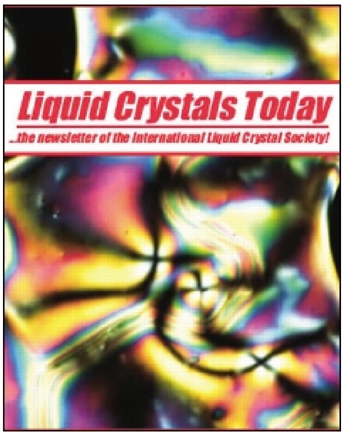

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Scattering displays from 'banana-smectics'

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Smectic liquid crystals of bent-shape molecules (banana-smectics) opened a whole new field in liquid crystals research, pioneered by groups in Tokyo [1], Boulder [2], Berlin [3], Halle [4], Budapest [5] and several other places. [6] The first scattering-type displays of these materials were presented recently. [7] It was observed that 'racemic' state of single-tilted polar smectic phase is scattering in the antiferroelectric OFF state and is optically clear in the ferroelectric ON state induced by electric fields. The chiral structure works in opposite way, i.e. it is transparent at zero fields and is scattering in the field ON state. In some cases these two structures may be reversibly interchanged implying their use in devices that consume energy only during switching from one stable state to the other.

This article is a summary of a cooperative work with Prof. L-C. Chien, Prof. G. Heppke, Dr D. Krüerke, Dr G. Nair, Dr H. Sawade and S. Rauch.

(*Received ????; accepted ????*)

1. Introduction

It is known that polar smectic layers of bent-shape molecules [1] lose the reflection symmetry, i.e. each layer becomes chiral [2] if the molecules tilt about the layer polarization.

The orientations of a left-handed and a right-handed banana-shaped molecules relative to the layer in which they are situated, are illustrated in Figure 1/a and Figure 1/b, respectively. **P** is the layer polarization and **n** is the layer normal. The angle q is formed between the average molecular axis of the layer and the layer normal.

The bulk structure is called racemic (rather should be called 'antichiral') if the chirality alternates in the adjacent layers, and is called chiral if the neighbor layers have the same handedness in macroscopic ranges. Most of the known SmCP phases have antiferroelectric (AFE) ground states, but the AFE arrangement can be switched to ferroelectric (FE) by external electric fields typically above 3 V/μm amplitudes and below the frequency $f \sim 10$ kHz.

The *racemic* AFE phase is synclinic (SmC$_S$P$_A$), i.e. the molecules of the adjacent layers tilt in the same direction. The racemic FE state has an anticlinic structure (SmC$_A$P$_F$) in which the optical axis is parallel to the layer normal independent of the sign of the external field.

In the *chiral* domains the AFE states are anticlinic (SmC$_A$P$_A$) and the optical axes are parallel to the layer normal regardless of the handedness. In the chiral FE states the director structures become synclinic (SmC$_S$P$_F$) and, depending on the sign of the electric field, the optical axes make angles $\pm\theta$ with the layer normal.

The practically useful feature of these states is the difference in their light scattering properties: the synclinic structures (AFE state of the racemic and FE state of the chiral structures) scatter light, whereas the anticlinic structures (FE state of the racemic and AFE state of the chiral structures) are transparent. This is due to the fact that the differently tilted synclinic domains are separated by defects, which are observable even without polarizers. Antiferroelectric and ferroelectric textures of the chiral state viewed without polarizers are shown in Figure 4. In the anticlinic OFF state (a) only focal conic defects are present due to the imperfect layer alignment, whereas in the synclinic ON state (b) the texture is full of defect walls separating domains with different handedness. Defects cause light-scattering because the refractive index of the defect is different from the uniform areas. Focal conic defects of Figure 4/a cause only a few percentage of scattering, whereas the defect walls of Figure 4/b scatter out 50% of incoming light.

Depending on the states where the fast switching takes place, two display modes can be distinguished.

2. Tilt Separation Mode (TSM-LCD)

This mode exists only in the racemic state of banana-shaped molecules. The switching takes place between the synclinic racemic AFE (OFF) and anticlinic racemic FE (ON) states, i.e. the film is opaque at zero fields and transparent, in virtually any directions, under electric fields. Switch can also be accomplished with changes in frequency under constant amplitude: at low frequencies the FE state, at high frequencies AFE state appear. The scattering is based on the spontaneous separation into oppositely tilted domains due to the equivalences of the tilt directions.

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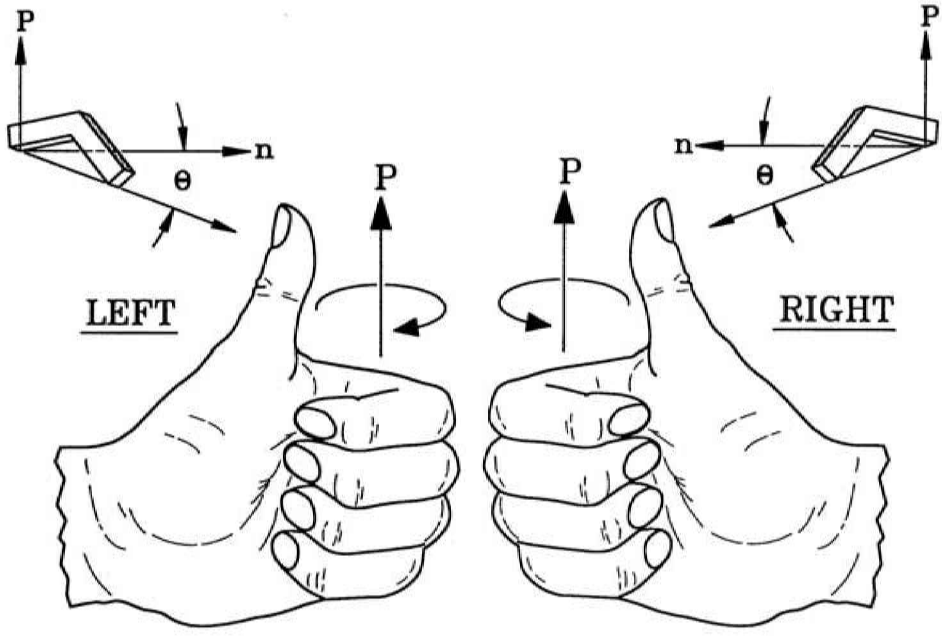


(a) (b)

Figure 1. Orientation of the average molecules with respect to the layer normal **n** and the layer polarization **P**. (a) Left-handed layer: the average molecular axis is oriented clockwise from the layer normal. This can be envisioned relative to a left hand: if the thumb of a left hand is pointing in the direction of layer polarization, the direction of the curling of the fingers represents the direction of the deviation of the molecular axis from the layer normal. (b) Right-handed layer: the average molecular axis of a right- handed molecule is oriented counter-clockwise from the layer normal. In this case, when the thumb of a right hand is pointing in the direction of layer polarization, the direction of the curling of the fingers represents the direction of the deviation of the molecular axis from the layer normal.

3. Chiral Separation Mode (CSM-LCD)

In this mode the material has chiral structure and the film is transparent in the anticlinic AFE structure at zero fields and opaque under low frequency electric fields in the synclinic FE state. Similar to the TSM-LCD, the switching can also be accomplished with changes in frequency under constant field amplitude. The scattering is due to the overall racemic nature of the phase, which results in the coexistence of left and right-handed synclinic domains separated by defect walls.

The switching between scattering and transparent states is demonstrated in reflection in the video where a black-and-white text is shown right behind a 10 μm film being in the chiral state. The text is fully visible virtually in any directions in the chiral AFE (OFF) state and completely blurred at the chiral FE (ON) state.

The switching time increases as the temperature decreases, but typically it is below 100-μs even more than 50°C below the clearing point. The scattered light intensity does not depend much on the light wavelength, i.e. the pictures are black and white. Color mode can be achieved by color filters, just as in other color LCDs.

Scattering-type liquid crystal devices have been known since the 1930s when Freedericksz and Tsetkov observed dynamic light scatterings in highly conductive nematics. [8] The first liquid crystal displays in wristwatches worked on this basis, too. [9] Polymer Dispersed Liquid Crystals (PDLC) [10], Polymer Network Liquid Crystals (PNLC) [12], SmC* [13] and 45° director tilt angle SmC$_A^*$ calamitic liquid crystals are examples of insulating scattering devices. [14].

The scattering efficiency of the banana smectics is comparable to the scattering of about 10-μm thick PDLC films. An important difference is that in banana smectics the scattering is caused by defect walls that run across the film and not by droplets. This explains our latest observations [15] that the scattering efficiency does not change significantly in the 2–10 μm sample thickness range. In fact, the transmission in the thinner films is better (~98% for 2 μm film) than in thick films (~96% in 10 μm). In addition, thin films require much smaller driving voltages (~10–15 V for 2 μm cells), which make them even more attractive for applications.

The liquid crystal devices of tilted banana smectics have commercial application possibilities in all areas where PDLC-s are currently used. This includes privacy windows, projectors, and the like. In addition, because the performance of banana smectics is superior in

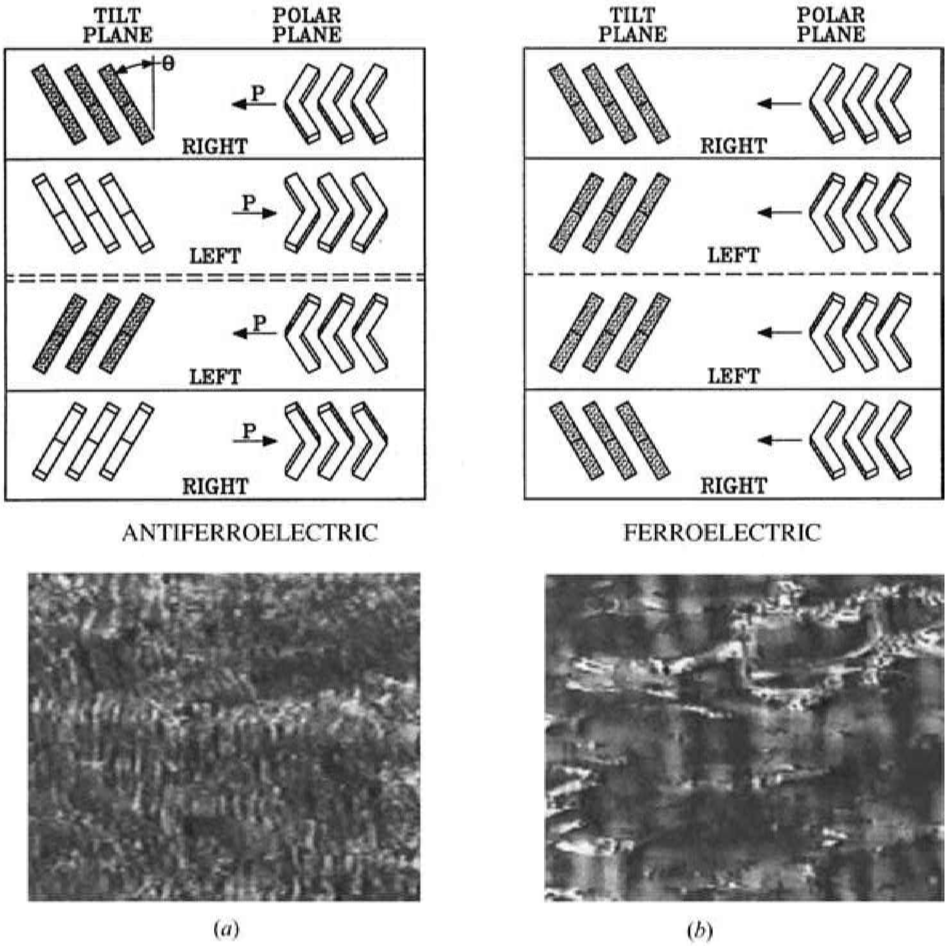
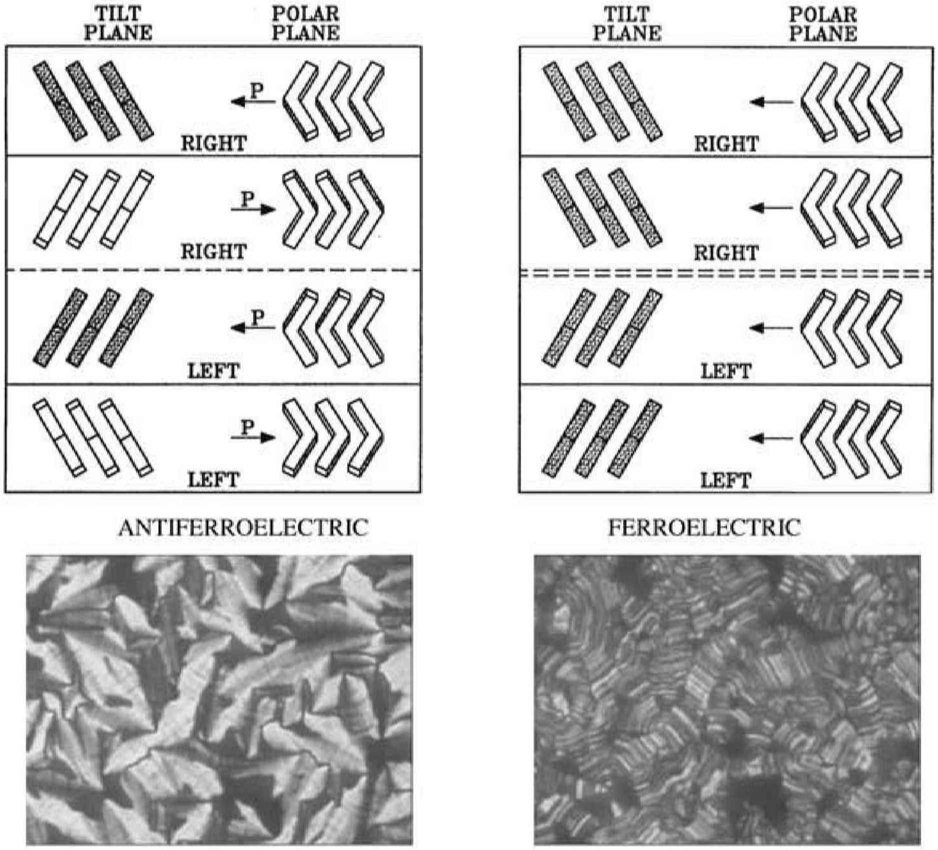


Figure 2. Orthogonal views of the *racemic* SmCP phase of non-chiral banana-shaped molecules and polarizing microscope textures viewed in tilt plane in antiferroelectric (AFE) and ferroelectric (FE) states (left and right columns). The 'Polar plane' contains the layer normal and the layer polarization (P), whereas the 'Tilt plane' is perpendicular to P. The molecular plane is tilted with respect to the layer normal. The single dashed line (‾ ‾ ‾) indicates synclinic interfaces in anticlinic state, whereas double dashed lines (═══) represents defect walls separating synclinic layers with opposite tilt directions. The pictures represent 100-μm × 70-μm areas.

several aspects—including larger viewing angle and faster switching, thinner films with smaller driving voltage—the application possibilities are broader. This capability would make it useful in cellular phones, laptops or palmtops, etc.

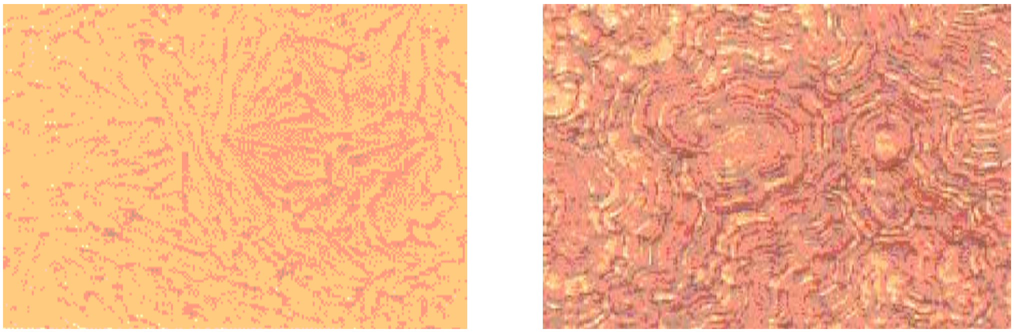
Although in the majority of the banana smectics the chirality is conserved during switching between AFE and FE states it was observed that in some materials strong fields cause a gradual change of the layer chirality. [16, 17] In some examples both the opaque racemic AFE and the transparent chiral AFE (OFF) states were found to be stable and could be interchanged. This implies their use in optical storage devices. For example we can envision privacy windows that consume energy only during the transformation from one state to the other. This transformation requires about the same time as needed to turn over one page in a book. Consequently such devices could be useful in future electronic newspapers, which do not use energy in the storage mode, but could also be transferred to fast switching video modes. During the transformation between racemic and chiral states, any state is stable, enabling multi-stable storage devices with gray-scale properties.

In addition to the achiral banana-shaped LC molecules, the above principles would work also in 'bowl-shaped' molecules (bent disks) that stack in columns and may form the so-called 'pyramidal phases.' Just like achiral banana-shaped molecules, bowl-shaped molecules may also be tilted with respect to the columns and are believed to be able to form racemic and chiral antiferroelectric domains. Symmetry-wise, the bowl-shaped molecules are essentially equivalent to the banana-shaped molecules, except that the banana-shaped liquid crystals form 2-dimensional fluids, whereas the bowl-shaped LCs



(*a*) (*b*)

Figure 3. Orthogonal views of the *chiral* SmCP phase of non-chiral banana-shaped molecules and polarizing microscope textures viewed in tilt plane in antiferroelectric (AFE) and ferroelectric (FE) states (left and right columns). The 'Polar plane' contains the layer normal and the layer polarization (P), whereas the 'Tilt plane' is perpendicular to P. The molecular plane is tilted with respect to the layer normal. Single dashed line (‾‾‾) indicates synclinic interfaces in anticlinic state, double dashed line (═══) represents defect walls separating synclinic layers with opposite tilt directions. The pictures represent 100-μm × 70-μm areas.



(*a*) (*b*)

Figure 4. Textures of 4-μm cells of a banana-smectic in chiral state viewed without polarizers. The pictures represent 100-μm × 70-μm areas.

form 1-dimensional fluids. It is also theorized [18] that mixtures of two antiferroelectric materials of chiral rod-shaped molecules may exhibit similar effects. If such compounds were not completely miscible, they could form micro-domains with opposite chirality. In the ferroelectric phase (where the polarization points in the

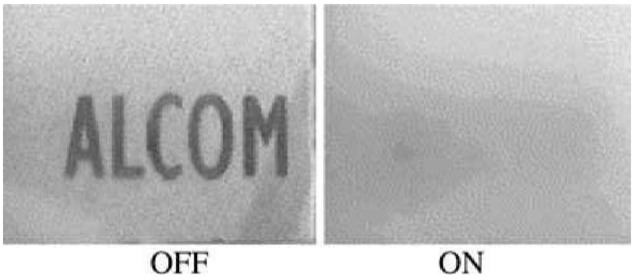


Figure 5. Electrically switchable light shutter in the chiral SmCP phase of non-chiral banana-shaped molecules. (a) Pictures illustrate 1 cm^2 areas of a 10-μm thick film at room temperature. At zero fields the film is transparent and the text 'ALCOM' placed right behind the cell is visible. At fields $E > 8$ V/μm the film is opaque and the text is blurred. See also the video showing the switching.

same direction), the optical axis in the different micro-segregated domains would be different. In the antiferroelectric OFF state, however, the optical axes would likely be the same. If, simultaneously, there were no defect walls between the domains in the antiferroelectric, but only in the ferroelectric state, it may exhibit an OFF-CLEAR/ON-SCATTER mode display. Moreover, it is not even necessary that the mixed materials be of opposite chirality. It is enough if the sign of the polarization (*i.e.*, the sign of the polarization-tilt angle coupling) were reversed. A racemic mixture of opposite enantiomers is necessary only in case of mixtures with the same sign of the polarizations.

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