# Complete In-Plane Retardation Switching with Over +/- 45 Degrees Swing Angle and 100-Microsecond Response Liquid-Crystal Technology

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## Abstract

***A complete in-plane retardation switching having over +/- 45 degrees swing angle liquid crystal technology is expected to be applied many varieties of uses including AR/VR/MR switching devices, phased array devices and so on. Moreover, 100 µs or faster optical response gives further attraction in terms of its uses. The liquid crystal technology discussing in this paper shows some unique properties both in terms of its drive mode and device configuration.***

## Keyword

In-plane retardation switching, smectic liquid crystal, SSD-LC, TE mode

## 1. Introduction

Fast optical speed has been continuous and endless proposition for liquid crystal technologies. For most of display devices, current liquid crystal technologies look good enough to provide their fast enough response speed. [1-3] On the other hand, if further fast response speed is available, such liquid crystal technology may open new application opportunities. Moreover, complete in-plane only retardation switching gives TE-mode optical response, which would be beneficial for some photonics switching devices. [4-6] In addition to these attractive features, applied voltage polarity response of this liquid crystal technology enables substantial force-off decay process, resulting in < 100 µs response time both at rise and decay processes, respectively. [7] In this paper, these unique properties of the liquid crystal technology will be discussed including the most updated empirical results.

This technology uses a smectic liquid crystal material showing its molecular director tilting from the smectic layer normal known as SmC, SmH, SmI sub-phase. Unlike ferroelectric liquid crystal materials, this technology uses spontaneous polarization free, or non-ferroelectric materials. This technology is called as SSD (Smectic Single Domain) liquid crystal technology. Despite a smectic layer structure which usually makes some complicated molecular alignment in a liquid crystal panel, most of SSD liquid crystals show quite uniform molecular stacking based on typical nematic liquid crystal molecular alignment technologies. [8]

## 2. About SSD-LC drive mode

Thanks to the SSD liquid crystal drive torque origin, SSD-LC panels show applied voltage polarity dependent swing direction. Dependent on vertically applied external electric field to the SSD liquid crystal layer, upward/downward direction electric field provides clockwise/counter-clockwise swing direction, respectively as illustrated in Figure 1.

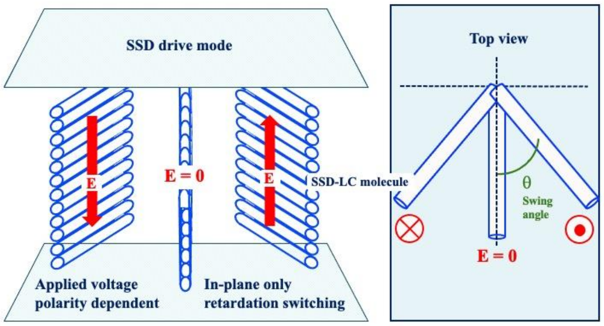

**Figure 1**. Initial molecular stacking and switching principle of an SSD LC drive mode

An SSD-LC drive mode uses specific sub-phased smectic liquid crystal materials. As a bulk, the SSD-LC material shows molecular directors tilted to the smectic liquid crystal layer. Smectic C, Smectic H, and Smectic I sub-phase liquid crystal materials are in use for the SSD-LC drive mode. Although such liquid crystal molecules show molecular director tilt, applying strong enough azimuthal anchoring at the substrates surfaces, in a liquid crystal panel, SSD-LC molecules lose their molecular tilt, resulting in similar status with smectic A phase. In short, the SSD-LC drive mode uses artificial Smectic A phase as illustrated in Figure 1.

The SSD liquid crystal molecular director switching is fulfilled in the same plane originally the molecules aligned, and this configuration enables complete in-plane retardation switching. SSD-LC panels complete in-plane retardation switching behaviors have been confirmed by several means including a concise comparison measurement between linearly and circularly polarized incident beam light throughput dynamic properties as shown in Figure 2. The comparison between circularly and linearly polarized incident beams light throughput dynamic behaviors, gives clear contrast as presented in Figure 2. The linearly polarized beam is obviously switched either positive or negative pulse voltage is applied. On the other hand, for circularly polarized beam, regardless pulse voltage is applied, the light throughput shows flat without any clear light switching. In addition to this concise measurement, polarimetry measurement also supports the in-plane only retardation switching of the SSD-LC panel as shown in Figure 3.

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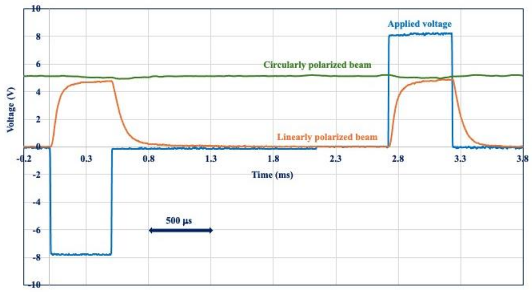

**Figure 2**. Dynamic light throughput behavior to linearly and circularly polarized incident beam, respectively.

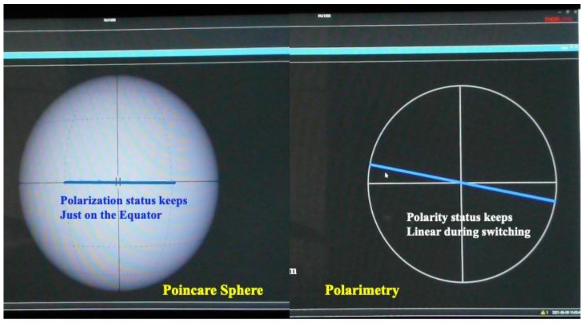

**Figure 3**. An SSD-LC panel's dynamic polarity switching behavior. The left figure shows Poincare sphere expression, and the right figure shows dynamic polarity behavior.

As shown in both Figures 2 and 3, the SSD-LC molecules keep almost complete in-plane retardation switching whole the way of their switching. The SSD-LC's complete in-plane retardation switching behavior enables TE-mode optical switching.

## 3. Over 45 degrees switching angle

An ideal swing angle for many applications is +/- 90 degrees which enable 2π retardation switching. Due to the smectic layer structure limitation, +/- 2π switching would be very difficult. On the other hand, over +/- 45 degrees and heading to +/- 90 degrees would be conceivable with a "soft" smectic layer structure. So far, these empirical approaches have confirmed ca. +/- 70 degrees, which is corresponding to ca. +/- 1.6π. Figure 4 shows observed light throughput of the SSD-LC panel under Crossed Nicol configuration. The swing angle is solely decided by applied voltage. As shown in Figure 4, with 500 µs duration pulse drive voltage, the swing angle reaches at 45 degrees, then further drive voltage increase provides over 45 degrees swing angle. Current SSD-LC panels enable ca. 70 degrees swing angle with 500 µs duration, 16 voltage drive waveform. The swing angle reaches at 45 degrees by ~ 5 V drive voltage, and further increase in drive voltage provides lowering light throughput as shown in Figure 4. When the swing angle surpasses 45 degrees under Crossed Nicol configuration, light throughput decreases as shown in Figure 4. With over 5 V drive voltage, light throughput curbs show a folded shape. If the swing angle reached at 90 degrees, the light throughput went down to zero level. As shown in Figure 4, with 16 V drive voltage, the minimum light throughput reaches at ca. 70 degrees.

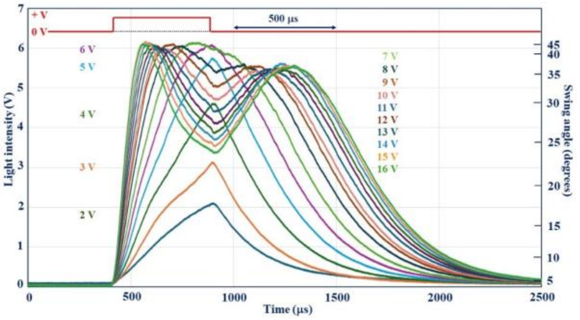

**Figure 4** Over 45 degrees swing angles by the SSD-LC panel. Under Crossed Nicols configuration, over 7 V drive voltage provides in light throughput for linearly polarized beam, which suggests over 45 degrees swing angle, and the swing angle shows up to ca. 70 degrees.

## 4. < 100 ms optical response

The other feature of the SSD liquid crystal technology is fast optical response showing faster than 100 µs. The SSD driving torque enables faster rise speed by increase in driving voltage, on the other hand, decay speed is not controllable by driving voltage. However, thanks to applied voltage polarity dependent response, with reverse voltage application, decay speed is accelerated effectively. This decay speed acceleration was reported at SID symposium in 2022 [7], and continuous investigation has provided faster decay speed as shown in Figure 5 reaching at nearly 50 µs both rise and decay times with 8 to 10 V 500 µs duration pulse drive voltage.

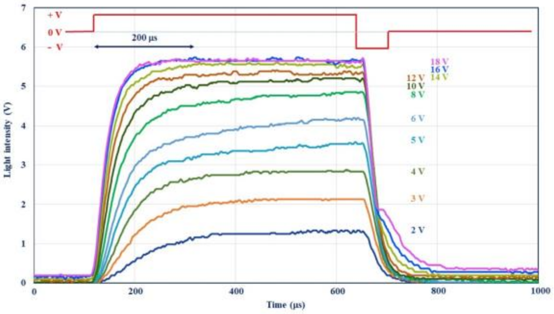

**Figure 5**. Both rise and decay times of the SSD-LC panel by applied voltage polarity dependent response.

The short reverse voltage significantly shortens decay time such as shorter than 80 µs. An SSD-LC panel shows somewhat "impact" type of driving torque in terms of its optical response behavior to applied pulse voltage width. Figure 6 presents one of the examples of the pulse width dependence of swing angle behavior. The pulse width dependence is dependent on applied pulse voltage. Figure 6 was obtained by 16 V pulse voltage case at 17C. As shown in Figure 6, the SSD-LC panel requires ca. 100 µs pulse width to reach at 45 degrees of swing angle.

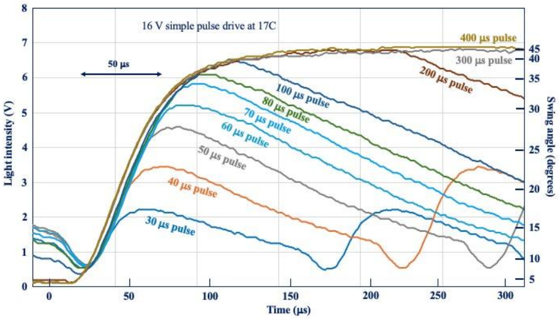

**Figure 6.** Applied pulse voltage width dependence of swing angle behavior of the SSD-LC panel.

In most of dielectric anisotropy coupling type of liquid crystal drive modes require long enough driving torque application to reach at the balanced position of the liquid crystal director, which suggests liquid crystal molecular optical response is a bit shorter than applied voltage duration. In some applications, in particular fast response required use cases, the difference between the optical response and required voltage application duration limits the use capability. Unlike such typical liquid crystal drive modes, the SSD-LC drive mode provides "impact" type of driving torque. To investigate the impact driving torque nature, the light throughput intensity (L) ramp-up steepness (dL/dt) is defined as unit second (ms) as illustrated in Figure 7.

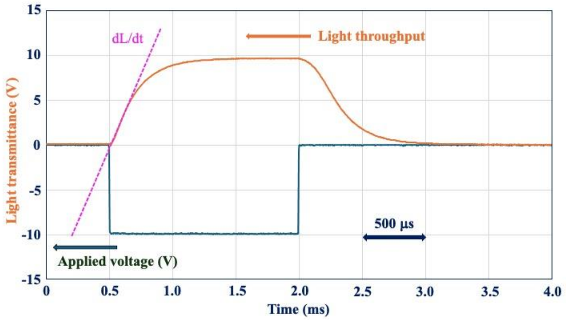

**Figure 7**. Definition of light throughput ramp-up steepness dL/dt.

## 5. A thought on driving torque of an SSD-LC panel

Applying 1.5 ms duration pulse at 16C, the relationship between dL/dt and applied pulse voltage was measured and got Figure 8 result.

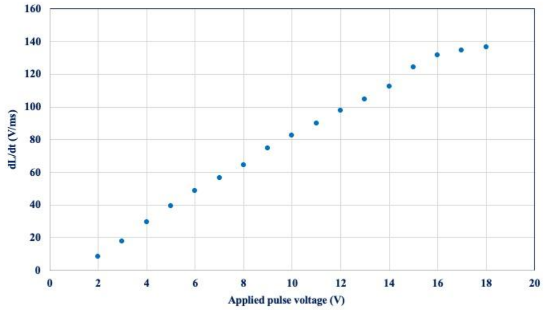

**Figure 8**. Applied pulse voltage dependence of light throughput ramp-up steepness dL/dt of the SSD-LC panel. Duration of the pulse voltage was 1.5 ms.

From Figure 8 result, substantial drive torque of the SSD-LC panel suggests linearly increase with increase in applied pulse voltage up to ca. 17 V. As discussed above, an SSD-LC panel shows impact type of driving torque, and the driving torque looks nearly in proportion to applied pulse voltage, not depending on square of applied voltage which is popular among dipole moment-based driving torque. Although the SSD-LC panel's driving torque is linearly increase with increase in applied voltage, the SSD-LC molecules do not have any spontaneous polarization unlike those with ferroelectric liquid crystal molecules.

Current conceivable driving torque of the SSD-LC molecules is quadrupole momentum [9]. It is still required to have more direct proof of quadrupole momentum-based driving torque, however, so far, all the observed electro-optic response profiles indicate quadrupole moment base driving torque so far. Further detail investigation exploring the driving torque origin of SSD-LC molecules are under way.

## 6. Possibility of 2p retardation switching

For a traditional display use, π retardation switching provides the maximum light throughput as a half lambda waveplate, and current SSD-LCs adequately provide π retardation switching. A < 100 µs optical response with nearly unlimited viewing angle property using the simplest vertical applied voltage configuration would have a great advantage as a typical direct view display application.

Although 2π retardation switching is not required for typical display uses, if 2π retardation switching is available with < 100 µs response time, specifically in-plane only retardation switching, such property provides a great benefit to current AR/VR applications as well as fast phase modulation devices.

The largest challenge to have 2π retardation switching in an SSD-LC panel is a compatibility with smectic layer structure. Unlike uniaxial aligned nematic liquid crystal case, SSD LC molecules are required two dimensional orders. Due to the two-dimensional order, smectic liquid crystal molecules are under restriction of virtual smectic layer structure. A typical SSD liquid crystal molecular long axis size is ca. 40 A, and this length governs the smectic layer spacing. On the other hand, a typical SSD liquid crystal molecular short axis is ca. 15 A. Therefore, if simply the SSD liquid crystal molecule changes its direction 90 degrees, which is corresponding to 2π retardation change, the smectic layer spacing needs to change from 40 A to 15 A. Such a larger structural change is, however, not easy in consideration of total free energy change keeping smectic two-dimension order. Even current obtained nearly 1.6π retardation switching may not be easy to explain why such a large swing angle is possible keeping the smectic two-dimensional order. Further detail investigation may clarify such a mysterious phenomenon in SSD-LC panels.

## 7. Concluding remark

Complete in-plane retardation switching all the way of response with < 100 µs response speed would attract some new application of liquid crystal technologies not limited in display uses, but also some photonics switching uses. A typical SSD-LC panel configuration uses vertical electric field to the LC layer, which enables the simplest electrode structure, and would get rid of some complicated fringe field influences. Such a simple electrode structure can maximize aperture ratio for better light throughput. Further investigation toward 2π retardation switching is challenging with possible new frontier in smectic liquid crystal devices. The SSD-LC technology may be attractive both for its fundamental science and practical applications.

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