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LIQUID CRYSTAL DEVICES

This invention relates to liquid crystal devices. Such devices typically comprise a thin layer of a liquid crystal material contained between glass slides. Electrode structures on the slides allow an electric field to be applied across the layer causing a re-ordering of the liquid crystal molecules to an ON-state. On removing the electric field the molecules relax back to their OFF state.

There are three known types of liquid crystal material, nematic, cholesteric, and smectic each having a different molecular ordering.

The present invention utilises a long-pitch cholesteric mixture in which the molecules naturally adopt a helical structure with the helix axes normal to the plane of the layer. The long-pitch cholesteric mixture is formed by mixing typically a few percent of a cholesteric liquid crystal material with a nematic liquid crystal. The pitch of the cholesteric mixture can be controlled by adjusting the concentration of the cholesteric liquid crystal material.

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- One known device is the twisted nematic device which uses a thin layer of a nematic material between glass slides. The slides are unidirectionally rubbed and assembled with the rubbing directions orthogonal. The rubbing gives a surface alignment to the liquid crystal molecules resulting in a progressive 90° twist across the layer. When placed between polarisers, with their optical axis perpendicular or parallel to a rubbing direction the device rotates the plane of polarised light in its OFF state and transmits without rotation in the ON state.
- 5 Small amounts of cholesteric have been added to the nematic material to ensure the 90° twist is of the same sense across the whole area of the device as explained in U.K. Patents Nos. 1,472,247 and 1,478,592.
- 10
- 15 A known type of device employing short-pitch cholesteric material is the phase change device. In its OFF, zero applied voltage, state the material is scattering to light. The cholesteric pitch is very small in comparison to the layer thickness. When an above threshold voltage
- 20 is applied across the layer its molecules rotate from their helical structure to lie parallel to the applied field. This is similar to the ON state of a positive nematic and is light transparent. On removing the voltage the material relaxes back to its light scattering OFF state. No cell
- 25 wall surface alignment is necessary with this type of device. An advantage of this device is the fast turn OFF time compared with the twisted nematic device and wide angle of view.

Another type of cell utilises a cholesteric material whose pitch equals the layer thickness. With homogeneous boundary conditions a plan state is induced with a 2π rotation of the director across the layer.

Inclusion of a pleochroic dye produces absorption of light in the OFF state. Application of a voltage re-orientates the liquid crystal and dye molecules giving higher transmission in the ON state. As the voltage is increased to just above threshold a scattering texture is formed, which clears after a further, substantial, increase of voltage to give the ON state. As the voltage is reduced there is a rapid reduction in transmission at the threshold voltage. The device therefore always shows significant hysteresis which is present irrespective of the rate of increase of voltage. This hysteresis limits the multiplexibility of this device. This device is described in I.E.E. Trans. on Electron Devices, Vol. ED 28 No. 6, June 1981, pp 719-823.

It has now been found that certain cholesteric liquid crystal cells incorporating a pleochroic dye and having about a $3/2$ twist exhibit a sharp transmission-voltage characteristic for rapidly increasing voltages, without hysteresis. A slow increase in voltage may still produce some hysteresis.

According to this invention a liquid crystal device comprises a layer of long pitch cholesteric liquid crystal material of positive dielectric anisotropy contained between two cell walls bearing electrode structures and being surface treated to align liquid crystal molecules in a tilted homogeneous structure characterised in that the surface alignment and natural pitch p of the cholesteric material are matched to provide a progressive molecular twist of greater than π and less than 2π radians across the layer with a uniform tilt direction, the ratio of layer thickness d divided by pitch p lying between 0.5 and 1.0 with a value of d less than $20\text{ }\mu\text{m}$ and further characterised by means for selectively absorbing transmitted light depending upon the molecular orientation of the liquid crystal material whereby the device may be switched directly between a light transmissive state and a non transmissive state with a sharp transmission/voltage characteristics without substantial hysteresis.

The means for selectively absorbing transmitted light may be either an amount of pleochroic dye incorporated in the liquid crystal material or two polarisers either side the cell.

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5 The amount of twist is preferably around $3\pi/2$. The surface alignment treatment results in a molecular tilt of between 0° and 30° or more but less than 90° (homeotropic alignment). A tilt of less than say 5° e.g. 2° may be termed low tilt and between say 5° and 70° termed a high tilt. Both low and high tilt may be used singly or in combination.

10 The device may operate in a transmissive mode or with a reflector in a reflective mode both with or without neutral or coloured polarisers.

15 Two or more devices may be arranged in series. This arrangement may use different colour dyes in each device so that a total of three colours may be observed. Alternatively the dyes may be similar so that a single colour of enhanced contrast between OFF and ON states is obtained. Furthermore each cell may have a different absorption so that eight values of absorption or grey scale are obtained.

20 Usually the pitch of a cholesteric liquid crystal increases with increasing temperature. The device may be enhanced by either
(i) choosing a liquid crystal material, or mixture of materials, with small or zero temperature dependence of pitch to maintain the optimum d/p over a wide temperature range; or
(ii) choosing a liquid crystal whose pitch decreases with increasing temperature to partially or wholly compensate
25 for variations in threshold voltage with temperature.

30 Additionally, or instead, the liquid crystal temperature may be sensed and the addressing voltage levels altered accordingly. One method of sensing is described in U.K. Patent No. 2,012,093 B.

The invention will now be described by way of example only with reference to the accompanying drawings of which:-

Figure 1 is a plan view of a matrix multiplex addressed liquid crystal display;

5 Figure 2 is a cross section of a display such as Figure 1 used in a transmissive mode;

Figure 3 is similar to Figure 2 but operates in a reflective mode;

10 Figures 4, 5 are schematic views of parallel aligned cell walls for explaining the matching of alignment;

Figure 6 is a diagrammatic view showing matching surface alignment and cholesteric twist directions;

15 Figure 7 is a graph showing transmissions of voltage characteristic for $3\pi/2$ single polariser dye display with low tilt surface alignment;

Figure 8 is similar to Figure 7 but for a high tilt cell;

Figure 9 is a graph showing cell switching voltages against d/p ratio for a low tilt cell surface alignment;

20 Figure 10 is a graph showing cell switching voltages against d/p ratio for a high tilt cell surface alignment.

The display of Figures 1, 2 comprises a liquid crystal cell 1 formed by a layer 2 of cholesteric liquid crystal material contained between glass walls 3, 4. A spacer ring 5 maintains the walls typically $6\mu\text{m}$ apart. Additionally numerous short lengths of $6\mu\text{m}$ diameter glass fibre may be dispersed in the liquid crystal material to maintain an accurate wall spacing. Strip like row electrodes 6_1 to 6_m , e.g. of SnO_2 , are formed on one wall 3 and similar column electrodes 7_1 to 7_n formed on the other wall 4. With m-row electrodes and n-column electrodes this forms an m x n matrix of addressable elements. Each element is formed by the interaction of a row and column electrode.

35 A row driver supplies voltage to each row electrode 6. Similarly a column drive 9 supplies voltages to each column electrode 7. Control of applied voltages is from a control logic 10 which receives power from a voltage source 11 and timing from a clock 12.

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In liquid crystal displays the ON and OFF states are visibly different. This is used for example to show digits as in watches, etc.

There are two conventional techniques for multiplex addressing displays, a so-called slow scan and a fast scan or r.m.s. mode. In the slow scan mode each element in a matrix is addressed with a voltage for a time sufficient to turn that element ON. This is repeated for each line of the matrix and then the whole matrix is re-addressed or refreshed repeatedly. In the fast scan mode each element required to be ON is addressed once per complete refresh cycle with a higher voltage level for a time less than the response time of the liquid crystal material and during the remainder of the refresh cycle receives a lower voltage. These voltages are set so that the r.m.s. level over many cycles is sufficiently high to maintain the required elements ON. Elsewhere the r.m.s. level is insufficient to cause elements to be in the ON state.

As an example of fast scan addressing an A.C. row voltage V_R is applied to each row in turn. As each row is addressed column voltages $\pm V_C$ are applied to appropriate column electrodes, the $\pm$ signs refer to the phase of the A.C. signal e.g. at 1KHz. This is repeated for each row until the whole cell is addressed. The process is repeated for the whole cell at a frame rate typically of 50Hz for a 10 line matrix whilst information is to be displayed. Each element required to be ON receives $V_R + V_C$ for one time interval per complete addressing cycle, i.e. frame time, and $\pm V_C$ for other time intervals. The r.m.s. value of $V_R + V_C$ and $n - 1(\pm V_C)$ is arranged to equal a desired V_2 level. Elements not required to be ON receive V_C , or $V_R - V_C$ for all time periods. The r.m.s. value of V_C , $V_R - V_C$ is V_1 . The display is formed collectively by ON elements receiving V_2 volts on a background of OFF elements receiving V_1 volts.

Alternatively the display may be collectively formed by OFF elements on a background of ON elements.

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To multiplex address a display having a large numbers of lines the ON/OFF transmission voltage characteristic must be very sharp, since the OFF elements in the display have to be held at a voltage V_1 which is only slightly lower than the ON voltage V_2 . The number of lines, n ,
5 (or level of multiplexing) that can be addressed can be related to the ratio of V_1 , V_2 voltages. For example for the optimised Alt and Pleschko addressing scheme (I.E.E.E. Trans. ED Vol. ED 21 1974 pp 146-155),

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$$\left(\frac{V_2}{V_1}\right)^2 = \frac{\sqrt{n} + 1}{\sqrt{n} - 1}$$

Decreasing $V_2 - V_1$ increases the value of n .

Present displays using the twisted nematic or Schadt Helfrich effect
15 without dyes can be multiplexed about 32 ways ($n = 32$). However dyed displays have previously been limited to around $n = 3$. As explained below displays of the present invention provide sharp ON/OFF transmission characteristics and hence high values of n .

20 The display of Figure 1 has been arranged as an orthogonal $m \times n$ matrix but may be arranged in other layouts. For example an eight bar digit can be displayed by a three row by three column matrix and multiplex addressed. The digits can be extended to a row of digit by adding column electrodes in groups of three.

25 For a transmissive display Figure 2 a polariser 13 may be arranged behind, or in front of the cell 1. The polarisation axis P of the polariser is parallel with the surface alignment direction R (see below) on the adjacent cell walls. An observer 14 views the display
30 illuminated by e.g. a tungsten bulb 15.

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Figure 3 shows a display having a reflector 16 behind the cell. A polariser 13 is mounted in front of or behind the cell 1 with its polarisation axis P parallel to the alignment direction R of the adjacent wall.

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As seen in Figure 2, 3 the components are separated. In practice they are in contact with one another. For example the reflector 16 may be a layer of aluminium sprayed or evaporated onto the rear cell wall 4.

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The cholesteric material used naturally forms a helical ordering in the layer 2 with the helical axis normal to the walls 3, 4.

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Liquid crystal molecules can be aligned at the cell wall surface by various alignment techniques. For example coating the surface with polyvinyl alcohol and unidirectional rubbing with a soft tissue. This results in a molecular alignment along the rubbing direction and with a tilt of the molecules of about 2° to the surface.

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Alternatively, as described in U.K. Patents Nos. 1,472,247, 1,478,592, 1,545,084, and 2,007,865 A MgF_2 may be evaporated onto the walls. Depending on the angle of evaporation, single or sequentially, the molecules are aligned and the angle of tilt may vary between zero and 30° or more.

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The cell is constructed to have a $3\pi/2$ molecular twist across the layer. Thus the two alignment directions on the assembled cell must be orthogonal. The cholesteric pitch p is chosen so that for a layer thickness d the molecules twist across the layer by $3\pi/2$ i.e. d/p is 0.75. Such a value of d/p matches the natural cholesteric twist to the surface alignment twist. It has been found that values of d/p may lie between 0.5 to 1.0.

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As noted above surface alignment by rubbing results in a surface molecules tilt of about 2° . The relative orientation of the two rubbing directions must be matched to the natural cholesteric rotation which may be left or right handed. The need for this matching is explained with reference to Figures 4, 5.

In Figure 4 cell walls 20, 21 are unidirectionally rubbed and assembled with the rubbing R in the same directions. For this cell the liquid crystal material is a nematic material, it is not optically active i.e. has no twisted structure. The liquid crystal molecules 22 are splayed, they are inclined towards the centre of the layer. When a voltage is applied the molecules rotate to align normal to the walls. Some molecules rotate clockwise others anti-clockwise to the ON state. This is the problem of reverse tip referred to in the prior art. It gives rise to a patchy appearance to the display.

Figure 5 is similar to Figure 4 except that the rubbing directions are opposite. This results in liquid crystal molecules 23 all inclined in the same direction towards one wall in the OFF state. When a voltage is applied all molecules rotate in the same direction to give a uniform appearance.

Figure 6 shows how the cholesteric twist and alignments are matched. Left plane 25 and right plane 26 have rubbing directions R_L and R_R respectively. Viewed from the left R_R is rotated anti-clockwise $3\pi/2$ from R_L . Passing from left to right the director is rotated clockwise by $3\pi/2$. The tilt angle across the centre of the layer is uniform. Intermediate planes are indicated for $\pi/2$ and π rotation. For a cholesteric that twists anticlockwise on passing through the layer the rubbing direction R_L is reversed. The orientation of the rubbing directions is critical. If one of the rubbing directions is opposite to that indicated in Figure 6 then there is a significant degradation in the sharpness of the electro-optic transmission curve.

The transmission against applied voltage characteristic for a low tilt (e.g. 2°) $6\ \mu\text{m}$ cell with a $3\pi/2$ twist incorporating a dye and using a single polariser shown in Figure 7. The lower curve shows transmission changes with a slowly increasing voltage, the upper curve shows transmission changes with a decreasing voltage. The decreasing voltage curve is obtained for both slow and fast reduction in voltage. A surprising effect is that for a rapid increase in voltage from V_1 to V_2 , marked by a broken line, the transmission change closely follows the upper curve. V_1 is below the steep ramp of the two closely spaced lines and V_2 is just above it. The display of Figure 1 is operated using R.M.S. values of V_1 and V_2 for OFF and ON elements respectively.

In the OFF state very little light is transmitted whilst substantially all of the light is transmitted in the ON state. For a liquid crystal material having a reasonably high birefringence (e.g. $\Delta n \gtrsim 0.15$) there is guiding of polarised light in the OFF state. If light from a source enters the layer polarised along the molecular axis of the liquid crystal and dye molecules and in a direction normal to this axis, it is both guided and absorbed across the layer. When the birefringence is low (e.g. $\Delta n \lesssim 0.15$) there is less guiding of polarised light, and a larger fraction of unpolarised light may be absorbed by the dye molecules allowing the device to be operated without a polariser.

When the cell is in the ON state the liquid crystal and dye molecules are re-oriented towards the normal to the walls, provided the material has positive dielectric anisotropy ($\Delta\epsilon > 0$). In this condition little light is absorbed by the dye.

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For high birefringence materials ($\Delta n \gtrsim 0.15$) it is preferable to use a single polariser to increase the absorption in the OFF state. For low birefringence ($\Delta n \lesssim 0.15$) it is preferable to use no polarisers to produce a brighter ON state.

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For high birefringence materials and layers of $12 \mu\text{m}$ or more a polarisation switch effect (c.f. the $\pi/2$ twisted nematic) is obtainable without a dye by using the cell between two polarisers.

- 10 Figure 9 shows the effect of varying the ratio d/p in the low tilt cell whose transmission characteristics are shown in Figure 7. As the layer thickness d to cholesteric pitch p increases above 0.5 the value of V_1 remains reasonably constant. However the value of V_2 increases gradually up to about d/p of 0.75 and then increases markedly.
- 15 Thus for low tilt cells the value of d/p is preferably within the range 0.5 to 0.75. The additional strain induced by the surfaces at values of $d/p < 0.75$ for a $3\pi/2$ twist, reduces the tendency of the cell to form a scattering texture just above the threshold voltage V_1 .

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Cells of $3\pi/2$ twist with surface alignments having high tilts, e.g. 30° , have a transmission characteristic shown in Figure 8. For applied voltages above V_1 the transmission changes rapidly with little hysteresis both for slowly and rapidly increasing and decreasing voltages. For this high tilt cell the variation of V_1 and V_2 with varying d/p is shown in Figure 10. Both V_1 and V_2 increase steadily with increasing d/p . Similar results obtain when the tilts are different on the two cell walls. For example one tilt may be zero or 2° and the other 30° with alignment matched to the

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30 twist direction as in Figure 6.

The invention may be operated as a multiplexed matrix array as described above with reference to Figure 1 or as a fixed legend display.

- 5 This device may be operated in a two-frequency mode where the cell is switched ON by a low frequency signal f_l and switched OFF by a high frequency f_h . The signal $f_l < f_c < f_h$ where f_c is the frequency at which the dielectric anisotropy of the liquid crystal material changes sign being positive at low frequencies to negative
10 at high frequencies.

Examples of suitable liquid crystal materials are:-

Catalogue Nos. E63, E70, E43, CB 15 available from B.D.H. Ltd., Poole, Dorset, England.

- 15 Biphenyl liquid crystal materials are described in U.K. Patent No. 1,433,130 and U.K. Patent Application No. 2,031,010 A. ZLI 1132 available from E. Merck, Darmstadt, W. Germany.

- Suitable dyes are anthraquinone dyes described in U.K. Patent
20 Applications Nos. 2,011,940 A, 2,082,196 A, 2,081,736 A, 2,093,475 A, available from I.C.I. Ltd., or from B.D.H. Chemicals Ltd. as D82, D86.

Example 1

- 25 Material E63 + 1.5% by weight of CB 15 + 1% Dye D82 (B.D.H.)
Cell thickness 6 μ m, low tilt alignment
 V_2/V_1 at temperature $T = 20^\circ = 1.165$
Maximum number, n, of lines which may be multiplexed using the
Alt & Pleshko technique: $n = 40$
30 $\frac{1}{V} \left(\frac{dV}{dT} \right) \simeq 0.5\%$ per $^\circ\text{C}$
Response time $t_{ON} \simeq 500$ ms
 $t_{OFF} \simeq 300$ ms
Contrast ratio 4:1.

The angle of view is extremely good with or without a polariser.

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Example 2

Liquid crystal cell thickness 8 μm , low tilt alignment

Materials ZLI 1289 (Merck)

+ ME 33 30% by weight (Merck)

5 + CB 15 1% by weight (B.D.H.)

+ D 82 dye 1% by weight (B.D.H.)

$$(V_2/V_1)_{T=20^\circ} = 1.160$$

$$n = 46$$

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Example 3

Cell thickness 8 μm low tilt alignment

Materials (B.D.H.) 3/5/7 CB

+ CB 15 1% by weight

15 + D 82 dye 1% by weight

$$(V_2/V_1)_{T=20^\circ} = 1.125$$

$$n = 72$$

Example 4

20 Cell thickness 8 μm , low tilt alignment

Material (B.D.H.) 3/5/7 CB 50% by weight

+ 3/5/7 CNPYR 50% by weight

$$(V_2/V_1)_{T=20^\circ} = 1.072$$

$$n = 200$$

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Example 5

Cell thickness 8 μm , low tilt alignment on one wall and high tilt alignment on the other wall.

Material ZLI 1557 (Merck)

30 + CB 15 0.9% by weight (B.D.H.)

+ D 82 dye 1% by weight (B.D.H.)

$$(V_2/V_1)_{T=20^\circ} = 1.063$$

$$n = 268$$

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Example 6

Cell thickness 8 μm , low/high tilt alignment

Material (B.D.H.) E 63

+ CB 15 1.1% by weight

+ D 82 dye 1% by weight

$$(V_2/V_1)_{T=20^\circ} = 1.141$$

$$n = 58$$

Example 7

10 Cell thickness 8 μm , low/high tilt alignment.

Material (B.D.H.) 3/5/7 PECH

+ CB 15 1% by weight

+ D 82 dye 1% by weight

$$(V_2/V_1)_{T=20^\circ} = 1.134$$

15 $n = 64$

Example 8

Cell thickness 8 μm , high tilt alignment

Material ZLI 1557 (Merck)

20 + CB 15 0.9% by weight (B.D.H.)

+ D 82 dye 1% by weight (B.D.H.)

$$(V_2/V_1)_{T=20^\circ} = 1.042$$

$$n = 590$$

25 Example 9

Cell thickness 8 μm , high tilt alignment

Material ZLI 1289 (Merck)

+ BCO Ester 30% by weight (B.D.H.)

+ CB 15 1.1% by weight (B.D.H.)

30 + D 82 dye 1% by weight (B.D.H.)

$$(V_2/V_1)_{T=20^\circ} = 1.075$$

$$n = 190$$

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Example 10

Cell thickness 8 μ m, high tilt alignment

Material (B.D.H.) E 120

+ CB 15 0.75% by weight

+ D 82 dye 1% by weight

$(v_2/v_1)_{T=20^\circ} = 1.08$

n = 170

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Table of properties of liquid crystal materials.

	Material	$\frac{k_{33}}{k_{11}}$	$\frac{\Delta \epsilon}{\epsilon_1}$
5	ZLI 1289 (Merck)	2.01	2.28
	ZLI 1289 + 30% ME 33	1.23	1.87
	ZLI 1289 + 30% BCO Ester	1.30	2.0
	E 120	1.01	1.09
	3/5/7 CB	1.55	2.91
10	E 63	1.93	3.19
	3/5/7 PECH	2.08	2.7



- ME 33 is $C_3H_7-O-COO-O-C_3H_7$
- 5 BCO Ester is $C_3H_7-C_6H_4-COO-O-C_5H_{11}$ 50%
- $C_5H_{11}-C_6H_4-COO-O-C_5H_{11}$ 50%
- 10 3/5/7 CB is $C_3H_7-O-O-CN$ 30%
- $C_5H_{11}-O-O-CN$ 40%
- $C_7H_{15}-O-O-CN$ 30%
- 15 3/5/7 PECH is $C_3H_7-H-C_2H_4-O-CN$ 30%
- $C_5H_{11}-H-C_2H_4-O-CN$ 40%
- 20 $C_7H_{15}-H-C_2H_4-O-CN$ 30%
- 25 3/5/7 CNPYR is $C_3H_7-C_4H_3N_2-O-CN$ 30%
- $C_5H_{11}-C_4H_3N_2-O-CN$ 40%
- $C_7H_{15}-C_4H_3N_2-O-CN$ 30%
- 30 CB 15 is $CH_3-CH_2-\underset{\substack{| \\ CH_3}}{CH}CH_2-O-O-CN$



Claims:-

1. A liquid crystal device comprising a layer of long pitch cholesteric liquid crystal material of positive dielectric anisotropy contained between two cell walls bearing electrode structures and being surface treated to align liquid crystal molecules in a tilted homogeneous structure characterised in that the surface alignment and natural pitch p of the cholesteric material are matched to provide a progressive molecular twist of greater than π and less than 2π radians across the layer with a uniform tilt direction, the ratio of layer thickness d divided by pitch p lying between 0.5 and 1.0 with a value of d less than $20\text{ }\mu\text{m}$ and further characterised by means for selectively absorbing transmitted light depending upon the molecular orientation of the liquid crystal material whereby the device may be switched directly between a light transmissive state and a non transmissive state with a sharp transmission/voltage characteristics without substantial hysteresis.
2. The device of claim 1 wherein the means for selectively absorbing transmitted light is an amount of pleochroic dye incorporated in the liquid crystal material.
3. The device of claim 1 wherein the means for selectively absorbing transmitted light is two polarisers arranged optically in front of and behind the layer of liquid crystal material.
4. The device of claim 2 wherein the molecular twist is about $3\pi/2$.
5. The device of claim 2 wherein the surface treatment provides a liquid crystal molecular tilt up to 5° and the ratio d/p lies between 0.5 and 0.75.
6. The device of claim 2 wherein the surface treatment provides a liquid crystal molecular tilt of between 5° and 70° on at least one cell wall.



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7. The device of claim 2 and further comprising at least one polariser.
8. The device of claim 2 and further comprising a reflector
5 optically behind the cell.
9. The device of claim 2 arranged optically in series with at least one other device of claim 2 with different colour dyes in the different cells.
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10. The device of claim 1 wherein the electrode structure on one cell wall is arranged in a first series of m separate electrodes and the electrode structure on the other cell wall is arranged in a second series of n separate electrodes to form an m x n matrix of separate
15 addressable elements.
11. The device of claim 10 wherein the first and second series of electrodes are connected to two sets of driver circuits controlled by a logic circuit for repetitively applying voltages from a voltage
20 source to the electrodes in a multiplexed sequence.
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