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Liquid Crystal Displays with High Image Quality and Fast Response Time

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Liquid crystal displays (LCDs) extend their application fields to TV as well as monitor from portable personal computers, owing to improvement in viewing angle and response time. In LCDs, display mode mainly determines the quality of display. Recently several display modes with high performance such as fringe-field switching (FFS), in-plane switching (IPS), multi-domain vertical alignment (MVA), and optically compensated bend (OCB), have been developed. In this talk, we will review trend of commercially available display modes and report improved FFS mode with high image quality and fast response time.

I. INTRODUCTION

Nowadays, liquid crystal displays (LCDs) play very crucial role among flat panel displays in markets of portable personal computers as well as monitors. The volume of LCD market in 1999 was $15 billion and is expected to be about $48 billion in 2005, surpassing that of cathode ray tube (CRT) [1]. Looking back on history of LCDs how they have been developed and commercialized, it is so much striking. LC material was found in 1888 by Reinitzer. However, after long time, LC's electro-optic reaction, *i. e.* electric field effect of nematic LC was studied and the first LCD prototype as digital clock was developed in 1960's. In early 1970, the first practical and portable personal calculator using dynamic scattering mode (DSM) mode was introduced into a market. The DSM device needs high driving voltage more than 10V. Therefore, the LC device was moved to low driving voltage twisted nematic (TN) device in 1975. At that time, it was driven by a passive matrix, limiting the information content. In order to overcome such limitation, active researches on thin film transistor (TFT) during late 1970's and early 1980's has been made and the prototype TFT-LCD using an amorphous silicon (a-Si) or high temperature poly silicon was made. In the middle and late1980's, several companies made a-Si TFT-LCD in various sizes with initial product target for a portable TV [2]. From early to middle of 1990's, many companies had launched TFT-LCD production lines and produced TFT-LCDs mainly for notebook computers with size up to 14.1″ using the TN device because it has great advantages in high resolution, lightweight, compactness, and low power consumption with enough image quality. In late 1990's, the LCDs extend their application field into the monitor as well as TV market with large size greater than 15.0″. Consequently, the improvements of the TN device on viewing angle and response time for motion picture were required.

In TFT-LCDs, the LCD mode that initial molecule alignment and the method of applying field are defined determines the image quality. Recently several new devices such as discotic film compensated TN, advanced super view (ASV) [3], in-plane switching (IPS) [4], fringe-field switching (FFS) [5], multi-domain vertical alignment (MVA) [6], patterned VA (PVA) and surrounding electrode (SE) [7], and other devices are developed and most of them are already commercialized. These devices show wide-viewing angle overcoming intrinsic problem that the twisted nematic (TN) has, and try to replace CRT in monitor and TV fields. Table 1 shows quality comparison between CRT display and LCD [8]. In luminance, contrast ratio and grey scale capability, the new devices are comparable to CRT though still need improvement in viewing angle. However response time is not so good compared to CRT display. In LCDs using nematic LC, the dielectric torque causes elastic deformation of the LC director initially confined and when the voltage relaxes to lower one, the director comes back to original state by restoring force of the LC director. Nematic LC is viscous liquid that has rotational viscosity between 80 mPa.s and 150 mPa.s, so fast response in microsecond level is difficult except a device with ferroelectric LC that has spontaneous polarization. However, for motion picture the response time less than 12 ms (75 Hz frame rate) is required and it is strongly dependent on the viscosity of the LC as well as the LC modes. Recently, to improve response time of the LCD an extensive work is under going. In this paper, how the LCD people have approached to develop the devices that exhibit high image quality and response time will be explained.

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Table 1. Quality comparison between CRT display and LCD.

	Minimum required performance level (Not good, good, better)	TFT-LCD in 2003	32 inch CRT in 2003
Peak display performance			Better
Peak Luminance (cd/m^2)	$300 < Good < 500$	Better	Better
Totally white luminance (cd/m^2)	$160 < Good < 400$	Better	Good
Contrast in brighter environments	$70 \leq Good \leq 100$	Better	Better
Contrast in Dark environments	$250 \leq Good \leq 350$	Good	Better
Grey-scale capability	Good = 8bit	Better	Better
Viewing angle (degree)	$120 < Good < 160$	Good	Better
Response Speed	Good$< 12ms$	Not Good	Better

II. WIDE-VIEWING ANGLE LC DEVICES

In viewing angle issues, the birefringence of LC has a viewing angle dependence and also wavelength dependency. Further there is leakage of light of crossed polarizers at off normal directions because the polarizer can not control light perfectly vibrating along vertical axis. Therefore, the change of image quality, *i. e.* variation of phase retardation (δ) as the viewing direction changes from normal direction is inevitable. What we can do best is minimization of it.

1. TN, Film Compensated TN and Super V

In twisted nematic (TN) mode, the LC director is rotated 90° from top to bottom substrate under crossed polarizers and vertical field is used as shown in Fig. 1. The device appears to be white before applying voltage. In the bright state *i.e.*, with applied voltage below threshold (V_{th}), the phase retardation between left (δ_1) and right (δ_2) is almost same so that the change rate of brightness as viewing angle increases is about same along azimuthal direction, resulting in symmetry in brightness. However, when the voltage is greater than (V_{th}) the LC director tilts up in one direction so that it is so much different along azimuthal direction and the uniformity is destroyed. When a driving voltage (V_{op}) for dark state is applied, the phase retardation at normal direction (δ_3) and δ_2 are almost zero, but δ_1 is not zero, giving rise to leakage of light. Conclusively speaking, the TN device shows bad image quality in grey scales and low contrast ratio at large viewing angle range due to leakage of light in certain direction.

In display, control of leakage of light at dark state is very important to obtain high contrast in wide viewing range. For this purpose, an optical compensation film using discotic LC has been developed. Fig. 2 shows a basic concept of compensation that the negative birefringence of half of the TN cell at dark state is compensated by positive birefringence of the discotic film. Consequently the residual birefringence is minimized under crossed polarizers so that the leakage of light is compressed, thus improving contrast ratio at off normal directions. However it still does show strong viewing angle dependency in grey scale. In order to overcome such dependency, the divided domain of one pixel with ratio (85:15) with different tilt angle on top and bottom substrate (named

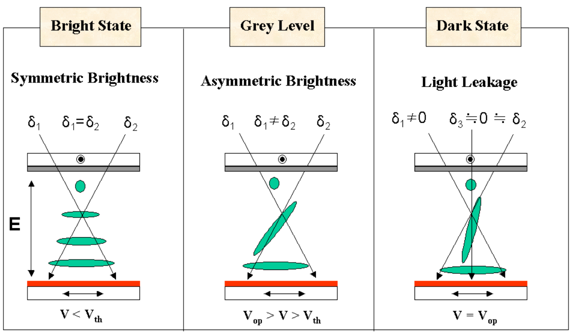


Fig. 1. Schematic drawing of the LC director configuration as increasing voltage in a TN cell.

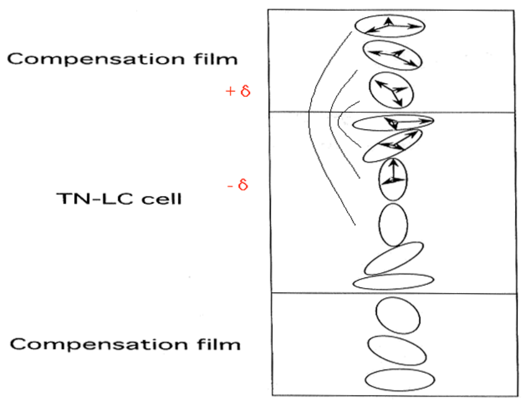


Fig. 2. Basic concept of optical compensation using discotic LC in a TN cell.

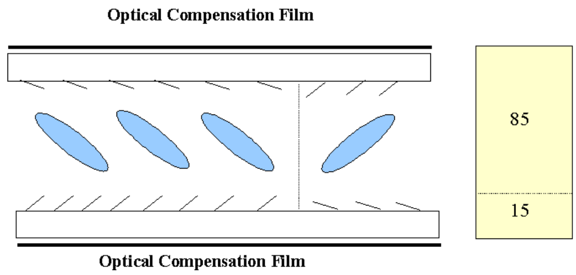


Fig. 3. Schematic drawing of two domain TN with different tilt directions in each domain and with different area ratio.

"Super V") has been suggested as shown in Fig. 3. In this way, the LC director tilts up in two directions so that the dependency of phase retardation as viewing angle changes is reduced, improving viewing angle though it is not still satisfactory. Another device to improve viewing angle dependency in grey sales is axially symmetric aligned microcell (ASM). In this device, the axially symmetric aligned TN structure is confined to polymer wall with square shape, as shown in Fig. 4 [9]. So when the voltage is applied, the LC director tilts up in all azimuthal directions so that the viewing angle dependency in grey levels is minimized.

2. IPS and FFS

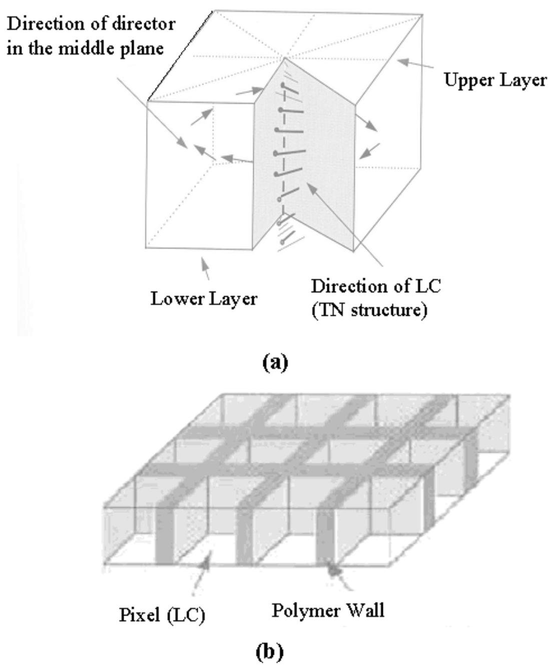
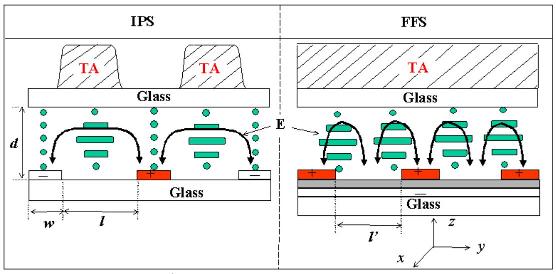


Fig. 4. (a) Director distribution and (b) polymer wall in ASM cell structure.



	IPS	FFS
l/d	>1	<1 or 0
l/w	>1	<1 or 0
Field	E_y	E_y, E_z
Electrodes	Metals or ITO	ITO

Fig. 5. Comparison of electrode structure and light transmittance between the IPS and the FFS devices.

In the TN device, the LC director tilts up along vertical field which is an intrinsic source for narrow viewing angle. Discarding such concept, new devices, IPS and FFS that the LC director rotates almost in plane have been suggested. In the IPS device, the LC molecules are homogeneously aligned with optic axis coincident with one of crossed polarizer axis, therefore the device appears to be black before applying voltage. When the voltage is applied, the horizontal field (E_y) is induced by source and common electrodes in slit form with a distance (l) such that the LC director rotates in-plane and phase retardation due to different propagation speeds of ordinary and extraordinary rays occurs, giving rise to transmittance. In this way, the change of δ value as viewing angle changes is reduced with relatively good dark state. However the device sacrifices light transmittance because the LC director above electrodes does not rotate. In order to solve such problem, the FFS device that utilize fringe field (E_y, E_z) with homogeneous alignment at initial state is suggested. The structure comparison between the IPS and the FFS devices are shown in Fig. 5. In the FFS device, fringe field drives the LC director to rotate above whole electrode giving rise to much high transmittance compared to that of the IPS device. In demerit, both devices show color shift along and perpendicular to the LC director due to different phase retardation value. In order to solve this problem, 2-domain IPS and 2-domain FFS devices that the LC director in one pixel rotates clockwise and anticlockwise to compensate difference of phase retardation along azimuthal direction are suggested as shown in Fig. 6. In this way, the color shift as the viewing direction changes is minimized, that is, the retardation values in vertical (δ_a) and horizontal (δ_b) directions are the same and consequently, the devices exhibit high image quality comparable to CRT display.

3. MVA, PVA and SE

In the VA devices, the LC molecules are vertically

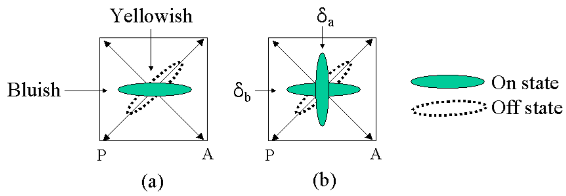


Fig. 6. Configuration of the LC director in one pixel of (a) normal IPS and (b) 2-domain IPS.

aligned to the substrates at initial state under crossed polarizers. The polarization state of linearly polarized light passed polarizer is not changed while passing the LC medium due to no phase difference, so that the light is blocked by the analyzer and the cell appears to be black. Though there is no leakage of light at normal direction, it occurs in oblique direction, especially in directions of 45° with one of optic axis of crossed polarizers. This is compressed by using negative birefringent film. All wide-viewing-angle VA devices need the compensation film. When a voltage greater than threshold voltage is applied, the LC director tilts down. If the LC director tilt down in one direction, again asymmetry in light luminance occurs, giving rise to strong viewing angle dependency. Therefore, several different approaches to make the LC director tilt down in four directions making 45o with respect to one of optic axes of crossed polarizers (see Fig. 7) have been suggested. In this way, the change rate of luminance given polar angle in all directions are about the same. In multi-domain VA device, the existence of disclination lines between the LC domains that lowers light transmission is inevitable as shown in a bright state of Fig. 7. In the MVA device, the LC molecules are almost vertically aligned with slight biased condition by protrusion on top substrate under crossed polarizers. The oblique field instead of vertical field by protrusion and slit patterned ITO on bottom substrate is induced to drive the LCs to tilt down as shown in Fig. 8 With zigzag shape of the protrusion

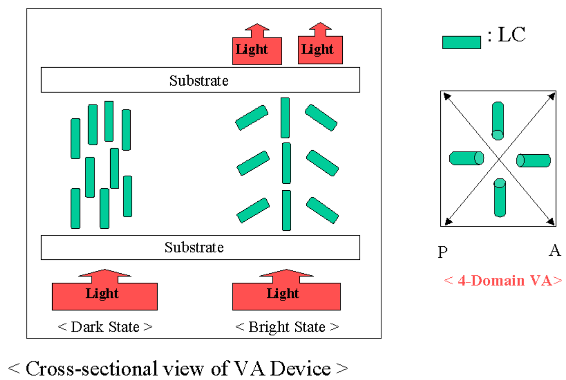


Fig. 7. The cell structure of the multi-domain VA devices and the LC director configuration of the 4-domain VA devices in a bright state.

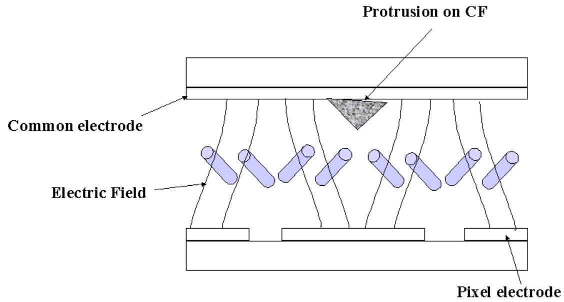


Fig. 8. The cross-sectional view of the MVA device with protrusion on top and patterned ITO on bottom substrates.

and the patterned ITO, the LC director can be tilted down in four directions. In the PVA and the SE devices, an oblique field induced by slit patterned ITO on top and bottom substrate drives the LC molecules vertically aligned to tilt down in several directions as shown in Fig. 9. The key design is how to pattern the ITOs for the LCs to tilt down stably.

4. Other VA devices

Another candidate for the VA device is combination of the vertical alignment and in-plane field driving, named VA-IPS [10]. In this device, the vertically aligned LC molecules with positive dielectric anisotropy tilt down in left and right directions by in-plane field, so 2-domain VA is formed as shown in Fig. 10. The device is very simple in manufacturing process but it has a high driving voltage and low transmittance. Recently new device upgrading the VA-IPS using oblique field by putting the dielectric layer and ITO on top substrate has been suggested [11]. The device shows improved light transmittance and extremely fast response time less than 16ms in all grey levels.

III. RESPONSE TIME IN LCDS

Response time in emitting displays like CRT is about microsecond level but over 10 ms in LCD. As a result, a phenomenon of the light transmittance corresponding to

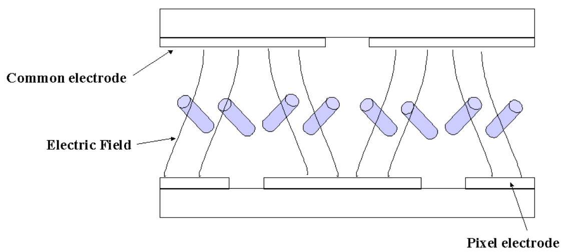


Fig. 9. The cross-sectional view of the PVA device.

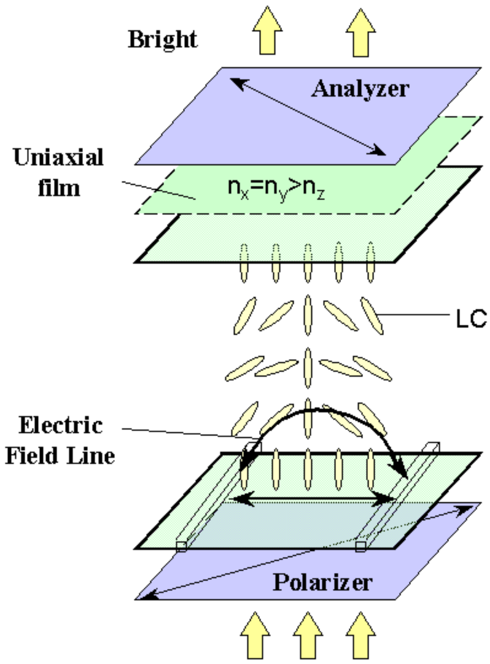


Fig. 10. The cell structure of the VA-IPS device with configuration of the LC director in bright state.

applied voltage between CRT and LCD is totally different as shown in Fig. 11. That is, CRT provides impulsive light transmittance given a data signal and a image is formed with a set of impulses. Consequently there is no blurring in motional image. However the LCD shows a static image, and as the result, edge smearing in moving object is observed [12]. In future LCD with fast response time less than few milliseconds, inserting a blank signal for the second half of every frame period is one way, so imitating light transmittance profile like in the CRT display as shown in Fig. 11. In the LCDs, two types of response time exist, on and off response times. For on response time, it mainly depends on rotational viscosity and the LC dynamics due to different electric field dependent dynamics. For off response time, it mainly depends on rotational viscosity, cell gap and elastic constants of the LC. To make the LCDs faster, the developments of low viscosity LC, lowering cell gap and control of the LC dynamics in a well-defined way are important. In TN and MVA devices, on-time response including all grey scales is widely spread in a range of 4∼ 60, that is, the ratio of slowest to fastest response (R) is about 10 but the IPS case is about 2.2 [13]. The comparison of response time in all grey levels among three devices is shown in Fig. 12. The low value of R in the IPS device is due to smaller energy difference in grey levels than that of the TN and MVA devices. For off response time, the R values are almost same among three devices, not very large though the absolute value of the IPS device is relatively small. Another approach to improve it intrinsically is using new display mode (OCB) [14]. Fig. 13 shows molecular dynamics dependent on applied voltage. The LC molecules initially in splay alignment transits to twist state and then to bend state as increasing voltage. The black and white states are controlled in bend state. In this device, the same flow direction (ν) in switching accelerates response time and it is below 10 ms in all grey levels though the rotational viscosity of nematic LC used is larger than 90 mPa.s. Nevertheless the device has a strong point in response time, the complicated dynamics renders commercialization of the device difficult. Utilizing fast response time of the device, recently full color LCD, named color field sequential LCD without color filter and with light emitting diode (LED) backlight thus improving panel transmittance at least 3 times is under developing [15]. In Table 2 is shown the summary of the LC devices that who has developed and commercialized, *i. e.*, it is under mass production (MP) or prototype (P).

IV. ULTRA-FFS DEVICE

In the FFS device, the LC with negative dielectric anisotropy is effective in light efficiency but the rota-

Table 2. Existing LC devices and development status.

LC Mode	Technology	Industry	Status
TN	Film Compensated TN	Sharp/Others	MP
	2-domain TN + Film (Super V)	Sharp	?
	Four domain TN (UV, Domain Control)	LG-P/NEC	P
	Multi domain TN (ASM)	Sharp	P
In-Plane Rotation	IPS	Hitachi/Others	MP
	FFS	Hyundai	MP
VA	MVA	Fujitsu/Others	MP
	SE, PVA	SE/SEC	P
	VA-IPS	Hyundai/SEC	P
	Upgraded VA-IPS	Fujitsu	P
OCB	Self Compensation + Film	Tohoku U./Others	P

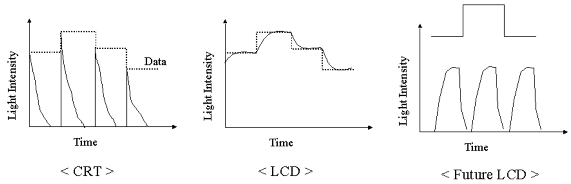


Fig. 11. Comparison of light emission profiles between CRT, LCD and future LCD.

tional viscosity is higher than 100 mPa.s. Recently, we have used a positive LC with low value of rotational viscosity and optimized light efficiency in a maximum way by optimizing rubbing direction and retardation of the cell [16]. When the positive LC is used, the LC director configuration is mixed states of the TN and the IPS modes in white state and also the area with TN-like configuration of the LC director mainly dominates the light transmittance. The first minimum condition of the TN device for maximum transmittance is 0.48 μm while it is about 0.3 μm for the IPS device. Therefore the FFS device with positive LC needs high retardation value of the cell for maximum light efficiency. The shape of pixel electrode is also changed into wedge form so that the LC director in homogeneous alignment in one pixel rotates in two directions, decreasing the bluish and yellowish color shift in certain directions as shown in Fig. 14. With such pixel structure, the color shift is strongly reduced compared with that of the normal FFS device, and further the leakage of light between pixel and data electrodes is automatically blocked since the direction between a field and the LC director is same. This results in low crosstalk in Ultra-FFS device. Consequently 2-domain FFS device shows high image quality like CRT, best among existing TFT-LCDs and fast response time of 28 ms.

V. CONCLUSION

In this paper, how the LCDs have been developed in performance, especially viewing angle and response time is reviewed. Last 5 years, the quality and the cost have been greatly improved together such that the application area is extending from notebook to monitor, TV and other application displays. The competitiveness of TFT-LCDs depends on performance and cost. The LC mode is the critical factor that determines the competitiveness. Notwithstanding development of many LC devices, only few are under production. In image quality viewpoint, 2-domain IPS and FFS devices seems best and are comparable to the CRT display though still needs further improvements in color reproduction and low contrast ratio in dark environment. Extensive improvement on response time is also required. At present, every industry is aggressively working on improvement of response time though it has an intrinsic difficulty, expecting less than 10ms within 2 years. Unfortunately at a present technology level, high quality TFT-LCDs lower yield, increasing production cost. In order to overcome such trade-off, a breakthrough in technology and production process is absolutely required and is under going. We expect that in 5 years, the LCD will match the CRT display in performance and cost, finally exceeding the CRT market volume.

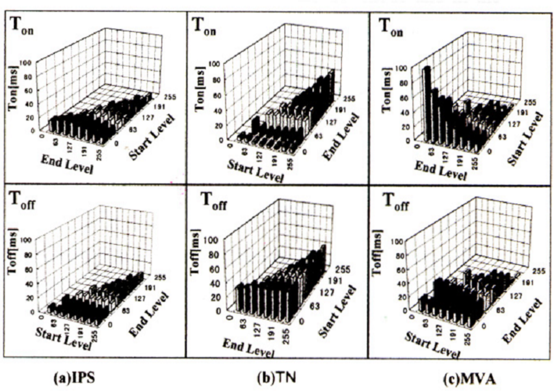


Fig. 12. The comparison of response times in all grey levels among three devices.

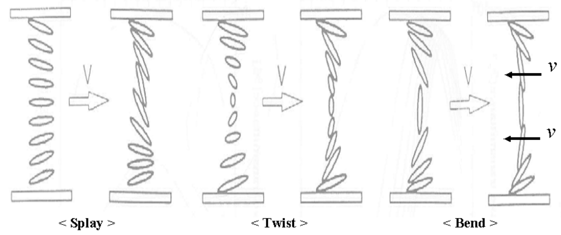


Fig. 13. Voltage-dependent dynamics of the OCB device.

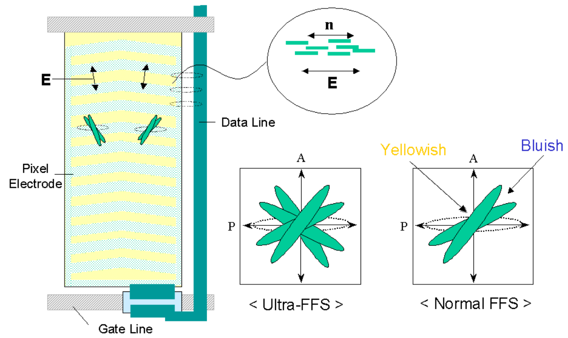


Fig. 14. The pixel structure of the Ultra-FFS device with configuration of the LC director in white state, comparing that of the normal FFS device, The P, A, n and E represents for polarizer, analyzer, the LC director and electric field, respectively.

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