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Liquid Crystals

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Novel liquid crystal mixtures for a surface-stabilized ferroelectric LCD

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We synthesized novel fluorine-substituted chiral compounds having a fluorine atom at an asymmetric carbon and a difluorinated biphenyl ring as a core of a liquid crystal molecule by means of an original method. The ferroelectric mixtures were obtained by mixing the chiral compounds with the non-chiral liquid crystal mixture with a wide SmC temperature range between −29°C (crystallized) and 78°C. They show a large P_s greater than $10\,\mathrm{nC\,cm^{-2}}$ at 5 wt % of the chiral compound. Two types of cell, called 'parallel' and 'antiparallel', were fabricated according to the relative direction of the rubbing direction on the substrates. The parallel cells filled with the FLC mixtures show the usual bistable SSFLC (surface-stabilized ferroelectric liquid crystal). The fast response time of 60 µs ($22\,V_{pp}$ pulse width 250 µs, at room temperature) was obtained. The apparent cone angle was 45·2° in the switching state and 40·5° in the memory state. On the other hand, the antiparallel cells show an unusual monostable behaviour, i.e. the director falls back to the original configuration when the applied voltage is switched off. The surface-stabilized monostable cells show very attractive characteristics for application for a TFT-active matrix LCD; a high contrast of 81 : 1, a fast response time (of the order of 1 ms), and an analogue-grey scale with excellent linearity within the low voltage range below 4 V.

1. Introduction

Displays based on ferroelectric liquid crystals (FLC) using the chiral smectic C (SmC*) phase are known as surface-stabilized ferroelectric liquid crystal displays (SSF-LCD) [1]. We have already reported the synthesis of fluorine-containing ferroelectric liquid crystals and the preparation of FLC mixtures with a wide SmC* temperature range. However, the response time of those liquid crystals is not yet sufficient [2]. In order to improve the response time, we synthesized new types of fluorine-substituted chiral compounds and prepared new FLC mixtures. An essential feature of the synthesis of the chiral compounds is the introduction of fluorine atoms to the core (in this case, a biphenyl ring) of the liquid crystal molecules. This suppresses the appearance of other smectic phases of high order except a smectic A phase and a smectic C* phase [3]. Another feature is the magnification of a spontaneous polarization (P_s). The distance between two dipoles (i.e. two carbonyl groups) or the introduction of two chiral moieties to both sides of a core, influences the magnitude of the spontaneous polarization. In this way, we synthesized six new chiral compounds.

In order to examine the electro-optic properties of the chiral FLC compounds, we prepared FLC mixtures of the chiral compounds with a non-chiral SmC mixture with a wide SmC temperature range. Two types of cell, called 'parallel' and 'antiparallel', were fabricated according to the relative direction of the rubbing direction on the substrate. The parallel 2 µm-gap cells filled with these FLC mixtures show the usual bistable SSFLC (surface-stabilized ferroelectric liquid crystal) behaviour. On the other hand, the antiparallel cells show monostable behaviour, i.e. the director falls back to the original configuration when the applied voltage is switched off. We have already reported details about a surface-stabilized monostable FLCD [4]. In this report, we mainly describe the ferroelectric liquid crystal materials and their electro-optic properties.

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2. Experimental

2.1. *Synthesis of the chiral compounds **DF-DFBP** and **F-DFBP-8***

The chiral compounds were synthesized according to the method described in the previous paper [2]. A chiral acid, (2*S*,3*R*)-2-fluoro-3-methylpentanoic acid, is prepared from L-isoleucine. The acid is converted to an acid chloride, followed by the reaction with 3,3′-difluoro-4,4′-biphenyldiol, its monoester or its monoether to give the chiral compounds.

The acid chloride (1 g), (2*R*,3*S*)-2-fluoro-3-methylpentanoyl chloride, was added dropwise to the solution of 3,3′-difluoro-4,4′-biphenyldiol (0·71 g) and triethylamine (1 ml) in dioxane and the mixture stirred for 1 h. The mixture was passed through a silica gel column using chloroform–hexane as the eluent. Removal of solvent and recrystallization from petroleum ether gave the chiral compound **DF-DFBP**; yield 200 mg, colourless crystals, NMR (270 MHz, $CDCl_3$) δ 1·05 (t, 6 H, CH_3), 1·1 (dd, 6 H, CH_3), 1·4–1·8 (m, 4 H, CH_2), 2·05–2·25 (m, 2 H), 5·08 and 5·25 (dd, 2 H), and 7·2–7·4 (m, 6 H); MS (70 eV), *m/z* (relative intensity) 454 (M^+, 5), 338 (20), 310 (6), 222 (100).

The compound **F-DFBP-8** was prepared by a similar method; colourless crystals, NMR (270 MHz, $CDCl_3$) δ 0·90 (t, 3 H, CH_3), 1·05 (t, 3 H, CH_3), 1·15 (dd, 3 H, CH_3), 1·2–1·7 (m, 12 H), 1·7–1·8 (m, 2 H), 2·05–2·25 (m, 1 H), 4·10 (t, 2 H, CH_2), 5·08 and 5·27 (dd, 1 H), and 6·9–7·45 (m, 6 H); MS (70 eV), *m/z* 450 (M^+, 14), 338 (10), 334 (14), 222 (100).

2.2. *Synthesis of the chiral compounds **F-DFBPB-8** and **F-DFBPH-8***

The 3,3′-difluoro-4,4′-biphenyldiol mono-4-octyloxybenzoyl ester was prepared by the reaction of 4-octyloxybenzoyl chloride and 3,3′-difluoro-4,4′-biphenyldiol in dioxane in the presence of triethylamine. The acid chloride (0·35 g), (2*R*,3*S*)-2-fluoro-3-methylpentanoyl chloride, was added dropwise to the solution of 3,3′-difluoro-4,4′-biphenyldiol mono-4-octyloxybenzoyl ester (1 g) and triethylamine in benzene and the mixture was stirred for 1 h. The mixture was then passed through a silica gel (chloroform–hexane). Removal of solvent and recrystallization from ethanol gave the triphenyl type of the chiral compound **F-DFBPB-8**; yield 0·68 g, colourless crystals, NMR (270 MHz, $CDCl_3$) δ 0·82 (t, 3 H, CH_3), 0·98 (t, 3 H, CH_3), 1·05 (d, 3 H, CH_3), 1·2–1·7 (m, 12 H), 1·7–1·8 (m, 2 H), 1·9–2·3 (m, 1 H, CH), 3·95 (t, 2 H, CH_2), 5·00 and 5·18 (dd, 1 H, CH), 6·90 (d, 2 H), 7·1–7·45 (m, 6 H), and 8·07 (d, 2 H); MS (70 eV), *m/z* 570 (M^+, 6), 480 (10), 404 (12), 338 (14), 234 (100), 221 (63), 121 (100).

The compound **F-DFBPH-8** having a cyclohexyl ring was prepared by a method similar to that described above; colourless crystals, NMR (270 MHz, $CDCl_3$), δ 0·90 (t, 3 H, CH_3), 1·05 (t, 3 H, CH_3), 1·12 (d, 3 H, CH_3), 1·15–1·35 (m, 16 H), 1·4–1·75 (m, 5 H), 1·9 (d, 2 H), 2·17 (d and m, 3 H), 2·55 (t, 1 H), 5·10 and 5·28 (dd, 1 H), and 7·1–7·4 (m, 6 H); MS (70 eV), *m/z* 560 (M^+, 25), 339 (100), 221 (95).

2.3. *Synthesis of the chiral compound **F-BDFBP-8***

The compound **F-BDFBP-8** was prepared from 4-hydroxybenzoic acid as a starting material. 4-Hydroxybenzoic acid was esterified with acetyl chloride in dioxane in the presence of triethylamine. The product, 4-acetyloxybenzoic acid, was converted to the corresponding acid chloride followed by the reaction with 3,3′-difluoro-4′-octyloxybiphenyl-4-ol in the presence of triethylamine to give 4-(4-acetyloxybenzoyloxy)-3,3′-difluoro-4′-octyloxybiphenyl. The compound was converted to 4-(4-hydroxybenzoyloxy)-3,3′-difluoro-4′-octyloxybiphenyl by removal of a protecting acetyl group which was achieved by refluxing in the mixed solution of methanol and tetrahyrofuran in the presence of lithium hydroxide for 3 h. The compound was reacted with the chiral acid chloride, (2*R*,3*S*)-2-fluoro-3-methylpentanoyl chloride. The obtained product was purified by passing through a silica gel, removal of solvent, and recrystallization from ethanol to give the chiral compound **F-BDFBP-8**; colourless crystals, NMR (270 MHz, $CDCl_3$) δ 0·85 (t, 3 H, CH_3), 1·02 (t, 3 H, CH_3), 1·10 (d, 3 H, CH_3), 1·2–1·7 (m, 12 H), 1·85 (m, 2 H), 2·0–2·3 (m, 1 H, CH), 4·08 (t, 2 H, CH_2), 5·07 and 5·25 (dd, 1 H), 6·95–7·45 (d and m, 8 H), and 8·30 (d, 2 H); MS (70 eV), *m/z* 570 (M^+, 15), 334 (3), 237 (95), 222 (37), 121 (100).

2.4. *Measurement of physical properties of the chiral compound and FLC mixtures*

The phase behaviour was monitored by DSC and polarized microscopy. The thermograms were collected with a Rigaku Denki DSC-8240 at heating/cooling rates of 2°C min^{-1}. The peak temperatures were taken to be the phase transition point and the samples were run under N_2. Phase texture observations were made with a Nikon OPTIPHOT microscope equipped with a Mettler FP82 hot stage. The spontaneous polarization P_s was evaluated by the triangular-wave method [5]. The helical pitches of the SmC* mixtures were much longer than the wavelength of light (table 3). This helical pitch is significantly different from the pitch conditions of the distorted helix FLCD proposed by Fünfschilling and Schadt [6].

Homogeneously aligned test cells for texture observation and electro-optic measurements were made using a conventionally rubbed polyimide layer on substrates with transparent electrodes. The cells were fabricated with a narrow gap shorter than 2 μm. Two types of cells, called 'parallel' and 'antiparallel' were fabricated according to the relative direction of the rubbing direction of the substrates. The test cells were filled with the FLC mixtures at a temperature above the clearing point *in vacuo*, and then cooled gradually down (-2°C min^{-1}) to room temperature.

The electro-optic measurements were made by using a polarized optical microscope (Nikon OPTIPHOT-POL), a wave-function generator (Analogic Corp., Model 2020), a digital oscilloscope (Phillips PM3320A), and a photomultiplier (Hamamatsu Photonics R-928).

For the case of the bistable cells, the response time was determined by the 0–90 per cent transmission change, when a rectangular wave of ± 10–30 V $\mu\mathrm{m}^{-1}$ and 250 μs pulse width was applied to the cells at 25°C.

In the case of the monostable cells, the test-signal pattern for evaluating electro-optic properties is shown in figure 5. A series of bipolar pulses with increasing amplitude were applied to the cells perpendicular to the substrates. The pulse width was 16·6 ms. To avoid damaging the liquid crystal materials the applied voltage was alternately changed in polarity. In our electro-optic measurements, the polarizer axis P was parallel to the rubbing direction R and the analyser direction A was perpendicular to the polarizer P. The response time is defined as the time required for an optical transmission change from 0 to 90 per cent or 100 to 10 per cent for each voltage where the maximum optical transmission for each applying voltage is normalized as 100 per cent.

3. Results

3.1. *Physical properties of the chiral compounds*

The chemical structures and their phase transition temperatures of the synthesized chiral compounds are shown in figures 1 and 2. The compounds (**F-BPB-8**, **F-BBP-8**, and **F-BP-8**) with no substituted fluorine atoms on the bipheyl ring are also listed as references in figure 1.

As expected, the new chiral compounds have no other smectic phases except a SmA and a SmC phase. This is in contrast to the reference compound **F-BBP-8**. Several compounds (**F-DFBP-8** and **DF-DFBP**) have no liquid crystal phase, as shown in figure 2.

3.2. *Preparation of the FLC mixtures*

The FLC mixtures were prepared by mixing the chiral compounds described above with a non-chiral SmC mixture having a wide temperature range between -13°C and 79°C [2]. The non-chiral SmC mixtures consist of three types of liquid crystals; phenyl pyrimidines (**PPm**), phenylbenzoates (**PB**), and difluorinated biphenyl cyclohexane-carboxylates (**DFBHC**). Their structures are shown in figure 3. The optimized non-chiral SmC mixture consisting of **PPm** 22 wt %, **PB** 20 wt %, and **DFBHC** 58 wt % shows the following phase sequence and transition temperatures:

$$\mathrm{Cr}\ \underset{-12\cdot9}{\overset{-29\cdot2}{\longleftrightarrow}}\ \mathrm{SmC}\ \underset{77\cdot5}{\longleftrightarrow}\ \mathrm{SmA}\ \underset{93}{\longleftrightarrow}\ \mathrm{N}\ \underset{105^{\circ}\mathrm{C}}{\longleftrightarrow}\ \mathrm{I}$$

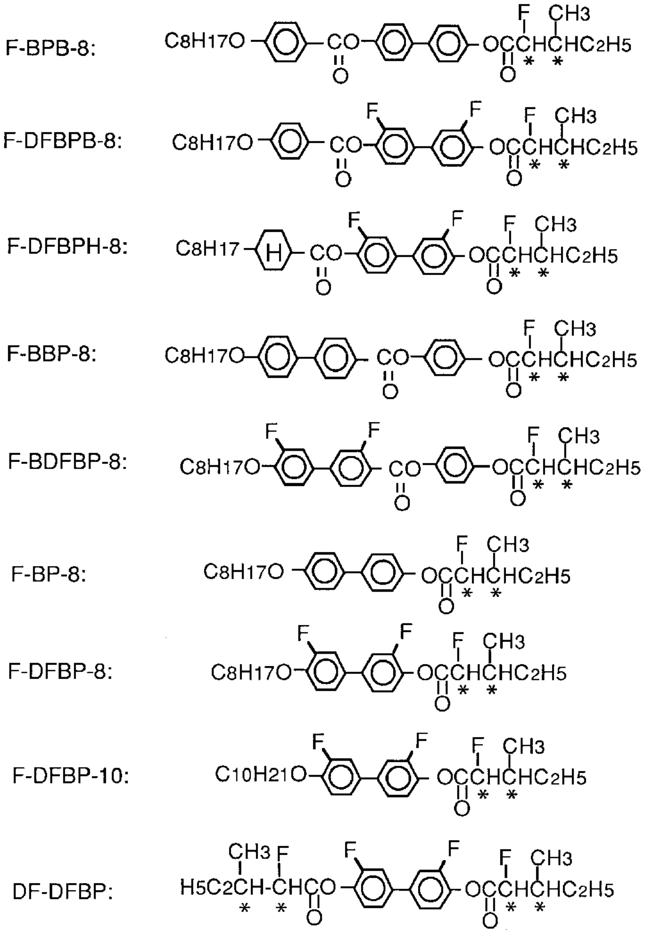

Figure 1. The structures of the synthesized chiral compounds.

The FLC mixtures **A–I** containing 5 wt % of the chiral compounds show phase sequence and transition temperatures (table 1). These mixtures also cover a wide SmC* temperature range between -26°C (crystallized) and 83°C.

3.3. *Spontaneous polarization of the new FLC mixtures*

The spontaneous polarization of the new FLC mixtures containing 5 wt % of the chiral compounds is shown in table 2. The mixture **H** and **I** containing the chiral compounds of the difluorinated biphenyl type **F-DFBP-10** and **DF-DFBP** shows a P_{S} greater than 10 nC cm^{-2} at 25°C.

The triphenyl type mixtures, **A–E**, have lower molecular concentration in an unit volume and show smaller P_{S} compared with the biphenyl type mixture. This is because of their higher molecular weight. The FLC

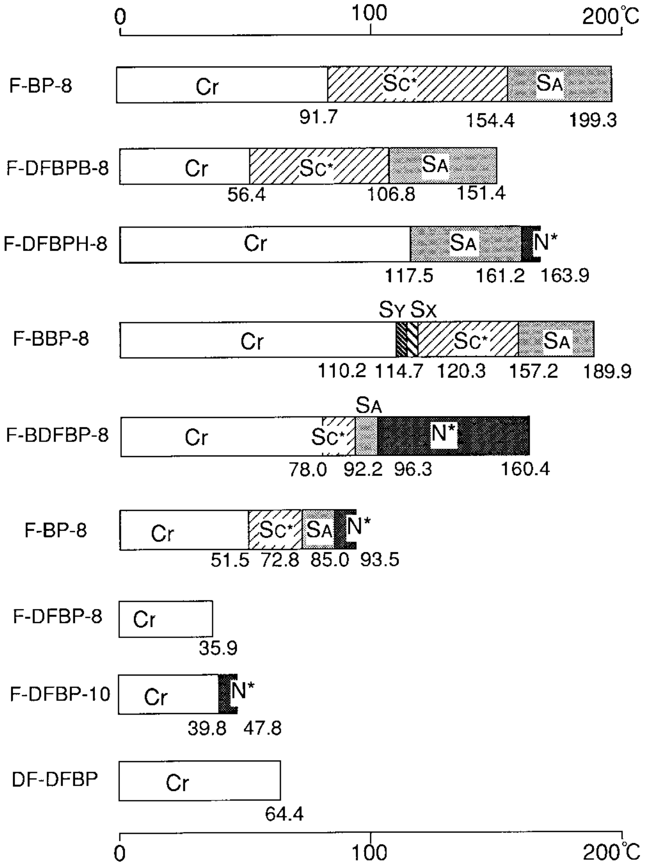

Figure 2. The phase transition temperatures of the chiral compounds.

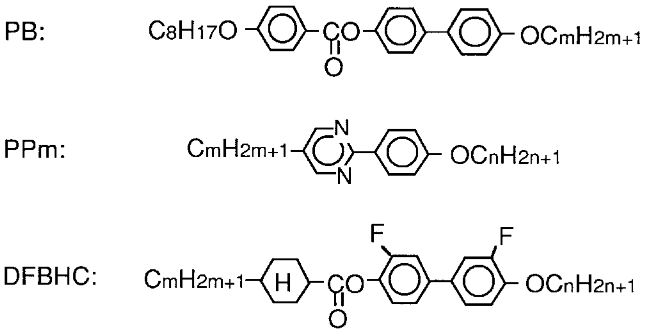

Figure 3. The structures of the non-chiral liquid crystals.

mixture **I** shows the largest P_S. This contains the chiral compound **DF-DFBP** having two chiral moieties on both sides of a difluorinated biphenyl ring.

The FLC mixture **G** containing the chiral compound of the biphenyl type **F-DFBP-8** shows a smaller P_S, than that of the mixture **H** containing the analogous compound **F-DFBP-10**. This may be due to impurities in the compound **F-DFBP-8**. This compound was difficult to purify by recrystallization because of its low melting point.

In the following, we concentrate on the FLC mixtures which show a large P_S containing the chiral compound **DF-DFBP**.

3.4. *The electro-optic properties of the new FLC mixtures*

We prepared the FLC mixture containing 10 wt % of **DF-DFBP** whose physical properties are shown in table 3.

The two types of cells, called 'parallel' and 'antiparallel', were fabricated according to the relative direction of the rubbing direction on the substrate, and filled with the LC mixture 1 shown in table 3.

The texture observations indicated that the parallel cells showed a multi-domain texture, while the antiparallel cells showed regular arrays of lines which are parallel to the rubbing direction (figure 4). These two types of cells also showed different electro-optic behaviour.

3.4.1. *Parallel cells*

The parallel cells filled with the LC mixture 1 show the usual bistable SSFLC behaviour. The electro-optic properties are shown in table 4. The response time was 60 μs with a pulsed electric field (± 22 V μm^{-1}, and 250 μs pulse width). The apparent cone angles were 45·2° in the switching state and 40·5° in the memory state, respectively.

3.4.2. *Antiparallel cells*

The antiparallel cells show surface-stabilized monostable behaviour, i.e. the director falls back to the original configuration when the applied voltage is switched off. As shown in figure 4, these cells show regular arrays of lines. The magnified observation in a polarized microscope under crossed polarizers shows that these stripes are parallel to the rubbing direction with a pitch of 2·3 μm. These stripes are not due to the smectic helical pitch since the slow axis in birefringence measurements indicated that the average director direction of the liquid crystal molecules coincided with the rubbing direction.

The optical transmission changes of the antiparallel monostable cell filled with the LC mixture 1 are shown in figure 5. The electro-optic properties of the antiparallel cells are shown in table 4. As described in the previous paper, the response time is of the order of 1 ms [4]. The rise time increases with increasing amplitude in the 1–5 V region, but decreases in the 1–5 V region. The fall time is always shorter (1–3 ms) and more constant than the rise time.

The apparent tilt angle increases with increasing applied voltage as shown in figure 6. The tilt angle changes linearly in the range from 1 to 5 V, nonlinearly for applied voltages greater than 5 V, and reaches 21·6°.

Table 1. The phase transition temperatures of the FLC mixtures (concentration of the chiral compound; 5 wt %).

FLC mixture		Phase transition temperature/°C								
No.	Chiral compound	Cr[a]		SmC*		SmA		N*		I
A	**F-BPB-8**	●	−12·9 (−26·9)	●	81·7	●	97·6	●	110·7	●
B	**F-DFBPB-8**	●	−13·8 (−27·8)	●	81·5	●	96·7	●	110·0	●
C	**F-DFBPH-8**	●	−14·0 (−26·1)	●	77·8	●	99·1	●	110·2	●
D	**F-BBP-8**	●	−21·0 (−33·3)	●	83·8	●	97·4	●	111·0	●
E	**F-BDFBP-8**	●	−14·3 (−27·8)	●	82·1	●	93·9	●	110·7	●
F	**F-BP-8**	●	−13·9 (−26·3)	●	76·5	●	93·5	●	105·5	●
G	**F-DFBP-8**	●	−13·9 (−29·5)	●	76·5	●	93·9	●	105·5	●
H	**F-DFBP-10**	●	−14·1 (−26·8)	●	74·3	●	92·4	●	103·9	●
I	**DF-DFBP**	●	−26·6 (−30·9)	●	71·7	●	88·1	●	104·0	●

[a] Phase transition temperatures between Cr and SmC*; the upper temperatures are on heating and the lower ones are on cooling.

Table 2. The spontaneous polarization of the FLC mixtures (concentration of the chiral compound; 5 wt %).

FLC mixture		P_s/nC cm^{-2}			Temperature range responding to an electric field/°C
No.	Chiral compound	T_c-50°C	25°C	Max	
A	**F-BPB-8**	4·4	5·6	8·7	−26∼85
B	**F-DFBPB-8**	4·7	5·3	8·7	−21∼84
C	**F-DFBPH-8**	6·6	8·1	11·6	−28∼85
D	**F-BBP-8**	2·5	3·0	4·3	−17∼88
E	**F-BDFBP-8**	3·5	4·2	7·5	−25∼88
F	**F-BP-8**	6·0	6·9	11·2	−23∼85
G	**F-DFBP-8**	4·8	4·9	8·9	−26∼80
H	**F-DFBP-10**	9·5	10·1	13·2	−24∼80
I	**DF-DFBP**	12·6	12·6	20·8	−30∼78

Table 3. The physical properties of the FLC mixtures.

LC mixture **1** (chiral 10 wt %)								
Phase:								
Cr	−30·6	SmC*	67·3	SmA	82·2	N*	100·1	I
Helical pitch:			N*		1·0 μm (T_c-5°C)			
			SmC*		2·5 μm (25°C)			
Spontaneous polarization (P_s):					11·5 nC cm^{-2} (25°C)			
LC mixture **2** (chiral 2 wt %)								
Phase:								
Cr	1·2	SmC*	52·1	SmA	59·5	N*	67·4	I
Helical pitch:			N*		5·7 μm (T_c-5°C)			
			SmC*		21·2 μm (25°C)			
Spontaneous polarization (P_s):					2·5 nC cm^{-2} (25°C)			

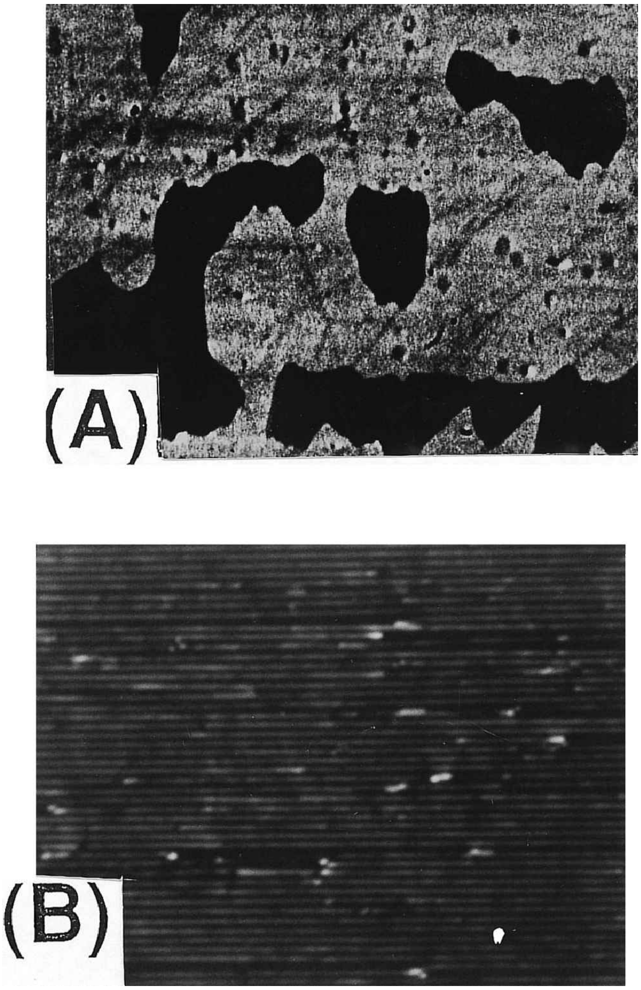

Figure 4. Texture observation of parallel cell (*A*) and antiparallel cell (*B*) filled with LC mixture **1** under crossed polarizers. The cell gap is 2.0µm.

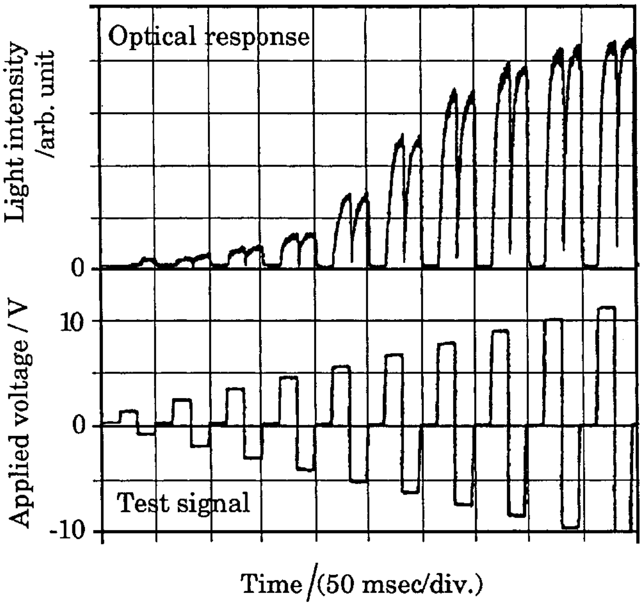

Figure 5. Optical transmission change of the monostable cell filled with LC mixture **1** under crossed polarizers on applying the test signal.

This is nearly equal to the bistable tilt angle 22·6°. The director tilts symmetrically with respect to the rubbing direction upon application of bipolar pulses. The optical transmission is calculated from the following equation,

$$I = I_0 \sin^2(4\theta) \tag{1}$$

by substituting the apparent tilt angle θ.

Using monostable cells, we formed an analogue greyscale display with the optical transmission increasing continuously with increasing applied voltage. However a periodic striped texture was formed on preparation of the monostable cells, and the contrast ratio was thereby limited to about 46 : 1. The contrast ratio was improved by turning the striped texture into a monodomain-like texture. The striped texture could be eliminated by using a new FLC mixture [LC mixture **2** (table 3)] containing 2 wt% of the chiral compound **DF-DFBP**, and by applying an electric field treatment [4]. Consequently a monostable cell with a monodomain-like texture could

Table 4. The typical electro-optic properties of parallel and antiparallel cells.

Property	Parallel cell	Antiparallel cell
Switching mode	Bistable	Monostable
Response time	60 µs [0–90 per cent] 22 µs [10–90 per cent] Pulse width 250 µs $\pm 22\,\mathrm{V\,\mu m^{-1}}$	2·7 ms [$\pm 11{\cdot}1\,\mathrm{V\,\mu m^{-1}}$]
Contrast ratio	14	46
Apparent cone angle	45·2° [On] 40·5° [Off]	43·2° [On]

The LC mixture **1** shown in table 3 was used.

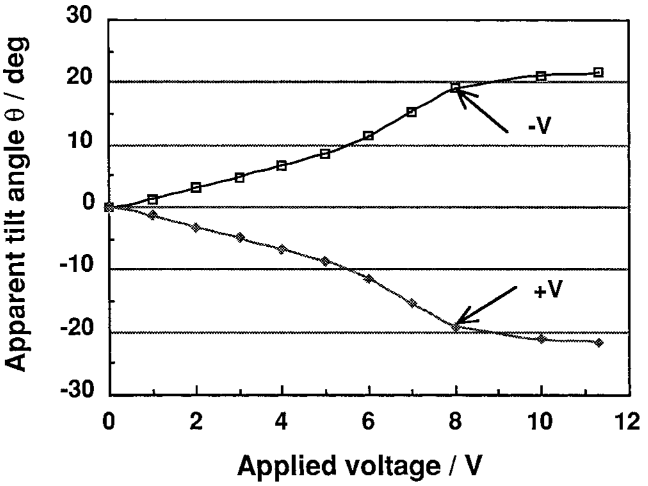

Figure 6. The apparent macroscopic tilt angle of the monostable cell (LC mixture **1**) as a function of applied voltage.

be obtained. Table 5 shows the characteristics of the monostable cells with and without an electric field treatment. In the monostable cell with the monodomain-like texture, a contrast ratio of 81 : 1; an analogue-grey scale with excellent linearity in the low driving voltage below 4 V; and a response time of the order of 1 ms was realized [3].

4. Discussion

The FLC mixtures containing the chiral compound **DF-DFBP** show a P_s greater than 10 nC cm^{-2} at 5 wt % of the chiral compounds. In the chiral compound **DF-DFBP**, two chiral moieties on both side of a difluorinated biphenyl ring may contribute to an increase of spontaneous polarization. The effect of fluorine substitution to a biphenyl ring suppresses the appearance of other smectic phases, except a SmA phase and a SmC phase [3].

When FLC mixtures containing the chiral compound **DF-DFBP** are used, different behaviours are observed in parallel and antiparallel cells. The parallel cells show the usual surface-stabilized bistable behaviour. In the parallel cells, it is believed that the liquid crystal molecules are grown and oriented from both sides of the alignment layers to make the smectic C* layers of a chevron structure. This is easily converted to a bookshelf structure showing good bistability by applying an electric field with 30 V_{pp} 100 Hz for several tens of seconds [7].

The antiparallel cells show the strange monostable behaviour, and a striped pattern is observed. The direction of the stripes coincides with the rubbing direction. Observing the texture in a microscope, one sees that the width of the bright space between black stripes increases with increasing amplitude of the applied voltage in the range 0–4 V. Above 4 V, the black stripes are suddenly changed into white lines, such as domain inversion switching, and then get brighter and wider. These stripes are on a 2·3 μm pitch at 0 V and on a 4·6 μm pitch above 6 V.

It is found that the striped domain is alternately aligned in antiparallel. In each domain, a cone angle of the director is 42° with voltage application between 10 V and −10 V, which is nearly equal to the bistable cone angle of 45·2°. We proposed the tilted cone axis model, i.e. the cone axis, tilted ±9° along the rubbing direction, alternately aligned in antiparallel (figure 7). By applying the electric fields, the director is tilting slightly in one domain, but largely as the domain inversion switching in another domain. By applying the opposite electric field, each domain behaves inversely. The formation of the striped structure is not clear in detail, but is probably due to a variety of the anchoring break, as reported Hauck and Koswig [8].

Table 5. The monostable cells with and without an electric field treatment*.

Electric field treatment	Without	With
Texture	Striped	Monodomain-like
Driving voltage	±5 V	±4 V
Response time	0·5 ms [On] 1·3 ms [Off]	1·3 ms [On] 0·7 ms [Off]
Contrast ratio	30	81
Analogue-grey scale	Nonlinear	Linear

*The LC mixture 2 shown in Table 3 was used.

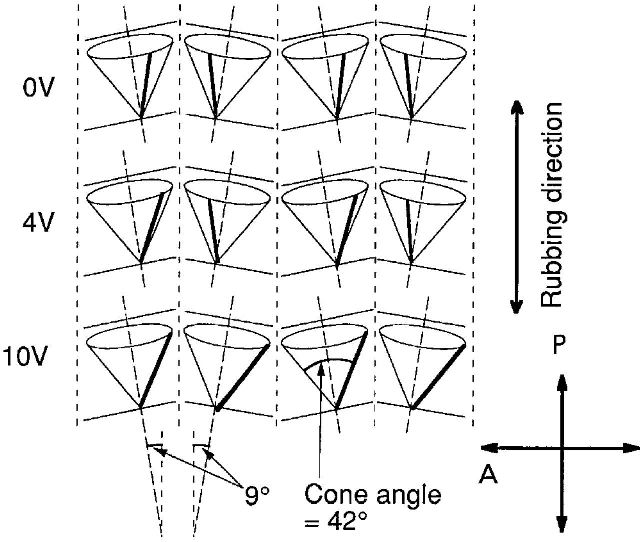

Figure 7. The director orientation model in a striped texture cell.

In particular this pattern formation is seen in antiparallel cells, but not in parallel cells. It is believed that the orientation structure of liquid crystals in antiparallel cells is related to a structured matching between SmC* layers grown from both of the surfaces of the alignment layers, and to an interaction between the liquid crystal molecules and the alignment layers. In order to clarify the switching mechanism, a structural investigation using X-ray scattering method is required.

5. Conclusions

We synthesized novel fluorine-substituted chiral compounds with a fluorine atom at an asymmetric carbon and a difluorinated biphenyl ring as a core by means of an original method. The ferroelectric mixtures were obtained by mixing the chiral compounds with nonchiral liquid crystals with a wide SmC temperature range between −29°C (crystallized) and 78°C. The FLC mixture containing the chiral compound **DF-DFBP** showed the largest P_s (greater than $10\,\mathrm{nC\,cm^{-2}}$ at 5 wt % of the chiral compound). Two types of cells, called 'parallel' and 'antiparallel', filled with the FLC mixtures were fabricated according to the relative direction of the rubbing direction on the substrates. The parallel cells show the usual bistable SSFLC (surface-stabilized ferroelectric crystal). The fast response time of 60 μs ($22\,\mathrm{V_{pp}}$ pulse, width 250 μs, at a room temperature) was obtained. The apparent cone angle is 45·2° in the switching state and 40·5° in the memory state. On the other hand, the antiparallel cells show an unusual monostable behaviour, i.e. the director falls back to the original configuration when the applied voltage is switched off. The surface-stabilized monostable cells show very attractive characteristics for application for a TFT active matrix LCD: a high contrast of 81 : 1, a fast response time (on the order of 1 ms), and an analogue-grey scale with excellent linearity within the low voltage range below 4 V.

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