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Advances in liquid crystal spatial light modulators

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ABSTRACT

Recent advances in our high-speed analog liquid crystal spatial light modulators (SLMs) will be presented. These advancements include higher pixel density, smaller pixel pitch, greatly improved optical efficiency, and higher speed operation. The new VLSI SLMs can utilize ferroelectric liquid crystal (FLC) or nematic liquid crystal (NLC) to achieve phase-only, amplitude-only and phase-amplitude-coupled modulation. These devices have applications in optical processing, optical storage, holographic display and beamsteering. Design criteria and experimental data will be presented.

Keywords: spatial light modulator, optical correlator, optical processing, beamsteering, liquid crystal

1. INTRODUCTION

Analog modulation provides precise control of an optical wave front when combined with high-resolution addressing structures. This continuous control is beneficial for correcting propagation distortion, steering a beam or beams, or encoding information. There exists a variety of spatial light modulators such as liquid crystal on silicon (LCoS), multiple quantum well (MQW), micro-electromechanical systems (MEMS), etc. One advantage that LCoS SLMs have over the other types of spatial light modulators is that the modulation curve is a function of the LC modulator and is not specific to the addressing structure. This flexibility allows a diverse set of modulators to be fabricated. Analog LC modulators capable of amplitude, bi-polar amplitude, phase-only, full complex and coupled amplitude and phase have all been demonstrated using a common VLSI backplane.

The desired modulation curve is generally application specific. If one needs to maintain signal level through the modulation process, the most efficient method is pure phase modulation, since it modulates the wavefront without reducing the signal amplitude. As a correlation-plane filter, a phase-only SLM with a modulation depth of 2π allows the phase of any input pattern to be correctly conjugated. Also, seamless (modulo- 2π) phase modulation permits large phase shifts to be correctly represented by a combination of pixels for phased-array beamsteering¹ and adaptive optics.² For encoding information suitable for direct detection, amplitude modulation is normally used. Bi-polar amplitude modulation optically represents data as positive and negative values (from 1 to -1 along one axis). This type of modulator is useful for performing mathematical operations such as differentiation.³ The bi-polar amplitude modulator used as a correlation-plane filter allows the phase and amplitude of symmetric patterns to be accurately analyzed. By optically combining pixels of the bi-polar modulator (with separate pixels representing the real and imaginary axes), full complex-unit-circle coverage is realized at the expense of reducing the space bandwidth product by a factor of four (i.e. bi-polar 512x512 converts to full-complex 256x256).^{4,5} This combination at the correlation plane allows the phase and amplitude of any filter pattern to be correctly represented by the SLM. Coupled amplitude and phase modulators generate complex modulation at each pixel, but the LC operating curve only provides partial coverage of the complex unit circle.⁶

Ferroelectric liquid crystals (FLC) are normally used as amplitude modulators, since the electro-optical effect is similar to a rotating waveplate. It is commonly believed that FLC modulators are binary (have only two states), but the binary FLC modulator is a specific LC modulator developed primarily for video-rate display applications. In displays that use binary FLC modulators, the gray-scale image is generated using time-averaging which requires hundreds of frame periods to produce 8-bits of gray level. To improve

on this digital-to-optical conversion (DOC) rate for information processing applications, analog FLC modulators are used to form full gray-scale images in one load cycle, where the response time of the analog modulator is equivalent to that of the binary modulator. The grayscale image is converted to a bi-polar (real axis) image simply by rotating the light's polarization with respect to the optic axis of the FLC modulator. FLC modulators are touted as being orders of magnitude faster than NLC's.⁷ Actually, this claim is only valid if the comparison involves LC modulators driven by low-voltage signals. If voltage level is not limited, then a variety of NLC modulators exist which have rise and fall times that rival the FLC modulators.⁸ The higher-voltage drive signals required for the sub-millisecond NLC modulators are more difficult to produce on high-resolution backplanes. On the other hand, it is easier to fabricate analog phase modulators using NLC materials, since parallel-aligned nematics act as variable retarders instead of rotating waveplates.

The ability to select an operating curve by only changing the LC modulator material or its alignment in order to meet the requirements of a particular application makes the basic LCoS SLM system more universal. Inexpensive custom production is important since most applications have a small number of customers. If the technology is adaptable, then the customer base is expandable by providing semi-custom systems for a wide range of applications. In addition to selecting the operating curve, it is possible to engineer the LC modulator to achieve other performance characteristics such as polarization-independent phase modulation⁹ or non-dispersive phase modulation.¹⁰ Since a common backplane is used for the different SLM products, volume production for this component is more appropriate. Volume manufacturing is achieved using the production line of a VLSI foundry to fabricate the silicon backplanes. This allows inexpensive copies to be produced. Therefore, the LCoS approach allows inexpensive backplane fabrication and custom assembly to be combined in meeting the needs of various SLM users. Unfortunately, the VLSI backplanes do impose some limitations and thereby restrict the LC modulator possibilities. This paper will discuss these limitations and describe some of the new LCoS SLMs being developed working within current limitations.

2. DESIGN & OPERATION OF LCoS SLMs

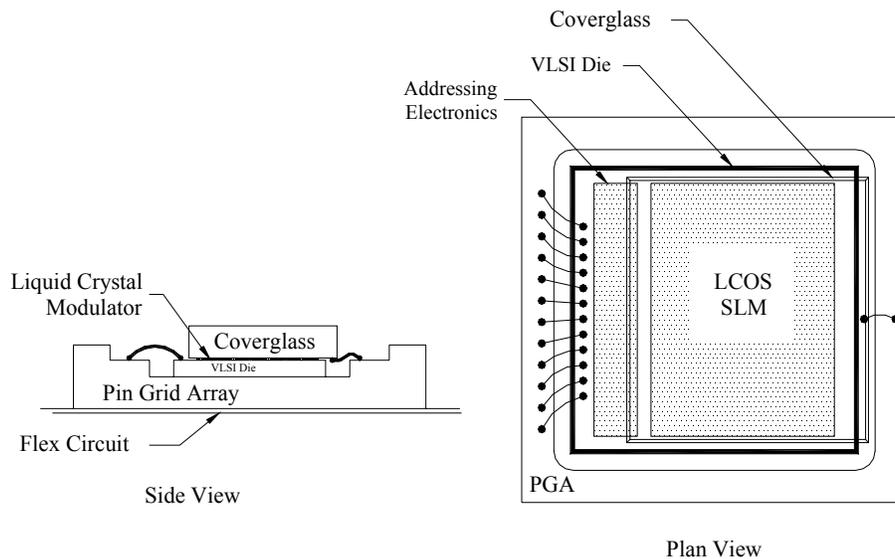


Figure 1: Basic configuration for LCoS SLM.

As shown in Figure 1, the SLM optical head consists of a layer of liquid crystal sandwiched between a cover glass and a VLSI backplane in a PGA (pin grid array) package. The VLSI backplane receives analog

voltage signals through a limited number of input lines and routes the signals to the appropriate phase shifter element using a multiplexer arrangement (refer to Figure 2). Each array element has a storage capacitor for holding the analog voltage level on the LC addressing electrode as the other array elements are loaded or refreshed with data. Therefore, the voltage across the LC layer remains constant until new data is loaded into the array. The load rate for the whole array is faster than the response of the LC producing a static pattern across the device. With this type of operation, data is quickly loaded into the array with a minimum number of electrical interconnects to the SLM.

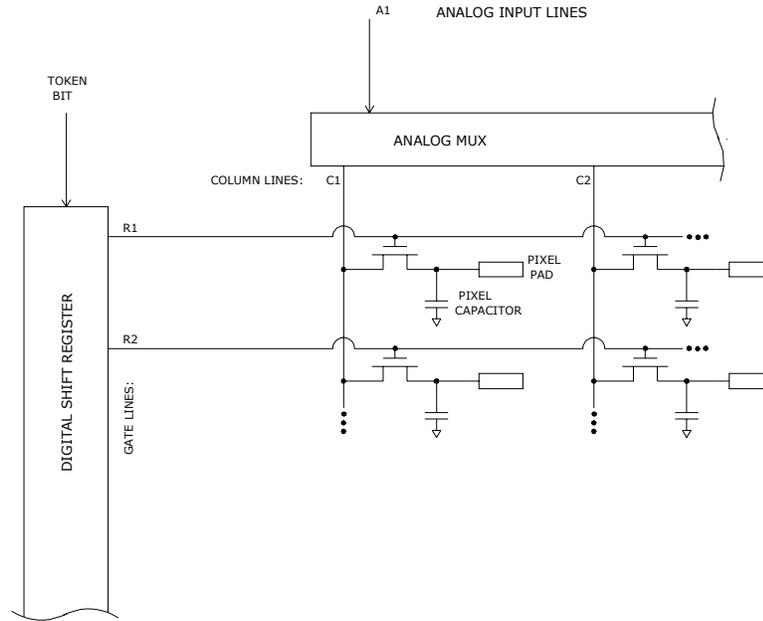


Figure 2: Block diagram of LCoS SLM addressing circuits.

As mentioned above, the addressing structure is fabricated through commercial VLSI foundries. Most semiconductor foundries are moving to smaller geometry processes (i.e. higher resolution lithography). The smaller geometries allow greater circuit integration and provide faster circuitry with less power consumption. Today, semiconductor foundries commercially offer process sizes ranging from a few microns to a couple tenths of a micron. As the process size decreases, smoother (shinier) metals are used and layer thicknesses are made more uniform by planarization techniques such as chemical-mechanical polishing (CMP). These process changes are meant to improve electrical yield, but they greatly contribute to the optical quality of the silicon backplane by eliminating topography that scatters light. Therefore, the general trend in semiconductor fabrication offers significant advantages for producing LCoS SLMs, but it is not all beneficial. Higher resolution lithography allows the electrode pitch to be reduced at the cost of reduced operating voltage.

For high-resolution backplanes, the spacing requires sub-micron foundry processes with design rules that allow the addressing circuits to be as tightly packed as the electrode structure. It is these spatial requirements that limit the operating voltage at the pixel. In the minimum one-gate-per-pixel design as shown in Figure 2, the actual drive voltage at the pixel is limited due to the body effect of the pass gates to some voltage less than the supply voltage. As the geometry of the pass gate decreases, the body effect increases which further reduces the voltage available at the pixel. Therefore, a small-geometry process may operate at supply voltages that rival larger-geometry processes, but these processes when used at their finest resolution detrimentally impact the drive capability of the device.

Voltage provides the field that switches the LC modulator. The amount of voltage needed for a particular LC modulator is a function of the LC material, cell thickness and LC alignment. It is possible to vary some of the LC parameters to achieve lower voltage operation, but there is always a performance price to pay. This price may come in the form of weaker alignments which affect contrast or response, or thicker cells which slow response, increase angle dependency and add to pixel-to-pixel cross talk. For example, the voltage needed to switch NLC molecules at the center of a cell is considerably less than the voltage needed to switch molecules near the cell's alignment layer which are strongly affected by surface forces. Therefore, it takes less voltage to get an equivalent change in retardance from a thick parallel-aligned cell than from a thin cell.

With higher-resolution backplanes, the smaller pixel area reduces the capacitance at each pixel. Capacitance is needed to store charge which represents the analog data at the pixel and provides the field amplitude for controlling the LC modulator. Unfortunately, the field at the pixel is depleted as the FLC modulator switches since the polar molecules of the FLC neutralize the charge stored at the pixel. A smaller capacitance causes the field to be neutralized faster, reducing the switching capability of the pixel.

To mitigate some of these restrictions, new high-voltage VLSI foundry processes are being explored. With a high-voltage backplane, it is possible to have an addressing structure for driving high-speed NLC (sub-millisecond phase-only) and FLC (2 KHz to 4 KHz grayscale) modulators. To address these different LC modulators, data is continuously loaded at a high data rate. The update rate is several thousand frames per second, which is achieved using high-speed drivers and parallel addressing techniques. This addressing technique for analog LCOS devices has been used by Boulder Nonlinear Systems (BNS) for several years and has been found to have several benefits. First, a fast update rate refreshes the charge stored at each pixel before it bleeds off. Since the field created by the charge switches the LC, a fast refresh cycle keeps the image from fading. With this capability, a strong field is maintained across the LC. A second benefit is that this technique reduces cross talk between pixels, since the active drivers are connected to a specific row and column line for a time period that is shorter than the response time of the LC. Therefore, the drive signal is confined to a single pixel, since it is the charge captured by the pixel capacitor and not the transient signal addressing the pixel that switches the LC. A third benefit is that this type of addressing scheme allows us to produce a variety of drive signals, thus giving us the capability to drive any type of LC modulator.

In addition to higher voltage, the other issues being addressed are modulator efficiency and optical quality of the backplane. Highly-efficient, optical quality modulators are possible if the VLSI addressing structure maximizes pixel fill factor and minimizes pixel topography. Our approach for achieving this type of performance is to use VLSI processes where sub-micron lithography, chemical-mechanical polishing (CMP) and shiny metal are available. With these types of process steps, the pixels are highly reflective (85%), have a large fill factor (80% to 90%) and are flat (planarized).

3. NEW SLM DEVELOPMENTS

Sub-millisecond Phase-only Operation

Most commonly used nematic liquid crystals exhibit a positive dielectric anisotropy. This means that they can be rapidly driven from an optically thick state to an optically thin state as the dipole moment couples to an applied field. However, for conventional materials, going from an optically thin state to an optically thick state requires time for the molecules to relax to the next voltage state, V_b . The time constant for relaxation, τ_{relax} is⁸

$$\tau_{relax} = \frac{\gamma_1 t^2}{k_{11} \pi^2 \left| \left(\frac{V_b}{V_{th}} \right)^2 - 1 \right|}, \quad (1)$$

where γ_1 is the material viscosity, k_{11} is an elastic constant that establishes the restoring force, and t is the cell thickness. Equation 1 shows that fast relaxation requires operation at voltage levels that are large compared to the threshold voltage (V_{th}) of the material. The higher voltage operation in this case makes use of the tightly bound molecules near the surface of the cell.

Instead of relying on relaxation, it is possible to drive the molecules into a high-retardance state if the dielectric anisotropy of the nematic LC changes sign (i.e. ϵ -perpendicular becomes greater than ϵ -parallel). The value of ϵ -parallel is frequency dependent where as ϵ -perpendicular is not. Therefore, the sign of the dielectric anisotropy is frequency dependent and it changes sign at relatively low frequencies in certain types of materials. These materials are called dual frequency materials. An investigation of some of these materials indicates that sub-millisecond response times for a modulation depth of 2π are possible if large drive voltages are used (± 12 volts peak-to-peak produces a 0.16 millisecond response as shown in Figure 3). This type of modulator also requires an addressing technique that provides a high frequency excitation (about 40 kHz) to produce the sign-changing drive signal. Fortunately, the high frequency signal is only needed to reset the LC modulator before a new pattern is written to the array. By applying a high-frequency drive signal to the common coverglass electrode, the LC modulator is quickly reset to its high birefringence state, allowing new data written to the VLSI backplane to be displayed within a millisecond if the VLSI backplane has sufficient voltage.

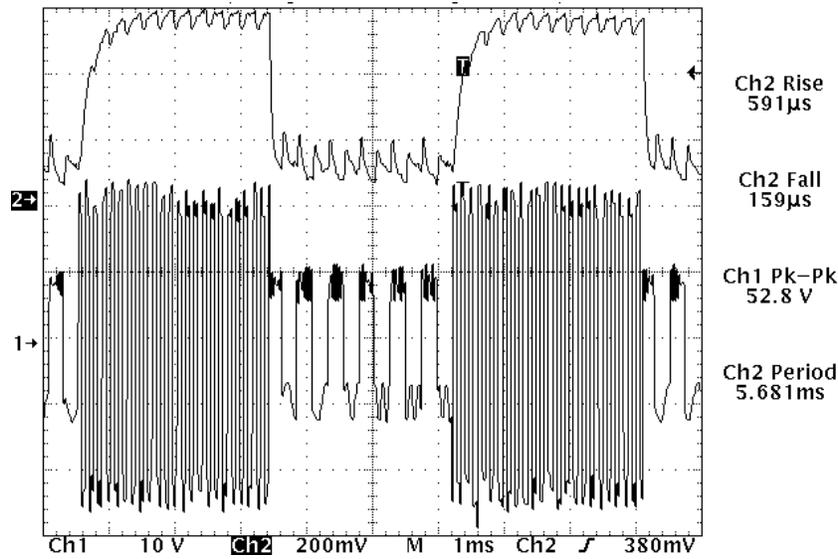


Figure 3: Oscilloscope outputs showing the drive signal (Ch1 - bottom trace) and the corresponding optical response (Ch2 - top trace) of a dual-frequency LC modulator. The on-to-off transition represents a π phase change for the transmissive cell, which is a 2π phase change in reflection.

To drive the dual-frequency liquid crystal materials with a high-resolution backplane, higher voltage levels than the standard 3.3 - 5 volt capability available from most sub-micron semiconductor processes are required. Fortunately, a few foundries are developing higher voltage processes. There are now 12 to 40 volt processes using sub-micron lithography. However, the gate sizes required by these processes limit the

spatial resolution of the backplane. Therefore, a voltage-versus-resolution tradeoff still must be addressed in the backplane design.

Recently, the design of a high-voltage analog 256x256 backplane has been submitted to a foundry for fabrication. The chip was designed for a 0.5- μm foundry process that uses CMP and shiny metal (~85% reflectivity). The device will have a pixel pitch of 24- μm with a flat fill factor of approximately 90%. The device will provide 12 to 14 volts at the pixel. The load period for one frame of data will be 115 μs . This load period is sufficient for sub-millisecond operation with a nematic dual-frequency modulator, but it is not sufficient for FLC modulators operating at over 2 KHz.

Two to Four KiloHertz Real-Axis (Bi-polar Amplitude) Operation

A 512x512 analog FLC SLM operating at 2 KHz has been demonstrated recently (refer to Figure 4). The effective digital-to-optical (DOC) rate for this device is 4.19 Gigabits/second. To increase the frame rate further, faster FLC modulators and faster load rates are needed. With analog FLC modulators, several load cycles are needed for each frame of data. In general, two to three load cycles are needed to write the image due to charge depletion, and another two or three are needed for DC balancing the modulator. Therefore, the load period for the array needs to be less than a 100 μs for operation above 2 KHz. In addition to fast load cycles, the backplane needs to supply sufficient voltage. In a study of various FLC material, image generation out to 4 KHz required drive signals of approximately 6 volts or more.



Figure 4: Analog 512x512 operating at 2 KHz. The image is captured by illuminating the SLM with a 250 μs laser pulse to capture only the true image.

To achieve the load rates and voltage levels required for 4 KHz operation, a new silicon chip for an analog 256x256 SLM has been designed and submitted to the foundry for production. The chip was designed for a 0.5- μm process with a pixel pitch of 18- μm and a pixel size of 16.8- μm square. Therefore the area fill factor will be 87%. The backplane will provide 6 to 8 volts at the pixel and will load the full array in approximately 41 μs .

The high frame rate SLM will be mounted on a flexible circuit that will be used to interface the SLM chip to the drive electronics. This design represents a new approach for BNS, since the plan is to wirebond the chip directly to the flex cable. A layout of the flex cable can be seen in Figure 5. Note that the cable is not drawn to scale. It will be approximately 168-mm in length and the width at the SLM chip end is approximately 12-mm. The large rectangle on the right depicts the location of the SLM chip. The left edge of the drawing shows the connector that will interface to our existing drive electronics.

In the past, the SLM chips have been bonded into a ceramic pin grid array (PGA) package (as shown in Figure 1). The use of the PGA package results in an assembly that is much larger than the SLM chip itself. This is caused by the need to use a large PGA package in order to obtain the large number of data lines required for a high-speed SLM chip. Bonding the chip directly to the flex cable allows the flex cable to be only slightly larger than the SLM chip itself. This will give the end user the ability to design a much smaller optical head.

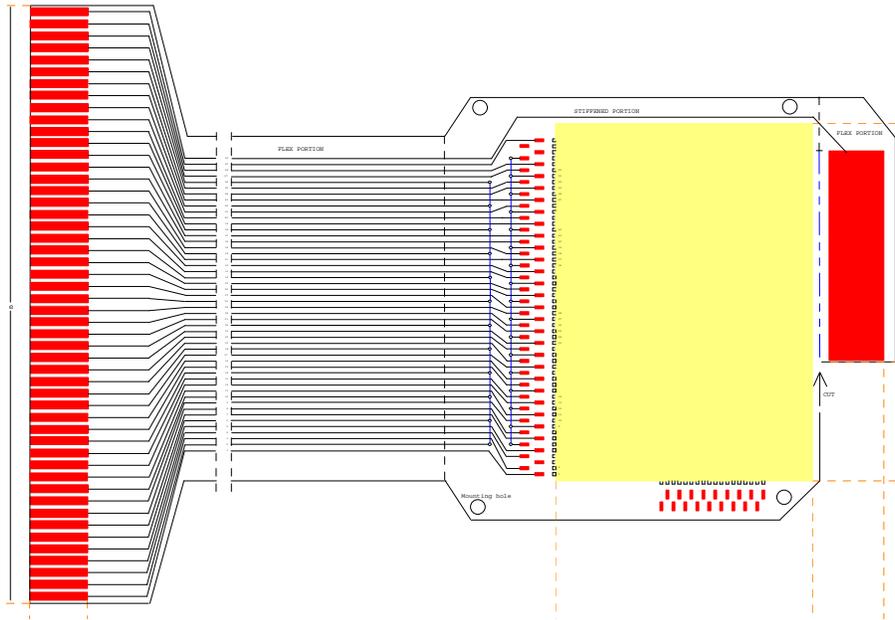


Figure 5: Layout of a flex cable for a fast-frame-rate 256x256 SLM.

The array size of the 256 x 256 SLM allows the frame to be loaded with 32 input lines at the 41 μ s rate. At 4 KHz, the analog 256 x 256 has the same DOC rate as a 512 x 512 operating at 1 KHz. To improve the DOC rate, it is possible to increase resolution to 512 x 512 and maintain the same load rates by increasing the number of inputs to the chip. However, this method results in a large device, since a relatively high voltage level is needed to drive the modulator. Another method is to increase the device resolution to 1K x 1K and operate at a 1000 Hz. This reduces the voltage level needed for the modulator making smaller (higher resolution) devices possible.

Higher Resolution Devices (7-micron 512x512 and 5-micron 1Kx1K)

A 7-micron 512 x 512 SLM has recently been demonstrated (refer to Figure 6). The backplane for this device was fabricated using a 0.35 μ m, 5-volt foundry process with CMP and shiny metal (~85% reflectivity). The device has a flat fill factor of approximately 84% and provides 3.2 to 3.7 volts (depending on supply voltage) at the pixel. The load period for one frame of data is 164 μ s. The pixel voltage and load rate restrict its operating speed to approximately 1 KHz. However, the small pixel pitch is very beneficial for reducing the size of an optical processor. With the 7-micron pixel pitch, the optical path length for a 4-F correlator is approximately 152 mm at an operating wavelength of 800 nm, if the detection plane camera has a 10-micron pixel pitch.

The amount of computing power versus the size and weight of the processor is a very important trade space for certain applications such as target tracking from missile and space-based platforms. Because of this, the improvement in DOC rates by increasing pixel density instead of increasing frame rate is being pursued, also. The next step is to develop a 1K x 1K device with a 5-micron pixel. Unfortunately, the smaller pixel

further restricts voltage and reduces capacitance. As discussed above, these reductions detrimentally affect FLC modulation. Therefore BNS is testing a new modulation technique which will offset these effects. This technique uses an analog FLC modulator which allows the coverglass voltage to be flipped, doubling the effective pixel voltage.



Figure 6: Image from 7-micron 512 x512 operating at 1 KHz.

Coverglass flipping has, in the past, not worked with analog FLC modulators for two reasons. First, FLC modulators need fields of both polarities to utilize the FLC's full modulation, speed and accuracy. With a coverglass-flipping FLC modulator, only one polarity is available to drive the molecules for any one image, and therefore the benefits of flipping coverglass are nullified. The second problem is that coverglass-flipping schemes have historically produced a modulation gradient across the SLM. This is a result of a decrease in LC settling time for the pixels addressed immediately before the coverglass is flipped. The hardware raster scans data onto the SLM, so there is no correct time to flip the coverglass; whenever the coverglass is flipped all the rows on the SLM are in different phases of settling.

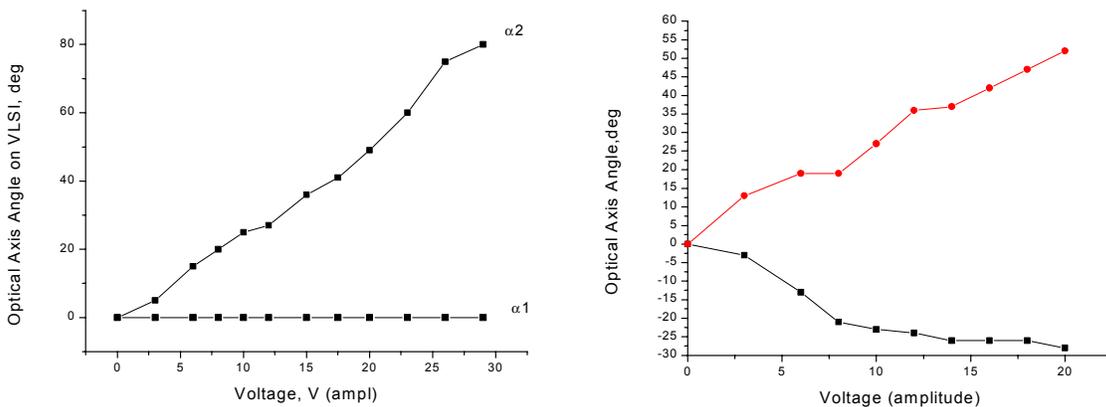


Figure 7: Left: field-treated FLC modulation characteristic. Right: normal FLC modulation characteristic.

These problems are solvable if the FLC molecules are field-treated to be pinned as a mono-domain at one extreme of their switching range. FLC consists of polar molecules that generally need both polarities to rotate through their full cone angle, and need to be driven to any given state presuming there is no physical force pinning them to a particular state. The pinned state acts as a modulation stop and as a restoring force to return the molecules to the pinned state when no field or a negative field is applied. A positive voltage will cause the molecules to rotate in one direction through the full cone angle. Figure 7 illustrates the difference in modulation characteristics between field-treated and standard FLC modulators.

Using a field-treated FLC modulator with characteristics like those shown in Figure 7 allows for correction of both the overall modulation errors and the duty-cycle mismatches between pixels caused by flipping the coverglass. This type of modulator allows the pixel to be smaller, since less voltage and capacitance are needed for sub-millisecond operation.

4. CONCLUSIONS

BNS is developing high-resolution SLMs for optical processing, beamsteering, active-diffractive optics, 3D display and wavefront correction using liquid crystal on silicon. With new VLSI foundry processes, these devices have better throughput and less intra-pixel distortion than the older devices. The new processes still use high-yield inexpensive fabrication techniques, which will ultimately result in lower cost for users. However, the sub-micron lithography places more electrical restrictions on the LC modulator, reducing its possible performance.

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REFERENCES

- 1) P.F. McManamon, E.A. Watson, T.A. Dorschner and L.J. Barnes, "Applications look at the use of liquid crystal writable gratings for steering passive radiation," *Opt. Eng.*, vol. 32, no. 11, pp. 2657-2664, (1993)
- 2) G. D. Love, "Wavefront correction of Zernike modes with a liquid-crystal spatial light modulator," *Appl. Opt.* **36**, 1517-1524 (1997).
- 3) A. VanderLugt, *Optical Signal Processing*, John Wiley & Sons, Inc. New York (1992).
- 4) R. Young, *et al.* "Hardware implementation details of a hybrid digital/optical correlator system," in *Optical Pattern Recognition XI, Proc. SPIE*, **Vol. 4043**, (2000).
- 5) T.H. Chao, H. Zhou and G. Reyes, "Grayscale Optical Correlator for Real-time Onboard ATR," in *Optical Pattern Recognition XII, Proc. SPIE*, **Vol. 4387**, (2001).
- 6) R.D. Juday, J.M. Rollins and S.E. Monroe, "SLM operating curves for statistical pattern recognition metrics," in *Optical Pattern Recognition XII, Proc. SPIE*, **Vol. 4387**, (2001).
- 7) M.J. O'Callaghan and M.A. Handschy, "Ferroelectric liquid crystal SLMs – from prototypes to products" in *Spatial Light Modulators: Technology and Applications, Proc. SPIE* **Vol. 4457**, (2001).
- 8) I.C. Khoo and S.T. Wu, *Optics and Nonlinear Optics of Liquid Crystals*, Singapore: World Scientific Publishing Co. (1993).
- 9) G.D. Love, "Liquid-crystal phase modulator for unpolarized light," *Applied Optics*, **Vol. 32**, No. 13, May 1, (1993).
- 10) J. Stockley, G. Sharp, S. Serati, P. Wang and K Johnson, "Liquid crystal grating based on modulation of circularly polarized light," in *Diffractive Optics and Micro-Optics*, **Vol. 5**, OSA (1996).