

## Polarization state of the diffraction peaks in In-Plane Switching cells

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### ABSTRACT

In-Plane Switching LCD's are an example of microscopic 2-dimensional structures. Because of their inherent periodicity in the cell structure, an incoming plane wave is split up in several diffraction orders. Our goal is to determine the polarization state of these different peaks and compare them with numerical simulations.

### INTRODUCTION

LCD's using the in-plane switching mode (IPS) have much better viewing angle characteristics than more classical types such as the twisted nematic and super twisted nematic LCD's. The optics of IPS-cells are usually studied by the transmitted intensity [1] or the intensity variation at the surface of a pixel [2]. But when a plane wave (e.g. laser beam) propagates through an IPS-pixel several diffraction orders appear, caused by the periodicity of the cell structure. In [3] this effect has been studied to produce high-resolution phase gratings with liquid crystals.

In this paper the intensity and the polarization state of the various diffraction orders are studied by comparing measurements and simulations. This is important because normally a display is not observed through a microscope, but from a certain distance. During the investigation the influence of the electrodes on the diffraction phenomenon is examined.

### DIFFRACTION MEASUREMENTS ON AN IN-PLANE SWITCHING LCD

The IPS test cell contains the Merck liquid crystal ZLI4792 and has a thickness of 4  $\mu\text{m}$ . The lateral dimension of the electrodes will further be indicated with the parameter L and the gap in between the electrodes with the parameter G. Figure 1 shows a schematic picture of the complete measurement setup. The light source of the measurement setup is a He-Ne laser, the laser beam ( $\lambda = 632.8 \text{ nm}$ ) propagates through a linear polarizer, the IPS test cell and a rotatable linear analyzer. The orientation of the polarizer is perpendicular to the rubbing direction of the alignment layers (which makes an angle of about 10 degrees with the direction of the ITO electrodes). After propagation through the LCD, several discrete diffraction orders can be observed because of the periodicity inside the IPS-structure. The purpose of our measurements and simulations is to determine the intensity and

polarization state of each diffraction order. The intensity of an order after it has propagated through the analyzer is measured with a photo-diode. A diaphragm is used to assure that only one diffraction order at a time reaches the photo-diode. Analyzing the polarization state of a diffraction order is done by measurements at different angles of the analyzer. The polarization state of a diffraction order is generally elliptic and according to the Stokes parameters [4] a measurement along 3 axes of the analyzer should be enough to find the shape and orientation of the polarization-ellips. But practice shows that the results are more accurate and reliable when doing measurements at a larger number of angles. The measurements have been done at angles from  $0^\circ$  to  $180^\circ$  in steps of  $10^\circ$ .

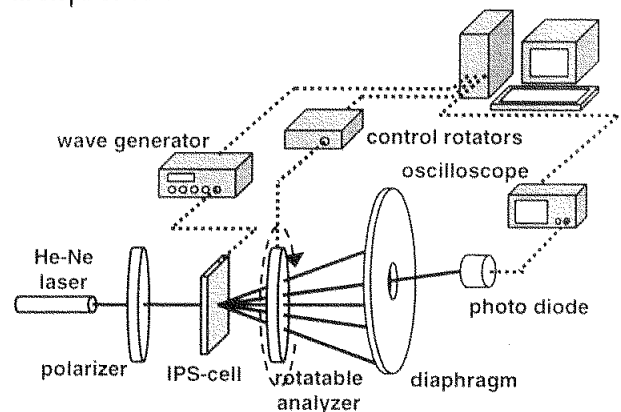


Figure 1. Schematic representation of the measurement setup

The ellips is determined by 3 parameters : the length of the two main axes and the angle over which the long axis of the ellips is rotated relative to the x-axis. The propagation of an arbitrary polarization through the analyzer can be calculated by the projection of the ellips on the non-absorbing axis of the polarizer.

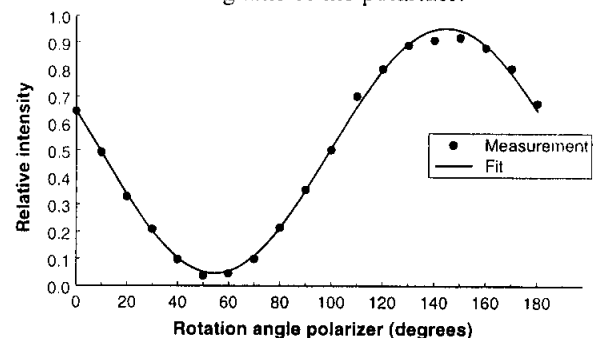


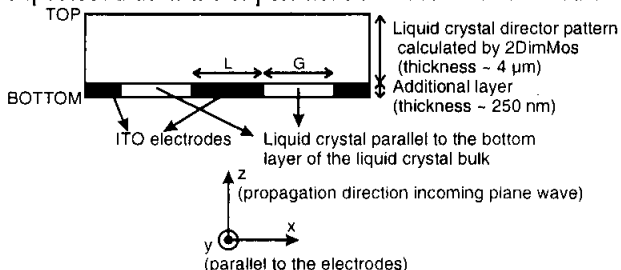
Figure 2. Performed measurements to determine the polarization state + the matching fit

By calculating this projection at the correct angles and solving the three ellips-parameters for the best fit with the measurements, the polarization state of the diffraction order is determined. Figure 2 shows an example of a measurement and the corresponding best fit. The intensity of each measurement is normalized to eliminate one parameter. The total intensity of each order can be found by summing the intensity along two orthogonal directions of the analyzer or by doing a separate measurement of each order without the analyzer. Out of these measurements, only the shape and orientation of the ellips are determined. With an extra measurement using a circular polarizer or a  $\lambda/4$  plate the sense in which the polarization-ellips is described can also be determined.

### SIMPLIFIED SIMULATION MODEL OF THE DIFFRACTION PHENOMENON

In reality, diffraction occurs when the plane wave enters the structure which contains the lateral variations. Once it has left the structure the effects of diffraction become visible. A full calculation of the propagation and diffraction of the incoming wave through the structure is tough and time-consuming. But because the IPS-cell has a limited thickness of about  $4 \mu\text{m}$ , the entering plane wave is assumed to suffer only lateral phase modulation inside the liquid crystal. In a first approach, the propagation through the liquid crystal can be calculated by using the Jones-calculus [5]. The director pattern of the liquid crystal layer is given in a regular rectangular grid. The Jones-calculus is carried out along the z-axis for each of the x,y gridpoints, assuming that the optical properties for this x,y coordinate extend over the entire plane. The Jones-calculus provides the phase and polarization state of the wave at each grid point at the top of the liquid crystal layer. The observed diffraction in the far field is calculated afterwards using the Fresnel-formula for diffraction [4].

An important observation is the diffraction occurring when no voltage is applied. The director pattern of the molecules is considered to be one-dimensional (all molecule directors parallel to the rubbing direction). Because there is no lateral variation no diffraction is expected. But in the experiment diffraction does occur.

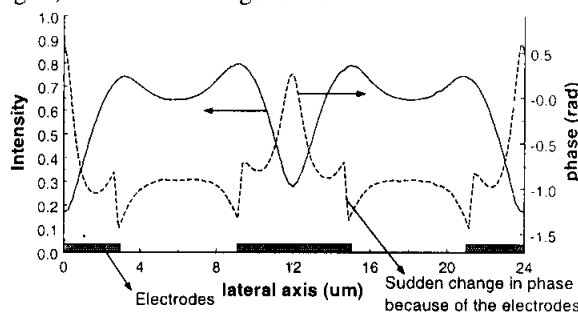


**Figure 3. Simulation model of the In-Plane Switching test cell**

This is due to the periodical electrode structure. The presence of interdigitated electrodes causes a periodical phase modulation. This is included in the model by

adding an extra layer at the bottom with either isotropic ITO for the electrodes or LC material parallel to the bottom layer for the regions in between (fig. 3).

To calculate the diffraction the modulated wave is decomposed in two waves with orthogonal linear polarizations (along the x- and y-axis) and the diffraction orders are calculated separately for both using a complex fast fourier transform (fft). Splitting up the wave is possible because two orthogonal waves cannot interfere with each other [4]. It is important not to neglect the phase information of the modulated waves (fig. 4) when calculating the fft.

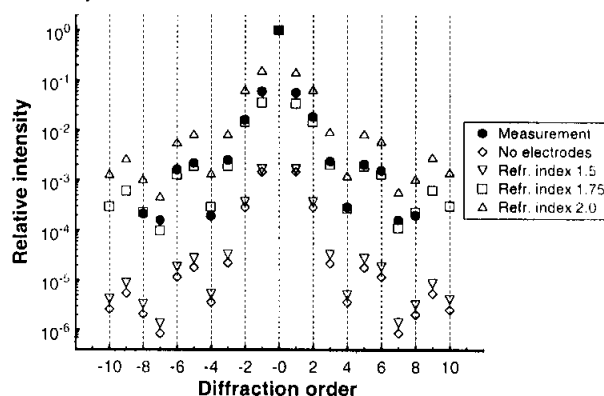


**Figure 4. Intensity and phase variation of the decomposed wave along the x-axis on the top surface of the IPS-Cell (IPS-parameters :  $L = G = 6 \mu\text{m}$ )**

By combining the two diffraction patterns and considering the phase information, the polarization state of each order is found. The choice for the orientation of the x-axis when decomposing the complex wave does not influence the result.

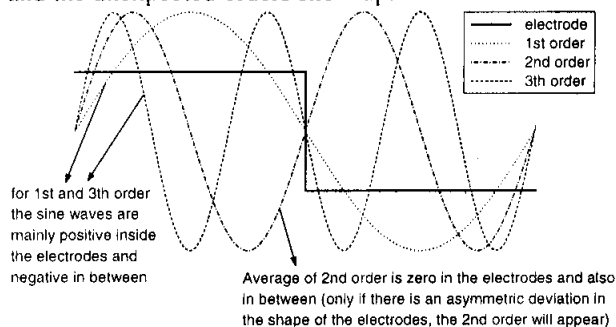
### COMPARISON OF MEASUREMENTS AND SIMULATIONS

According to the specifications of the manufacturer the thickness of the ITO is about 277 nm. The refractive index of the ITO is subject to deposition parameters. By choosing an appropriate value for the refractive index it is possible to get a good resemblance between the simulated intensity pattern and the measured one (fig. 5). The best fit is found for a refractive index of 1.77. The values in the graph are scaled so that the intensity of the zero order is 1 for all series.



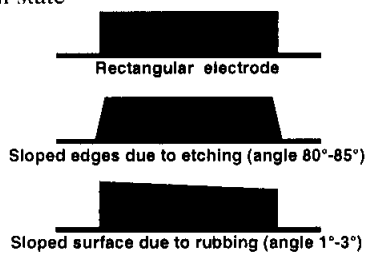
**Figure 5. Relative intensity of the diffraction orders at 3 Volts for different refractive indices of the ITO (IPS-parameters :  $L = 18 \mu\text{m}$ ,  $G = 6 \mu\text{m}$ )**

When looking at the diffraction orders when no voltage is applied, Fourier analysis predicts that certain diffraction orders disappear. E.g. in a symmetric cell (width of the electrodes equals the gap in between) the even orders should vanish, because their average contribution in between and inside the electrodes is zero (fig. 6). In the intensity profile of figure 5 the orders  $\pm 4$  have an intensity that is 10 times lower than those of their neighbours. If the electrodes are perfectly symmetric they should disappear at 0 Volts. Of course when a voltage above threshold is applied an additional phase modulation of the liquid crystal layer is applied and the unexpected orders show up.



**Figure 6. Comparison between diffraction orders and the shape of the electrodes**

The reason that some of the main orders do not disappear at 0 Volts might be some asymmetry in the electrode shape (fig. 7). One possibility is that the top surface of the electrodes is not entirely flat. A small slope could be present caused by the rubbing process. Another possibility is that the electrode has no straight but sloped edges. When looking at the etching process, this is more likely. These adaptations have their main influence on the intensity pattern, not on the polarization state

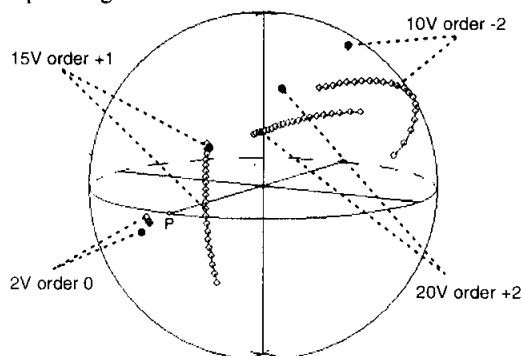


**Figure 7. Asymmetries in the shape of the electrodes causing missing diffraction orders to appear**

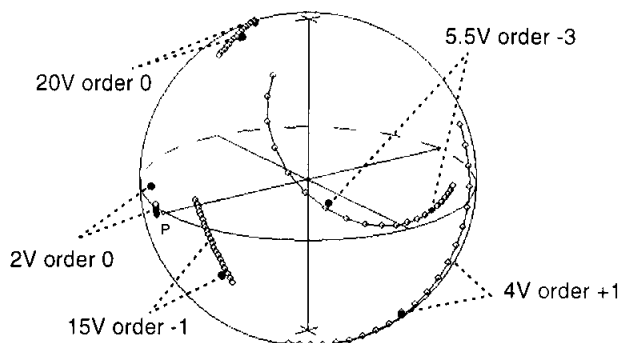
For some structures, at higher voltages the experiment also shows additional orders between the main orders which were expected by diffraction. These are due to a different response to a positive and a negative voltage applied between two neighbouring electrodes. This doubles the period of the structure and the number of diffraction orders. They are visible in the experiment, but their very weak intensity makes it difficult to measure them with our setup.

Simulation and experimental results on the polarization state correspond well for most orders and voltages. Figures 8 and 9 show some examples represented on the Poincare-sphere [4] for two IPS-structures with different

dimensions (L and G). Because the intensity drops very fast with higher orders, the polarization state could only be measured accurately until the third order. On the Poincare-sphere linear polarizations are located on the equator while the azimuth angle represents the ellipticity. The point P indicates the entrance polarization. Only some of the results are shown in the Poincaré sphere to avoid overlap. Both figures show measurements of polarizations together with the corresponding simulation for an electrode thickness varying from 0 to 500 nm. The thickness of the electrodes is generally the only adaptable parameter in the deposition process, normally the refractive index cannot be adjusted. The hollow circles connected with a line represent the simulations and the black spots the corresponding measurements.



**Figure 8. Polarization state of the diffraction orders (IPS-parameters : L = G = 6 μm)**

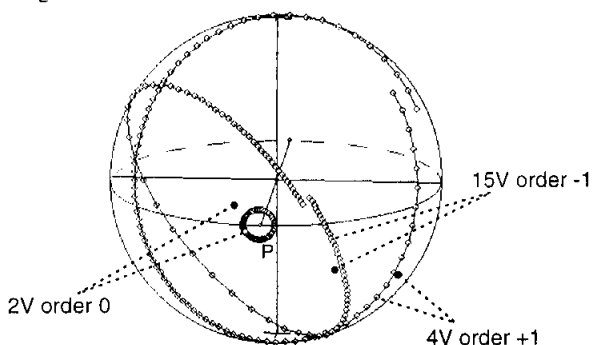


**Figure 9. Polarization state of the diffraction orders (IPS-parameters : L = 18 μm, G = 6 μm)**

A rather good agreement between measurements and simulations is seen at higher voltages. In ref. [2] it was shown that deviations from the Jones-calculus may occur at rapid variations in refractive index (of the order of a wavelength). Especially small differences in intensity occur on top of the electrodes. But because of the very small region in which they happen they have only an impact on the higher order diffraction terms, which are less important because of their weak intensity. In contrast with expectations for the Jones-calculus, the simple approach to calculate the transmission through the two-dimensional layer is apparently still adequate to predict the polarization state of the diffraction orders emerging from it at high voltages.

A first point to note is that at 0 Volts the polarization state is not perfectly linear as expected. Even if the incoming polarization is parallel or perpendicular to the rubbing direction it is impossible to make every diffraction order disappear. Because all molecules are parallel to the rubbing direction when no voltage is applied it's not possible to describe this phenomenon with the used director patterns and the Jones-calculus. A possible reason is that the alignment of the molecules is less good near the edges of the electrodes. This would also be a feasible reason for some unexpected orders at 0 Volts.

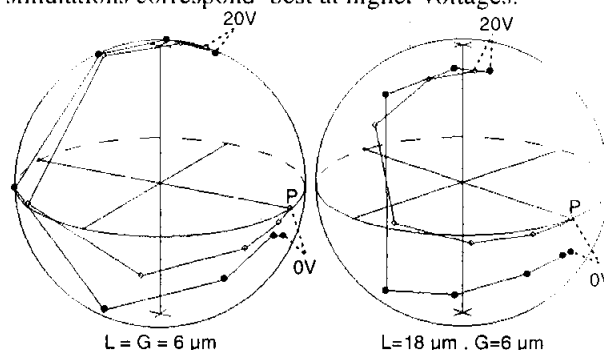
It is clear that the thickness of the electrodes plays an important role in the evolution of the polarization state. To get an estimation of the influence of the electrodes on the polarization state, the following rule is used : assuming that in the additional layer the molecules in between the electrodes stay along the alignment layer and the polarization of the light is perpendicular to this direction, there is only a constant phase delay between the two regions. All possible phase delays lie in an interval ranging from 0 to  $2\pi$ , which is comparable to a thickness varying from 0 nm to  $\lambda/(n_{ITO}-n_0)$ . In our case this gives a value of about 2200 nm.



**Figure 10. Polarization state of the diffraction orders (IPS-parameters : L = 18  $\mu\text{m}$ , G = 6  $\mu\text{m}$ , simulation until an electrode thickness of 2200 nm)**

Figure 10 shows a simulation of three of the polarizations in figure 9, but this time up to a thickness of 2200 nm. From figure 10 it is clear that for each diffraction order a curve the polarization will describe when varying the thickness of the electrodes can be distinguished. The curve gives an idea about the influence of the electrodes on the polarization state of the electrodes. When there is only a phase difference after propagation through the electrodes and the regions in between, we would expect the curves to form closed loops. The reason they don't is because also in the bottom layer the molecules will have a slight tendency to orient themselves along the electrical field. Then the wave passing between the electrodes suffers from birefringence and the polarization is not linear anymore after propagation through the extra layer. To keep this effect as small as possible the electrodes should be as thin as possible and the refractive index of the ITO should be as close as possible to the one of the liquid crystal.

In figure 11 the evolution of the main order polarization is shown when varying the applied voltage. The voltages plotted are : 0, 2, 3, 4, 5.5, 10, 15 and 20 Volts. The figure shows that the measurements and simulations correspond best at higher voltages.



**Figure 11. Polarization evolution of the main order at different voltages (not linearly distributed) for the two IPS-structures of figures 8 and 9**

To improve the performance of the display as much as possible it's important that the curve starts at the entrance polarization (point P) and passes as near as possible to the opposite point on the sphere.

## CONCLUSIONS

The Jones-calculus, originally meant to calculate the transmission through one-dimensional structures, is still quite adequate to calculate the transmission through two-dimensional thin layers. In particular when the diffraction pattern emerging from it is to be studied.

When an additional layer is added to the simulation model, it is possible to investigate the influence of the electrodes on the polarization state of the diffraction orders and explain the diffraction occurring when no voltage is applied.

## REFERENCES

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