Chapter

# In-Plane Retardation Switching Behavior at Certain Types of Smectic Liquid Crystals

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## Abstract

Smectic liquid crystals' layer structures and their influence on electro-optic characteristic properties are studied. Some background research works have revealed that a certain type of tilted smectic liquid crystal to the smectic layer normal showed some distorted out-of-plane retardation change. With intentional distortion of out-of-plane retardation change even provides almost in-plane only retardation change. In a certain type of smectic liquid crystal and its specific alignment condition, such a certain type of smectic liquid crystal panel shows in-plane only retardation switching. A more comprehensive study is still required, and such type of smectic liquid crystal panel provides unique electro-optic properties that have not been reported.

**Keywords:** smectic liquid crystal, smectic layer, tilted smectic, in-plane retardation, out-of-plane retardation, chevron layer, bookshelf layer

## 1. Introduction

Some smectic liquid crystals are known to show very different electro-optic effect compared to those of most of nematic liquid crystals. Although among nematic liquid crystals, some show unique electro-optic effect, most of nematic liquid crystals use their anisotropy of dielectric constant originated from dipole-momentum as their driving torque coupled with externally applied electric field. Under the restriction of orientational order on nematic liquid crystals, the dipole-momentum driving torque is fairly predictable. On the other hand, smectic liquid crystal molecules have some more restriction in their molecular switching than those of nematic liquid crystals due to their higher order molecule-molecule interactions than those for nematic liquid crystals. Such restriction may not be simply interpreted by higher viscosity as a bulk effect, but would be considered more intrinsic molecule-molecule interaction. Since the meaning of restriction does not mean slower optical response, but rather faster optical response than much less viscous nematic liquid crystal cases in a certain case of smectic liquid crystal electro-optic device. One of the purposes of this series of investigations is to understand how such restriction influences on retardation switching behavior such as in-plane and/or out-of-plane switching under the premise of in use for electro-optic devices such as display devices, phase modulation devices, beam steering devices and so on. In general, weaker molecule-molecule interaction gives more straightforward driving torque as the result of driving torque coupling from externally applied stimulation such as electric field application. Since externally applied electric field is literally a field effect regardless the applied field is on liquid crystal layer, alignment layer, and more complex portion of interface area between those two different dielectric layers. Some detailed investigation of dielectric relaxation effect and its influence both on electro-optic response profile and surface accumulated charge influence on electro-optic performance are widely investigated [1–12]. Thanks to orientational order nature of most of nematic liquid crystal molecules, their electro-optic response profile is mostly described and predictable without significant consideration of those different dielectric layers relaxation and surface charges influence except for some unique cases. One of the unique cases includes even existence of second harmonic generation with nematic liquid crystal molecules such as 5CB [13]. In spite of some unique cases, most of nematic liquid crystal cases, their electro-optic behavior is still somewhat predictable, and more importantly, such unique cases in nematic liquid crystal cases may be beneficial to consider more complicated smectic liquid crystal cases' electro-optic behavior.

It would be one of the interested topics to investigate smectic liquid crystal molecular switching behavior governed by the smectic layer structure, specifically the layer restriction influence on in-plane and out-of-plane retardation change. With expected smectic liquid crystals' two-dimensional order, it is reasonably expected showing some different retardation switching behavior familiar with most of nematic liquid crystal cases. One of the examples is surface stabilized Ferroelectric Liquid Crystal (SSFLC) case using artificially unwounded helical structure of chiral smectic liquid crystals such as SmC* phase liquid crystals [14]. Unlike most of nematic liquid crystal devices in use which use the concept of strong anchoring, SSFLC device prefers much weaker surface anchoring as long as it has well enough uniform molecular initial alignment at the surface of the substrate. This requirement comes from SSFLC panel's driving torque origin. Unlike dielectric momentum based driving torque for most of nematic liquid crystal devices, SSFLC devices use spontaneous polarization as their driving torque origin. Spontaneous polarization gives applied voltage polarity sensitive torque. Therefore, if its surface anchoring is strong anchoring, which means no molecular orientation change regardless applied voltage, such a strong anchored SSFLC device shows asymmetric electro-optic effect due to surface electrical polarization effect formed by asymmetric surface anchoring in terms of surface area's smectic liquid crystal molecular packing mainly governed by non-uniform smectic layer stacking such as Chevron 1 uniform structure described in later on this chapter. Therefore, an ideal surface anchoring for SSFLC panels is one-time surface anchoring just to have initial alignment, and once uniform alignment is obtained, surface should not have any restriction to molecular switching as "zero-anchoring force". However, even it is an ideal situation, such surface anchoring may not be easy to realize as an actual device, so that it would be necessary to find out any alternative way to provide substantial "zero-anchoring" after obtained initial alignment with smectic liquid crystal devices. One of such approaches is so-called slippery SSFLC device, [15], or weak surface anchoring effect on nematic liquid crystals [16]. A slippery surface is effective to avoid some significant conflict between the strong anchored surface area's liquid crystal molecules and bulk area's much less influenced surface anchoring effect liquid crystal molecules under application of externally applied electric filed. Thanks to almost freely moving surface area's liquid crystal molecules, surface area's and bulk area's could eliminate any catastrophic conflict under applied electric filed, resulting in more natural and stable molecular switching. However, such slippery surface is not easy to provide large area in uniform manner; moreover, such weak surface anchoring may have some long-term reliability concern. Since one of the reasons in current nematic liquid crystal devices' strong anchoring choice was long term reliability and stability reason. However, using spontaneous polarization as a smectic liquid crystal driving torque, choice of surface anchoring whether strong or weak is still a big question. Some approaches to get rid of this dilemma have been investigated. Surface clinic effect [17–31] is one of those investigations. Use of DeVries type of smectic liquid crystals is also one of the potential approaches [32, 33]. Unlike SSFLC cases, surface clinic effect is like induced polarization base. Anti-ferroelectric liquid crystals are also other approaches [34–38]. Both surface clinic and anti-ferroelectric liquid crystal cases have the common ground in their initial surface anchoring. Both do not have spontaneous polarization at the initial alignment stage, but show induced spontaneous polarization. The expression of induced spontaneous polarization is contradiction. However, this expression gives intrinsic effect of those cases. Absence of externally applied electric field, both cases do not show any spontaneous polarization. Once externally applied electric filed unpins a certain balance, each liquid crystal's potential polarization synchronizes, resulting in bulk level of spontaneous polarization. Both cases are certainly providing some great hint to get rid of the dilemma discussed above. This series of research works are to seek out any practical means to get rid of the dilemma between strong and weak surface anchoring in a smectic liquid crystal device. For the sake of this purpose, first, current known ferroelectric liquid crystal device's molecular alignment effect on its electro-optic effect was investigated. Then, any possible way to avoid using spontaneous polarization as a driving torque was investigated. As the investigation means, it turned out that knowing in-plane and out-of-plane retardation switching behavior as the result of molecular switching is very effective to learn a certain type of smectic liquid crystal molecular stacking. In addition to above investigation, it is also discussed that how in-plane only retardation switching is beneficial for some phase modulation devices.

A clarification of actual definitive relationship between smectic layer structure and electro-optic switching behavior requires comprehensive research works. Even such a comprehensive research work is a large amount of work, some approaches penetrating specific point would be beneficial as one of the large amount of works. This series of research works have focused on tilted smectic liquid crystals as their influence on electro-optic performance, specifically on in-plane and out-of-plane retardation switching behavior.

## 2. Ideal SSFLC molecular stacking geometry

Before some unique molecular switching behaviors are discussed, first, an ideal SSFLC molecular switching would be confirmed in terms of initial molecular stacking models and their switching behavior. As shown in **Figure 1**, with an ideal bookshelf layer structure, each liquid crystal molecule rotates its spontaneous polarization uniformly and simultaneously from the top to the bottom substrates. At an ideal smectic layer structure, all of smectic liquid crystal molecules move simultaneously known as Goldstone mode [39], and maximize the power of spontaneous polarization. This movement is also reciprocal in terms of spontaneous polarization switching. Since the spontaneous polarization switching is completely reciprocal, there is no smectic layer structure change during the switching. Therefore, the bookshelf smectic layer structure is supposed to provide the most stable electro-optical switching.

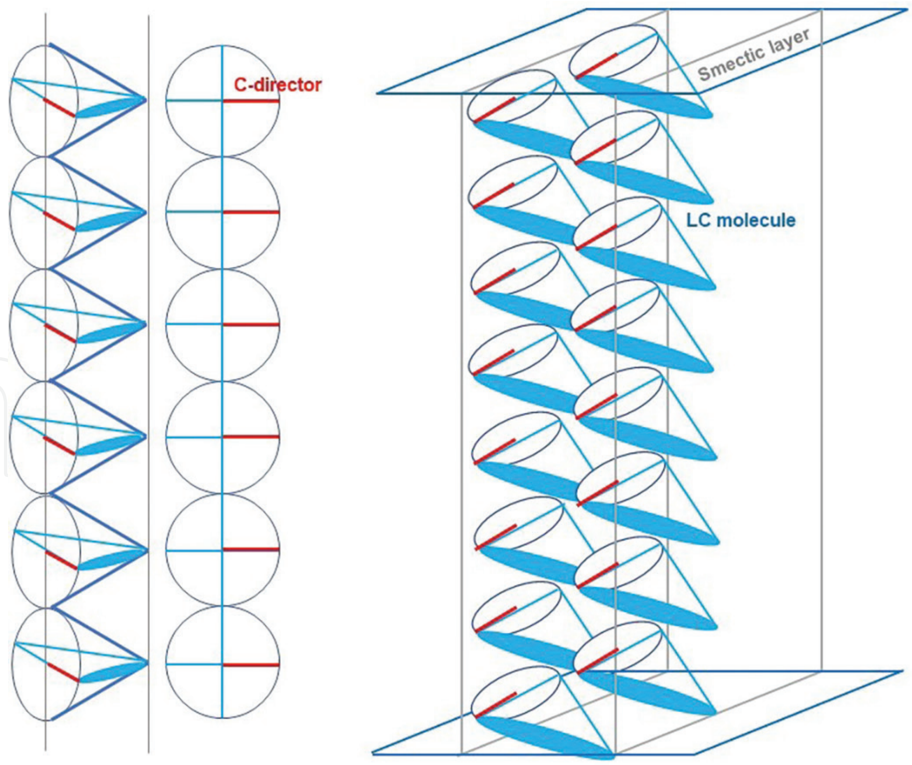


**Figure 1**
*An ideal smectic layer structure known as "bookshelf" layer. At an ideal bookshelf layer structure, all of smectic liquid crystal molecules move simultaneously known as goldstone mode, resulting in maximizing power of the spontaneous polarization.*

## 3. Typical SSFLC molecular stacking geometries

Most of typical smectic layer structures with tilted smectic liquid crystals are, however, not a bookshelf structure, but a chevron layer structure. Actual chevron layer structure has many variations in its detail structure; however, there are two typical chevron layer structures widely known as Chevron C1 uniform and Chevron C2 unifrom as shown in Figures 2 and 3, respectively. In a Chevron C1 uniform layer structure, c-directors at the upper half of the chevron layer structure and c-directors at the bottom half of the chevron structure have opposite direction, resulting in reduction of the power of bulk spontaneous polarization as shown in **Figure 2**. This situation is, however, just the initial molecular alignment structure, and such uneven c-director structure creates some complicated electro-optic switching behavior. In a Chevron C1 structure, at the kink area where the two opposite chevron leaning angles meet together, two different directions of c-directors have conflict to rotate their direction under the externally applied electric field. Actual dynamics of the kink area's conflict is not easy to clarify, specifically when time resolved local kink area's chevron layer structure change requires nano-scale layer analysis. Some local smectic layer structure analysis has been published using soft X-ray (Synchrotron Radiation) beam [40, 41]. Even using soft X-ray beam, it is still not easy to clarify sub-milliseconds dynamic response of local layer structure. Therefore, until new time resolved local smectic layer structure analysis methodology is developed, most of practical means to estimate influence of c-director packing on electro-optic switching behavior would be an optical measurement at visible wavelength including in-plane and out-of-plane retardation measurement.

At a Chevron C2 uniform geometry shown in **Figure 3**, the kink area's c-directors have almost the same direction, but not really the same direction unlike those of a bookshelf layer structure. Even such kink area's c-director conflict is not easy to

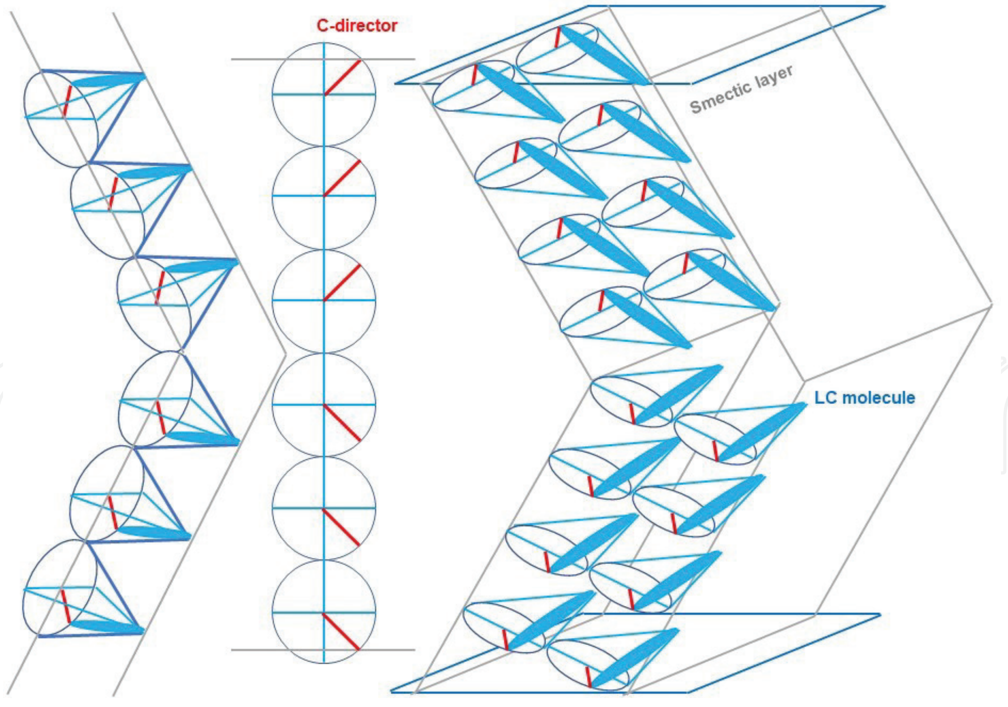


**Figure 2**
*c-Director packing geometry of a Chevron C1 uniform layer structure. Due to opposite c-director directions from the top substrate and from the bottom substrate, at the center area known as "kink" area, two opposite directions of c-directors have conflict of their packing. Such c-director packing conflict is also problematic when externally applied electric field induces c-director packing change.*

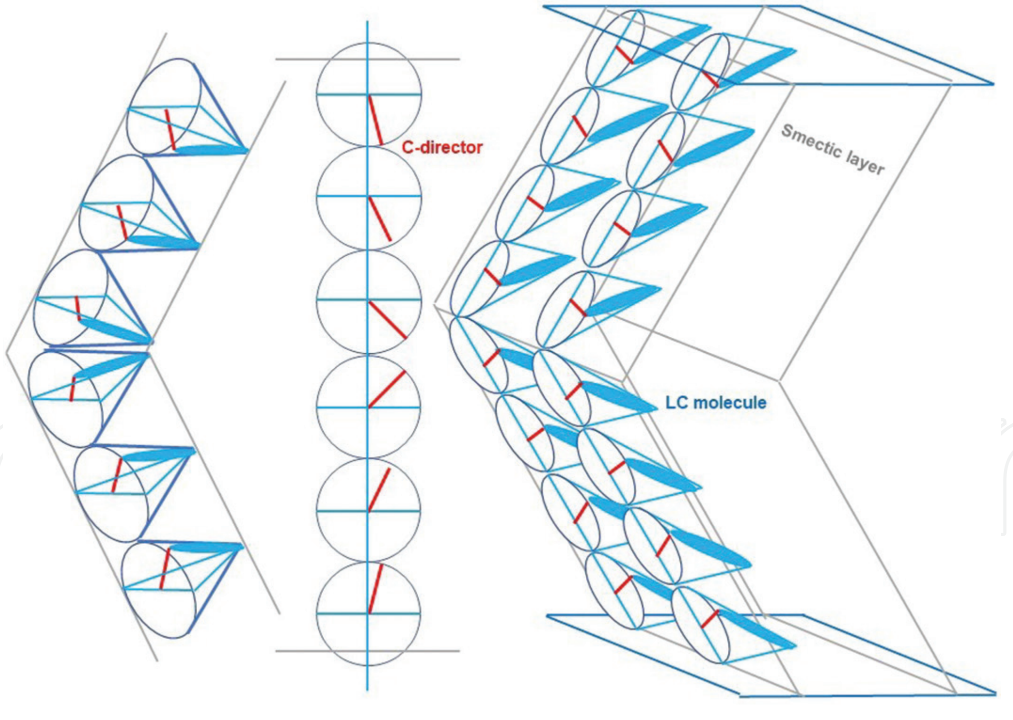


**Figure 3**
*c-Director packing geometry of a Chevron C2 uniform layer structure. Unlike C1 uniform configuration, at the kink area, c-director's directions both from the upper and the bottom substrates have nearly same direction. This is effective to minimize conflict in c-director packing while molecular switching is in process by an externally applied electric field.*

minimize, C2 structure's kink area's conflict is less competitive than at C1 structure. A kink area's c-director conflict is sometimes making even irreversible smectic layer structure change. There are many published reports on smectic layer instabilities, most of them are about rotation of smectic layer itself which is a large scale of layer structure change [42–46]. This investigation's interest is, however, some local areas' layer structure distortion, and its consecutive electro-optic response behavior. As discussed above, such local area's smectic layer structure change is not easy to retrieve directly. One of the practical means to estimate if there is an irreversible or non-reciprocal local smectic layer structure change would be electro-optic response change, specifically a ratio between in-plane/out-of-plane retardation change as discussed later in this chapter. As a realistic choice of smectic layer structure, most of practical approaches using ferroelectric liquid crystals are using Chevron C2 uniform configuration. Thanks to overall same direction of c-directors both from the upper and the lower substrates directions, at the kink area, a minimum conflict in c-director packing geometry is reasonably expected. This minimum c-directors conflict at the kink area would be able to avoid irreversible or non-reciprocal smectic layer structure change as illustrated in **Figure 4**.

Depending on the kink area's influence, mainly size wise as how many numbers of liquid crystal molecules are restricted by the kink effect at the center portion of the panel, reciprocal and non-reciprocal layer structure change provides some significantly different optical effect. In an actual SSFLC device case, not only smectic layer structure, but also depolarization effect should be in consideration, though [47]. The depolarization effect is the result of dielectric relaxation or rearrangement by polarization switching. In addition to a typical dielectric relaxation of dielectric materials, switch of spontaneous polarization creates a large amount of charge transfer, and the transferred charges remain in the panel at least for a while due to the nature of spontaneous polarization (with absence of externally applied electric field, spontaneous polarization still keeps internal electric field in the SSFLC panel), resulting in formation of depolarization effect. Such depolarization works as weakening of externally applied electric filed, when next time an externally electric field is applied. This weakening effect of the applied electric field requires very complicated driving voltage control. It is about transient charge transfer including liquid crystal's

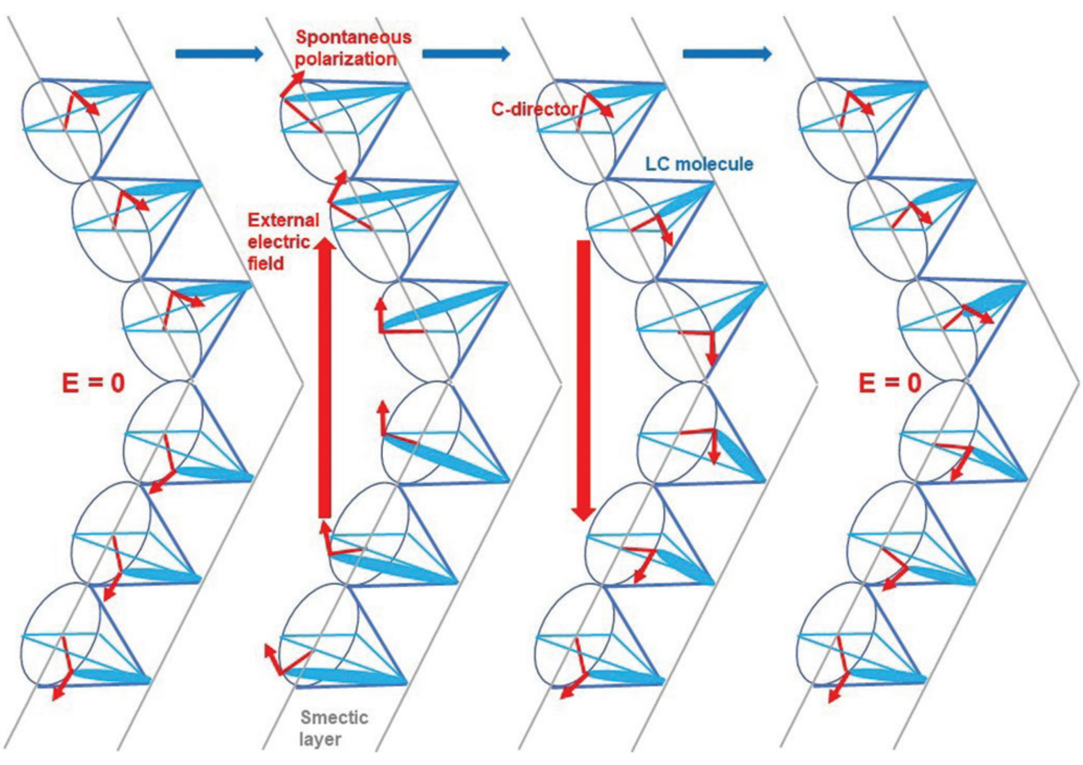


**Figure 4**
*A non-reciprocal smectic layer switching of Chevron C1 uniform structure. Due to significant conflict in c-director packing at the kink area, repeating driving sometimes provides irreversible c-director packing after removing driving voltage. This results in instable electro-optic switching.*

own charge mobility, liquid crystal-surface alignment layer interface potential barrier, and electrode-alignment layer potential barrier, and so on. These charge transfer matters are common with nematic liquid crystal devices; however, more complicated situation at SSFLCDs is their polarity sensitive behavior. Dielectric anisotropy based driving torque does not tell the difference of polarity, resulting in much more room for the surface charge influence. On the other hand, spontaneous polarization based driving torque tells the difference in polarity, resulting in bias voltage effect, if internal polarization has asymmetric structure in terms of polarity.

## 4. Polarization shielded smectic liquid crystals

As previous works clarified [42, 47], depolarization effect is one of the most influential factors to destabilize spontaneous polarization switching, which disturbs SSFLC cells memory effect accompanied with the cell's internal depolarization structure. At a typical SSFLC cell, due to existence of permanent spontaneous polarization, regardless absence of externally applied electric field, the SSFLC cell forms internal polarization structure. Once externally electric field is applied, most of liquid crystal molecules change their orientation making total spontaneous polarization direction along with the applied electric field. In this process, due to spontaneous polarization switching, the cell internal dielectric materials which are the ferroelectric liquid crystal layer and its alignment layer try to neutralize polarization. This process is known as depolarization process. Such depolarization process is, however, ends up weakening total spontaneous polarization structure in the cell. This is the major reason why the memory effect of an SSFLC cell is destabilized [42, 47].

Through the investigation of SSFLC molecular switching in terms of both the smectic layer and surface accumulated charges influence, the authors group proposed and showed some new approach minimizing influence of surface accumulated charges as well as layer structure influence on molecular orientation change. The concept of this new approach was to minimize spontaneous polarization keeping the basic response of an SSFLC cell. According to this concept, such a modified SSFLC driving mode is called as polarization shielded smectic (PSS) liquid crystal mode [48–50]. Although it was not clear of the reason, in the course of the PSS-LCD investigations, it turned out that some of PSS-LC cells showed a quasi-bookshelf layer structure. One of the reasonable assumptions of the bookshelf layer structure of the PSS-LC cell was very small spontaneous polarization, and its consecutive small depolarization effect. Major component of the PSS-LC chemical formula is shown in **Figure 5**. They have Naphthalene-ring core structure connected by carbonyl polar portion as the common structure [51–53].

Using the same smectic liquid crystal mixture shown in **Figure 5**, polymer assisted ferroelectric liquid crystal response phenomenon was investigated how the bookshelf layer structured small spontaneous polarization liquid crystal molecules show any specific electro-optic response, specifically its retardation switching behavior using polymer assisted ferroelectric liquid crystal configuration [54–56]. The detail of this empirical result is published [57]. **Figure 6** shows the result.

In **Figure 6**, Δ is in-plane retardation angle, and Ψ is out-of-plane retardation angle. The significant difference in retardation angle change behavior between Δ and Ψ with doped oligomer amount strongly suggests some enhancement and suppression effects in polarization switching behavior. With relatively small doping ratio such as 5 mol%, in-plane retardation (Δ) shows significant increase. On the other hand, out-of-plane retardation shows opposite tendency. These two retardation switching behavior suggests possible suppression of out-of-plane retardation change keeping in-plane retardation change large enough.

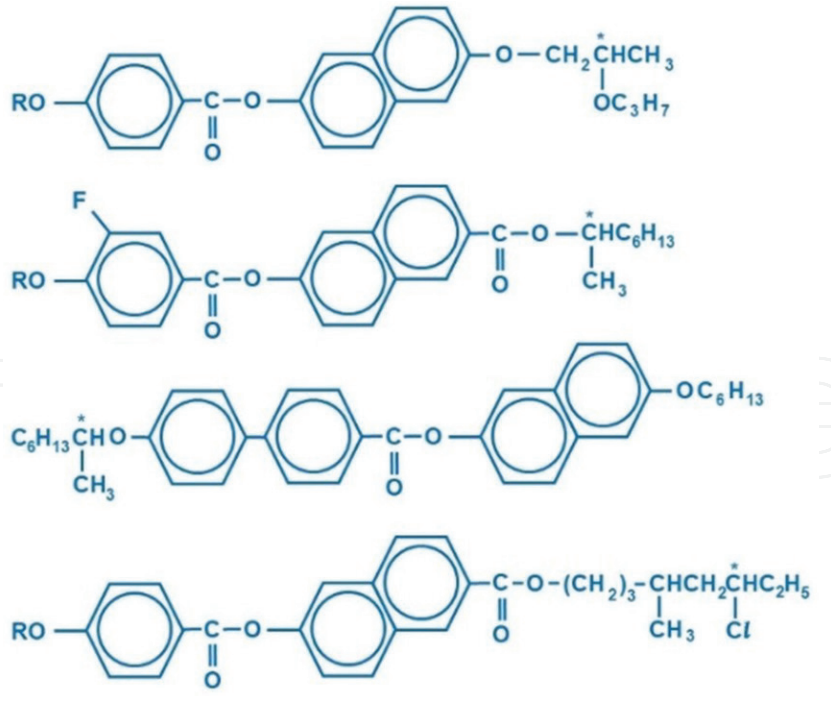


**Figure 5**
*Major component of naphthalene-ring base chiral smectic liquid crystal molecules for the bookshelf SSFL panel preparation.*

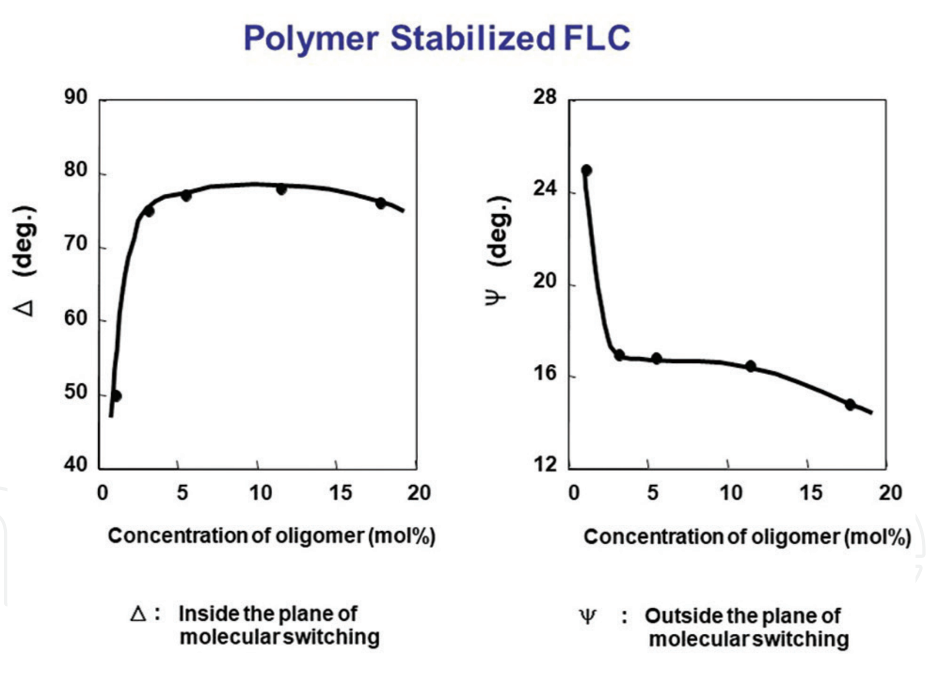


**Figure 6**
*In-plane (Δ) and out-of-plane (Ψ) retardation change depending on doping rate of photoreactive oligomer with the bookshelf layer structure ferroelectric liquid crystal panels.*

## 5. Possibility of active suppression of out-of-plane retardation change

Above experimentally clarified possible suppression of out-of-plane retardation switching in chiral smectic C phase liquid crystal panel may naturally lead possible completely in-plane only retardation switching without showing any out-of-plane retardation switching. If it happens, molecular switching behavior does not follow half circle cone edge anymore like a typical SSFLCD's case, and liquid crystal molecules swing in the same plane where the liquid crystal molecules' initial alignment plane. For this specific purpose to investigate possible in-plane only molecular

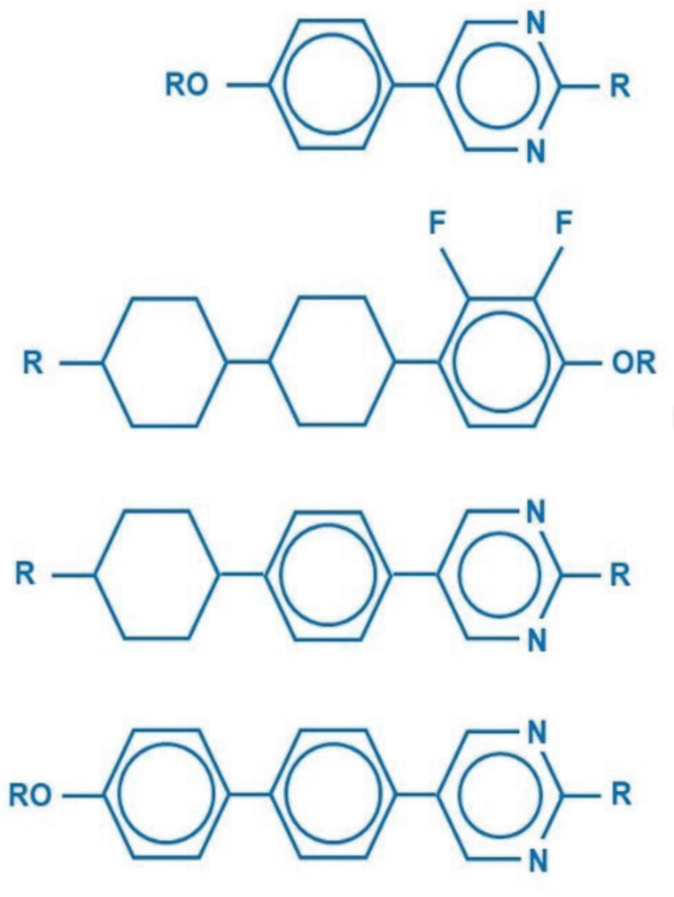


**Figure 7**
*Major liquid crystal component for smectic C phase mixture.*

swing movement behavior, new smectic C phase liquid crystal mixture was formulated. **Figure 7** shows main component of the smectic C phase (non-chiral) liquid crystal mixture. This mixture does not contain any chiral materials, resulting in non-Chiral mixture showing smectic C phase at room temperature as a bulk liquid crystal. With this mixture, if the mixture shows artificial smectic A like alignment, which means no molecular tilt to the smectic layer normal, was investigated using RN-1199 mechanical buffed alignment layer and 2.4–2.6 μm gap panels. The texture at the extinction angle with the crossed Nicole set polarized microscope photo is shown in **Figure 8**. This photo was taken with 2.4 μm gap panel. The prepared liquid crystal mixture showed smectic C phase at over 32°C, and it kept smectic C phase at most 47°C. Over the smectic C phase in temperature, the mixture showed smectic A phase. The **Figure 8** texture photo was taken at 35°C elevated temperature from the room temperature. At 35°C, the obtained uniform liquid crystal molecular alignment gives over 4000:1 static contrast ratio using coherent 514 nm diode laser optical system with crossed Nicole configuration that would be good enough for most of application (refer **Figure 15**). Since the series of investigation is under the premise of applying electro-optic devices such as display devices and phase modulation devices, not only large area's uniform molecular alignment, but also very tiny area's pixel to pixel uniformity with its unit size of few tens of microns square are required with static contrast ratio of over 3000:1 for a consideration of application.

As shown in the texture in **Figure 8**, this liquid crystal panel shows smectic A like texture at smectic C phase temperature as a bulk liquid crystal. It also showed electro-optic response above 32°C, however, below 32°C, and over 47°C temperature, the liquid crystal panel did not show any electro-optic response. The extinction angle of the liquid crystal panel at 35°C was slightly shifted from mechanical buffed angle. However, such slight angle shift from mechanical buffing direction is not unique

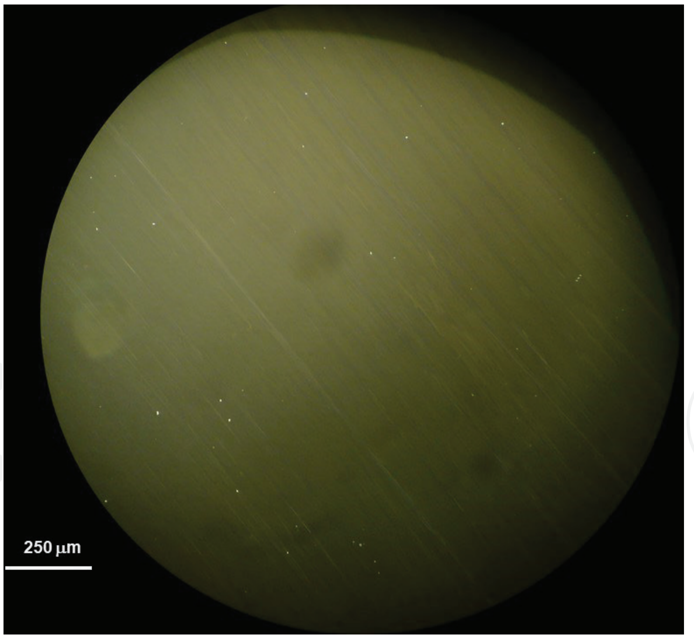


**Figure 8**
*A texture of artificial smectic A liquid crystal panel using smectic C phase mixture as a bulk state. This panel uses RN-1199 mechanical buffed alignment layer with panel gap of 2.4 μm.*

with this particular case, and sometimes an alignment layer gives relatively large retardation as the alignment layer itself shows an angle shift between liquid crystal panel's extinction angle and mechanical buffing direction. The shifting angle around 3–4° was not the same with that at smectic A phase of the panel. At the smectic A phase temperature, the panel shows ~1 to 2° shift at the extinction angle. The shifting angle direction was same both at the smectic A and artificial smectic A phase. This mixture has nematic phase above smectic A phase, however, its temperature range was very narrow such as less than 2°, and it was not easy to confirm its extinction angle with accurate enough measurement. Using these panels with elevated temperature at 35°C, if the smectic A like aligned panel shows in-plane only retardation switching was measured. For in-plane only retardation change confirmation, two different electro-optical measurements were compared. As illustrated in **Figure 9**, crossed Nicole linear polarizers measurement and crossed Nicole with quarter wave plates measurement were investigated. The crossed Nicole measurement does not distinguish in-plane and out-of-plane retardation change. Regardless in-plane only or mix between in-plane and out-of-plane retardation change, the crossed Nicole set up shows some electro-optical light throughput changes. On the other hand, the crossed Nicole with quarter wave plate measurement whose incident light to a liquid crystal panel is circularly polarized light shows some light throughput change only with out-of-plane retardation change.

**Figures 10–12** compared crossed Nicole and crossed Nicole with ¼ lambda plates measurements of the smectic A like initial alignment panel by changing applied electric filed strength. **Figure 10(a)** was from crossed Nicole result, and **Figure 10(b)** was with ¼ lambda plates result. The applied voltage both for crossed Nicole and with ¼ lambda plates set-up were the same: 2 ms duration bi-polar pulse voltage having 2 V height both for positive and negative directions. Light intensity scale at crossed Nicole and with ¼ lambda plates is different. Using circularly polarized light, if the liquid crystal panel's retardation change does include out-of-plane retardation change, basically, the light throughput from the liquid crystal panel is through without any light intensity modulation. In these experimental works, the designed panel gap was 2.4 μm at 35°C. Therefore, externally applied electric field strength is 2 V/2.4 μm–0.83 V/μm. It would be reasonable to discuss molecular

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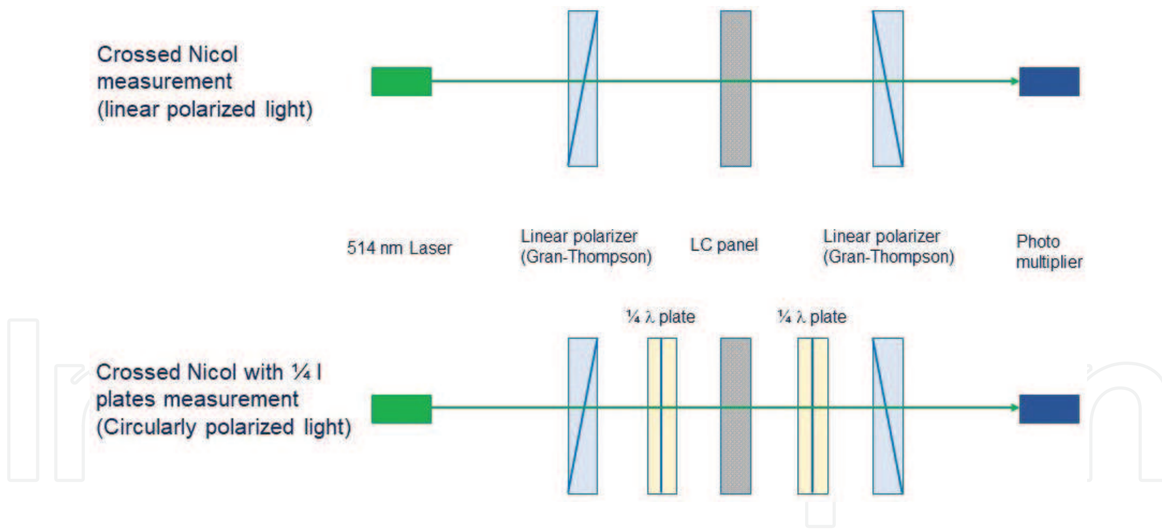


**Figure 9**
*Electro-optic measurement set-ups. One is using crossed Nicole linear polarizers. Linearly polarized incident 514 nm laser beam is modulated by the liquid crystal panel. The crossed Nicole set-up shows some light intensity change either the liquid crystal panel's retardation change including both in-plane and out-of-plane retardation change or only in-plane retardation change. The bottom set-up uses a pair of ¼ lambda wave plates, which change the incident light to circularly polarized light instead of linearly polarized light. In this measurement set-up, if the liquid crystal panel has both in-plane and out-of-plane retardation change, or only out-of-plane retardation change, the photo multiplier detects some light intensity change. If the liquid crystal panel has only in-plane retardation change, circularly polarized incident light does not have any amplitude modulation, resulting in no light intensity change.*

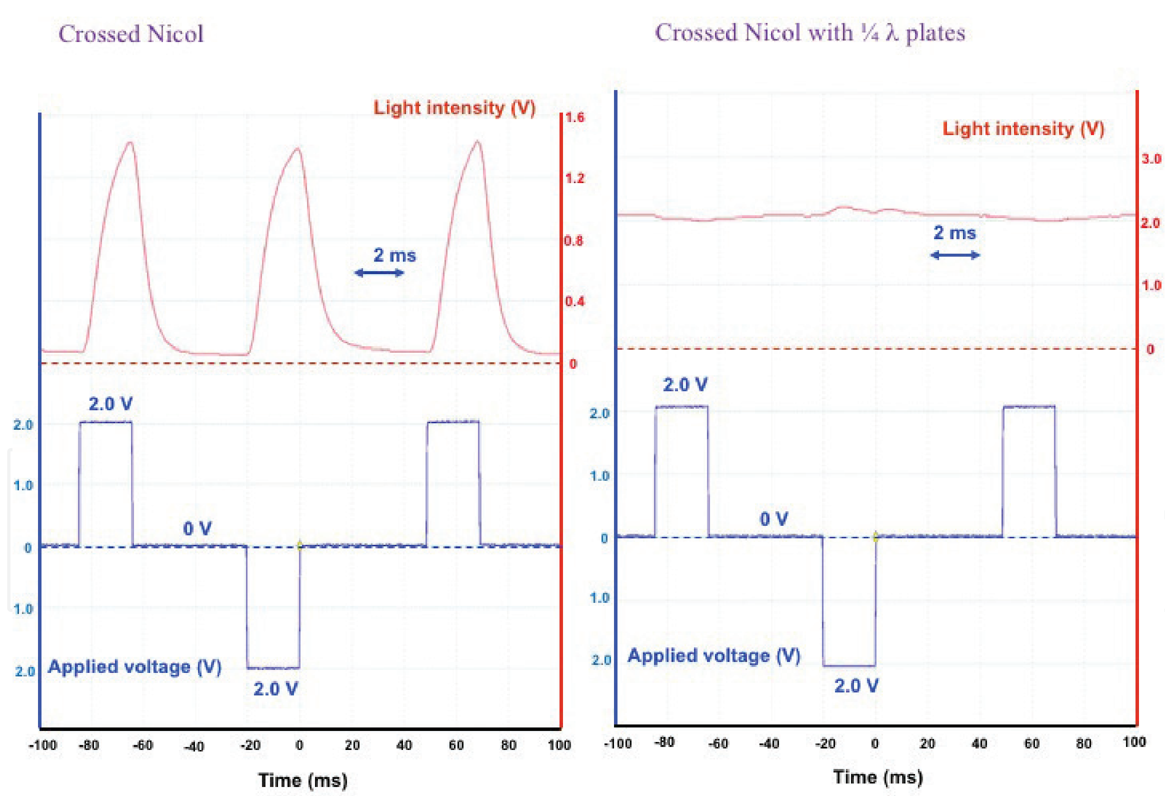


**Figure 10.**
*(a) Light intensity profile with crossed. Nicole optical set-up with 2 V pulse. (b) Light intensity profile with crossed. Nicole and ¼ lambda plates set-up with 2 V pulse.*

response behavior with applied electric field strength, rather than voltage. On the other hand, at this particular molecular stacking configuration case, it is still not clear if externally applied electric field represents effective applied electric field. Because the expected driving torque on this particular case is still not clear, but clear that it is not from dielectric anisotropy coupling, not from spontaneous

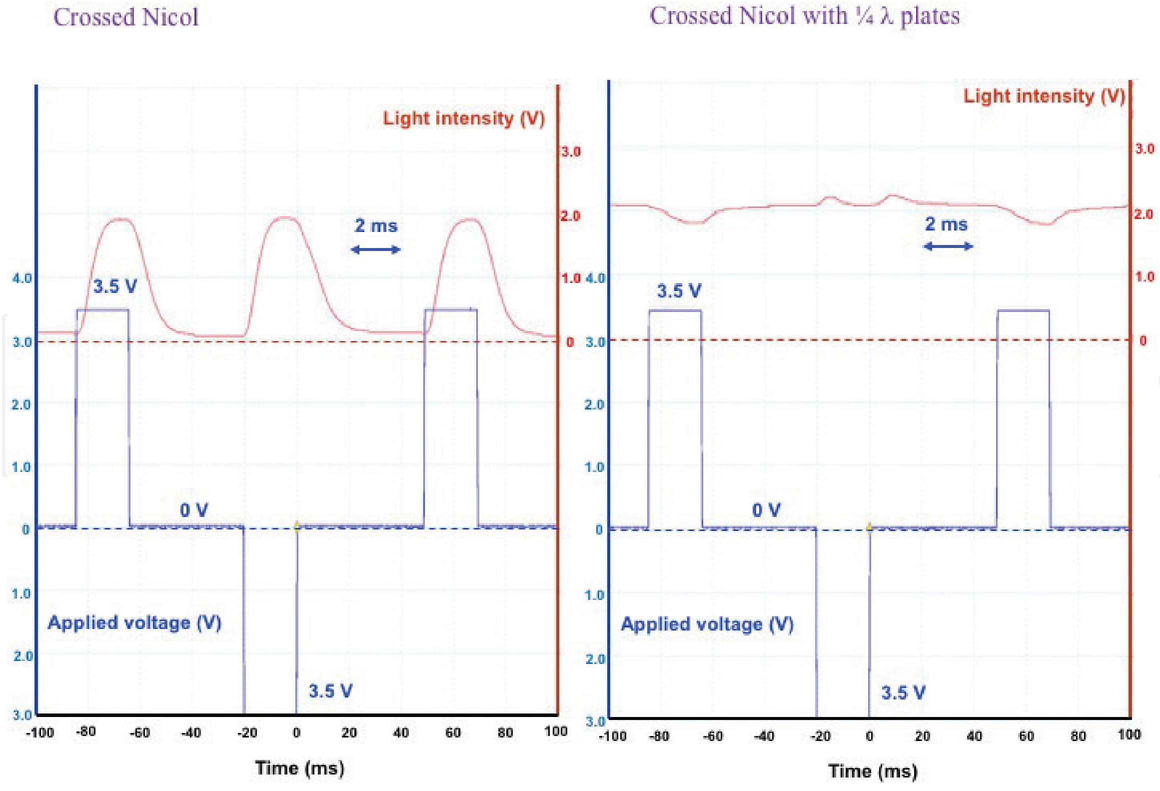


**Figure 11.**
*(a) Light intensity profile with crossed. Nicole optical set-up with 3.5 V pulse. (b) Light intensity profile with crossed. Nicole and ¼ lambda plates set-up with 3.5 V pulse.*

polarization. Most likely, it would be quadrupole momentum base [57, 58], and if it is really from quadrupole momentum base, we may need to figure out what external

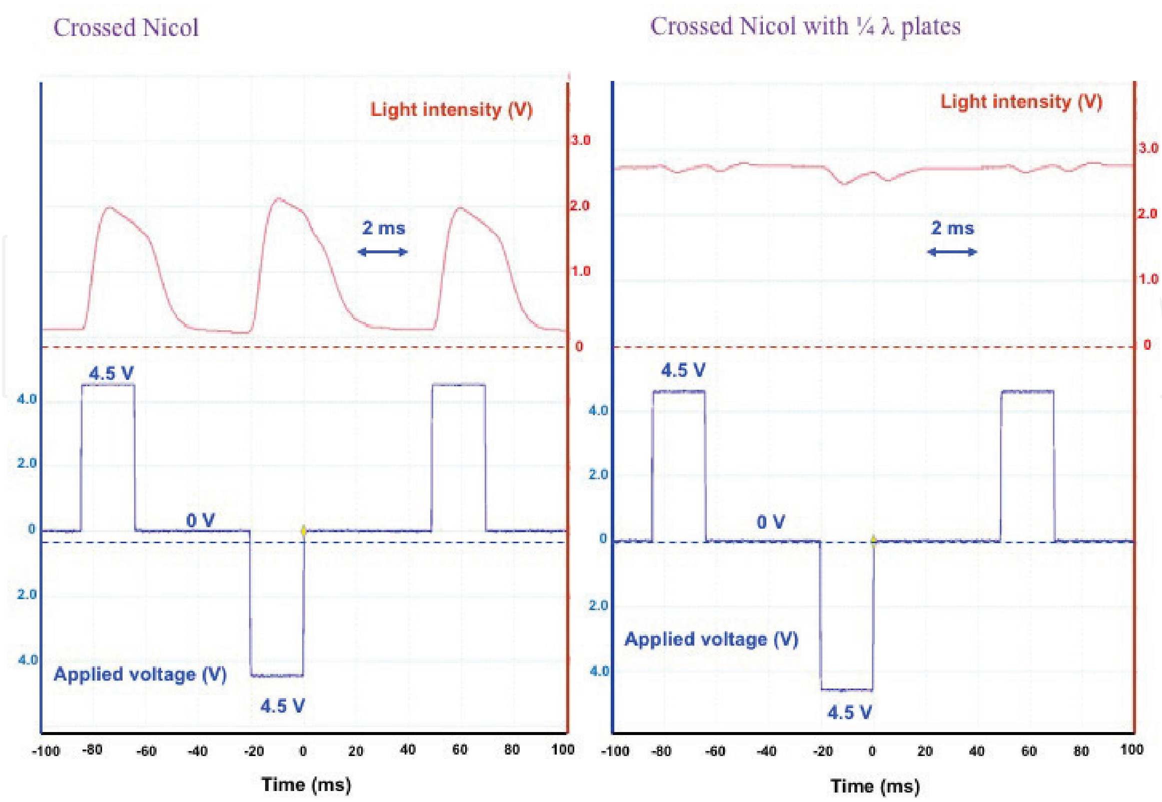


**Figure 12.**
*(a) Light intensity profile with crossed. Nicole optical set-up with 4.5 V pulse. (b) Light intensity profile with crossed. Nicole and ¼ lambda plates set-up with 4.5 V pulse.*

excitation is the most appropriate to discuss the influence, however, it might be too early to conclude from current obtained empirical results, yet.

**Figure 10(a)** and **(b)** comparison clearly suggests the smectic A like initial alignment smectic liquid crystal panel has almost in-plane only retardation change. Following **Figures 11** and **12** show some influence of further increase in applied voltage on the in-plane/out-of-plane retardation change.

With increase in applied voltage, **Figure 11(b)** shows no-complete flat light intensity profile, but shows some change at each applied pulse voltage edge. This change strongly indicates some involvement of out-of-plane retardation change. Further higher applied voltage shows some interesting amplitude modulation profile as shown in **Figure 12(a)** and **(b)**. **Figure 12(a)** and **(b)** show the light intensity profiles both at crossed Nicole and with ¼ lambda plates set-up results with 4.5 V pulse voltage, respectively. Unlike lower applied voltage cases, 4.5 V voltage gave at least two-step wise light intensity profile at **Figure 12(a)**: crossed Nicole set-up case. The measured liquid crystal panel has 2.4 μm gap between two counter transparent electrodes gap. Therefore, applied electric field strength at 4.5 V would be ca. $1.88 \times 10^6$ V/m. From typical liquid crystal device point of view, this level of electric field is somehow typical strength. Therefore, it is reasonably assumed that there was no particular electric field discharge influence on these measurements. A comparison between **Figures 11(a)** and **12(a)** also suggests possible over 45° molecular optical axis rotation under the premise of almost in-plane only retardation change. **Figure 11(a)** clearly shows saturated light intensity during 2 ms pulse voltage application. On the other hand, **Figure 12(a)** shows decrease in light intensity after the light intensity reached at the peak light after the pulse voltage was applied, also shows slower light intensity decay after the pulse voltage is removed. The light intensity decrease during the pulse voltage application suggests over 45° liquid crystal molecular axis rotation under the premise of almost only in-plane retardation change.

Since the measurement set-up used cross Nicole, if birefringence optical medium changes its optical axis over 45°, light intensity should be decreased.

Slower light intensity decrease right after the applied pulse voltage is removed also supports possible over 45° molecular optical axis rotation. It is reasonably assumed that during pulse voltage application, molecular optical axis rotates over 45°, and right after the pulse voltage is removed, the liquid crystal molecular axis continuously comes back to the original position which gives the light extinction. If this view is correct, apparent two-step wise light intensity change is not really two-step, but monotonical decrease in light intensity along with liquid crystal optical axis rotation from over 45° to heading to 0°. For further detail investigation whether really the smectic liquid crystal optical axis rotates over 45°, slightly different formulated smectic liquid crystal mixtures were prepared showing more uniform initial molecular alignment. Using the newly formulated smectic liquid crystal mixtures, if really the optical axis rotates over 45° was investigated. **Figure 13** is the result of this investigation.

**Figure 13** strongly indicates over 45° optical axis rotation under the premise of almost in-plane only retardation change. In **Figure 13**, at 4 V pulse voltage application, the reached light intensity is close to the light intensity given by the parallel Nicole configuration. This suggests that the optical axis at 4 V pulse voltage application gave almost 45° rotation from the initial extinction angle (0°). At 8 V pulse voltage, during 1 ms pulse voltage application duration, the light intensity shows decrease right after it reached the maximum. Also right after the pulse voltage is removed, the light intensity showed sharp increase, then decrease continuously. This light intensity change profile is reasonably interpreted as over 45° rotation.

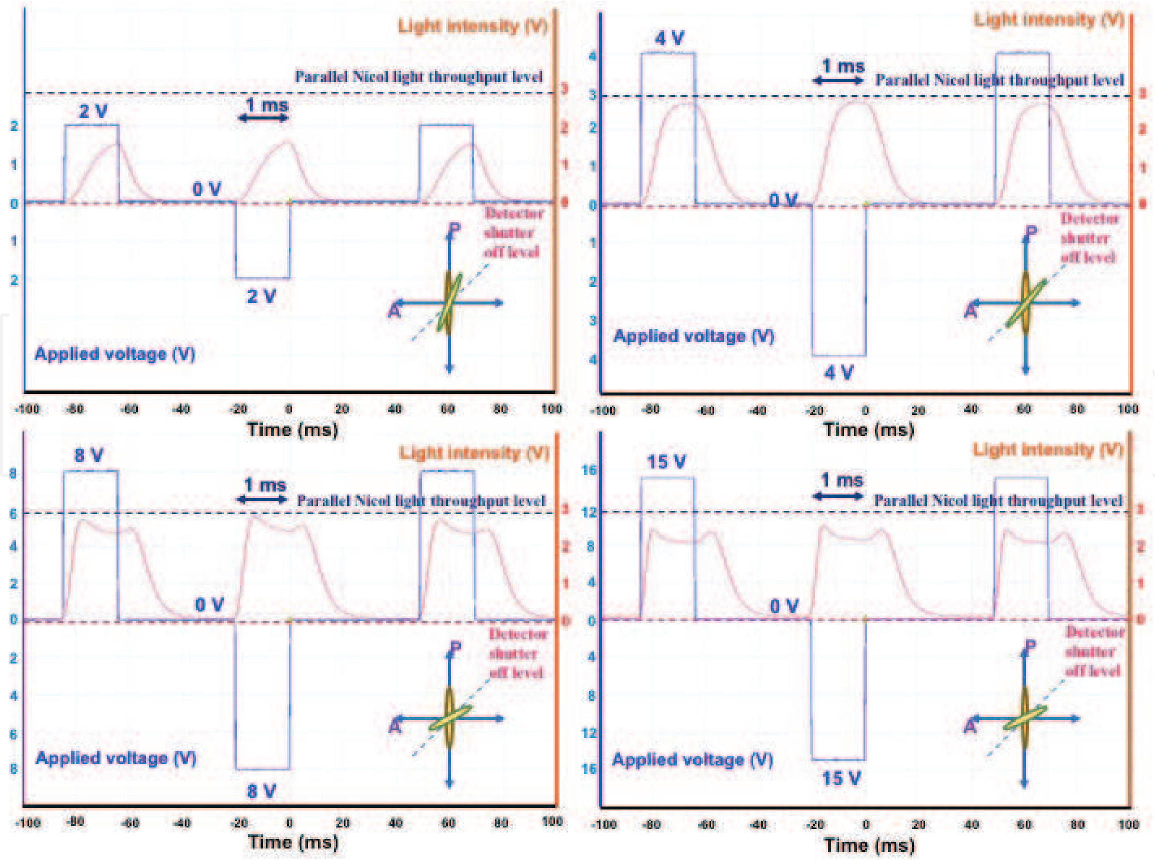


**Figure 13**
*Light intensity profiles depending on applied electric field strength using the crossed Nicole optical set-up with 1 ms pulse voltage. Up to 4 V pulse voltage, light intensity gives almost maximum intensity. 8 V pulse voltage gives "bump" in light intensity during pulse voltage application, which strongly indicates over 45° optical axis rotation. Further increase in pulse voltage such as 15 V even gave lower reachable light intensity during pulse voltage application. This also indicates over 45° rotation under the premise of almost in-plane only retardation change.*

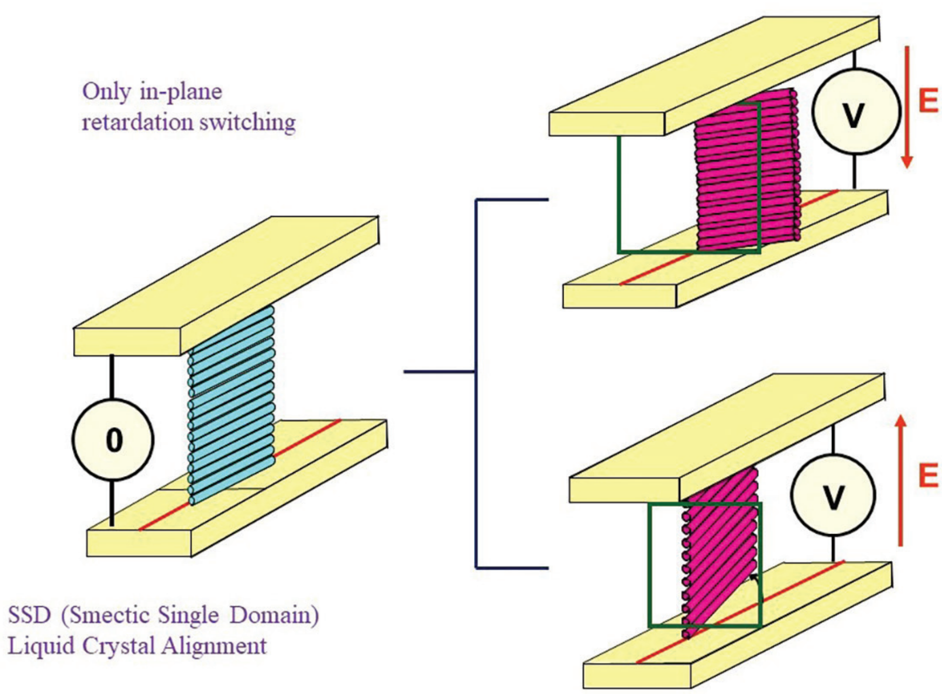


**Figure 14**
*An overall concept of smectic single domain (SSD) liquid crystal molecular switching behavior. At the initial molecular alignment configuration, all of smectic liquid crystal molecules align uniformly forming like "liquid crystal wall". When downward voltage is applied to the liquid crystal panel, the "liquid crystal wall" rotates clockwise direction. When upward voltage is applied, the "liquid crystal wall" rotates counter-clockwise direction.*

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With further increase in applied voltage such as 15 V, the apparent reachable light intensity is even decreased. This is possibly due to photo detector's sampling time issue. It is still required more detail investigation to conclude in-plane only retardation switching with this particular smectic liquid crystal cases, as a general understanding with above investigations, an overall liquid crystal molecular behavior is illustrated in **Figure 14**.

Although some detail is still missing, as an overall concept for the smectic single domain (SSD) liquid crystal molecular switching behavior may be reasonable. However, there is one big question here. The question is "Is it possible to rotate over 45 degrees" in a smectic layer structure? As of today, this question has no rational answer yet. As discussed above, to give a rational answer to the question, it would be required intense local smectic layer structure analysis, specifically some dynamic layer structure change. Therefore, at this moment, only some speculation is given here. All of the speculation should be subjected to be verified with reasonable enough both empirical and theoretical evidences, though.

## 6. Necessity of further investigations

As discussed above, whether over 45° optical axis rotation is really happening or not is based on all assumption based on some indirect empirical results. Although they are all assumptions, there are some suggestive empirical results. **Figure 15** shows light leakage amount depending on applied pulse voltage strength at **Figure 9**
type of crossed Nicole optical set-up measurement. As shown in **Figure 10**, when applied pulse voltage is relatively low such as 2 V for 2.4 μm gap, during zero voltage application time duration, the SSD-LC panel shows very low light leakage, which means most of liquid crystal molecular optical axis stays at the initial extinction position. However, when applied pulse voltage increased over ca. 4.5 V,

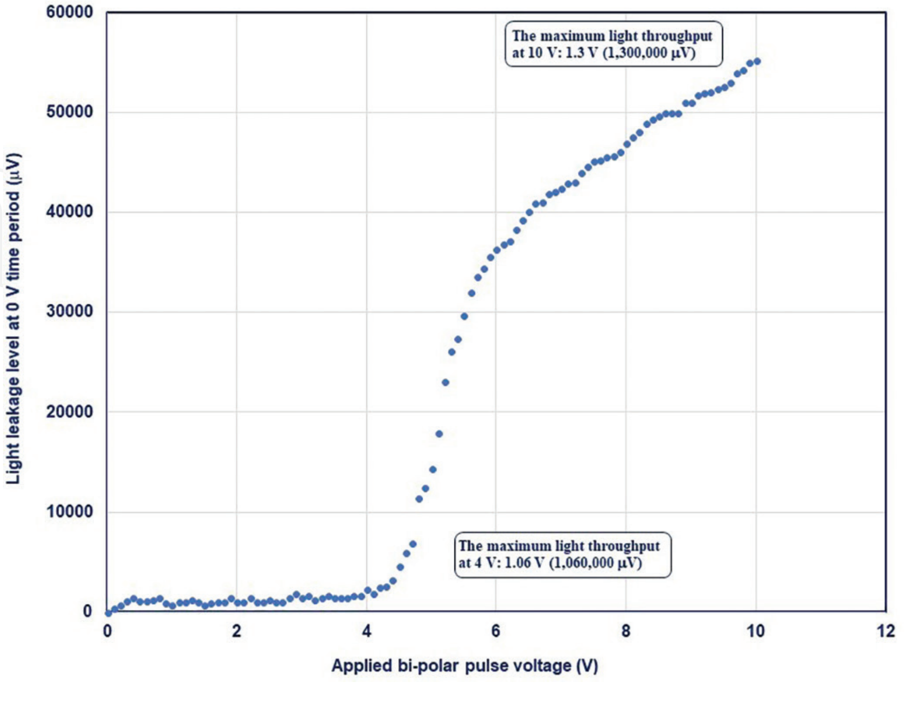


**Figure 15**
*Light leakage level during zero-voltage application depending on pulse voltage strength of the SSD-LC panel. Up to ca. 4.5 V, light leakage level is very low, and over 4.5 V, light leakage shows significant increase by voltage increase. This pulse voltage dependence of light leakage level strongly suggests some influence on the initial liquid crystal optical axis position change.*

suddenly the light leakage level increased. This indicates that voltage application to the SSD-LC panel induced some smectic layer structural change, resulting in no more initial extinction position at zero voltage duration. It looks like dependent on SSD-LC mixtures; some mixtures did not show reversible measurement result. This means that once over ca. 6 V pulse voltage was applied to 2.4 μm gap, the SSD-LC panel never showed the original very low light leakage. Some SSD-LC mixtures, however, showed reversible light leakage phenomenon even after higher voltage was applied. There are some potentially relevant research works to give some reasonable interpretation to above empirical results. One is very local smectic layer structure change by high voltage application. Iida et al. investigated local smectic layer structures of ferroelectric liquid crystal panels using Synchrotron radiation beam [40]. This research works clarified existence of narrow walls in a smectic layer structures. Such narrow walls might be possible interpretation of **Figure 15** result. Even the SSD-LC molecular optical axis stays at extinction position normal to the smectic layer, if for some reason, the smectic layer itself changes its structure, liquid crystal molecular optical axis is no more parallel to the incident linear polarized light, resulting in light leakage at zero voltage application duration. The other relevant possibility is giant-block twist grain boundary reported by Fernsler et al. [59] This possibility might be, however, relatively small, or righter in the SSD-LC case. Since most of SSD-LC panels, the initial alignment textures are quite clean, and there is no particular microscope level of visible size of defects. However, it might be possible having much smaller size of grain boundary structure than visible wavelength size.

A narrow wall and possible local twisted boundary effects might be fairly possible interpretation to understand **Figure 15** results. Moreover, why over 45° of SSD-LC molecular swing in the same orientation plane is possible with significant layer spacing shrink (if it really shrinks, though) is the question. It would be more intense research works not only local, but relatively large scale structures, but also much larger area of continuous theory deal might be necessary [60–63].

## 7. Concluding remarks

Smectic liquid crystals have been somewhat difficult to obtain clean molecular alignment for display and phase modulation devices purpose level of high static contrast ratio such as over 3000:1, and this difficulty would be one of the major reasons preventing from practical applications. The difficulty in uniform and clean molecular alignment might be mainly due to existence of smectic layer structure. Required well enough balance between healthy construction of smectic layer structure and surface anchoring needs somewhat tricky technique. However, at least in a certain type of smectic liquid crystals case, an initial liquid crystal molecular alignment is already equivalent from those of most of nematic liquid crystals. Still some specific difficulty remains that are not necessary to consider at most of nematic liquid crystal cases. Even if the initial liquid crystal molecular alignment is perfect, the remaining difficulty is if the initially obtained alignment is preserved by driving with externally applied electric field. One of the practical means to get rid of instability of smectic layer and molecular alignment has been clarified to use non-spontaneous, non-anisotropy of dielectric constant base driving torque. At this moment, however, it is not clear yet what is the real driving torque of SSD-LC cells except for some reasonable assumption of quadrupole momentum base. This remaining difficulty still needs further investigation. Regardless required further detail investigation, this series of investigations clarified possible in-plane only retardation switching. Moreover, such an in-plane only retardation switching also indicates over 45° molecular optical axis rotation. In-plane only retardation switching with over 45° swing angles would provide q liquid crystal device new application field. Under the premise of smectic layer restriction, it would be required to give a reasonable interpretation why over 45° rotation is allowed.

This series of investigation may open both practical application opportunity of some smectic liquid crystal devices, specifically for fast response (~200 μs) in-plane only retardation switching devices, and fundamental research necessity to clarify nature of such smectic layer structures.





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