

The invention relates to a liquid crystal display (LCD) cell comprising a highly twisted nematic liquid layer which is disposed between two plates having electrodes and surface orientations and polarisers and which has a positive dielectric anisotropy.

The invention relates more particularly to an LCD cell of the kind set out wherein the nematic liquid crystal layer has a very small optical path difference.

It has been known for some time that LCD cells having highly twisted nematic liquid crystals, despite their intensive interference colours in the off state, have advantages over similar cells having a 90° twist. The term "highly twisted nematic structures" is to be understood as denoting structures having a twist of more than 90° . Of course, doping with chiral additives is usually necessary to produce such a twist.

The main advantages of liquid crystal cells having highly twisted nematic structures are a very steep electro-optical characteristic and a wide viewing angle range. The steep electro-optical characteristic results in high multiplex ratios which are necessary to provide displays of high information density.

Apart from earlier proposals for high-twist liquid crystal cells based on the guest-host effect, one of the first high-twist nematic liquid crystal cells without any colouring additive was the one disclosed in European Patent Application No. 131 216 of Amstutz, H. et al. The liquid crystal of this cell has a twist of from 180° to 360° . The polarisers are offset at angle

of from 20° to 70° relatively to the orientation directions on the plates. The ratio d/P between the layer thickness and pitch of the liquid crystal is between 0.5 and 0.95. The cell requires a special wall orientation on the electrode surfaces, leading to high tilt angles of the nematic director. Wall orientations of this kind are complex to produce and therefore expensive.

The patent application GB-A-2 145 837 describes a liquid crystal display cell using a high-twist, chirally doped, nematic liquid crystal with a natural pitch P and positive dielectric anisotropy.

Subsequently, increasing work has been done in various places on the development of liquid crystal cells having high-twist nematic structures, because LCDs are being increasingly used in large-area high-density-information applications and high multiplexibility is essential for this particular use. Thus, many angle ranges between 90° and 360° for the twist and for the arrangement of the polarisers relatively to the surface orientations and to one another and for the proportions of the optical anisotropy Δn , the electrode distance or thickness d and the natural pitch P of the chirally doped nematic liquid crystal relatively to one another have been suggested. Various advantages have been alleged for each of the disclosed high-twist structures, with the emphasis on improved multiplexibility and improved range of viewing angles. A disadvantage was found to be the intensive interference colours of such display cells which, if colour variations are to be avoided, call for very

accurate plate spacing and, therefore, expensive production processes. Also, the strong inherent colouring of such displays is an obstacle to their use as neutral-colour electro-optical switches such as are required inter alia for colour TV or for coloured display screens.

The problem which it is the object of the invention to solve arises from the present need for even better LCD cells with more particularly less inherent colouring, the possibility of producing grey tones, simple production, short switching times together with high optical contrast, reduced dependence upon viewing angle, good multiplexibility and a display picture little affected by variations in the plate spacing of the cell.

It has now been found that, using a special combination of cell and material parameters, much better results can surprisingly be achieved than previously known from high-twist nematic liquid crystal displays.

The LCD cell according to the invention is distinguished by the combination according to the characterising part of claim 1.

The angle range just defined includes both positive and negative contrast displays of the cell.

In positive contrast displays electrically energised segments appear dark on a bright background

whereas in negative displays the situation is the converse.

Embodiments of the invention will be described hereinafter with reference to the drawings wherein:

Fig. 1 is a diagrammatic exploded view of an LCD cell according to the invention;

Fig. 2 is a diagram showing the arrangement of angles, the surface orientations and the polarisers relatively to one another, and

Fig. 3 illustrates a voltage-contrast curve of a preferred embodiment.

The LCD cell according to the invention is of very similar construction to known cells, such as twisted nematic LCDs (Schadt and Helfrich, Appl. Phys. Lett. 18, 127 [1971]), so that there is no need here to go into constructional details. It comprises a liquid crystal layer 1 disposed between two plates 2, 3 which are disposed substantially plane-parallel to one another and which are made of a transparent material, such as glass, acrylic glass, plastic films or the like. A polariser 5 is disposed in front of plate 3 and is preferably connected thereto, for example, by sticking. A polariser 4 is similarly associated with the rear plate 3. The plates are separated from one another by a spacing d.

On their surfaces facing the liquid crystal the plates 2 have conventional electrode coatings 6

segmented for the display of characters or dots. Also, the surfaces are so treated as to exert a directional effect on the adjacent liquid crystal molecules and thus determine the direction of the nematic director $\hat{n}$. The treatment resides, for example, in rubbing the surface in one direction or in the oblique evaporation coating of orienting layers etc; it is not necessary, but neither is it disadvantageous, to provide a tilt angle. The result of this treatment will be called surface orientation for the purpose of the present description. An arrow 7 indicates the surface orientation on the front plate 2. The surface orientation on the rear plate 3 extends parallel to that of the front plate and is indicated by an arrow 8. As will become apparent hereinafter, it is not vital for the surface orientations of the two plates to be parallel to one another. Variations in both directions are possible without substantial impairment of cell operation.

The front plate polariser 4 is so disposed that its polarisation direction extends substantially parallel or perpendicular to the surface orientation of the plate 2. The rear polariser 5 is so disposed that its polarisation direction extends perpendicularly or parallel to the surface orientation 8 of the plate 3 when the cell is operated in positive contrast display.

The liquid crystal 1 is a nematic liquid crystal doped with chiral additives. The crystal 1 therefore takes on a spontaneous twist having a predetermined pitch P . As a result of co-operation between the spontaneous twist, due to the chiral additives, and the

surface orientation the crystal assumes a twist of 180° . This results in the twist, shown in Fig. 1, of the nematic directors $\hat{n}_1$, on the front plate and $\hat{n}_2$ on the rear plate of 180° relatively to one another.

Fig. 2 illustrates the relative angular relationships of the nematic directors and the polarisation directions. As previously stated $\hat{n}_1$ is the nematic director on the front plate 2 and $\hat{n}_2$ is the nematic director on the back plate 3. The angle of twist between the two nematic directors has the reference ϕ . This angle is 180° in the preferred embodiment. However, it can vary on either side of 180° . Satisfactory results are obtained with absolute values of ϕ of between 120° and 260° for either a right-hand or left-hand twist.

The front polarizer 4 has a polarization direction P_1 . In this embodiment such direction extends parallel to the nematic director $\hat{n}_1$. However, the direction P_1 can vary by an angle β from the nematic director $\hat{n}_1$, satisfactory results being obtained in the range $0^\circ < \beta < 360^\circ$. However, the direction P_1 can be perpendicular to the nematic director $\hat{n}_1$ and the polarization direction P_2 can be parallel to $\hat{n}_1$. Here again satisfactory results are obtained within a range of variation $0^\circ < \beta < 360^\circ$. The polarization direction P_2 of the rear polarizer 5 is rotated relatively to the polarization direction P_1 of the front polarizer 4 by an angle ψ which in the preferred embodiment of a positive contrast display is 90° (crossed polarizers). However, the angle ψ can be between 0° and 180° . Contrast reversal occurs at angles ϕ and β , which are

equal in other respects, when $\psi = 0^\circ$ (parallel polarizers). In another preferred embodiment for a negative contrast display, $\phi = 180^\circ$, $\beta = 0^\circ$ and $\psi = 135^\circ$. The variation spreads are indicated by corresponding shadings in the diagram of Fig. 2.

In an especially preferred embodiment, for example, $\phi = -175^\circ$, $\beta = 350^\circ$ and $\psi = 70^\circ$ (positive contrast) and $\phi = 175^\circ$, $\beta = 5^\circ$ and $\psi = 135^\circ$ (negative contrast); the following liquid crystal mixture (mixture A) in a layer $d = 5 \mu\text{m}$ thick was used:

<u>Component</u>	<u>Concentration</u> (weight %)
$\phi d(4)CP$ = p-[trans-4-(4-pentenyl)cyclohexyl]benzonitrile	8.780
3CP02 = 1-ethoxy-4-(trans-4-propylcyclohexyl)benzene	7.320
3CPS = p-(trans-4-propylcyclohexyl)-phenyl isothiocyanate	11.700
4P(1)P = p-(5-butyl-2-pyrimidinyl)-benzonitrile	4.870
3CAP2 = 4-ethyl-1-[2-(trans-4-propylcyclohexyl)ethyl]benzene	4.390
4CEPO2 = trans-4-butylcyclohexanecarboxylic acid p-ethoxyphenyl ester	10.730

5CEP01	= trans-4-pentylcyclohexane-carboxylic acid p-methoxyhexyl ester	10.730
4CEC4	= trans-4-butylcyclohexane-carboxylic acid trans-4-butylcyclohexyl ester	9.280
4PP(1)P	= p-[5-(4-butylphenyl-2-pyrimidinyl)benzonitrile	4.400
Ød(4)CPP	= 4'-[trans-4-(pentenyl)cyclohexyl]biphenylcarbonitrile	6.850
Od(4)CPP3	= 4'-[trans-4-(4-pentenyl)cyclohexyl]-4-propylbiphenyl	5.850
5CPAC4	= 1-[2-(trans-4-butylcyclohexyl)ethyl]-4-(trans-4-pentylcyclohexyl)benzene	9.750
5CPPAC4	= 4-[2-(trans-4-butylcyclohexyl)ethyl]-4'-(trans-4-pentylcyclohexyl)biphenyl	5.350

This mixture was also given an appropriate chiral additive.

A second embodiment of the invention was prepared using the following mixture "B":

<u>Component</u>	<u>Concentration</u> (weight %)
Ød(3)CP = p-[trans-4-(3-butenyl)-cyclohexyl]benzonitrile	10.000
ld(3)CP = p-[trans-4-(3E-pentenyl)-cyclohexyl]benzonitrile	10.000
4P(1)P = p-[trans-4-(3E-pentenyl)-cyclohexyl]benzonitrile	6.000

5CC(0)d (3)Ø	= r-1-cyan-1-(3-butenyl)-cis-4-(trans-4-pentylcyclohexyl)cyclohexane	10.000
4CEC4	= r-1-cyano-1-(3-butenyl)-cis-4-(trans-4-pentylcyclohexyl)cyclohexane	12.000
5CEC3	= trans-4-pentylcyclohexanecarboxylic acid trans-4-propylcyclohexyl ester	12.000
3CEC3	= trans-4-propylcyclohexanecarboxylic acid trans-4-propylcyclohexyl ester	10.000
5CPAC4	= trans-4-propylcyclohexanecarboxylic acid trans-4-propylcyclohexyl ester	12.000
5CPPAC4	= trans-4-propylcyclohexanecarboxylic acid trans-4-propylcyclohexyl ester	4.000
3CEPCd(3)1=	trans-4-propylcyclohexanecarboxylic acid p-[trans-4-(3E-pentenyl)cyclohexyl]phenyl ester	8.000
5CPAPAC4	= 4-(trans-4-pentylcyclohexyl)-4'-[2-(trans-4-butylcyclohexyl)ethyl]-1,1'-ethylene-dibenzene	6.000

This mixture too was given an appropriate chiral additive.

The designation of the components is known to those skilled in the l.c. technology. Reference is made in this connection, for example, to the publications of Schadt, M. et al in Mol. Cryst. Liq. Cryst. 122 (1985) 241ff and in Proc. Int. Displ. Res. Conf., San Diego (1985).

All the relevant parameters of these two mixtures "A" and "B" and of cells with these mixtures are compiled in the following Table 1.

Table 1

Parameter	Mixture "A"		Mixture "B"	
Clearing point T_{cl} [°C]	81		77	
Melting point T_m [°C]	<-30		<-30	
Diel.const. parall. ϵ	8.99		10.3	
Dielec. anisotropy $\Delta\epsilon$	4.31		6.2	
n_o	1.482		1.499	
Optical anisotropy Δn	0.088		0.125	
k_{11} [10-12N]	11.13		11.34	
k_{22} [10-12N]	4.98		4.47	
k_{33}/k_{11}	1.31		1.04	
Viscosity $\eta(+22^\circ\text{C})$ [mPa·s]	24		27	
Viscosity $\eta(-20^\circ\text{C})$ [mPa·s]	350		460	
Optical path difference $\Delta n \cdot d$ [μm]	0.44		0.625	
Twist angle	-180°	-90°	-180°	90°
Electrode gap [μm]	5	6	5	8
$2d/p$ (p = pitch)	0.55	0	0.6	0

The electro-optical results compiled in the following Table 2 were obtained with these mixtures. The results achieved with the novel cell according to the invention are in each case compared with the values obtained with the same liquid crystal mixtures in a conventional twisted nematic (TN) cell.

Table 2

		Mixture "A"		Mixture "B"	
		New cell	TN cell	New cell	TN cell
V ₁₀ ($\theta = 0^\circ$)	[V]	2.33	2.09	1.91	2.00
V ₅₀ ($\theta = 0^\circ$)	[V]	2.41	2.44	2.01	2.24
Steepness of transmission curve P ₀ ($\theta = 0^\circ$)		0.032	0.169	0.052	0.121
r _T ($\theta = 0^\circ$) [%/°C]		-	-	~-0.28	-0.28
r _{θ} (V = V ₁₀) [%/° θ]		-	-	-0.081	-0.49
Multiplex ratio N _{max}		1008	42	390	77

θ = Viewing angle

Key to Table 2:

- V₁₀ denotes the optical threshold voltage at 10% extinction (or transmission);
- V₅₀ denotes the voltage at 50% transmission;
- p₀ denotes the steepness of the transmission curve at a viewing angle $\theta = 0^\circ$ in accordance with the formula

$$P_0 = \frac{V_{50} - V_{10}}{V_{10}}$$

- $N_{\max}$ denotes the maximum number of multiplexible lines according to Alt and Pleshko

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

- r_T denotes the temperature dependence of the threshold of voltage V_{10} between 0°C and 40°C ;

$$r_T = \frac{V_{10}(40^\circ\text{C}) - V_{10}(0^\circ\text{C})}{40^\circ\text{C}} \cdot \frac{100\%}{V_{10}(22^\circ\text{C})} [\%/^\circ\text{C}]$$

- r_θ denotes the angular dependence of the threshold voltage V_{10} between $\theta = 10^\circ$ and 40° ;

$$r_\theta = \frac{V_{10}(40^\circ) - V_{10}(0^\circ)}{30^\circ} \cdot \frac{100\%}{V_{10}(10^\circ)} [\%/^\circ\theta]$$

- θ denotes the light incidence angle or viewing angle.

In this exemplified embodiment with mixture "A" the product $\Delta n \cdot d$ was $0.44 \mu\text{m}$ and with mixture "B" $0.625 \mu\text{m}$. It can be set to the range $0.25 < \Delta n \cdot d < 0.7 \mu\text{m}$ with good results.

The absolute value of the ratio of layer thickness d to the natural pitch P is approximately 0.3 in the present embodiment and can be varied with good results in the range $0.2 < d/P < 0.8$.

Fig. 3 shows the contrast curve characteristic of the electro-optical behaviour and taken in white light. The extreme steepness of this curve shows that a cell of this kind can provide a high multiplex ratio. In fact multiplex ratios of more than $1000 : 1$ at a contrast of $5 : 1$, have been achieved (see Table 2). Also, the angle dependence is much better than with 90° TN cells (Table 2) and at least equally as good as in other known high-twist cell structures. The very reduced waviness of the curve both in the "off" and "on" states is a result of the low inherent colouring of the cell (black-white or white-black contrast).

Especially good results were achieved with the configurations compiled in Tables 3 and 4 below having defined values for the products $\Delta n \cdot d$ and for the angle ϕ , β and ψ . These configurations therefore represent preferred embodiments of the invention. The doping with chiral additives is selected in each case so that the resulting pitch together with the plate gap provides the desired twist angle ϕ . Table 3 contains configurations which result in a positive contrast; table 4 contains configurations for negative contrast.

Table 3

ϕ (°)	$\Delta n \cdot d$ (μm)	β (°)	ψ (°)
180	0.4-0.7	0 ± 20	90 ± 20
"	"	90 ± 20	-80 ± 20
210	0.4-0.5	0 ± 20	90 ± 20
"	"	90 ± 20	-80 ± 20
"	0.6	0 ± 30	90 ± 20
"	"	100 ± 20	-90 ± 30
"	0.7	10 ± 30	70 ± 30
"	"	110 ± 20	-110 ± 20
240	0.4	10 ± 20	95 ± 20
"	"	100 ± 20	-90 ± 20
"	0.5	30 ± 20	95 ± 15
"	"	120 ± 20	-90 ± 25
"	0.6	30 ± 25	85 ± 20
"	"	120 ± 25	-90 ± 25
"	0.7	30 ± 25	80 ± 30
"	"	130 ± 30	-100 ± 25
270	0.5	30 ± 30	80 ± 20
"	0.6	50 ± 30	70 ± 30
"	"	140 ± 30	-100 ± 30
"	0.7	60 ± 30	60 ± 30
"	"	140 ± 30	-110 ± 30

Table 4

φ (°)	$\Delta n \cdot d$ (μm)	β (°)	ψ (°)
180	0,4	25 ± 20	40 ± 20
"	0,5	30 ± 20	30 ± 20
"	"	125 ± 20	40 ± 20
"	0,6	40 ± 20	10 ± 20
"	"	130 ± 20	10 ± 20
"	0,7	60 ± 20	150 ± 20
"	"	150 ± 20	150 ± 20
210	0,4	40 ± 20	50 ± 20
"	"	130 ± 20	50 ± 20
"	0,5	45 ± 20	30 ± 20
"	"	135 ± 20	30 ± 20
"	0,6	60 ± 20	10 ± 20
"	"	150 ± 20	10 ± 20
"	0,7	80 ± 20	160 ± 20
"	"	170 ± 20	160 ± 20
240	0,5	160 ± 20	30 ± 20
"	0,6	75 ± 20	20 ± 20
"	"	170 ± 20	10 ± 20
"	0,7	0 ± 30	170 ± 20
"	"	85 ± 20	170 ± 20
270	0,5	170 ± 20	40 ± 20
"	0,6	10 ± 20	20 ± 20
"	"	100 ± 20	20 ± 20
"	0,7	30 ± 40	10 ± 20
"	"	125 ± 40	10 ± 20

The cell hereinbefore described can be operated in transmission and in reflection.



C L A I M S

1. A liquid crystal display (LCD) cell comprising a highly twisted, chirally doped nematic liquid crystal disposed between two plates having electrodes and surface orientations, and polarisers, the liquid crystal having a natural pitch P and a positive dielectric anisotropy, characterised by the combination of: a twist angle ϕ between 120° and 260° , a product of refractive index anisotropy and liquid crystal thickness $\Delta n \cdot d$ between 0.2 and $0.7 \mu\text{m}$ and a thickness/pitch ratio d/P between 0.2 and 0.8 .
2. A cell according to claim 1, characterised in that the twist angle ϕ is 180° .
3. A cell according to claim 1, characterised by $\phi = 180^\circ$; an angle β between the surface orientation direction and the polarization direction of the plate on the light incidence side of 0° and an angle ψ between the polarisation direction of the plate on the light incidence side and the polarisation direction of the plate on the light exit side of 90° .
4. A cell according to claim 1, characterised in that $\phi = 180^\circ$, $\beta = 0^\circ$ and $\psi = 135^\circ$.
5. A cell according to claim 1, characterised in that the angle $\beta = 0^\circ \pm 10^\circ$ and the angle $\psi = 90^\circ \pm 40^\circ$.
6. A cell according to claim 1, characterised in that $\beta = 0^\circ$ and $\psi = 135^\circ$.



7. A cell according to claim 1, characterised in that $\beta = 90^\circ \pm 10^\circ$ and the polarisers are crossed.

8. A cell according to claim 1, characterised in that $\Delta n \cdot d$ is $0.4 - 0.6 \mu\text{m}$.

9. A cell according to claim 1, characterised in that the ratio d/P of thickness to pitch is from 0.25 to 0.4.

10. A cell according to claim 1, characterised in that the cell is operated in reflection.