some minimum value, V_{on} , the segment will turn on and if it is below some lower value, V_{off} , the segment will turn off. The maximum ratio of the RMS voltage across a selected element (V_{on}) to that across a nonselected element (V_{off}) hence decreases as the number, N , of scanned rows increases and is given by the ratio

$$V_{on}/V_{off} = [(N^{1/2} + 1)/(N^{1/2} - 1)]^{1/2} \quad (1)$$

Rearranging eqn. 1 gives the maximum number of rows, N_{max} , which can be multiplexed in any display responding to the RMS voltage as

$$N_{max} = [(V_{on}^2 + V_{off}^2)/(V_{on}^2 - V_{off}^2)]^2$$

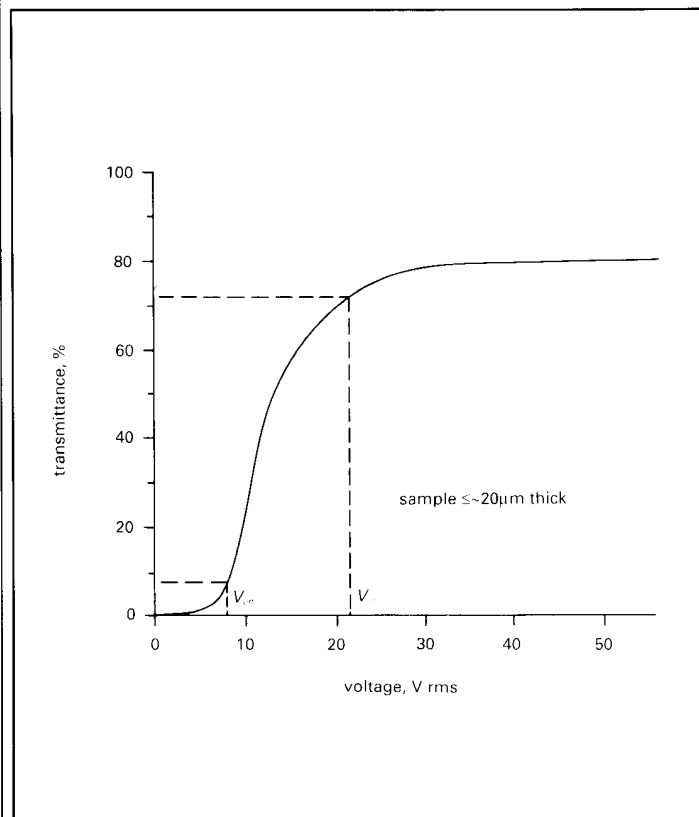
The multiplexing level therefore

depends primarily on the difference between V_{on} and V_{off} . Eqn. 1 clearly shows that V_{on}/V_{off} is typically required to be close to unity for highly multiplexed displays (i.e. when N is large). The difference between these voltages is determined by the slope of the transmittance against voltage curve between the chosen transmittance levels of the on- and off-states (usually 90% and 10% transmission for an acceptable contrast between the on- and off-states). A typical transmission against voltage curve for a PDLC sample is shown in Fig. 4. Obviously the steeper this slope, the larger the number of rows which can be multiplexed.

Droplet uniformity is important since any variations in the droplet size, shape or orientation along the major axis of the cavity causes a dispersion in the threshold switching field for the film as a whole, reducing the sharpness of the response curve. However, even with uniform droplets the voltage threshold is often poorly defined. A gradual 'turn-on' characteristic for these films results from the

electrical properties (the resistivity and dielectric constants) of the LC and polymer materials. In a simple electrical representation, both the LC and the polymer material can be represented by parallel RC circuits. Polymer material is both in series and in parallel with the liquid crystal and thus the film can be viewed as a complicated arrangement of parallel RC networks (which are in series and parallel with each other). Some of the applied voltage is, therefore, inevitably dropped across the solid polymer which, in turn, acts to reduce the electric field experienced by the liquid crystal from the usual value (applied voltage/cell thickness). The threshold field for these films, for this reason, is often apparently greater (typically 5 to 10 times) than the values expected from calculations of the threshold field for individual droplets.¹⁰ Applying a field causes the LC molecules to reorientate, so that their largest value of dielectric permittivity is parallel to the field direction and this acts to increase the 'effective' dielectric constant of the droplets. In addition, since there is polymer in series with the droplets, the voltage across the liquid crystal is reduced *pro rata* during the field-induced molecular reorientation. A gradual turn-on characteristic is thus usually inevitable for these films. This effect is more pronounced in thicker films and in films utilising LC materials with a large dielectric anisotropy, particularly at low temperatures where the dielectric anisotropy tends to increase. High dielectric anisotropies are, however, generally desirable (as with conventional LC devices) to produce fast turn-on times and low threshold voltages. The effect of temperature and film thickness on the turn-on characteristic can be seen in Fig. 5.

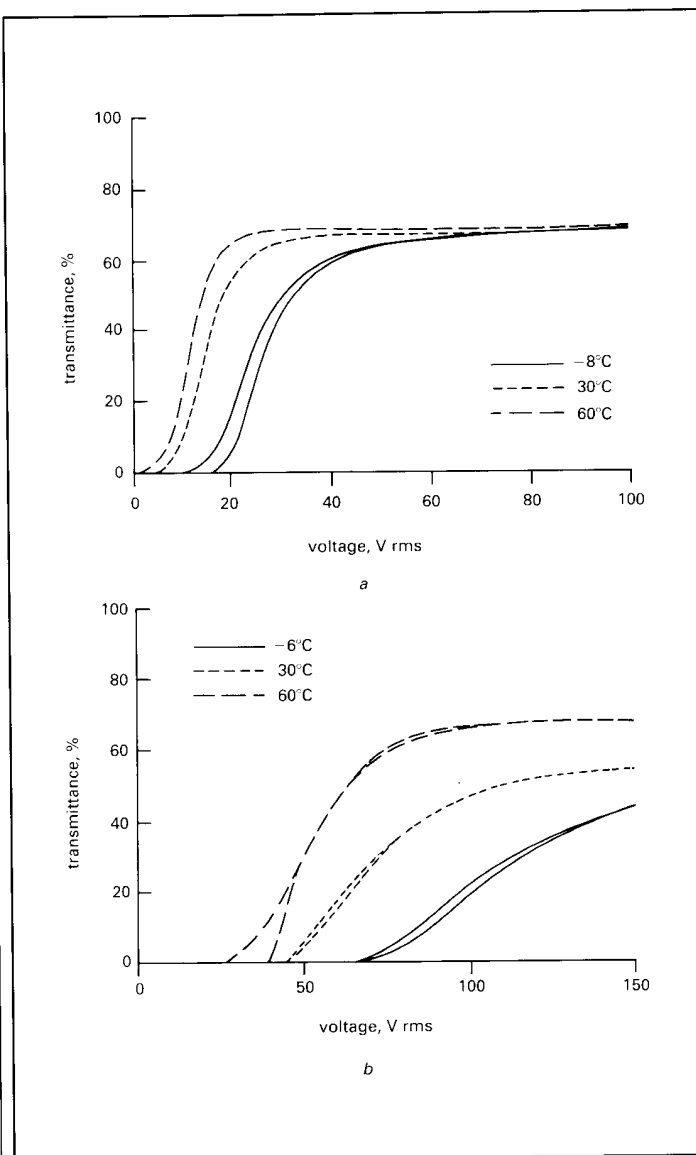
For the above reason, achieving high levels of intrinsic multiplexing (more than 3 or 4 lines) is difficult and with many films only direct driving is possible. However, a 1-in-7 duty cycle has been demonstrated with PDLC films using dual frequency addressing (DFA) to increase the steepness of the transmittance against voltage curve. DFA requires the use of a LC material whose dielectric anisotropy, $\Delta\epsilon (= \epsilon_{para} - \epsilon_{per})$, changes from positive to negative at a particular value of the driving frequency called the crossover frequency, f_c . At frequencies below f_c the applied



4 Typical transmittance against voltage curve, showing the voltage levels which would define the off and on states for display applications

voltage aligns the molecules parallel to the applied field (causing the film to become transparent), but increasing the signal frequency above f_c causes the LC molecules to align perpendicular to the field (thereby producing the scattering state). The increased complexity of the drive circuits demanded by the need to provide drive voltages at two frequencies is not a serious disincentive with modern integrated-circuit techniques. However, the operating temperature range of DFA devices using currently available materials is limited to relatively small ranges above room temperature¹⁴ because f_c increases exponentially with increasing temperature and practical considerations require that f_c must be above about 24 Hz (to avoid flicker) and below 15 kHz (to avoid sample heating).

Seven lines clearly do not constitute a high-information display, but this could be increased (e.g. by a factor of 2 or 4) by increasing the number of address lines to achieve what amounts to a reduction in the overall multiplexing level. However, active matrix techniques can be used even with poorly defined voltage thresholds to produce high-resolution images in small display sizes.^{13,15} PDLC films with a two inch square (5 cm) 500 by 500 matrix have been reported by Doane *et al.*¹⁵ Active matrix displays require a nonlinear conducting element to be placed in series with each display element. Each nonlinear device, typically a transistor, provides a nonlinear response compatible with the fastest addressing time and the isolating effect of such elements enables the stored charge to be dissipated across the display element in a time compatible with the LC response. This addressing technique provides a 100% duty cycle irrespective of that of the addressing waveform (i.e. a performance compatible with that of a direct-drive display but without the interconnection complexities). The main drawback with this technique is the added complexity of the film fabrication process which restricts the size of the display and inevitably increases costs. Comprehensive discussions of active matrix display technology and the problems association with the production of larger area active matrix LC devices are given by S. Morozumi¹⁶ and by G. Stix,¹⁷ respectively.



5 Transmittance against voltage curves for two similarly constructed PDLC films of differing thickness: (a) 17.5 μm ; (b) 60 μm . These results are reproduced from Reference 24, Montgomery *et al.* SPIE, Vol.958, 1988, pp.104-111

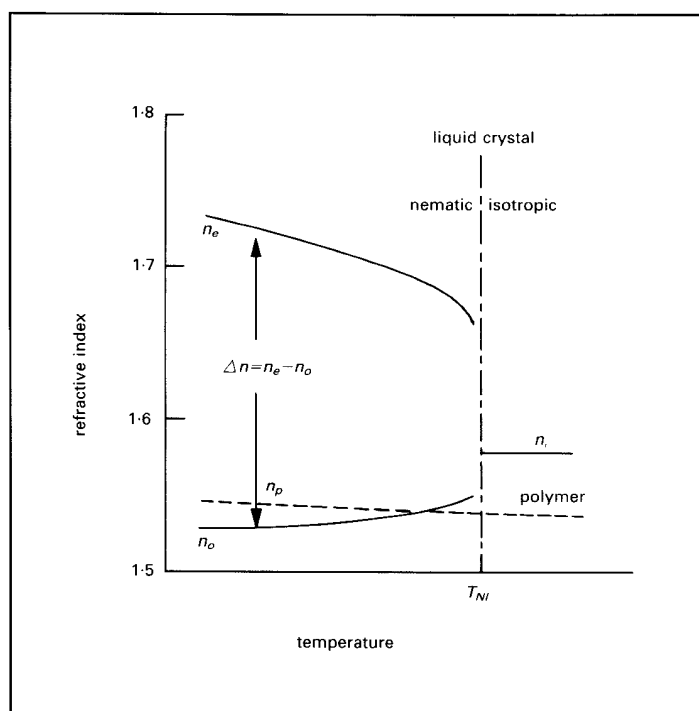
5 Refractive index matching

In general, the refractive indices of the liquid crystal and the polymer must be suitably matched to produce low off-state and high on-state transmissions, but this index matching condition can be strongly affected by both the angle at which the light is incident and the temperature.

Angular dependence

In the transparent, field-aligned state, normally incident light sees little change in refractive index in crossing the polymer/nematic

interfaces and is transmitted without refraction. However, obliquely incident light is scattered in proportion to the angle of incidence, since the effective refractive index seen by the light becomes increasingly different from n_o , as the angle of incidence increases. Under diffuse lighting conditions, light impinges on the film from many directions and the obliquely incident light is scattered into a range of angles within the film. Some of these scattered rays hit other droplets, producing further scattering, before reaching



6 Schematic representation of the temperature dependence of the refractive indices of the component materials

the wall of the film. Any scattered light reaching the wall (dielectric/air interface) at an angle beyond the critical angle becomes trapped in the film, travelling back through the film to be scattered again. This enhances backscattering and reduces film transmission. Therefore, although these films are transparent to normally incident light, all light incident at large angles undergoes scattering. The angular dependence of the scattering causes a 'haze' in the transparent state under diffuse lighting. The 'haze' value^{*11,18,19} is used to define the film clarity in the transparent state. Residual 'haze' is highly dependent on the constituent materials and is usually adjusted by altering n_p relative to n_o . Haze values of <5% have been achieved by this method but 7–10% is more typical.²

The chosen index-matching condition (i.e. n_p/n_o) influences both the angular position of maximum transmission and the angular breadth of the transmission peak.¹⁸ When n_p/n_o is

* Haze is defined as the percentage of transmitted light, on passing through the sample, which is forward scattered into an angle greater than 2.5° away from the incident beam direction (ASTM standard D-1003).

≥ 1 , maximum transmission occurs for normally incident light with the angular breadth of the transmission peak being broadest for the matched case, $n_o = n_p$. However, a narrower transmission peak can be advantageous in some applications, such as coatings for windows, where it is desirable to control direct sunlight at some angles but permit high visibility at others. When n_p/n_o is less than 1, the angular position of maximum transmission is shifted away from normal incidence, with the incident angle for maximum transmission depending on the value of this ratio and the LC birefringence.¹⁰ Films of this type may be useful as angular discrimination filters.

Temperature dependence

In the off-state n_p and n_o are intentionally mismatched to produce a scattering state with the degree of scattering depending on the LC birefringence, Δn ($= n_e - n_o$). In general, Δn increases with decreasing temperature and often changes at a faster rate than n_p , which leads to increased scattering and a rapid decrease in off-state transmittance as the temperature decreases below the isotropic/nematic transition. The temperature dependence of the

refractive indices of typical component materials is shown schematically in Fig. 6.

In the on-state, n_p is usually chosen to match n_o at some temperature. This match, however, will not necessarily hold at other temperatures, since n_o typically decreases as the temperature decreases whereas n_p increases. The on-state transmittance is, therefore, only maximised at the temperature where $n_o = n_p$, and any change from this temperature can cause the index mismatch to increase, thereby decreasing the transmittance. The difference in the rates of change of the indices with temperature is usually more pronounced at temperatures near to the liquid crystalline transition temperature, T_{NI} . This is an intrinsic problem with LC materials and achieving optimum film performance relies on choosing the film operating temperature range to be as far below T_{NI} as possible¹⁹ and on the use of LC mixtures with a very wide nematic temperature range.

6 Contrast ratio

Contrast ratio (CR) is an important measure of performance for any electro-optic display. The CR is mainly dependent on the light-scattering properties of the films, but extensive CR studies²⁰ have shown that the perceived CR also depends on both its definition and the procedure used to measure it.

Values of CR can be obtained by viewing either the unscattered light (e.g. the ratio of the transmission [or brightness] in the on- and off-states) or the scattered light (e.g. the ratio of the light rejected in the off- and on-states). Values of CR obtained from measurements of rejected light are determined primarily by the on-state transmittance, whereas those obtained from measurements of the unscattered light are dominated by the off-state transmittance. The contrast of displays in which the rejected light is viewed (e.g. compact direct-views displays) can, therefore, often be improved by using thinner films which are more transparent in the on-state. However, when the CR is dominated by the off-state transmittance (e.g. projection and many light control applications) the extent to which the off-state scattering can be improved without decreasing the on-state transmittance is the important factor. The most direct approach to decreasing the off-state transmittance is to increase the

film thickness, but this, firstly, increases the film activation voltage and, secondly, decreases the operational viewing angle. The latter results from unavoidable refractive index mismatches which render a hazy appearance to the powered film as the viewing angle increases. An alternative approach is to increase the scattering efficiency of the individual droplets which, in turn, depends on the mismatch between n_c and n_p ($=n_o$). Obviously, using a LC material with a large birefringence ($n_c - n_o$) will increase the mismatch and produce stronger scattering. However, since the optic (bipolar) axes of the droplets are usually aligned randomly in the off-state, the scattering efficiency of these films is effectively reduced to that of a collection of droplets with effective refractive indices (in the off condition), n_{eff} , ranging from n_o to n_c such that $n_o > n_{eff} > n_o (= n_p)$. The off-state scattering efficiency is, therefore, improved if the LC molecules are aligned so that n_{eff} approaches n_o , the value most different from n_p . This can be achieved by forcing the LC molecules to align in two mutually orthogonal directions, one for each state (i.e. on and off). One way to achieve this is to elongate the LC droplets, e.g. by stressing the polymer matrix during or after polymerisation. This aligns the symmetry (bipolar) axis of the droplets along the stretch direction to produce a plane or even uniaxial alignment of the LC in the off-state.^{5,6} Another technique is to use the dual-frequency-addressing (DFA) scheme, mentioned earlier, to switch the film between the on- and off-states¹⁴ to provide the two mutually orthogonal directions required to produce $n_{eff} = n_c > n_o$ (and hence n_p).

7 Applications

This technology is particularly suited to the production of low-power consumption, large-area displays and light valves — an application to which other LC display technologies have proved ill-suited. The commercial potential of these films also encompasses many applications: architectural windows; interior windows, partitions and screens; electronic displays and signs; and automobile sunroofs.

Colour displays

PDLC displays can be coloured by incorporating dyes in the LC and/or binder. Transmission mode displays also allow the use of

coloured backlighting. Liquid crystals can, in general, be used with dyes to produce either black-and-white or colour displays. The addition of a high-order-parameter pleochroic dye to the nematic produces a film which possesses a controllable absorption as well as a controllable scattering. Such devices are generally called 'dyed-phase change' or 'guest-host' displays. In the unpowered film the presence of the nematic/dye



7 Side profile of a commercial integrated colour display panel (Courtesy of the Taliq Corporation, Sunnyvale, CA)

system in the droplets, whose bipolar axes are either orientated randomly (near spherical droplets) or parallel to the film plane (oblate droplets), results in the absorption of all incoming polarisations and causes the film to appear black. The application of a field causes the dye molecules to become perpendicular to the polarisation vectors of the incoming light, thereby reducing the optical absorption of the film to produce the clear on-state. The use of pleochroic dyes in these films produces strong visual contrast between the on- and off-states. Reflective coloured displays can be constructed by mounting guest-host films in front of coloured fluorescent reflectors. In the powered state, light entering the film experiences low absorbance and minimal scattering. The coloured reflector is seen clearly, resulting in a powered state with high brightness and colour purity. The unpowered film appears dark since the incoming light is both strongly scattered and absorbed (the predominant effect). Displays constructed in this manner are thin and do not require a backlight for high visibility in ambient light. The freedom from the need for polarisers allows improved

brightness and wide viewing angles (typically 160°) to be achieved with these devices (in addition to saving the cost of the polarisers). Even though the use of pleochroic dyes results in an increased response time for the nematic, commercial guest-host film displays usually exhibit fast response times (millisecond rise times and millisecond to tens of milliseconds decay times). These displays are constructed on a flexible substrate and can readily be fabricated into large or irregularly shaped devices. The properties of these devices permit the manufacture of integrated control panels and thick-film touch switches in one thin lightweight panel (see Fig. 7). This type of design is readily adapted for a number of control panel-type applications (see Fig. 8).

A simple alternative method of producing PDLC colour displays is to incorporate a nonpleochroic dye in the polymer matrix.²¹ This produces increased reflections within the film, which increases the path length of the scattered light, thus colouring the output light. These films can be fabricated to produce coloured characters on a dark background or dark characters on a coloured background. The contrast with the latter is further improved by the addition of a pleochroic dye to the LC. This can be yet further improved by the incorporation of a nonpleochroic dye within the polymer matrix to produce a display in which there is no parallax between the dyed area and the LC. Patterns can be formed in films using pleochroic dyes in the LC and nonpleochroic dye in the binder to provide red, green and blue (RGB) triads for full-colour displays. Whilst it is true that, with a system of this sort, two-thirds of the light is lost, the brightness obtained has, nevertheless, been shown to be superior to that normally achieved with TN devices and filters.²¹ Furthermore, the low parallax combined with the thinness of these films allows them to be sandwiched together to produce complementary or subtractive colour displays. Multilayer subtractive colour displays are advantageous in this respect since they can be constructed without the large light losses associated with an RGB triad colour system.

It is noteworthy that the use of a dye absorption mechanism in these films for outdoor applications requires the use of



8 Fully integrated control panel consisting of a reflective-mode display which is laminated to membrane switch layers and a graphic overlay (Courtesy of the Taliq Corporation, Sunnyvale, CA)

dyes which are stable when exposed to solar ultraviolet radiation. In this respect, many early coloured systems tended to photo-oxidise or photobleach (i.e. exhibit a noticeable discolouration) after prolonged exposure to solar radiation. Ultraviolet light degradation is still a problem since no dyes which are compatible with PDLC film materials and which have adequate ultraviolet radiation stability for outdoor applications appear to be available at this time.⁹ One interim solution may be to incorporate a commercial ultraviolet radiation absorbing film into the structure.

Large-area light valves

The dispersal (and encapsulation) of liquid crystals in polymeric materials has permitted the fabrication of large-area field effect devices. Single piece light valves greater in area than three square metres have been constructed.¹¹ Large-area displays have not generally been possible with previous liquid crystal technologies because the production of uniform spacing, which is required to produce a uniform optical response, is difficult over large areas. This problem usually restricts the size of traditional devices to less than 0.1 m square. In PDLC films,

however, the polymer acts to maintain a constant spacing between the ITO layers, allowing a uniform optical response to be achieved.

Most large-area films at present are prepared by emulsifying the nematic LC in an aqueous mixture containing colloidal polymer particles (i.e. NCAP type films). This emulsion is applied to ITO substrates using a continuous coating process before drying. Electrical contact to the ITO is usually achieved with conductive thick film inks. These films are usually laminated to glass or to rigid sheets of plastic to create a wide variety of window constructions for both architectural and automotive applications, although the further development of films formed from the simpler phase separation processes may lead to the production of 'free-standing' large-area light valves.

Present constructions exhibit all of the good properties of existing glass and plastics window products but with the added advantage of variable light control⁵ (see Fig. 9). Films may be laminated to single sheets, between sheets or in the air gap of double glazing, depending on the relative importance of weight, space efficiency, thermal insulation, solar heat reflection and operational environment (i.e. indoors or outdoors) in the chosen application.

Windows can be produced with a clear state whose clarity permits visibility approaching that of glass and a scattering, translucent state which can, by adjustment of the material and processing parameters, be varied from providing totally obscured vision (privacy applications etc.) to only providing shade as with standard tinted glass (shading and glare-reduction applications). Electrically controlled windows for indoor architectural applications are commercially available in the USA and Japan and are expected to become commonplace in the buildings of the next century. Common present applications include conference room walls (see Fig. 10), partitions in operating theatres and offices, and retail displays.

Automotive prototypes have also been fabricated,² but the commercial realisation of products, such as solar control sunroofs, is likely to be a longer term prospect, since there are additional requirements which



9 Present large-area films exhibit all the good properties of existing glass but with the added advantage of variable light control (Courtesy of Fred Nobile, Linear Optics)

need to be addressed. In this respect, modern automobile designs tend to favour increased glazing areas, which increase the solar heat load on the interior and make the development of energy control products a necessity. These materials must also provide the optical and environmental properties required to withstand the higher temperatures and solar exposure expected in this application. Solar control applications, in general, require the scattered light to be directed away from the film (or absorbed, invoking the problems mentioned in the preceding section), to prevent the passage of solar energy, and not merely to be scattered slightly as with variable transmission windows. The solar attenuation characteristics of present films are discussed by G. P. Montgomery^{9,22} and P. Van Kronenburg *et al.*² An additional requirement is the development of materials and fabrication processes compatible with the manufacture of the complex curved products necessary for this type of application.

Automotive applications

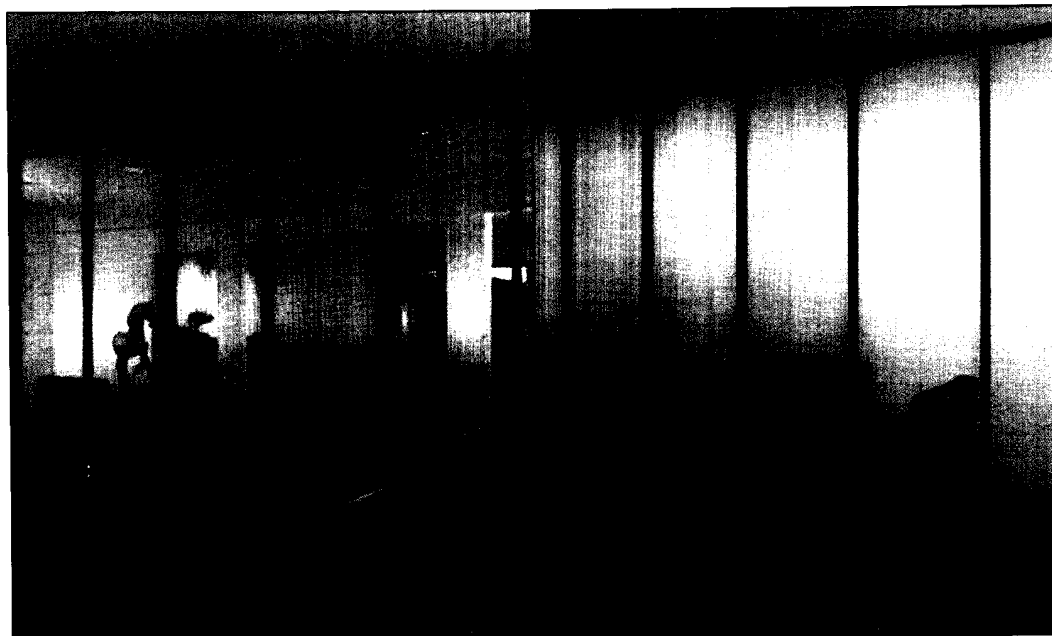
PDLC films could have many applications within the automotive industry. Possible automotive applications apart from the privacy control windows and solar control sunroofs already

mentioned include a wide variety of information displays. The first automotive application of these films is expected to be as instrument panel displays. There is a large (present and future) market for automobile displays. Future automobiles are likely to require three categories of display: an engine cluster; a multimode display, suitable for displaying and controlling environmental and diagnostic functions; and a moving-map display for navigational purposes.

The high brightness, ease of incorporating colour, robust environmental properties and adaptability to shaping and moulding associated with PDLC films makes them an attractive option for automotive multicolour dashboard instrument panels such as the engine cluster which could be shaped to the contour of the dashboard. Automobile dashboard (direct-view) displays, however, also require: a constant ratio of at least 15:1,²⁰ an operating temperature range from approximately -30 to 85 °C,^{7,23} and a response time of less than 1.5 seconds at -30 °C.²³ High contrast PDLC direct-view displays are possible with innovative lighting conditions, and prototype PDLC dashboard displays operating in both the transmission mode (backlit) and in the reflective mode (fabricated onto a metal mirror)

have already produced contrast ratios greater than 25:1.²⁰ PDLC film operation at the upper end of the temperature range can be readily achieved with the correct choice of liquid crystal mixture and polymer binder material. Meeting typical automotive display requirements at temperatures as low as -30 °C is likely to require the use of broader range, lower viscosity nematic mixtures than at present. However, present PDLC films have been reported with operating temperature ranges⁹ of -15 to 80 °C and which exceed automotive display requirements at temperatures as low as -10 °C (< 0.5 s on and off times, for a 17.5 µm film with a 60 V_{RMS} drive).²³

Multimode and moving-map displays will present much more information than the engine cluster (which typically has a low data content) and thus will require greater attention from the user. The use of head-up displays could offer a much safer approach to presenting the above data than the use of direct-view head-down displays. Reflective head-up displays, similar in concept to those used in military aircraft applications, are likely to be very applicable to future automotive displays. In this application high-intensity projection would be essential for the display to be effective in bright sunlight and colour would be useful to call the



10 Large-area films providing privacy at the touch of a button in a conference room (Courtesy of the Taliq Corporation, Sunnyvale, CA)

drivers attention to various warning symbols. Light shutters fabricated from PDLC materials are particularly suited to light projection applications.

Projection applications

In projection applications the extremely low light loss in the transparent state and the low absorption in the scattering state of PDLC films produce bright projected images and minimise cell heat dissipation problems, respectively. The latter, in turn, permits the use of high-power light beams. The highly directed light characteristics of projection systems allow contrast ratios of greater than 100:1 to be readily achieved with current PDLC materials and projection optics. PDLC light intensity modulators can be used in combination with dielectric mirrors to produce a full colour projection system.^{13,15} In this system the incoming achromatic light beam is separated by three dielectric mirrors into blue, green and red component beams. The intensity of each component is varied by an active matrix PDLC modulator (500 x 500 matrix, 5 cm square). The three colour channels are recombined by an additional set of dichroic mirrors to produce a single light beam of arbitrary colour hue and intensity. This technique with accurate mirror alignment and PDLC positioning provides a very efficient low-loss projection system.

8 Summary

PDLC films in many ways can be considered to possess the durability and processing advantages of polymers coupled with the electro-optic responsiveness of liquid crystals. The main advantages of this technology are: simplicity of construction; the possibility of very large sizes (up to 3 m² in area); adaptability (moulding, shaping and flexible displays); the absence of polarisers (simplifying construction and leading to high brightness); low power consumption (> 1 μ W/cm² for some binder materials); robust environmental properties (resistance to sunlight, moisture and thermal variations) and fast switching times (submillisecond times are possible).

This technology at present, however, suffers from some limitations, namely high driving voltages (typically 30 to 70 V) in comparison to many other liquid

crystal displays, the need for controlled lighting for scattering displays and the difficulty in achieving reasonable levels of intrinsic multiplexing. Improvements in the above should be achieved in the future with a greater knowledge of phase separation processes (leading to a better control of film morphology), light scattering properties and switching mechanisms in these films.

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