23.1: *Invited Paper:* Stability of Hysteresis-Free Passively Adressed FLC Display with Inherent Gray Scale

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Abstract

The steadiness of hysteresis-free passively addressed FLC display with an inherent memorized gray scale is governed generally by relationships between dispersion and polar parts of FLC anchoring energy with solid substrates.

1. Introduction

Passively addressed bistable ferroelectric liquid crystal displays (FLCD) are well known for a long time but generation of the hysteresis free grey scale was always a problem for FLCD [1]. Surface stabilized FLC structure with a bistable switching cannot provide an intrinsic grey scale, unless a time or space averaging process is applied [2]. The inherent physical gray scale for passively addressed bistable FLCD can be only if FLC possesses ferroelectric domains [3, 4] that appear at high spontaneous polarization P_s>50nC/cm^2.

First condition of FLCD operation steadiness is the bistability steadiness. For evaluations of display cells bistability steadiness a new criterion S_b:

$$S_b = (½\, V_c - |V_{sh}|) / \delta V \qquad (1),$$

related to FLCD hysteresis loop (Fig. 1) was proposed in [5].

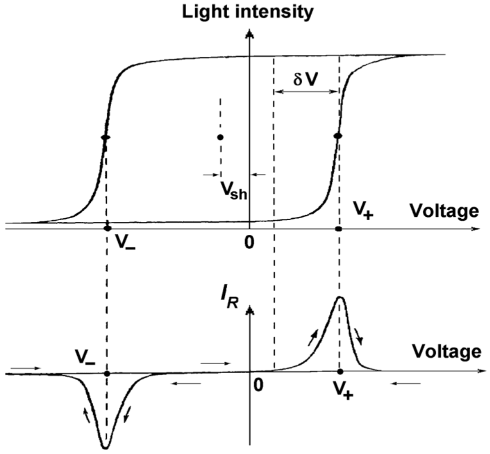

Fig. 1: Top - a typical hysteresis loop of FLC cell exhibiting a shift *V_{sh}* of the hysteresis loop center regarding zero voltage; bottom – a typical polarization reversal current of FLC cell.

A shift V_{sh} of the hysteresis loop center regarding zero voltage, which usually takes place in FLC cells, can be evaluated according to Fig.1 as:

$$V_{sh} = ½\,(V_+ - V_-) \qquad (2),$$

while the voltage coercivity V_c in (1) is:

$$V_c = V_+ - V_- \qquad (3).$$

The parameter δV in (1) indicates a region inside the hysteresis loop where the light intensity at the output of FLC cell depends on applied voltage magnitude, or the polarization reversal current is non-zero (Fig. 1, bottom).

Evidently, the bistability is steady, if

$$S_b>1 \qquad (4).$$

The best condition for FLC bistable switching is the symmetrical hysteresis loop with $|V_{sh}| \to 0$ and $\delta V \to 0$ according to the bistability steadiness criteria (1) and (4), while the hysteresis-free gray scale of FLCD requires also a certain relation between these two values [5,6]. The relation can be found, if we suggest that the "black" state is the basic one (Fig. 2), so the threshold V_{thB} of the bright level addressing is not less than the saturation voltage V_{SD} of the "black" state addressing:

$$V_{thB} \ge V_{SD} \qquad (5).$$

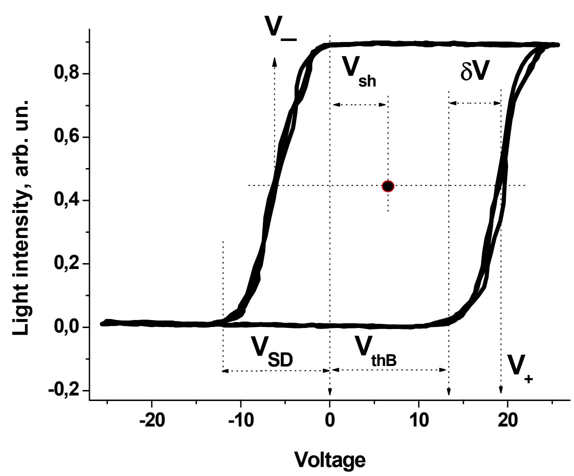

Fig. 2. Typical FLCD hysteresis loop under the triangular voltage, *f*=50 Hz. Here V_{thB} is the threshold voltage of bright level addressing, V_{SD} is the saturation voltage of the "black" state addressing.

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The inequality (5) provides addressing of all the levels of the light transmission using the right branch of the hysteresis loop. The left branch of the hysteresis loop doesn't play any role, if the driving voltage exceeds V_{SD} value. Just in this case the hysteresis free FLC addressing of all light transmission levels (gray scale) can be obtained. The voltages V_{thB} and V_{SD} can be defined from Fig. 2.

$$V_{thB} = \frac{1}{2}V_c + |V_{sh}| - \delta V, \qquad V_{SD} = \frac{1}{2}V_c - |V_{sh}| + \delta V \qquad (6).$$

The combination of (1), (4), (5) and (6) leads to the following inequality:

$$1 \le \frac{|V_{sh}|}{\delta V} \le \frac{V_c}{2\delta V} - 1 \qquad (7),$$

that means necessary and sufficient conditions of the hysteresis free gray scale FLCD addressing and the steady bistability at the same time. Origin of it is that the left branch of the hysteresis loop will be excluded out of electro-optical response, if (7) is valid and, additionally

$$|U| \ge |V_{SD}| \qquad (8),$$

where U is the driving voltage pulses amplitude.

Actually, inequalities (7) and (8) provide the hysteresis free electro-optical response because of the hysteresis loop center shift, and this was confirmed experimentally [7].

The static (f=10^{-4}-10^{-2}Hz) hysteresis loop center shift V_{sh} regarding zero voltage can be expressed through the spontaneous polarization P_s and difference ΔW_p of polar parts of FLC energy anchoring with boundaries[8]:

$$\Delta W_P = P_s V_{sh} \qquad (9).$$

The static voltage coersivity V_c can be expressed through the spontaneous polarization and a coefficient W_Q of the anchoring energy dispersion part [8]:

$$V_c = 8W_Q / P_s \qquad (10).$$

According to (7), one need to adjust V_c, $|V_{sh}|$ and δV to get steady operation of passively addressed FLCD with hysteresis free gray scale. It can be done due to FLC material science (because W_Q depends on FLC chemical structure) and a special treatment of surfaces, which confine FLC layers, because ΔW_P depends on polarity of solid surfaces.

2. Approaches to increasing of the static voltage coercivity.

Increasing of the voltage coercivity V_c that is necessary at any case to get steady FLCD operation according to (7) means first of all increasing of W_Q coefficient. It is known [8] that

$$W_Q = W_{QN} \sin^2\theta \qquad (11).$$

where θ is the molecular tilt angle.

It was shown in our experiments that W_{QN} magnitude depends mainly on two basic features of FLC molecular structure. First, W_{QN} strongly depends on molecular lengths, Fig. 3.

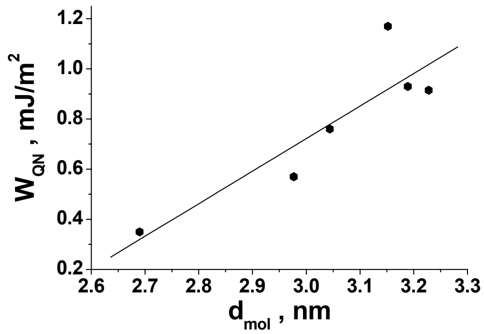
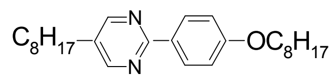
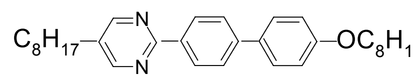


Fig. 3. Dependence of W_{QN} on FLC molecular length.

Second, W_{QN} magnitude at fixed FLC molecular length drastically increases when a rigid molecular core extent increases. For instance, for phenylpirimidine



W_{QN}=0.2mJ/m^2 but biphenylpirimidine



exhibits W_{QN}=1.4mJ/m^2. The W_{QN} magnitude in binary mixture of phenyl-pirimidine and bi-phenyl-pirimidine depend linearly on molar concentration of compounds, Fig. 4.

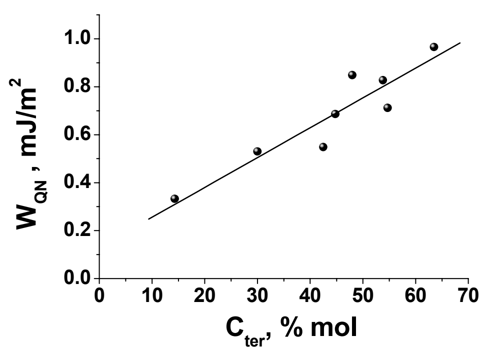


Fig. 4. Dependence of W_{QN} magnitude of binary mixture of phenylpirimidine and biphenylpirimidine on molar concentration of biphenylpirimidine.

So, for highest V_c value FLC mixtures should be composed of molecules that possess extremely large rigid molecular core extent and extremely long aliphatic molecular chains. Both these requirements are generally in contradictionary with conditions of ferroelectric smectic C* existence. Nevertheless, we developed such a kind of FLC mixtures. FLC display cells based on these mixtures shows static voltage coersivity V_c>3V, Fig.5.

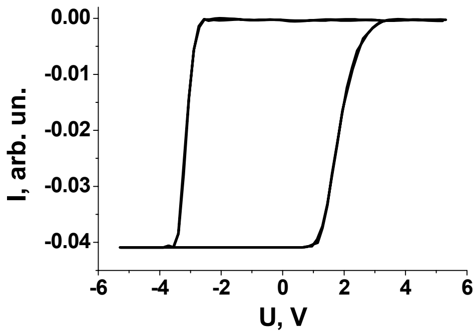


Fig.5. Hysteresis loop of 1.5µm FLC cell, f=5·10^{-3} Hz.

It is quite enough to give assurances of steady FLCD operation because usually $|V_{sh}| \le 0.6V$ [5].

3. Controlled Hysteresis Loop Center Shift and Memorized Hysteresis Free Gray Scale

3.1 Surface Polarity and the hysteresis loop center shift

Our experiments [5] show: the difference ΔW_p and consequently V_{sh} can be controlled at asymmetric boundary conditions [5], when only one of two ITO surfaces of FLC cell is covered with an aligning layer that can be considered under certain technological conditions as statistical island nanostructures (Fig. 6). The typical

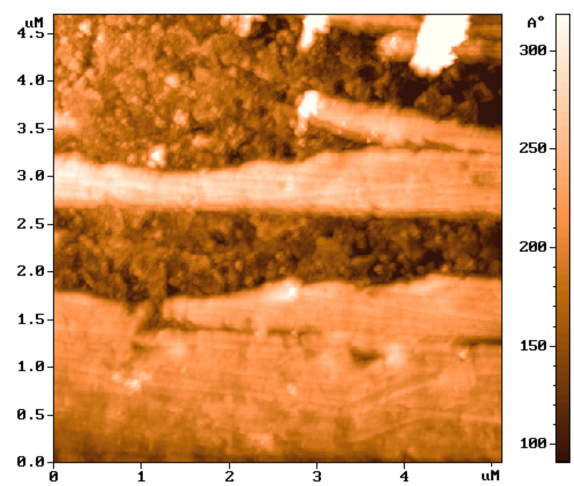


Fig. 6. AFM scan of ITO covered with broken aligning layer [9]. Well-known SOLVER NT AFM technique was used for evaluation of the surface. The averaged aligning layer thickness is 9 nm.

thickness of aligning layer islands is 3÷15 nm, in plane averaged dimension of islands is about 500 nm÷5µm, and an averaged distance between islands is about 500 nm÷5µm also. Variations of mentioned above parameters of such a surface nanostructure result in changing the aligning surface polarity and controlled shift of a hysteresis loop center (Fig. 7). In this manner a new electro-optical phenomenon – hysteresis free optical response is provided, if inequality (7) is satisfied, in spite of the hysteresis itself, of course, exists.

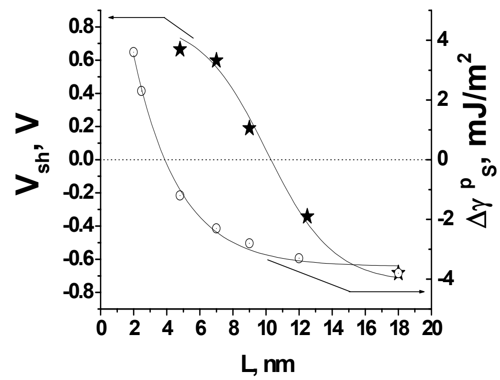


Fig. 7. Left axis (*)– dependence of V_{sh} magnitude of FLC display cell (the FLC layer thickness is 6 µm) under asymmetric boundary conditions on averaged thickness *L* of island aligning structure, right axis (o)– dependence of a difference $\Delta\gamma_S^P$ between polarity of ITO and ITO, covered with the aligning layer on averaged thickness L of island aligning structure.

Typical hysteretic free and memorized (after the driving voltage switching off) gray scale of passively addressed FLCD is shown in Fig. 8.

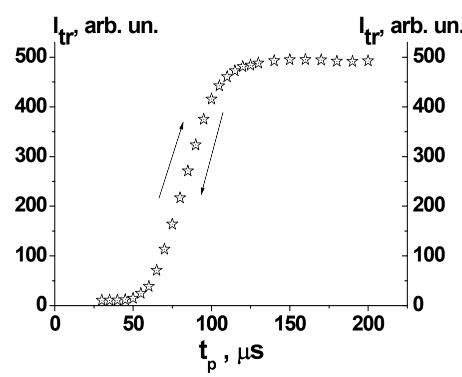


Fig. 8. Dependence of memorized gray scale levels of 6µm FLC cell on driving voltage pulse duration at the driving voltage amplitude of ±15V.

3.2 Adjustment of Hysteresis Loop Steepness

The hysteresis loop steepness δV (see Figures 1 and 2) depends strongly on thickness of aligning layers (Fig. 9) and on spontaneous polarization (Fig. 10). Origin of these dependencies, coupled with polar interactions between the FLC and aligning layer, is still under consideration.

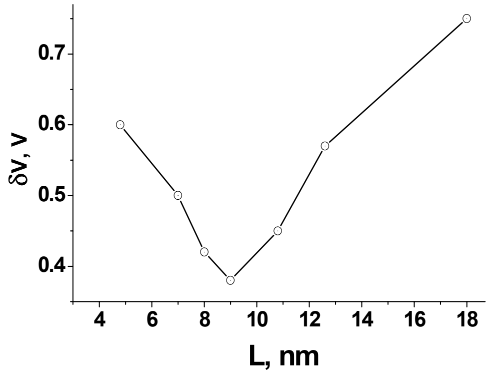


Fig. 9. Dependence of the hysteresis loop steepness of 1.5 μm FLC cell on aligning layers thickness.

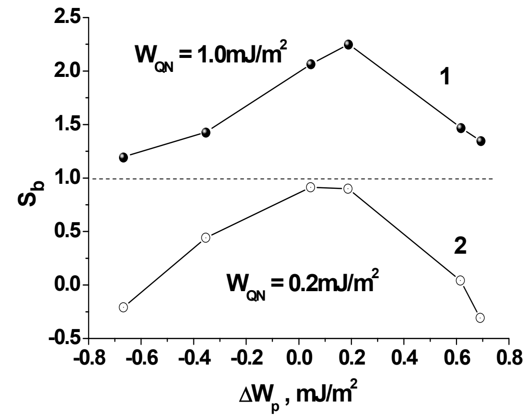


Fig. 11. Dependencies of the bistability steadiness parameter of FLC cells on ΔW_P magnitude

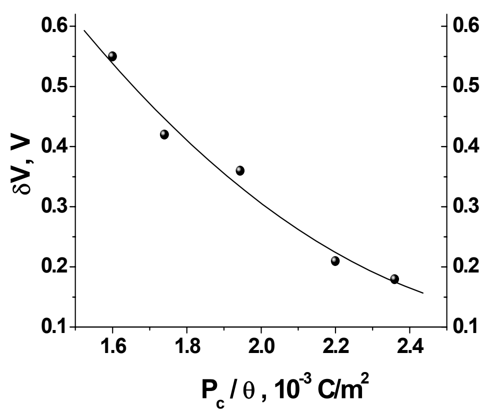


Fig. 10. Dependence of the hysteresis loop steepness of 1.5 μm FLC cell on spontaneous polarization normalized on the tilt angle.

4. General Condition of Passively Addressed FLCD Steady Operation

The general condition of passively addressed FLCD steady operation both in binary bistable mode and at hysteresis free gray scale addressing is illustrated with Fig. 11. According to this condition, if W_{QN} exceeds a threshold (W_{QN}≥1mJ/m^2, curve 1 in Fig.11) then the bistability will be steady at any change of ΔW_P, which can be obtained in experiment. On the contrary, at W_{QN}≤0.2mJ/m^2 the steady bistability will never exist. So, the most principle requirement for steady bistable operation of FLCD: W_{QN} must exceed some threshold value (1mJ/m^2), which was evaluated experimentally in this work. If W_{QN} below this threshold then the bistability can exist only at certain relationship between polarities of solid substrates confining the FLC layer (see Fig. 11).

5. Impact

Conditions of steady operation of hysteresis free passively addressed FLCD with inherent gray scale have been proved. The objectivation includes development of basic physical ideas for description of the steadiness, creation of FLC mixtures and aligning layers according to the basic ideas, and manufacturing the display cells exhibiting the steady operation.

6. Acknowlegements

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