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An Overview of Wide-Viewing-Angle LCD Using Inter-Digital Electrodes

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1. ABSTRACT

We have compared the performance of wide-viewing angle technology using interdigital electrodes, which are in-plane switching (IPS), fringing field switching (FFS) and finger on plane (FOP).What we have found is that IPS has the fatest response, FOP has the largest process window, and FFS can provide the similar transmittance as FOP but with more difficult process. The basic properties of these technologies will be reviewed in this paper.

Keywords: wide-viewing angle; liquid crystal display; in-plane switching, fringing field switching, finger on plane

2. INTRODUCTION

Applications of LCDs to the huge potential market of desktop monitor and LCD TV have just been started. It is generally expected that there will be around 10% replacement of CRT in the monitor market in the year 2001. For these markets, large area LCD is necessary in which the development of wide viewing angle technology is one of key issues.

In these years, many techniques have been developed to overcome the above limitation. The most populare techniques are film-compensated TN-LCD, multi-domain vertically align (MVA) LCD, in-plane-switching (IPS) LCD, optically compensated bend (OCB) LCD. Each technique has its own advantages and drawbacks; however, it seems that none of them can dominate the LCD monitor market at this moment. Hitachi has done much effort and given many contributions on the IPS mode. However, according to the IPS structure, several different techniques are published such as Hyundai's fringe-field-switching (FFS) [1], comb-on-plane (COPS) [4] and ERSO's Finger-on-Plane (FOP) [5][6] which is similar to the second version of FFS [2]. In order to distinguish, we use FOP and FFS as the names of the structures shown in Fig. 1c and Fig. 1b, respectively. All of these techniques use the inter-digital electrodes. In this paper, we will have an overview of the wide-viewing-angle LCD using inter-digital electrode, especially focus on the comparison of IPS, FFS and FOP.

3. OVERVIEW OF IPS, FFS AND FOP

3.1 Structure description

Fig. 1a, 1b and 1c show the structures of the three technologies describing the difference in light transmitted area and electrode structure. In the IPS cell, the distance between electrodes is larger than the cell gap and the width of the electrode. Then the homogeneously aligned liquid crystal molecules do mainly twist deformation in horizontal plane by the horizontal electric field, giving rise to light transimttance. However, the molecules above electrodes do not go through twist deformation but tilt. As a result, the area that light can be transmitted is reduced. In the FFS and FOP cell, both the common and pixel electrodes are transparent. The distance between electrodes is very small around 0-1um in FFS cell, and is about 3-5um in FOP cell [1][2]. As a result, the electric field parallel to the substrate can not be formed but instead the fringing field is formed in the whole area. Because the pretilt angle of LC director is very low, only Ey has contribution to the dielectric torque when a negative LC is used. Almost in whole areas, the Ey exits such that the liquid crystal molecules do twist

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deformation in plane and resulting in light transmission. In the IPS cell, both negative and positive liquid crystal material can be used, while in FFS and FOP, only negative type liquid crystal is suitable. Nowadays, the negative liquid crystal is more expensive and does not have many choices. Otherwise, the dielectric anisotropy of the negative LC is smaller compared to that of the positive LC, such that the driving voltage may get higher for FFS and Fop cells. This may be a disadvantage for FFS and FOP compared to IPS.

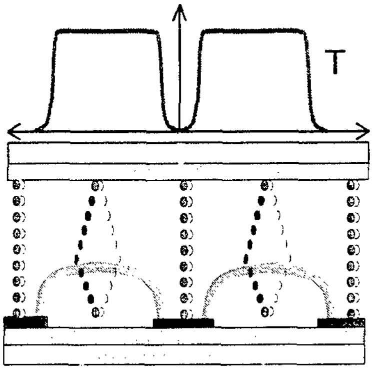

Fig. 1a IPS cell

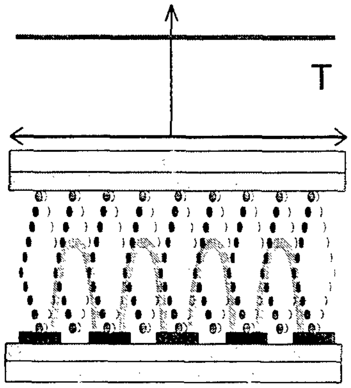

Fig. 1b FFS cell

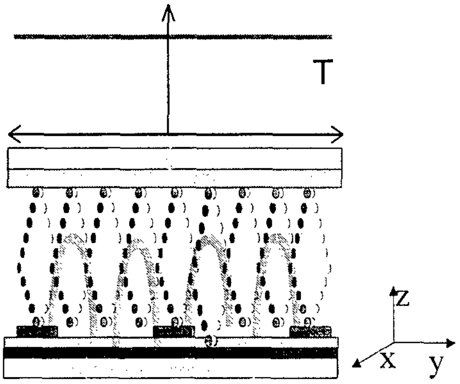

Fig. 1c FOP cell

For IPS cell, both the pixel and common electrodes are formed of metal and the pixel electrode can be built with the data bus at the same time; the common electrode can be built with the scan bus at the same time. Therefore, the number of the process is not large. Samsung has developed a 3-masks process in the IPS TFT process [23]. Compared to the IPS cell, both FFS and FOP need 2 or 3 more processes because the pixel and common electrodes in FOP and FFS are formed of ITO. For the FFS process, it is more difficult to control the very thin distance between electrodes. But for the FOP, the upper and lower electrodes have larger alignment tolerance. On the other hand, In the IPS cell, the pixel and counter electrodes are formed using data and scan bus metals that the thickness at least above 1000A, the LC molecules do not align so well in the dark state and may cause light leakage [3]. However in the FFS and FOP cell, the pixel and common electrodes are ITOs having a thickness about 400A, so good alignment of LC is obtained without extra process.

In order to avoid the current leakage due to the TFT off state and voltage drop due to the feed through of the scan line, we should have a capacitance as large as possible. In the traditional pixel design, the large storage capacitor gets better image quality but less light transmission. In Fig. 2a to 2c, the pixel structure of IPS, FFS and FOP are shown. For the IPS and FFS cell, both need additional area to form the storage capacitor. But for the FOP cell, it is very good that the overlap areas of the common and pixel electrodes can be treated as the storage capacitor and get a very high aperture ratio. Hyundai claimed that their design could achieve about 90% light efficiency of the TN mode [1][2]. And ERSO has developed a 12.4" SXGA FOP-TFT LCD in which a sub-pixel size is 64um*192um with 80% aperture ratio [6]. In IPS cell, the metal electrodes occupy additional aperture ratio such that IPS gets the lowest aperture ratio compared to the other two modes.

	IPS	FFS	FOP
Electrode distance	larger	Very small	zero
Field useful	Ey	Ey, Ez	Ey, Ez
Electrode	Metals or ITO	ITO	ITO
LC material	Positive and negative	negative	negative
Storage capacitor	Need additional area	Need additional area	Self-formed
Process number	few	larger	larger
Aperture	lowest	middle	Highest

Table 1

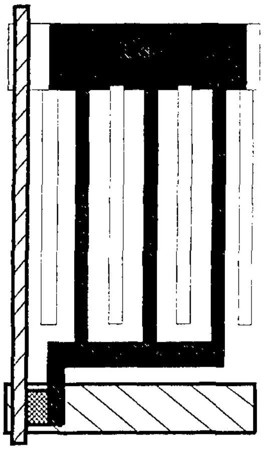

Fig. 2a IPS pixel structure

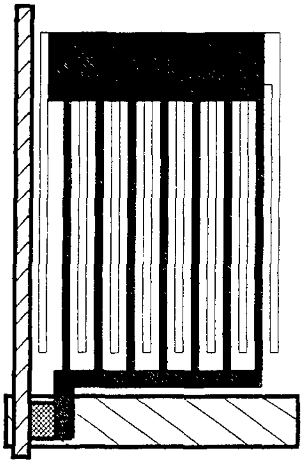

Fig. 2b FFS pixel structure

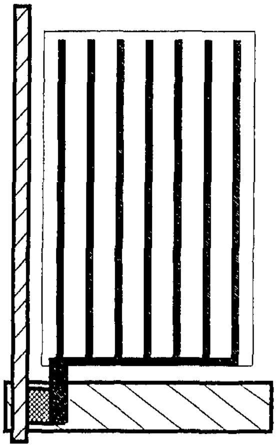

Fig.2c FOP pixel structure

The brief comparison of the three structures is shown in Table 1.

3.2 Electro-optic characteristics

Fig. 3a and Fig. 3b show the light transmission along the y direction corresponding to IPS and FOP respectively. For the IPS mode, because the distance of the electrodes is larger, in the light transmission area, the horizontal electric field is almost the same for each y position. The LC molecules for each horizontal position twist similar angle as shown in Fig. 4a resulting in almost the same light transmission as Fig. 3a shows. For the FOP and FFS cell in which the fringe field dominate such that the electric field has larger difference in every horizontal position. For a given voltage, the LC molecules twist for different degree as shown in Fig. 4b resulting in different transmittance as shown in Fig. 3b. If we define the light efficiency as light detected (T) divided by the light transmission area (A) (Eff=T/A), the IPS cell gets the highest value although the FOP gets the highest light transmission due to the highest aperture.

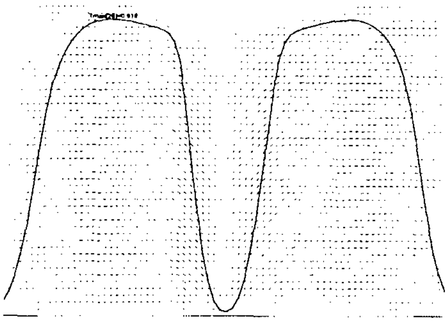

Fig. 3a Light transmission profile of IPS

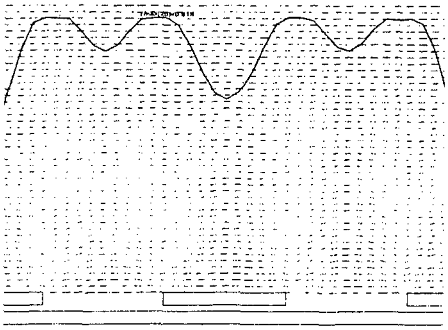

Fig. 3b Light transmission profile of FFS and FOP

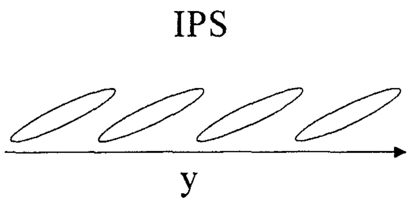

Fig. 4a Top view of LC distribution along the y direction

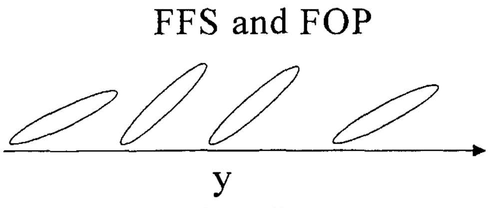

Fig. 4b Top view of LC distribution along the y direction

The color shift is very serious in the IPS mode while the viewing angle is large especially at the direction of 45 degree azimathal angle (ϕ) from polarization axis of polarizer. The status is shown in Fig. 5a. While the viewing angle is parallel to the director, blue shift occurs due to the small Δnd, and yellow shift occurs due to the large Δnd when perpendicular to the director. In the FOP and FFS cell, the color shift is not so bad compared to the IPS cell because the LC director inhomogeneously distribute as shown in Fig. 5b. Fig. 6a and Fig. 6b show the experiment results of the color shift for white level near the maximum transmission of IPS cell and FOP cell respectively for polar angle (θ) range is less than 60 degree in all ϕ angles. One can find that the IPS cell gets the worse result but the FOP is not also good enough to eliminate the dispersion problem. People have used herring-bone shape electrode structure to form a two domain IPS [11] and can get good results. Actually, this structure can be applied to the FOP and FFS cell, too. However when a two-domain structure is used, the light transmission will decrease a little.

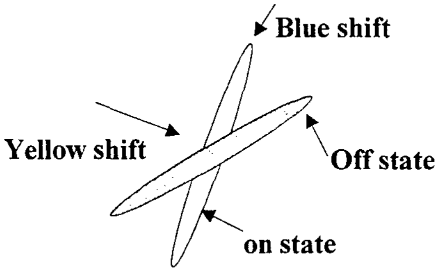

Fig. 5a Average effect for the LC distribution

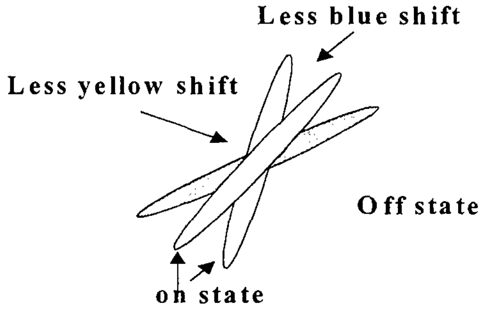

Fig. 5b Average effect for the LC distribution

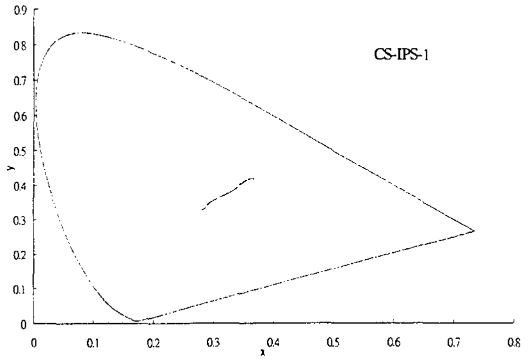

Fig. 6a Color shift for IPS

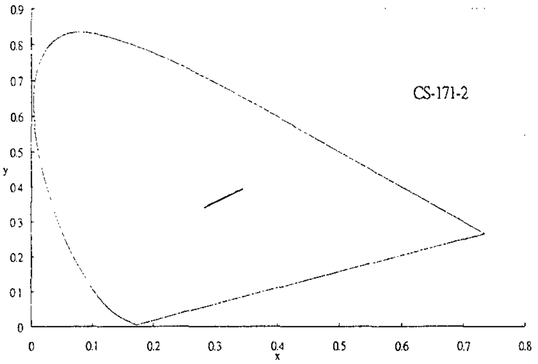

Fig. 6b Color shift for FFS and FOP

The gray level inversion is not a serious problem in the IPS, FOP, and FFS cell. As shown in Fig. 7a, the regions where no gray levels inversion of the IPS cell are very large [8]. The FOP and FFS cell have the same property according to our simulation results. Fig. 8a and 8b show the simulation results of the light transmission of 8 gray levels of IPS and FOP cells at the direction of 45 degree azimathal angle (ϕ) from polarization axis of polarizer, respectively. From Fig. 8a and Fig. 8b, one can find that only the two darkest gray levels cross over at about 45 degree. In IPS and FOP, two-domain modes can obtain estimate the inversion of gray scale. Due to the perfect dark state, the IPS, FFS and FOP can get large region where the contrast ratio over 10. Fig. 7b shows the iso-contrast curves for the FOP cell [2]. We find that the IPS, FFS and FOP have the similar iso-contrast contours according to our simulation results.

Because the cell gap is shorter than the distance between electrodes, the black resin with high specific resistance but not metal is often used as the black matrix material in order to avoid disturbing the electric field in LC layer in the IPS cell [17]. However, in the FFS and FOP cell, the electrode distance is very small or zero, the field strength caused by Cr BM of upper substrate does not affect the field distribution much in modulated area.

Hyundai has checked that the influence of the Cr BM of FFS is very small [3]. On the other hand, ERSO has developed the ITO on top structure for FOP cell in which BM is not necessary because it uses the ITO to shield the fringe field caused from data and scan line [6]. Such structure can get very high aperture ratio.

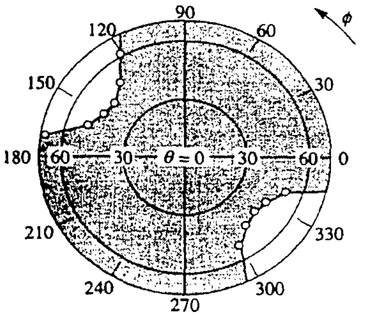

Fig. 7a Gray level inversion regions of IPS [8].

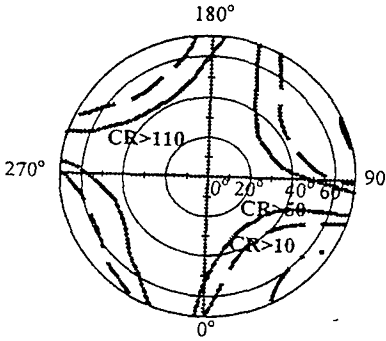

Fig. 7b Iso-contrast curve of the FFS cells [2].

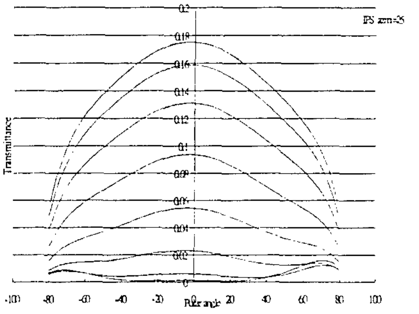

Fig. 8a 8 gray levels of IPS

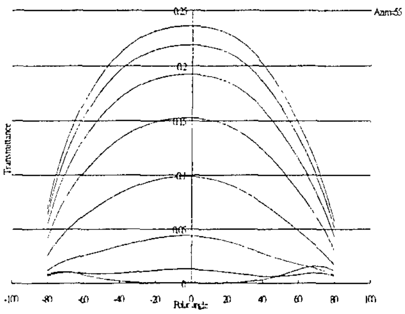

Fig. 8b 8 gray levels of FOP

Cross-talk caused by the source bus-line has two origins. One is capacitive coupling between the source bus-lines and the pixel electrods. Fluctuation of the pixel electrode potential $\Delta Vp=(Csp/Ct)\ \Delta Vs$, where the Csp, Ct and ΔVs are capacitance between the source bus line and a pixel electrode, and total capacitance of a pixel and variation of the source bus line potential, respectively. In the IPS cell, Ct is small because the capacitance of the LC is very samll compared to traditional TN cell. But for the FOP cell, because the Cst is very large that the total capacitance is very large, too. Such that the FOP has less cross-talk issue than the FFS and IPS cells. The second origin is the leakage of the source bus line potential to the optical switching medium in a pixel between the two electrodes which are driving the LCs. This is especially serious in the IPS cell and some methods are published to shield the leakage field. But in these methods, not additional process is needed or the loading of the data bus increase causing a voltage wave distortion. According to this point, IPS suffers more problems than FFS.

For the IPS, FFS and FOP cell, it is one of the advantages that the driving waveform of the scan driver can be simplified. For a good quality of image, one has to consider the voltage coupling of the scan bus when the gate voltage turns off. Ct includes Clc, Cst, and Cgd, where Clc, Cst, and Cgd represent the capacitance of liquid crystal, storage capacitance and capacitance between gate and drain. When the voltage of scan line changes, it causes the pixel potential drop as $\Delta Vp=\{Cgd/(Cgd+Clc+Cst)\ \Delta Vg$. Unfortunately the value of Clc is not constant and varies with voltage that will cause the pixel potential asymmetric. In most cases, we can not just change the common voltage level to compensate the voltage drop because the value of Clc is not small compare to Ct and the flicker will occur. One can use a 3-level or 4 level driving wave form as shown in Fig. 9 to compensate the voltage difference in the traditional TN cell. In the IPS, and FFS and FOP cell, the value of Clc is much smaller than that of TN cell, we can get more symmetric pixel potential by just using a simpler 2-level driving wave-form as shown in Fig. 9.

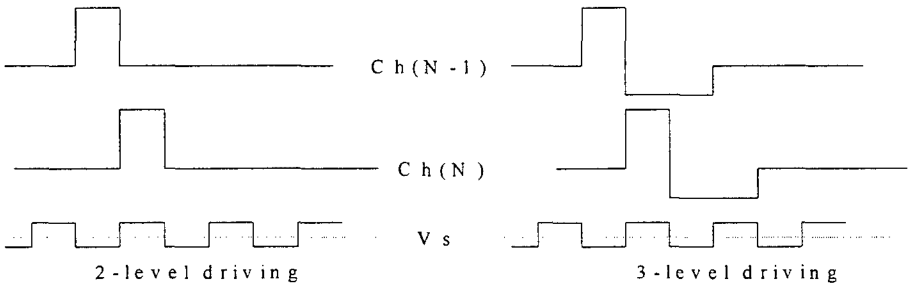

Fig. 9 The driving wave-form of the Scan bus

The IPS cell is critical to the cell gap [14]. Hitachi claimed a method based on enlargement of effective cell gap with the extrapolation length that generated with weak-anchoring effects at liquid crystal and alignment layer interface [15]. But a weak anchoring boundary may have the hysterics phenomenon. We have compared the cell gap tolerance of IPS and FOP [6]. V-T curves shown in Fig. 10b correspond to cell gap d1-d4 of FOP LCD and those in Fig. 10a to cell gap D1-D3 of IPS LCD. The two V-T curves of d2 and d4, with cell gap deviation of ±5% from d3, almost coincide with curve of d3. For curve d1 with larger cell gap deviation～-11% from d3, the 6V transmittance (T(6V) is 97% of on-state (6V) transmittance of cell gap d3. For IPS LCD with similar cell gap deviation (Dl and D3 with ±12.5% deviated from D2), differences in Von and on-state transmittance are larger as shown in Fig. 9a. From the comparison, it is obvious that FOP LCD have smaller cell gap dependence in terms of on-state voltages.

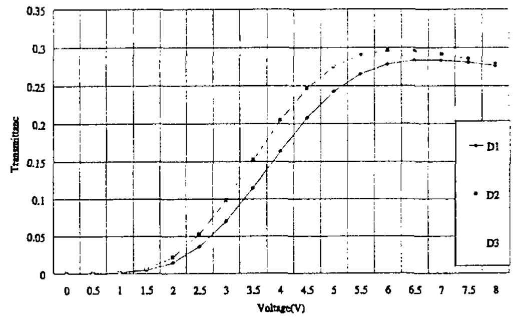

Fig. 10a Simulation results of the cell gap variations in IPS LCD.

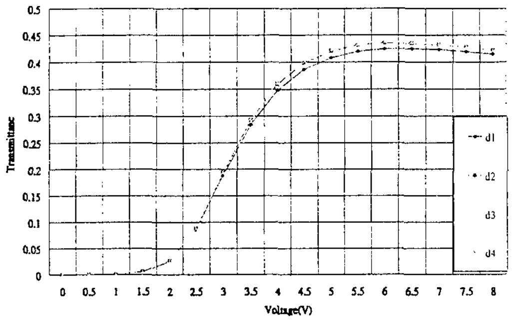

Fig. 10b Simulation results of the cell gap variations inFOP LCD

The response time of the IPS cell has the relation as follows:

$$Ton= \gamma / \varepsilon_0 \Delta \varepsilon (E^2-E_c^2), \quad Toff= \gamma d^2 / K_2 \pi^2.$$

Where γ , d , K_2 and $\Delta \varepsilon$ are the rational viscosity cell gap, elastic constant of twist deformation and dielectric anisotropy of liquid crystal, respectively. Due to that the value of K_{22} is smaller than K_{11} and K_{33}, the response time of IPS, FOP and FFS is slower than traditional TN cell. But for the switching times between gray levels of IPS cell are fast than that of TN and MVA cells [11][19]. Some methods to increase the response time are published. Hitachi used proper LC material, smaller cell gap and high voltage (15V) to improve the response time to 20 ms [11]. IBM Japan improved the switching speed by adding a chiral agent to negative $\Delta \varepsilon$ nematic liquid crystal [20]. FFS and FOP cell use the negative type liquid crystal which has the higher value of γ and lower value of $\Delta \varepsilon$ such that the response time of these two modes is slower than IPS mode.

It is well known that the IPS mode has high value for the voltage holding ratio (VHR) [21][22]. The VHR has relation with time constant (R*C) and discharge path. Fig. 11a, b, c and d show the equivalent circuits for IPS, FFS, FOP and TN cell respectively. Due to the discharge path, IPS gets higher VHR than TN. The equivalent circuit of FFS is the same with IPS, but the value of capacitance is larger than that of IPS and the value of resistance is smaller than that of IPS because the electrode distance in FFS is smaller than that in IPS. For the FOP cell, the value of the storage capacitance is very large such that it has perfect property for VHR. The residual DC can be divided into two reasons. One is the ion absorption in the PI and liquid crystal interface and the other one is the discharge capacity for each layer. The first reason has relation with the material and we will not discuss here. The second one has relation with the equivalent circuit, too. With the same behavior with VHR, FOP will get the highest value of Rdc, FFS and IPS are the next, and TN is the smallest one. But if we consider both reasons together, it is hard to distinguish between IPS and FFS and FOP.

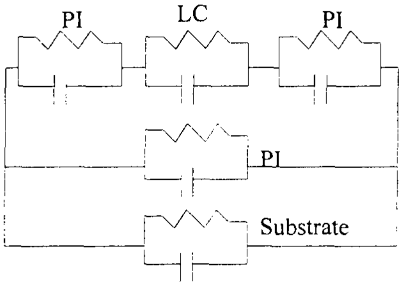

Fig. 11a The equivalent circuit of IPS

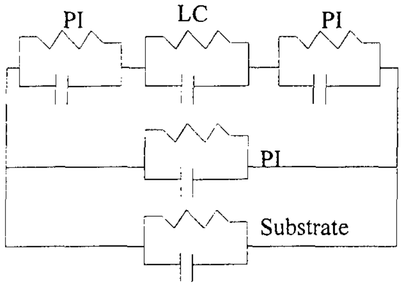

Fig. 11b The equivalent circuit of FFS

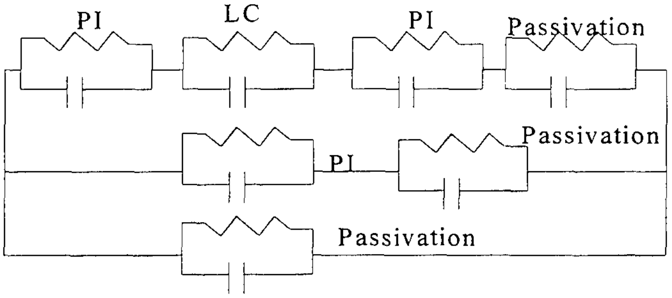

Fig. 11c The equivalent circuit of FOP.

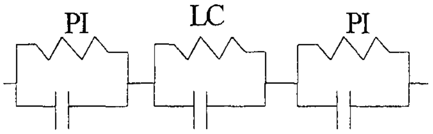

Fig. 11d The equivalent circuit of TN

The brief comparison of the three structures mentioned above is shown in Table 2 as follows.

	IPS	FFS	FOP
Color shift	worse	Less worse	Less worse
Response	faster	slow	slow
Light efficiency (T/A)	higher	high	high
Light transmission	lowest	high	highest
Gray-level inversion	good	good	good
VHR	good	good	perfect
Rdc	bad	bad	bad
Viewing angle	perfect	perfect	perfect
Cell gap tolerance	bad	good	good
BM material	limited	flexible	flexible
Cross-talk	Not good	better	Best

Table 2

4. CONCLUSION

In the paper, we have compared the structures and the electro-optics properties between the IPS, FFS and FOP cells. The three modes are very good in viewing angle, VHR and gray level inversion. The IPS cell has the simpler process and faster response but lowest light transmission. FOP has the largest aperture and less cross-talk, but 2-3 more process are needed. FFS is not so good compared to the FOP cell. Otherwise, the residual DC property of the FFS and FOP are not investigated much, one can put more effort on it.

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