Liquid Crystal in Precision Optical Devices

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ABSTRACT

While the liquid crystal industry is primarily driven by the display industry, increasingly important applications in science and engineering have emerged such as beam steering, wavefront modulation and polarization switching and control. We will discuss some of the differences in construction techniques needed to produce a precision optical device rather than a flat panel display along with development work being carried out at Meadowlark Optics in some of the above areas. These include polarization switches capable of greater than 5000:1 contrast and high efficiency beam steering for precision interferometer gauges.

Keywords: polarization switching, polarization switches, liquid crystals, spatial light modulators, beam steering

1. INTRODUCTION

It was roughly 30 years ago that the first liquid crystal (LC) display devices were made at RCA[1]. These were dynamic scattering devices and were soon replaced by the more practical twisted nematic (TN) mode display which manipulates the polarization state of light and which in one form or another has dominated the industry ever since. From these beginnings a multi-billon dollar industry has arisen. A niche market, which has greatly benefited from the research and development associated with that industry is the use of liquid crystals in the precision Optics market.

The primary characteristics which make LC's useful in both displays and Optics are that they are uniaxial, birefringent materials with an Optics axis associated with the macroscopic orientation or director of the molecules and the ease with which their molecules will change alignment in response to an outside stimulus. In other words, a low voltage will tend to align the s axis of an LC either parallel or perpendicular to itself, depending on the type of liquid crystal. Since both types of devices utilize these features it comes as no surprise that in general aspect a precision s and a display pixel are quite similar. In Figure 1 and 2 we compare and contrast the construction of examples of these two types of devices. Figure 1 is the side view of a typical pixel in a twisted nematic type display. Figure 2 shows the construction of a liquid-crystal variable-retarder (LCVR) precision s also employing nematic liquid crystals. Both are composed of two glass (borosilicate or fused silica to avoid ionic contamination) plates separated by spacers a few microns in size and filled with liquid crystal. In both the LC is aligned at the surfaces by a rubbed polyimide. The voltage across the cell is varied using the transparent conducting indium-tin oxide (ITO) electrodes. This voltage will change the alignment of the molecules in the center of the cell while those at the surface are fixed and supply a restoring torque. However, due to their different target audiences there are significant differences in the details. In liquid-crystal displays visual performance, cost and weight are of paramount importance while in precision Optics the user may be more concerned with retardation accuracy, wavefront distortion, and light scattering.

The first difference, which may be noticed on actually seeing the two devices, is their thickness. In order to save weight and cost, the display industry uses as thin of glass substrates as possible. While 1.1mm thick glass substrates had been the standard, recently there has been a move to even thinner glass at 0.7mm. On the other hand, to achieve good surface flatness of $\tilde{\ }$ or better over a 25mm clear aperture we need to use a thick, polished flat glass of at least 1.5mm and preferably 2.0mm or more. The difference here is significant especially when one considers that the stiffness of the glass increases as the cube of the thickness. A more subtle difference is in the needed quality of the glass substrates. A precision optic will have much tighter specifications on the permissible scratch and dig, inhomogeneities, inclusions and striations than a display designed to be viewed by the human eye at a distance.
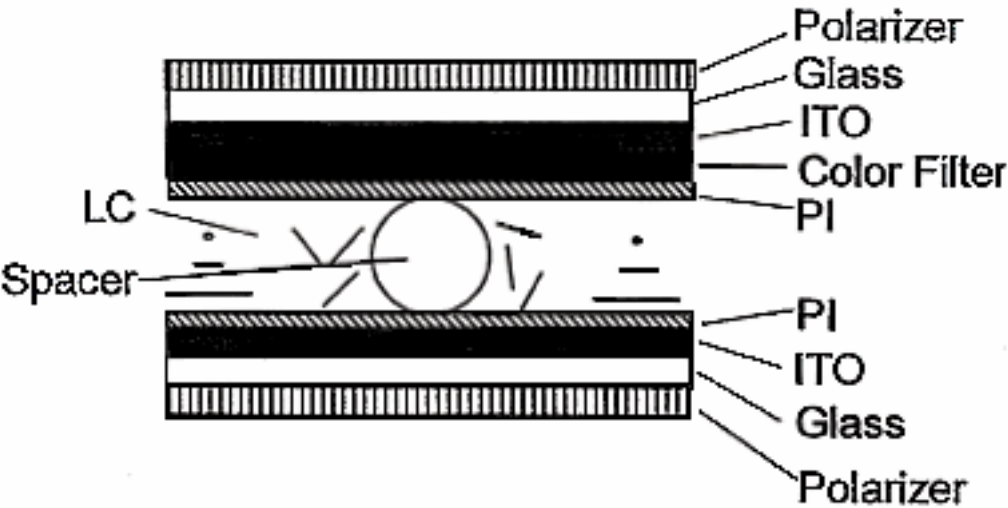
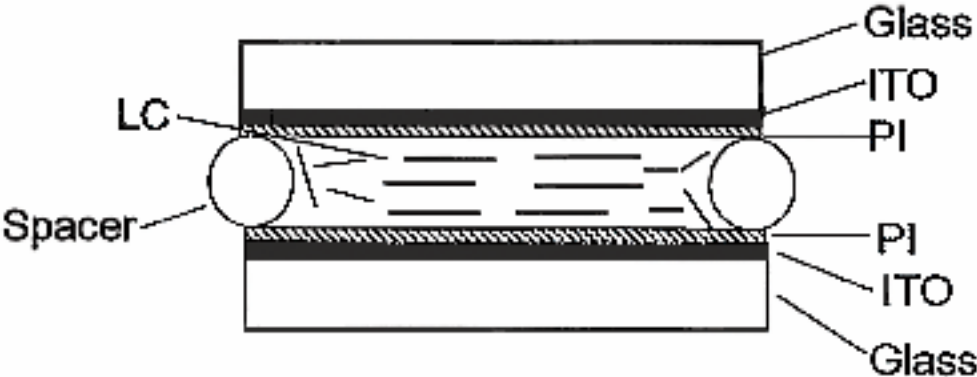Figure 1: Diagram showing the typical stackup of a liquid-crystal pixel

Figure 2: Diagram showing the stack up of an LCVR.

Another difference is in the placement of the spacers. In a large-scale display these are distributed throughout the pixelated areas, whereas for a precision application this will often result in an unacceptable amount of scattering. Consider that a typical 5μm spacer will distort the liquid crystal around it on the order of a cell gap spacing or another 5μm producing a scattering center 15μm or more across. To avoid this it is necessary to place all of our spacers in the edge seal glue around the optic and

outside the clear aperture. Other differences include the lack of a color filter in most optical as opposed to display devices, and the application of an anti-reflective (AR) coating on the precision optic. The ITO layer is also made thinner in the optic. This will increase its sheet resistance, which is rarely a concern in a compact optical device, but will improve transmission and power handling.

Also note the lack of polarizers on the LCVR. Since the eye is inherently an intensity rather than phase detector, polarizers are a necessity in the case of displays. While we can and do regularly use polarizers with our LCVRs turning them into variable attenuators and choppers, this in not necessary. As the name implies a variable retarder can be used directly as a phase device, basically as an easily automated Soleil-Babinet compensator. It is for this reason why a parallel nematic rather than a twisted nematic is used in the LCVR. Twisted nematic devices provide a better field of view than the parallel-aligned device, however, this twist means they cannot be viewed as a simple retarder. A parallel-aligned cell, on the other hand, will look like a simple retarder. As the voltage is increased, the liquid crystal's optic axis tips and it simply appears, for normal incidence, that the retardation drops while the axis orientation remains the same. However, it must be remembered this is true only for normal incidence.

Besides the variable retarder and attenuator mentioned above an interesting application the LCVR makes possible is a polarization rotator. This is accomplished by placing the LCVR in a Senarmont configuration with a polarizer in front of it and a quarter-wave plate behind it both with their axis at 45° to the s axis of the LCVR. The LCVR will turn the linearly polarized light into elliptically polarized. This in turn will be converted to linearly polarized but rotated light by the quarter-wave plate with the degree of rotation dependent on the retardation of the LCVR.

2. POLARIZATION SWITCH

While a parallel-aligned cell may generally be more useful there is at least one precision application for which the twisted nematic mode is ideally suited. This is as a polarization switch. The basic arrangement is shown in Figure 2. p-Polarized light is fed into the LC cell. At 0 volts the liquid crystal rotates the polarization by 90° into s-polarized light which is reflected from the polarizing beamsplitter. When a high voltage is applied to the cell the polarization is unchanged and the
p-Polarized light passes through the beamsplitter. A parallel-aligned cell is able to accomplish the same task but requires much tighter control of the voltages.
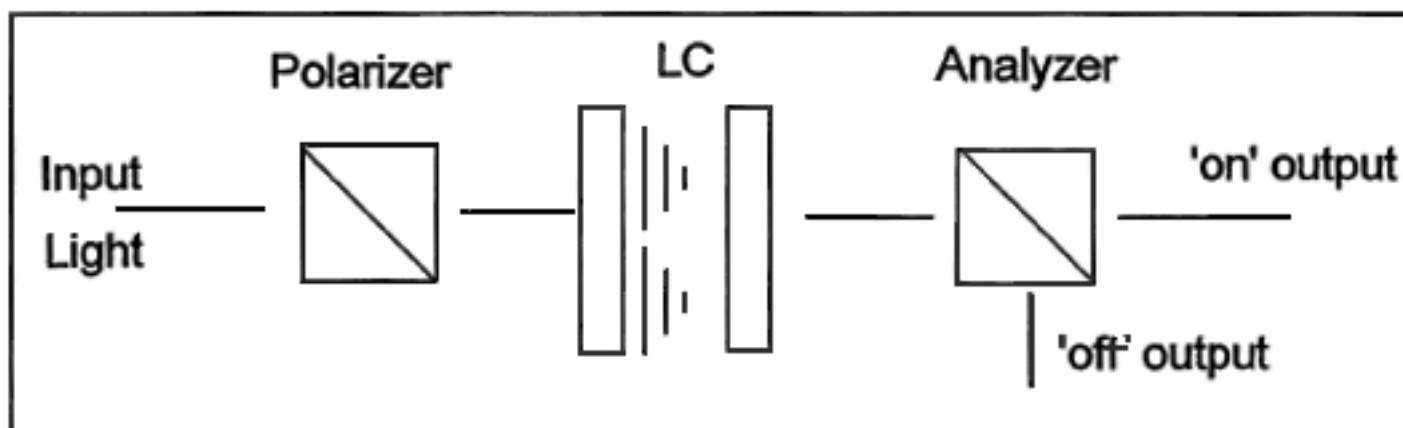
Figure 3: Arrangement for a polarization switch incorporating a twisted nematic LC. The light passes straight through when a high voltage is applied to the LC while its polarization state is rotated and it is reflected at the analyzer polarizing beamsplitter when zero volts is applied to the LC.

As mentioned before, the polarization state passing through a twisted nematic is not a simple function. However, as shown by Gooch and Tarry[2,3] for a 90° twist cell the transmission between ideal parallel polarizers is given by

$$T = 1/2 \; \frac{\sin^2\left(\frac{u}{2}\sqrt{1+u^2}\right)}{1+u^2}$$

where T, the transmission, is for unpolarized light and

$$u = 2d\left(\frac{\beta}{\lambda}\right)$$

In the above, d is the cell thickness, β is the birefringence, and λ is the wavelength of the light. The transmission equals 0, i.e. perfectly linear polarized 90° rotated light, when $u = \sqrt{3}, \sqrt{15}$, etc.

The above of course applies to an idealized cell. With a real liquid crystal, performance is ultimately limited by director fluctuations. The director and therefore s axis of an actual L.C. is not static but fluctuates about the average direction[4] on all length scales. This fluctuation results in scattering from one polarization state into another, and is on the order of 10^6 times that of an isotropic fluid. Minimization of this effect is difficult. It will be lowered by the stronger liquid crystal elastic constants, higher applied field, and thinner cells. However, these parameters do not yield easily to operator control. In the case of the elastic constants there is not a great amount of variation from liquid crystal to liquid crystal. The applied field may be made large in the 'on' or high voltage state but must be near zero in the 'off' or low voltage state, and the needed thickness of the cell is primarily set by the Gooch-Tarry equation shown above and the desired wavelength.

Fortunately, over a typical cell thickness, ~ 10μm, these intrinsic scattering affects of the liquid crystal are small, and the performance of the device will generally depend on the accuracy of construction. Some of the more mundane factors upon which performance depends are: twist angle, flatness, cell spacing, and defects. For example, an error of one degree in the twist angle will result in roughly a one-degree error in the polarization state, dropping the ultimate contrast to about 3000:1. The need for accurate control of the cell flatness and thickness are obvious from the above equations. Thus the thickness, L.C. birefringence, and light wavelength must be closely matched. Figure 4 shows measured contrast ratio results from such a polarization switch. The measurements were taken using calcite polarizers and a CARY spectrometer. The upper relatively flat curve was taken using crossed polarizers and is the ratio of the transmission at low voltage to that at high voltage. The peaked curve is taken with parallel polarizers and is the ratio of the transmission at high voltage to that at low voltage. As can be seen the contrast ratios are roughly 8000:1 at the design wavelength at 1550nm. It is unclear whether director fluctuation limitations are becoming important at these values since instrument and polarizer errors are becoming seriously limiting factors at these high contrast ratios.
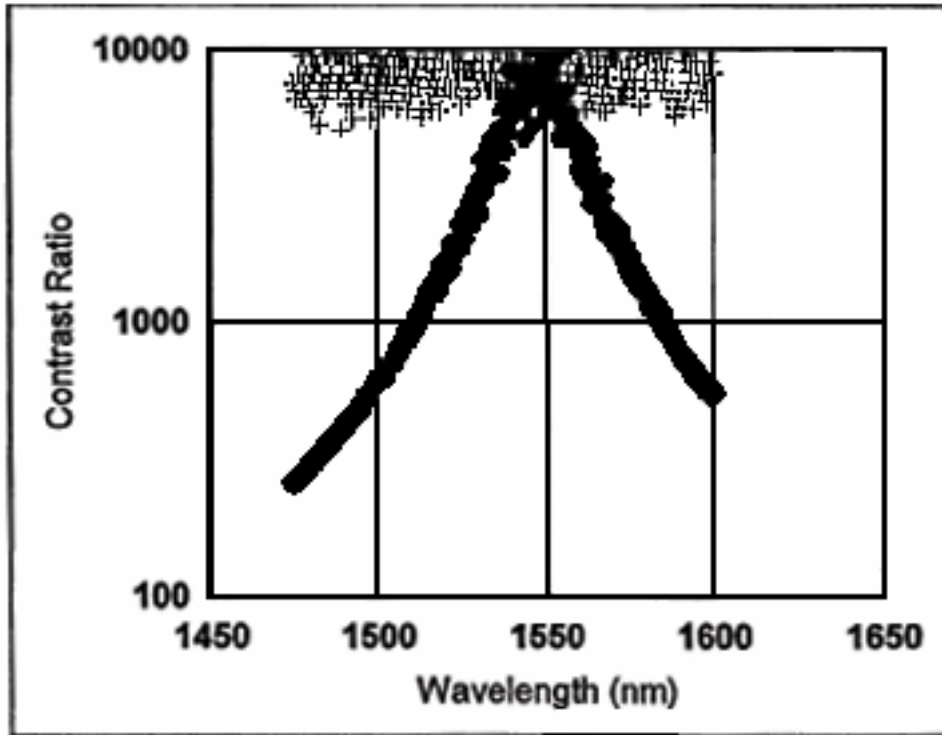
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Figure 4: Contrast Ratio of a twisted nematic polarization switch designed for 1550nm light. Data for the upper curve (+) was taken between crossed polarizers and is the ratio of transmission between low and high voltages. Data for the peaked curve was taken between parallel polarizers and is the ratio of transmission between high and low voltages.

3. BEAMSTEERING

In most instances it is not feasible to directly steer a light beam with liquid crystals in the same way a mirror or prism can be used. To reproduce the thousands of waves of stoke provided by any ordinary wedge prism would require a similarly thick liquid crystal cell. Thus beam steering with liquid crystal typically is accomplished through the magic of 2π resets. An adjustable diffractive optical element is formed by pixelating the liquid crystal device and forming a series of integer 2π stair step phase ramps across the surface in imitation of a blazed grating. The beam steering angle, or first order diffraction angle, of such an arrangement is given by the usual equation.

$$I\sin(\theta) = \lambda$$

Where I is the repeat distance and θ is the steering angle. Thus as the angle increases the width of each ramp becomes thinner and thinner. Also the diffraction efficiency of such a device in the far field with I steps per phase ramp is given by

$$\eta(I) = \left(I\, \frac{\sin(\frac{\pi}{I})}{\pi} \right)^2$$

where we have assumed the wavelength and repeat distance have been matched[5]. For a reasonable efficiency of 81% at least 4 steps are needed in each ramp. Thus, for example, Meadowlark Optics makes a spatial light modulator with 6μm pixel spacing - 3μm pixel width with 3μm spacing. Assuming four steps per ramp this gives a 24μm diffraction grating repeating distance or approximately 1.5 degrees of steering for 633nm light.

While the above is the typical method of producing beam steering with liquid crystal devices there are certain situations where a different approach may be desired. For example if one is not in the far field then the individual steps of the phase ramp will still be evident. Or if the pixel feature sizes become impractically small for the desired tuning angle and diffraction efficiency. In these cases a possible solution is to place a voltage gradient across each liquid crystal pixel forming a smooth rather than stair stop phase ramp[6,7]. When compared to a 4 step binary device, one with gradient addressed pixels in principle could yield 4 times the beam steering amplitude with nearly diffraction efficiency.

At Meadowlark Optics we have been developing a device for beam steering under a phase II SBIR grant from NASA. The goal is to replace mechanical/piezoelectric mirror movements required in a precision interferometric gauge. While the mechanical movement can actually be accomplished much faster than with a nematic liquid crystal device it sets up unwanted vibrations which are difficult to damp on a space borne satellite. In this application a large stroke is not needed, but one is working with a collimated laser beam and thus in the near field over large distances. A gradient voltage device therefore can improve wavefront while simplifying driver and electrical connection complexity. The device is essentially as shown in Figure 5. The voltage gradient across the lower substrate results in a larger voltage to the ground plane here on the right of the cell, which in turn leads to more highly tilted liquid crystal molecules and a lower retardation value for the incoming light. Thus the outgoing beam is tipped as shown. A couple of points should be noted here. First, this is true only for light polarized in the plane containing the molecules, the other polarization states direction will be unaffected. Second, in the actual devices instead of a ground plane a second perpendicular gradient is applied to the upper plate in order to provide for two-dimensional steering of the beam.
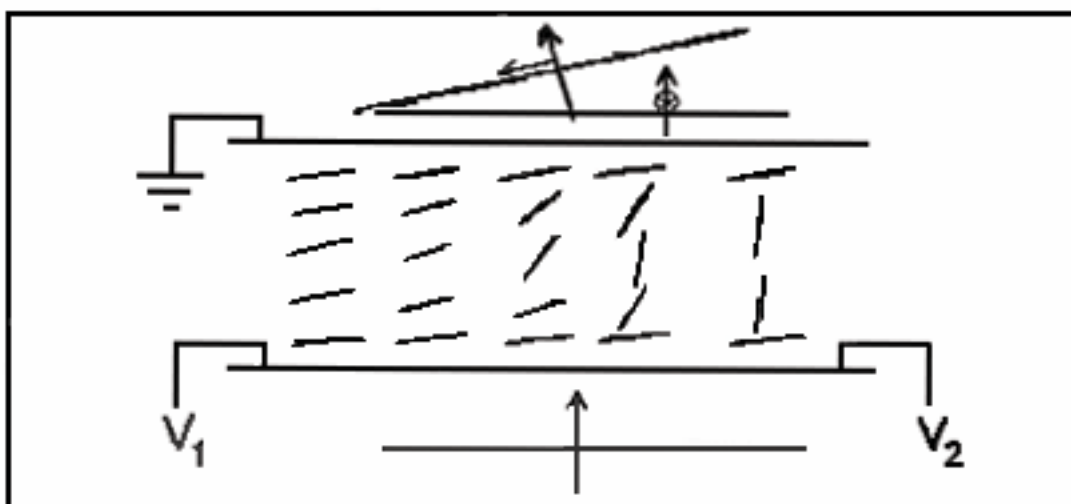

Figure 5: Diagram of a one-dimensional gradient voltage
liquid-crystal beam steerer.

Figure 6 shows the retardation per micron of a relatively high birefringent liquid crystal (β~0.2). From this we see that the amount of tilt stoke is a maximum of approximately 0.35 waves per micron thickness of liquid crystal. However, it is also apparent that this curve is highly nonlinear at the higher voltages. Thus for a single pixel device with good wavefront one is limited to the lower voltage region of ~ 1 to 2 volts. Fortunately approximately 65% of the stroke occurs here. As an example Figure 7 shows the amount of tilt and astigmatic aberration generated in a test cell as the voltage gradient applied was increased. As can be seen for up to 3 waves of tilt the aberration remained well under $\lambda/5$. Other aberrations such as coma, focus, and spherical were even less, as expected from the shape of the retardation versus voltage curve.
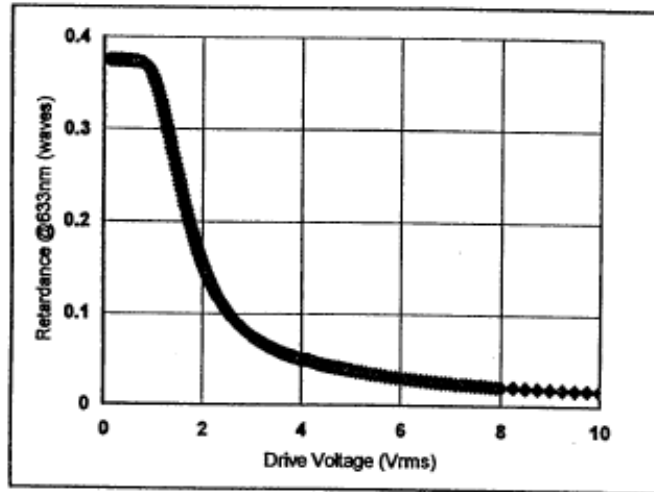

Figure 6: Retardation/micron versus voltage of a relatively high birefringence liquid crystal
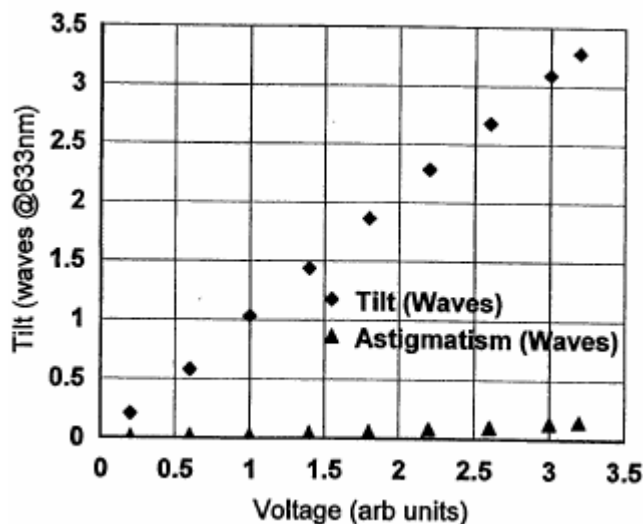
Figure 7: Graph showing waves of tilt and increase in astigmatic aberrations
as a function of the voltage gradient across a test cell.

One of the key technical challenges in building this type cell is the transparent conducting electrode. It must be of high enough resistance so that joule heating is not a problem but low enough so that the capacitive impedance of the liquid crystal is large compared to the resistance of the film. To that end we have developed a conducting film with resistances between 10^5 and 10^6 Ω/square, which is transparent in both the visible, and IR.

4. CONCLUSION

Liquid crystals are endowed with extremely useful properties, which have allowed them to function as excellent displays and in a number of unique optical devices. With due care they can also perform well in precision optical applications where tight specifications on wavefront, polarization purity or other optical performance parameters are required.

ACKNOWLEDGMENTS

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