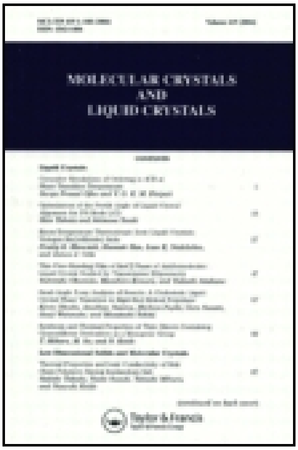


Molecular Crystals and Liquid Crystals
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gmcl20

# The Influence of Interface Controlled Effects on the Processes in Semiconductor-Liquid Crystal Structures

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Version of record first published: 22 Sep 2006

To cite this article: Artsrun H. Arakelyan, Vladimir M. Aroutiounian, Vachagan A. Meliksetyan & Sarik R. Nersisyan (2006): The Influence of Interface Controlled Effects on the Processes in Semiconductor-Liquid Crystal Structures, Molecular Crystals and Liquid Crystals, 453:1, 29-41

To link to this article: http://dx.doi.org/10.1080/00908310600653493

*Mol. Cryst. Liq. Cryst.*, Vol. 453, pp. 29–41, 2006

ISSN: 1542-1406 print/1563-5287 online
DOI: 10.1080/00908310600653493



# The Influence of Interface Controlled Effects on the Processes in Semiconductor-Liquid Crystal Structures

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*We discuss peculiarities of nonlinear and electrooptical processes caused by the influence of an external electric field acting along the interface between a semiconductor substrate and a liquid crystal (LC). It is shown that the specific interaction between surface atoms of semiconductor and interfacial molecules of LC leads to significant changes in the anchoring conditions of LC molecules on the semiconductor substrate. Significant enhancement of the strength of optical nonlinearity in homeotropically oriented LC cells is experimentally observed. The characteristic time of conventional reorientation induced by AC-field in planar LC-cell is decreased by up to one order of magnitude due to the presence of external longitudinal electric field. The results of observations can be attributed to reorientation of the interfacial layer of LC molecules due to the influence of the tangential electric field. These phenomena provide opportunities for increase of the operation speed of LC photonics components. Enhanced optical nonlinearity of LC can widen the dynamic range of laser beam and optics characterization devices that are based on orientational optical processes.*

**Keywords:** electrooptic effects; interface; liquid crystal; nonlinearity; semiconductor

## 1. INTRODUCTION

Introduction of new methods and technologies of light modulation and optical signal processing generates vast variety of applications and rapidly developing photonics market. In the information age, optical

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technologies are becoming increasingly essential in many aspects. From this point of view the semiconductor–liquid crystal (S-LC) structure may be considered as one of the most prospective. Indeed, these structures are very promising for applications, since both constituents are very sensitive to such external influences as the light and electric field; moreover practically all the contemporary monitoring of technique is based on the electrical and light signals manipulations. The use of semiconductor and liquid crystal materials in a unified structure could lead to essential enrichment of its functional capabilities. Such structures have already been used in spatial light modulators (SLM), liquid crystal light valves (LCLV) as well as in LC displays with active matrix. Also, recently the use of S-LC structure as a non-linear element for laser beam intensity testing was suggested [1].

The LC reorientation time is the main prohibitive factor in decreasing the response time of LC devices. Thus, improving the dynamic as well as other characteristics of LC cells is a challenging task of ultimate importance.

Experimental study of the processes taking place in the S-LC structure is in its initial stage, but some results obtained recently are very promising from the practical point of view. First, it is the new type of orientation effect in LC, caused by the specifics of binding between LC molecules and surface atoms of semiconductor [2–4]. Further study of interaction of this effect with conventional electrooptic effect showed the reciprocal influence of one effect on the other. The most interesting feature of the observed influence is that the characteristic times of the conventional effect orientation and relaxation significantly decrease with increase of the "surface" orientation degree. This phenomenon is caused by the changes in LC orientation on semiconductor substrate surface. Relaxation time decrease is important not only as an opportunity for essential acceleration of the operation speed of photonics elements, but also in view of possibilities to control the processes in LC by influencing the semiconductor substrate. It is necessary to emphasize that it is the high sensitivity of semiconductors to external excitation that makes these materials very promising. The availability of S-LC structures is more obvious taking into account the tremendous progress achieved by semiconductor technologies. Thus, good understanding and modeling of effects discussed in this work will enable development of innovative photonics devices based on S-LC structures controlled by boundary effects. Actually the obtained interaction between the surface-induced and conventional electrooptic effects showed influence of the effects on each other. The most interesting feature of the observed phenomenon is that the characteristic times of the conventional reorientation effect and its relaxation significantly decrease when the "surface" orientation degree increases.

The discussed aspects confirm the importance of detailed study of S-LC structure under various external influences. As the most important in this respect we consider both the further study of interaction between "surface" and conventional electrooptic effects and exploration of possibility to influence the nonlinear processes by changing the degree of "surface" orientation.

## 2. EXPERIMENT

In study of the electrooptic effects a planar nematic LC E48 was used. Cells of five different thicknesses were used: 1 μm, 5 μm, 10 μm, 23 μm and 36 μm. One of the substrates of the cells was glass with ITO coating, whereas the second substrate for each cell was made of a semiconductor Si. To facilitate application of the surface DC field along the interface between the semiconductor and the LC, electro-conductive contact layers were attached to the edges of the semiconductor substrate, in areas not contacting the LC. An additional contact was coated on the back surface of the semiconductor substrate to enable application of an AC field across the LC cell (Figure 1).

External bias voltage of two different types was applied to the cells. The first type is a 1 kHz AC field as it is usually applied across LC cells leading to the well-known Freedericksz effect. The second type is a DC voltage applied along the semiconductor. Note that application of AC field along the semiconductor does not result in any effect. As we have reported earlier [2–4], a new type of orientational effect takes place upon application of a constant electric field along the interface.

The investigation of dynamic characteristics of the reorientation effects was implemented through measurement of the variations in

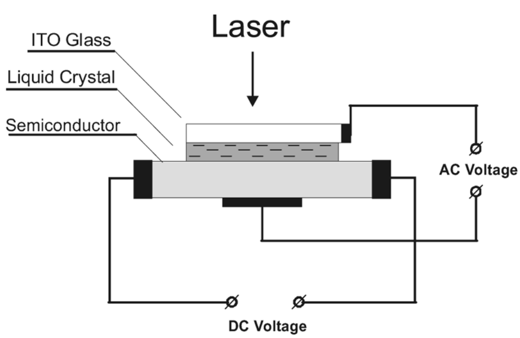


**FIGURE 1** General scheme of cell.

the polarization of a test laser beam reflected from the semiconductor substrate. The number of oscillations in the laser beam at the output of the polarizer corresponds to the phase shift of the beam, and is a measure of the magnitude of reorientation of the LC. We used two types of lasers with wavelengths 628 nm and 530 nm and maximum powers of about 20 mW. AC field ($\approx$1 kHz) of variable strength was applied across the LC cell simultaneously with the fixed DC field (up to 47 Volt) along the surface, and the influence of this field on the threshold and dynamic characteristics of the Freedericksz effect was studied. We used various regimes of the field to switch-on and switch-off corresponding orientational effects. It turned out to be quite useful, since the characteristic times of the investigated effects were essentially different.

With the purpose to determine influence of the DC field application along the semiconductor surface in case of homeotropically oriented cells we investigated also the characteristics of optical reorientation. Nematic liquid crystal (NLC) 5CB dye-doped with Antraqinone-2 (AQ-2) was used as LC; the cell thickness was 36 μm, specified by teflon layer. All other characteristics of the cell are similar to those of the cells used for electrooptic effect measurements. Since in the case of a massive semiconductor substrate it is impossible to register the interference fringes formed as a result of phase modulation, we worked out a special device allowing the measurements in reflected beam regime.

## 3. OBTAINED RESULTS

Earlier it was determined, that it is possible to achieve a significant increase in operating speed of electrooptic effects due to creation of

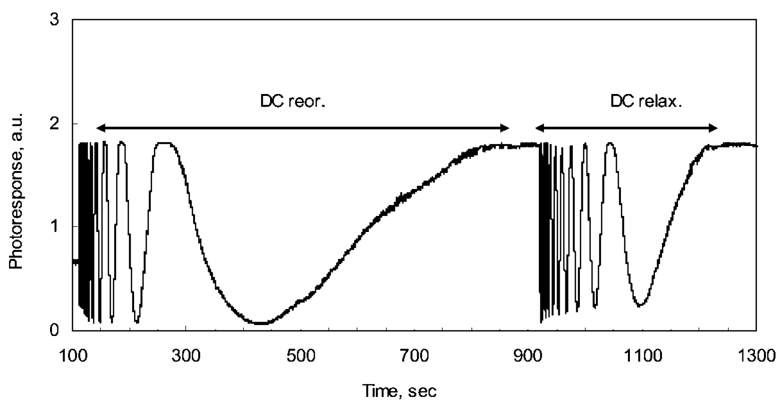


**FIGURE 2** Typical oscillogram for "surface" reorientation and relaxation.

conditions for "surface" reorientation for S-LC structure based cells [2]. Analysis made in [4] confirms the fact that regardless of the value of AC amplitude and cell thickness the characteristic times of reorientation and relaxation essentially decrease in the presence of DC field. Moreover, the ratio of these times in absence of "surface" reorientation to times, obtained at maximum used values of "surface" field, was 5–8 times. In the current study we analyze the influence of the AC field on the "surface" reorientation phenomenon. Consequently, we compare the durations and number of oscillations for "surface" reorientation process obtained for different initial conditions. Typical oscillogram when only the DC "surface" field is present is shown on Figure 2.

If before the DC field application conventional reorientation took place, one can observe certain changes depending on values of the AC field amplitude. Actually, at relatively low amplitude (exceeding by a negligible margin the threshold of Freedericksz transition) the number of oscillations due to the DC effect increases Figure 3.

At the same time the process duration not only does not increase but also slightly decreases in spite of increasing degree of DC reorientation. The further increase of the AC field amplitude leads to decrease in number of DC oscillations together with significant reorientation time reduction, as it is presented in Figure 4.

Note that such behavior is in agreement with results early obtained in [4], where it was shown that the number of DC oscillations was constant at the pre-threshold values of the AC-field, it increases near the threshold of AC-field induced reorientation, and then decreases and disappears when the amplitude of AC field is too high. The originality

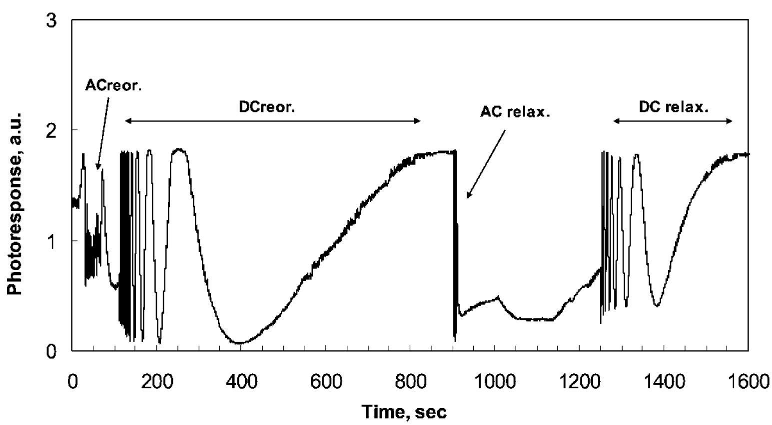


**FIGURE 3** Typical oscillograms observed at alternating turn-on and turn-off of conventional transverse (AC) and "surface" (DC) fields.

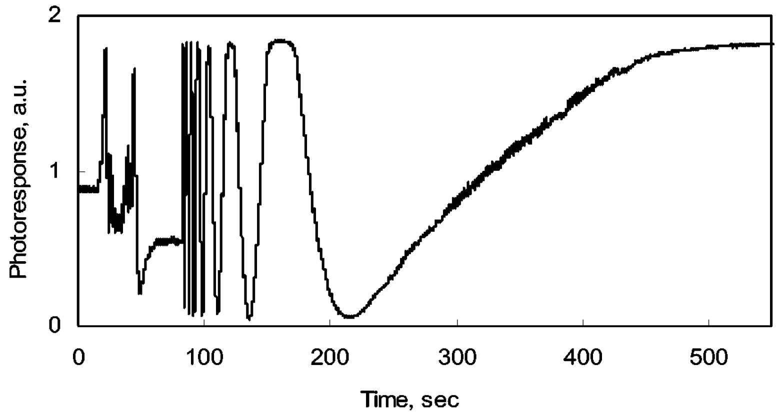


**FIGURE 4** Typical oscillograms of AC and following DC reorientation observed at relatively high value of AC field amplitude.

of our observations is that the "surface" effect accelerates in the presence of AC field, which is analogous to the decrease of characteristic time of conventional electrooptic effect under the DC field influence. These results once again confirm that both conventional and "surface" effects have similar nature with respect to reorientation of LC director.

Earlier in [4] the material effect of DC "surface" field on the reorientation and relaxation times of bulk effect was established. As it follows from our observations the inverse effect also takes place, although it becomes apparently weaker in comparison with the bulk effect acceleration. In any case the main factor influencing the dynamic characteristics of the observed orientational processes is the change in the anchoring conditions of LC molecules on the semiconductor substrate induced by the DC field.

Since the DC "surface" field essentially influences the characteristics of electrooptic effects, it would be useful to find possibilities of controlling also other phenomena taking place in S-LC structure. Particularly we investigate influence of "surface" field on the dynamic characteristics of optical nonlinearity. It follows from our experiments that optical nonlinearity in liquid crystal media significantly increases when DC field is applied to semiconductor substrate of S-LC structure. Figure 5 presents the data on fringe number as a function of "surface" field, obtained for different intensities of incident light. It is evident that regardless of the chosen value of light intensity the number of the rings increases simultaneously with the DC field enhancement. It also must be emphasized that in each case the observed phenomena

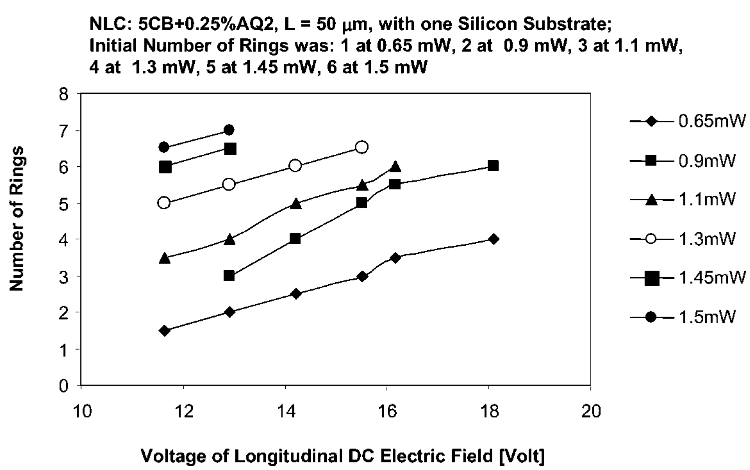


**FIGURE 5** Number of rings as a function of "surface" DC field for different beam intensities.

have threshold character, since the increase of number of the rings starts with value of DC "surface" field of about 12 V. Nevertheless, application of DC "surface" field exceeding the threshold value leads to increase of the ring number and consequently in the degree of LC media nonlinearity. We also studied the dynamic characteristics of cells. The results are presented on Figure 6. The data on Figure 6a are obtained in the following way. In the beginning with the help of neutral filters we chose the level of light intensity, allowing only one ring formation (for the cell used in the experiment this level

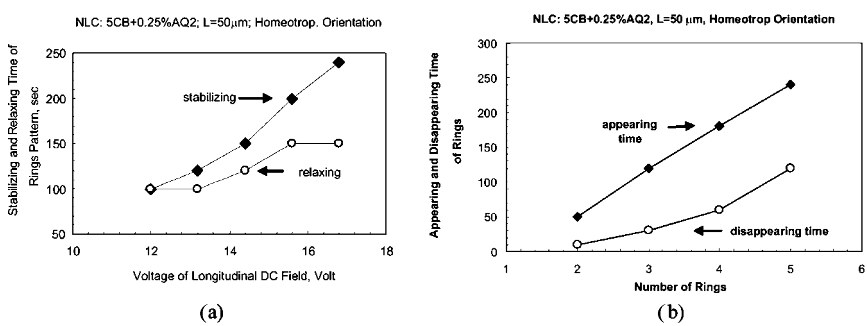


**FIGURE 6** a) Stabilization and relaxation times for each ring formed with gradual change of DC field amplitude; b) The dynamics of formation and disappearance of rings at DC field amplitude ≈17 V.

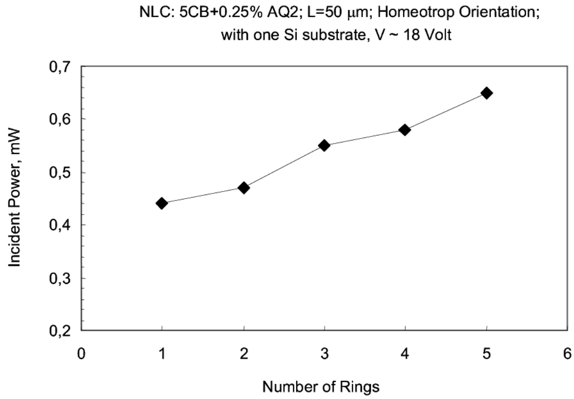


**FIGURE 7** Disappearance of rings when the beam power is reduced. In the experiment the DC field amplitude was ≈17 V.



corresponds approximately to beam power ~0,65 mW). Then we gradually increased the amplitude of DC "surface" field, and we waited for some time at each subsequent value of DC up to that moment, when one new ring forms. In this manner we obtained that first additional ring forms at external DC voltage ~12 V, while further increase in DC voltage leads to consecutive formation of new rings the number of which achieves up to 5 at DC voltage ~17 V. Figure 6b also shows the data representing the dynamics of each new ring formation, which demonstrates the sluggishness of the process. Presented on Figure 7 are the times for stabilization and disappearance of fringe patterns corresponding to consecutive number of rings caused by DC voltage application. As it follows from Figure 7, certain time is needed for formation of each next ring when the constant DC voltage is turned on, or for its disappearance, when DC voltage is turned off.

Figure 7 shows the threshold behavior of GON effect controlled by DC "surface" field. Actually, in the absence of DC field the intensity for first ring formation was ≈0,65 mW. However, application DC field leads to essential decrease of this intensity down to ≈0,43 mW.

## 4. DISCUSSION

It is important to emphasize that, despite the essentially different nature of electrooptical and nonlinear optical processes taking place in S-LC structures the "surface" field application influences both processes. First, it is the dynamic as well as threshold characteristics, since the main influence of the DC field is the significant acceleration of electrooptical processes. However, it must be emphasized that decrease in threshold value is observed for both electrooptical and non-linear processes. It is likely that the main factor responsible for the observed effects is the induced by the DC field change in anchoring conditions of the LC molecules on the semiconductor substrate. This statement is also confirmed by the fact that those effects become most apparent when DC field ensures considerable current along the semiconductor substrate surface. Actually, earlier, based on the study of photocurrent flow across the S-LC interface it was suggested in [5], that the mutual binding of the LC molecules and "dangling" bonds of atoms on the semiconductor surface has evidently polar nature. The possibility of polar bonds formation on the S-LC boundary was proposed also in [6]. Consequently, when the flow of charge carriers takes place in the immediate vicinity of surface it may lead to strong influence of binding conditions. Such consideration confirms the importance of a thin surface layer formed on the S-LC structure for processes taking place under various external influences. Unfortunately, the exact quantitative analysis is very difficult here due to the complexity of the microscopic structure of the transition layer.

The main problem is to understand the mechanisms, leading to change in binding conditions, which in turn results in facilitation and the consequent acceleration of processes of reorientation and relaxation of LC under the influence of DC field applied to semiconductor substrate. Such behavior may be explained by the decrease of anchoring energy. However, if we assumed that the observed effects are caused by the anchoring energy reduction as a result of decrease of the elasticity coefficient we would have had difficulties explaining the acceleration during the process of relaxation. Indeed, as it is well known (see e.g., in [7]) the characteristic times of relaxation are inversely proportional to the elasticity coefficient and therefore the relaxation time should grow if the elasticity coefficient decreases. However, here we have the opposite effect. Difficulties also arise when we try introducing the idea of "resulting" time, which takes into account DC field's influence. With such approach influence of the DC "surface" field will be strong when the cell is thick and vice versa. However, as a matter of fact, the operation speed of S-LC structure increases maximally in the case of thin cells.

Here we must emphasize another interesting phenomenon observed in our experiments. Actually, for initialization of the reorientation process, caused by the DC field application of any longitudinal field is not sufficient. More specifically, when the semiconductor resistance is very high we cannot obtain DC reorientation. The process becomes apparent only when some charge transfer along the semiconductor surface takes place. At present time it is very difficult to present a detailed explanation of such behavior since the microscopic structure of the interface layer is unknown. Nevertheless, we think that the current formation process is (at least partially) responsible for the DC reorientation process and consequently for both electrooptical and non-linear processes. Indeed, as was mentioned above, there are many indications, that the dipolar bonds play an important part in the formation semiconductor-liquid crystal (S-LC) interface. As it is shown in [8] the LC molecules in the first monolayer on the solid substrate are tilted by certain angle different from the bulk angle. On the other hand, in our experiment the weakening of corresponding bonds to a certain extent is possible when the charge transfer along the interface takes place. Especially significant influence should occur when charge carriers from transient interfacial layer participate in current formation. Participation of such carriers in photocurrent flow along the substrate surface was obtained in the preliminary studies of spectral dependence of S-LC structure photoconductivity (these results are not presented here and will be published upon completion).

Thus we can assume that the DC "surface" field and the resulting charge carrier flow leads to change in the formation of bonds on the semiconductor surface. A consequence of the mentioned weakening may be both the initiation of DC reorientation process and the influence of this effect on the parameters of electrooptic as well as non-linear processes in S-LC structure.

On the other hand, work [4] analyzed the influence of DC "surface" reorientation on the dynamic of conventional bulk reorientation (Freedericksz transition). It showed that both phenomena have similar nature with respect to reorientation of LC director. Nevertheless, the origins of these effects are essentially different: the conventional effect starts by reorientation of the LC molecules in the bulk of the cell, whereas the "surface" reorientation is stimulated first at the boundaries of the cell on the semiconductor substrate. However, when reorientation process takes place in the wall boundary layer, the anchoring energy on the surface cannot be considered infinite. Moreover, since reorientation process is caused by the applied DC field, the value of anchoring energy depends on the value of DC "surface" field. Thus, in order to describe the change in surface conditions under the DC field influence it will be helpful to introduce such physical characteristic which allow taking into account the "surface" reorientation. We believe that from this point of view the most important parameters are "surface" friction or "surface" viscosity, since the conventional coefficient of viscosity enters directly in all expressions for characteristic times of electrooptic effects (see e.g., in [7]), as well as in expressions describing the GON phenomenon [9].

We suggest introducing the coefficient of "surface" viscosity, which on one hand will depend on the DC field amplitude and on the other hand should influence the value of some "effective" viscosity. Let us remind here that the concept of "effective" viscosity was introduced in [10] to allow taking into account the role of back flow in nematics. Moreover the coefficient of "effective" viscosity introduced in [10] was also controlled by external electric field, although this field has a bulk nature. We suggest that in our case introduction of similar parameter is also useful. However, it will differ from the viscosity introduced in [10].

In summary, we suggest to consider the process of reorientation under simultaneous influence of both the DC "surface" field and the conventional bulk AC field as taking place through the two discussed channels, surface and bulk, so that reorientation through each channel may be described with his inherent (specific) viscosity coefficient. To introduce the "effective" viscosity here we will act similarly to the case of current flow when two resistances are placed in parallel. In the absence of DC "surface" field we will consider the degree of binding on the surface as very high (hard anchoring). This way, the corresponding "surface" coefficient will approach infinity in analogy with the case when one of the resistances in electric circuit is infinite. Then the process of reorientation will take place only in one conventional way and the viscosity coefficient of will also be conventional. In case when the surface channel participates in reorientation process the surface viscosity coefficient reduces and the effective coefficient will be smaller compared to the conventional one. As a result, both reorientation and relaxation times will be reduced in accordance with the experimental data. Thus, in the framework of suggested mechanism it will be easy to explain the dependence of changes in operation speed on the values of the DC "surface" field. Moreover, by introducing the idea of specific bulk viscosity (adjusted for unity of length), it will be possible also to take into account the thickness of LC layer.

Thus introduction of the "effective viscosity" allows to successfully explain the observed results. Actually, when the current flow along the interface leads to weakening of binding between the LC molecules and semiconductor surface it results in reduction of "surface" viscosity. According to the mechanism described above this effect will lead to decrease of the "effective" viscosity and finally will result in reduction of reorientation and relaxation characteristic times of electrooptic processes. We would like to especially emphasize that the "effective" viscosity notion successfully explains not only the dynamic characteristics of electrooptic effects, but also the observed character of the nonlinear effects. Actually, it is well known [9] that number of rings formed as a result of GON effect rises as the LC viscosity decreases.

Thus, both the increase of rings number at DC field application and decrease of the light intensity value corresponding to beginning of interference pattern formation also justifies the introduction of "effective" viscosity notion.



## 5. CONCLUSION

The results of this work are interesting from both applied and scientific points of view. Actually the problem of interaction between LC molecules and the adjacent surface is one of the most important in LC physics. Further study of external influences significantly affecting surface conditions will help to deeper understand the processes taking place in LC media. This is confirmed by the obtained results, and provides new possibilities for controlling electrooptic and nonlinear optical processes in the cells based on the S-LC structure. Applied value of observed effects is confirmed by the possibility to increase the operating speed of electro-optical devices based on S-LC structures, such as spatial light modulators, LC displays with active matrix and others. Moreover, the DC "surface" field will also allow to control threshold characteristics of GON phenomena. Thus, it provides opportunities to further widen the dynamic range of devices for laser beam intensity measurements. It is very important that the achieved progress in interface controlled effects is not final and may be improved. Further advance in understanding the details of the processes considered in this work, and subsequent optimization of cell manufacturing technologies can lead to essential improvement of S-LC structure characteristics. Moreover, modern semiconductor micro and optoelectronic technologies provide broad opportunities to implement S-LC structures with various predetermined properties.

In summary, the results of this work allow to confidently state that advancing research in this field will help to introduce innovative photonics elements to the market. Such elements will utilize features of semiconductor-liquid crystal interface controlled by external electric and optical signals.

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