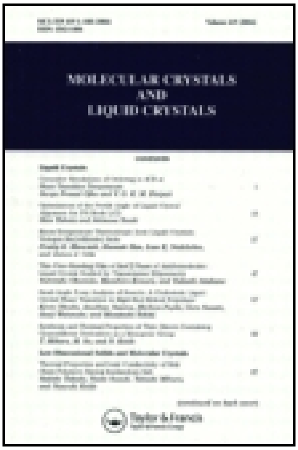

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INVESTIGATION OF SWITCHING PROCESSES IN SmC* LIQUID CRYSTAL SAMPLES WITHOUT AND WITH CROSSED POLARIZERS

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Abstract. Electrooptical responses of planar oriented SmC* liquid crystal samples were investigated with and without crossed polarizers by applying A.C. square voltages with different D.C. bias voltages. The switching processes due to the birefringence and the transient light scattering were analized simultaneously. From the results we deduce some conclusions on the structure of the sample.

INTRODUCTION

Ferroelectric chiral smectic C (SmC*) liquid crystals have attracted significant attention because of the possibility of their application as high speed switching devices[1].

In planar oriented SmC* liquid crystals under the influence of a sufficiently high electric field director reorientation takes place when reversing the polarity. Due to the refractive index anisotropy, the different director alignments (corresponding to the different polarity of the electric field) result in different light transmission intensities between crossed polarizers. We refer to this switching mode as crossed polarizer mode (CPM).

For thickness (d) is shorter than the pitch (p)

the director orientation remains stable even after the electric field is switched off. This type of bistable electrooptical switching was investigated by Clark et al.[1,5] who found very short switching times in the range of 0.1-1 μsec.
In the case when the cell thickness is larger than the pitch a helical structure, accompanied by disclination lines, is present in the sample[2]. Applying an electric field larger than the so called unwinding critical field E_C a homogeneous unwound structure forms. Reversing the polarity of the field a different homogeneous structure is created resulting in transmitted light intensity variation. (see e.g.[2,7,8]). In the first part of this article we report on our investigations of this type of switching by a step-wise reversed electric field. In order to find out more about the sample structure we measured the different switching times as the function of the D.C. bias field and at different cell thicknesses.

Due to the molecular rotations during the switching, light scattering occurs[3,10]. As a result of this process a transient light intensity decrease can be detected without polarizers. This transient light scattering mode was investigated by Ozaki and Yoshino[3]. It was found that this effect results in a very good contrast when the sample thickness is large compared with the helical pitch. Our aim is to investigate the switching times, detected with and without crossed polarizers simultaneously. For this purpose we investigated the transient light scattering mode (TSM) on the same sample where the crossed polarizer mode was investigated. These results are presented in the second part of this paper.

EXPERIMENTAL

The experiments were carried out on a homogeneous planar oriented liquid crystal binary mixture Fk4[4,6] with the phase sequence

$$I \xrightarrow{67^{\circ}C} Ch \xrightarrow{63^{\circ}C} SmA \xrightarrow{29^{\circ}C} SmC^{*} \xrightarrow{16^{\circ}C} SmI^{*}$$

The pitch p in the SmC^{*} was about 5 μm and homogeneous planar oriented thick samples (with helical structure) with 15 μm, 30 μm and 60 μm sample thicknesses were used. The sample thicknesses were controlled with an accuracy of ± 2 μm and were checked by capacitance measurements.
The samples were illuminated by a He-Ne laser beam and the transmitted light was detected by a photodiode. The signal of the detector was displayed in an oscilloscope screen.
We measured the switching times when the samples were between crossed polarizers (crossed polarizer mode=CPM) and without any polarizer (transient light scattering mode=TSM).
The switching processes were analized as the function of reversed field and the D.C. bias field amplitudes.
In all experiments the sample was thermostated at $T=23^{\circ}C$

RESULTS

A. CROSSED POLARIZER MODE (CPM)

When the polarity of the applied field was reversed step-wise as shown in Fig.1.a (and when its amplitude was larger than a certain threshold voltage (U_{th})) the intensity of the light transmitted through the polarizers and the cell generally changed as indicated in Fig.1.b.

The switching time was determined as it is usual (the time while the transmitted light intensity changes between the 10% and the 90% of its maximum value).

The directions of the crossed polarizers were chosen so that in one of the unwound states of the sample there was a complete extinction.

FIGURE 1. Tipical light transmission in CPM.
a. Applied voltage on the sample
b. Signal of photodiode

In the case of symmetric voltages (no bias, U_0=0) we found that the contrast increased with increasing applied voltage up to a threshold value U_{th} beyond which it was constant.

For U_{th} we got the following values:

at $d=15\,\mu m$ $U_{th} \approx 2V$ ($\Longleftrightarrow E_{th} \approx 1.3 \times 10^5$ V/m)

at $d=30\,\mu m$ $U_{th} \approx 7-8V$ ($\Longleftrightarrow E_{th} \approx 2-2.5 \times 10^5$ V/m)

and at $d=60\,\mu m$ $U_{th} \approx 9-10V$ ($\Longleftrightarrow E_{th} \approx 1.5-1.8 \times 10^5$ V/m)

Unfortunately we have no idea why the E_{th} at sample thickness $d=30\,\mu m$ is larger than in the other two cases.

The dependence of the switching times $\tau_{UP}(U)$ and $\tau_D(U)$ on the voltage U for the sample thickness $d=30\,\mu m$ is shown in Fig.2.

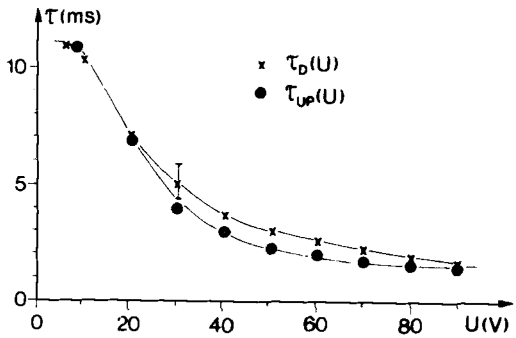

FIGURE 2. Switching times $\tau_{UP}(U)$ and $\tau_D(U)$ versus applied step-wise voltage U with bias voltage $U_o=0$ V in case of planar oriented SmC^* liquid crystal Fk4. Sample thickness $d=30\,\mu m$, $T=23^0C$.

Within the error of our measurements we found that

$$\tau_{UP}(U) = \tau_D(U) \equiv \tau(U) \qquad (1)$$

In this equation $\tau_D(U)$ (or $\tau_{UP}(U)$) means the switching time when the polarity of the applied voltage changes from + sign to - sign (or from - sign to + sign).

At different D.C. bias voltages ($U_0 \neq 0$) we found the following facts:

$$\tau_D^{U_0}(U) = \tau_{UP}^{-U_0}(U) \qquad (2)$$

$$\text{if } U_0 > 0 \text{ than } \tau_{UP}^{U_0}(U) < \tau(U) \text{ and } \tau_D^{U_0}(U) > \tau(U) \qquad (3)$$

$$\text{so if } U_0 < 0 \text{ than } \tau_D^{U_0}(U) < \tau(U) \text{ and } \tau_{UP}^{U_0}(U) > \tau(U) \qquad (4)$$

$\tau_{UP}^{U_0}(U)$ and $\tau_D^{U_0}(U)$ mean the switching times when a bias (U_0) was applied.

For $U_0 = \pm 10$ V we presented the results in Fig.3.

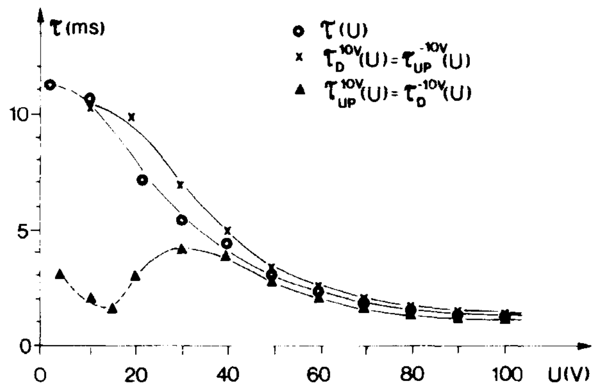

FIGURE 3. Switching times $\tau_{UP}^{U_0}(U)$ and $\tau_D^{U_0}(U)$ versus applied reversed voltage in case of D.C. bias voltages: U_0=+10 V, U_0=-10 V and U_0=0 V

We explain the local minima in the curve $\tau_{UP}^{10\ V}(U)$ by noting that below $U \sim 20$ V the ratio of the transmitted light intensities in the two unwound states (the contrast) increased with the applied voltage, that is in this range there was no saturation yet in the director aligning process.

In Figs 4a and 4b we presented the switching times versus the D.C. bias voltage U_o when the amplitude of the A.C. voltage was U=60 V. Simultaneously we presented the $\tau(U \pm U_o)$ functions and found that

$$\tau_D^{U_o}(U) = \tau(U-U_o) \qquad (5)$$

$$\tau_{UP}^{U_o}(U) = \tau(U+U_o) \qquad (6)$$

From the symmetrical responses of the material to the applied fields we conclude that the structure of the sample is symmetric with respect to the sign of the spontaneous polarization. It means that without an electric field the alignment is anti-parallel at the bounding plates.

Furthermore, from equations 5 and 6 we see that the switching time is primarily determined by the voltage which switches the spontaneous polarization to the other direction parallel to the reversed electric field. Within the error of our measurements the voltage which holds the spontaneous polarization in the ordinary direction (if it is larger than the unwinding critical voltage U_c) does not play any essential role. This fact is in a good agreement with the assumption that above U_c the sample structure does not vary.

We also measured the switching time $\tau(U)$ at

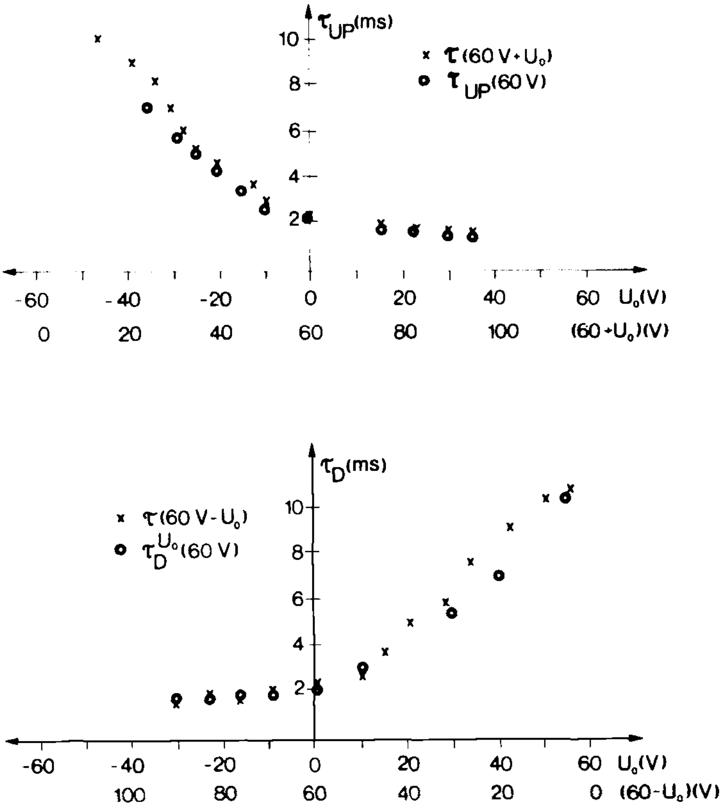

FIGURE 4. The switching times at CPM as the function of D.C. bias voltages U_0 when the amplitude of the step-wise voltage is U=60 V

sample thicknesses d=15 μm and d=60 μm. The results are plotted together with that of sample thickness d=30 μm in Figure 5. This figure shows that for each sample thickness there is a linear part with the same slope. However increasing the value of 1/E the switching time function $\tau(1/E)$ deviates from the linearity. We define an electric field E_o, as the field where the actual switching time is the half of the value that one would obtaine by extrapolation from the linear part. E_o varies with the sample thickness:

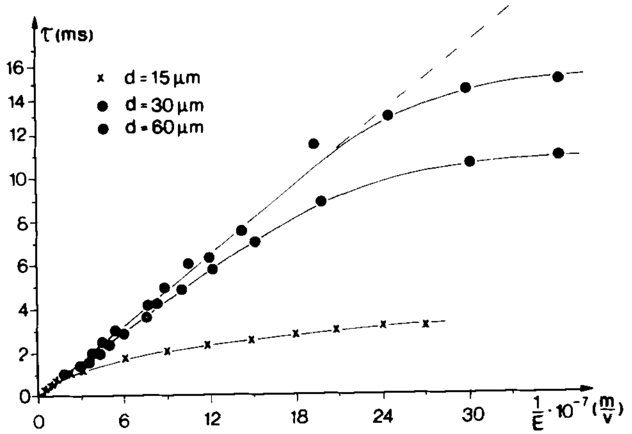

FIGURE 5. Switching times versus the reciprocal value of electric field 1/E in case of sample thicknesses d=15 μm, d=30 μm and d=60 μm.

From Fig.5 we obtain :

at d=15 μm $E_o=1.2\times10^5$ V/m ($E_{th}=1.3\times10^5$ V/m)

at d=30 μm $E_o=2.6\times10^5$ V/m ($E_{th}=2-2.5\times10^5$ V/m)

and at d=60 μm $E_o=1.6\times10^5$ V/m ($E_{th}=1.5-1.8\times10^5$ V/m)

Taking into account the error of measurements we can say that $E_o = E_{th}$ for all the sample thicknesses. Considering the dinamical equation for the director[5,9] it is clear that $\tau \sim 1/E$ only if the applied electric field is large enough to unwind the helix completely ($E > E_c$).

In this case the dynamical equation for the director reads

$$-\eta \cdot \dot{\varphi} = P_0 \cdot E \cdot \sin\varphi \qquad (7)$$

which has the solution

$$tg(\frac{\varphi}{2}) = tg(\frac{\varphi_0}{2})\ e^{-\frac{t}{\tau}} \qquad (8)$$

where - η is the rotational viscosity coefficient,

- P_0 is the spontaneous polarization
- φ is the azimuth angle,
- $\varphi_0 = \varphi(t=0)$

and - $\tau = \eta/(P_0 \cdot E)$ (9)

is the switching time.

Knowing the value of the spontaneous polarization P_0, Eq.9 makes possible to determine the rotational viscosity from the slope of the linear part of the curve τ vs. 1/E ($E > E_c$). The spontaneous polarization is $P_0 = 10^5$ Q/m at $T=23^0C$[6] hence we obtain that e.g. at $T=23^0C$ $\eta = 0.2$ poise.

From Fig.5 we can see that the linearity of the τ vs.1/E does not hold when $E < E_c$ though $E > E_{th}$ that is the electrooptical contrast is maximal. Possibly in this field internal the electric field cannot unwind the structure completely. There are some distortions very near to the surfaces, but this region is so thin that it cannot influence the electrooptical contrast.

The behaviour of these distortions and their relationship to the switching processes in the field region $E < E_c$ will be the object of our furthcoming paper.

B. TRANSIENT LIGHT SCATTERING MODE (TSM)

When we remove the crossed polarizers and apply a sufficiently high amplitude step-wise voltage (see Fig.6a) the transmitted light intensity varies as we can see on Fig.6b.

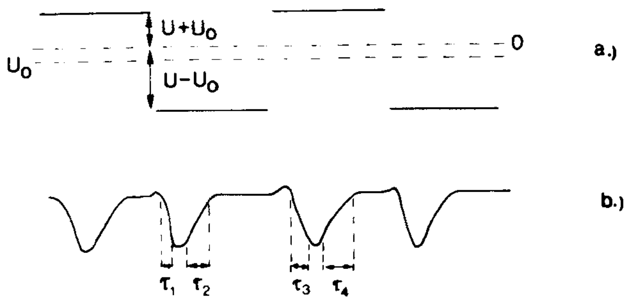

FIGURE 6. Tipical light transmission in TSM for Fk4 with sample thickness d=30 μm
a. Applied voltage
b. Signal of the photodiode

In case of no D.C. bias $\tau_1(U)=\tau_3(U)$ and $\tau_2(U)=\tau_4(U)$. The voltage dependence of these switching times presented in Fig.7.

The definition of $\tau_i(U)$ (i=1,2,3,4) are the following:

- $\tau_1(U)$ and $\tau_2(U)$ are the rise time and the decay time respectively when the applied voltage polarity changes from + to - sign.

- $\tau_3(U)$ and $\tau_4(U)$ are the rise time and the decay time respectively when the applied voltage polarity changes from - to + sign.

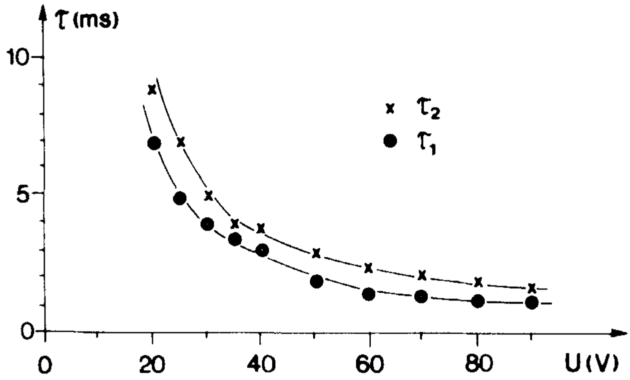

FIGURE 7. Switching times $\tau_i(U)$ $(i=1,2)$ versus the amplitude of applied step-wise voltage U with bias voltage $U_0=0$ for Fk4 in TSM at $T=23^0C$

Results for an applied D.C. bias voltage of $U_0=\pm$ 10 V are shown in Fig.8.
On this figure we can see that (within the error of our measurements)

$$\tau_1^{10\ V}(U)=\tau_3^{-10\ V}(U) \text{ and } \tau_2^{10\ V}(U)=\tau^{-10\ V}(U)$$

furthermore,

$$\tau_1^{10\ V}(U)>\tau_3^{10\ V}(U) \text{ and } \tau_2^{10\ V}(U)>\tau_4^{10\ V}(U)$$

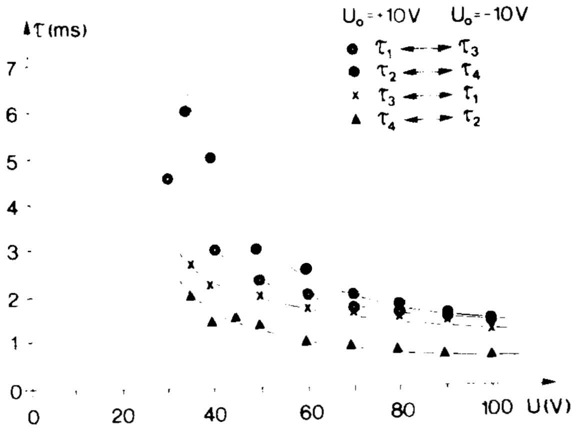

FIGURE 8. Applied voltage dependence of switching times of τ_i (i=1,2,3,4) at $T=23^0C$ in TSM for Fk4 sample with the thickness d=30 µm.
The D.C. bias voltage is $U_0=\pm 10$ V

In order to compare $\tau_i^{\pm 10V}$ (U) (i=1,2,3,4) and $\tau(U \pm 10\ V)$ we plotted these functions on the same figure (see Fig.9a and 9b).
From Fig.9a and 9b we can see that (within the measuring error)

$$\tau_1^{10\ V}(U) = \tau_1(U-10\ V) \text{ and } \tau_2^{10\ V}(U) = \tau_2(U-10\ V)$$

and

$$\tau_3^{10\ V}(U) = \tau_1(U+10\ V) \text{ and } \tau_4^{10\ V}(U) = \tau_2(U+10\ V)$$

respectively.

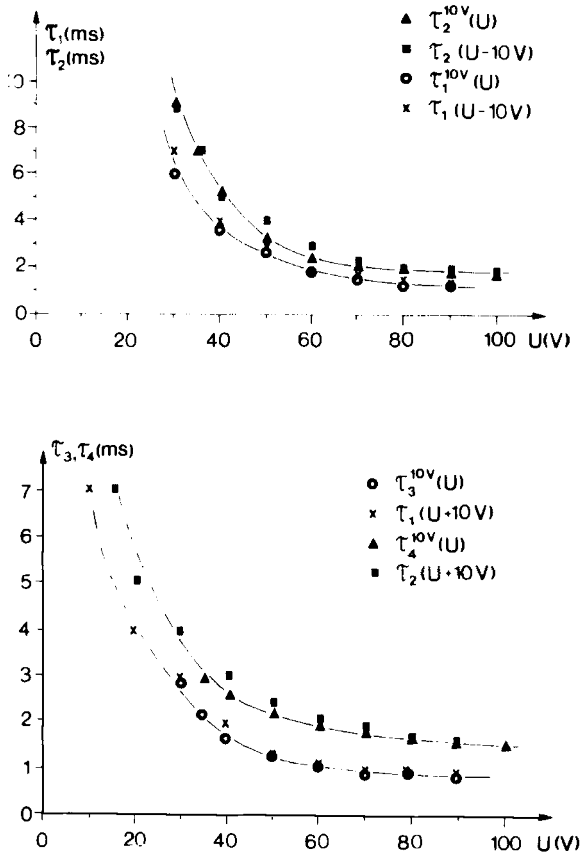

FIGURE 9. Comparison of the switching times at TSM as the function of applied voltage U when the applied D.C. voltage is $U_{\delta}=\pm10$ V and $U_{\delta}=0$ V

Completing the measurements at other nonzero D.C. bias voltages we always observed similar facts, that is:

a. $\tau_1^{U_o}(U) > \tau_3^{U_o}(U)$ and $\tau_2^{U_o}(U) > \tau_4^{U_o}(U)$

b. $\tau_{1,2}^{U_o}(U) = \tau(U-U_o)$ and $\tau_{3,4}^{U_o}(U) = \tau(U+U_o)$

c. $\tau_1^{U_o}(U) = \tau_3^{-U_o}(U)$ and $\tau_2^{U_o}(U) = \tau_4^{-U_o}(U)$

These facts coincide with those we got from our CPM studies (see Figs.4a and 4b). From these results we concluded that the switching times are primarily determined by the amplitude of the field reversing the spontaneous polarization, and that the boundary conditions are symmetrical resulting in antiparallel alignment at zero electric field.

FURTHER REMARKS

Comparising Figs.2 and 7 we obtain that

$$\tau_1^{TSM}(U) + \tau_2^{TSM}(U) = (1.5\pm0.3)\cdot\tau^{CPM}(U)$$

From this fact we conclude that the transient light scattering mode is slightly more sensitive to the variation of the director configuration than the crossed polarizer mode. Thus when we see saturation in the transmitted light intensity via crossed polarizers, the light scattering is still going on.

Theoretically, the light scattering (due to depolarization) may be visible even through crossed polarizers thus disturbing the electroptical response in CPM.

Supposing that the intensity of transient light scattering, attenauted by the crossed polarizers, is comparable with that of CPM a superposition of two switchings can be seen.

From the nature of the light scattering it is evident, that the intensity of the TSM increases with the sample thickness[10]. Actually we obtained for the Fk4 that even at sample thickness d=30 μm the intensity of the TSM attenauted by the crossed polarizers (I^{TSM}) is negligable compared to the intensity of CPM(I^{CPM}), namely

$$I^{TSM}/I^{CPM} < 1/20$$

However the increment of the value I^{TSM} is so large when the sample thickness is increased from d=30 μm to d=60 μm, that than I^{TSM} is comparable with I^{CPM}, namely

$$I^{TSM}/I^{CPM} \sim 1$$

thus the electrooptical picture in CPM is affected very seriously by the light scattering. A typical transmitted light intensity as the function of time is presented in Fig.10.

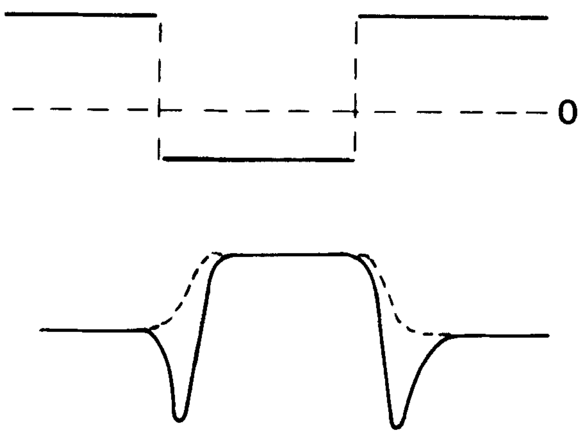

FIGURE 10.

Typical light transmission in CPM for Fk4 with sample thickness d=60 μm.

a. Applied voltage
b. Signal of the photodiode

CONCLUSION

We investigated the switching processes in planar oriented SmC^* liquid crystal samples between crossed polarizers and withcut any polarizers. Applying to the sample an electric field (if its value is larger than a certain threshold one) apart from the possible distortions very near to the bounding plates a uniform director alignment occurs having a net spontaneous polarization parallel to the field. Switching off the electric field, after some time a helical structure forms. But reversing the electric field polarity (if the amplitude of the electric field is larger than the threshold one) switching takes place. We found that the switching time is independent of the amplitude of the original field and is determined by the amplitude of the one with opposite polarity.
By this type of measurements we can decide (analysing the applied field polarity dependence of response times) whether the alignment without electric field is parallel or antiparallel. E.g. in cells filled with Fk4 antiparallel alignment was always found. (In aligning we did not use any surface treatment). Knowing the value of the spontaneous polarization and measuring the slope of $\tau(1/E)$ we calculated the value of the rotational viscosity. Our results and conclusions with and without polarizers are in good agreement.
Finally we pointed out that the light scattering can influence the characteristics of that switching which is related to the refractive index anisotropy.

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