Liquid crystal on silicon infrared scene projectors

Teresa K. Ewing[*a], William R. Folks[**b]
[a]Boulder Nonlinear Systems, 450 Courtney Way #107, Lafayette, CO, USA 80026-2786
[b]College of Optics and Photonics, University of Central Florida, 4000 Central Florida Blvd. Orlando, FL 32816

ABSTRACT

As the deployment of IR sensors increases in the military arena, so does the need for testing, calibration and training in realistic infrared environments. This paper introduces liquid crystal on silicon (LCOS) technology and discusses key elements required to successfully transition these displays to the infrared. The resulting devices are not only appropriate for infrared scene projectors, but can also be used as infrared adaptive optics or non-mechanical beamsteering elements.

Keywords: Infrared scene projection, liquid crystal on silicon, infrared display.

1. INTRODUCTION

IR capable dynamic displays are primarily required in the dedicated "hardware-in-the-loop" (HWIL) scene simulation laboratories of the various DOD components, where military IR sensors (e.g. missile seekers) are characterized and tested. A number of technologies have been pursued in the past to generate IR scenes, each with associated advantages and disadvantages. Resistive emitter arrays are the most prevalent technology, achieving good dynamic range and response times. However, the very nature of resistive emitter technology, namely that the resistive elements themselves generate the radiation required, limits high temperature operation[1]. Digital micro-mirror devices (DMD), such as those used in many commercial visible scene projectors, are mass-produced and inexpensive, but must be used in a pulse-coded modulation scheme to generate grayscale. Liquid crystal devices have been attempted, either in an optically addressed format (LCLV)[2] or as transmissive active matrix devices, but in both cases, the LC layer was fairly thick, resulting in slow switching speeds and flickering displays. An inexpensive, high speed, lightweight IR display capable of achieving both high pixel counts and high apparent temperature is needed. Since the specifications of the numerous IR sensors under test vary and/or cannot be predicted in the future, the display device must be adaptable to a number of spectral bands (visible, SWIR, MWIR, LWIR).

Liquid crystal display technology has made enormous strides over the past few decades. LC displays are now incorporated into hundreds of consumer products such as laptop computers, digital cameras, cell phones, thermostats and digital watches. Much of this success is due not only to drastic improvements in LC material science, but in parallel development of high-resolution lithography processes, compact electronics, and lightweight interconnects. Liquid crystal on silicon devices capitalize on these advances. Backplanes are fabricated using the same foundry processes used to manufacture computer chips, ensuring that a fabrication source will always be available. The output from a VLSI foundry run is multiple wafers of die, or 100's of backplanes, resulting in an extremely low unit die cost. In addition, innovations in VLSI fabrication are pushed, and well-funded, by the computer industry.

With LCOS technology, the output optical modulation is independent of the silicon backplane and is determined by the type of liquid crystal used, its layer thickness and the cover glass used. The pixels themselves are a highly reflective metal, usually aluminum, and reflect well at all wavelengths. This means that a common VLSI backplane is used for visible, NIR, MWIR and LWIR devices. The same backplane can also be used with a variety of LC materials, resulting in different modulation schemes. This flexibility is particularly important in the IR where many LC materials may be absorptive or speed limited.

[*] tewing@bnonlinear.com; phone 1 303 604-0077
[**] wfolks@creol.ucf.edu; phone 1 407 823-6800

2. LCOS DISPLAY OPERATION

Liquid Crystal on Silicon is the marriage of two components; liquid crystals, which have a voltage variable optical response, and VLSI backplanes, which provide active electronic circuitry in a compact package. Figure 1 shows a cross-section of a typical LCOS display. A thin layer of liquid crystal material is placed between a VLSI die and a cover glass. The VLSI die is basically an array of metal pixels that serve as both individual electrodes and mirrors. The cover glass is coated with a thin layer of conductive material, so thin in fact that the film is transparent. The individual pixels and the cover glass serve as electrodes on opposite sides of the liquid crystal layer. By changing the voltage at each pixel, one can manipulate the orientation of the liquid crystal molecules and in turn, can change the polarization of the light at that pixel. Light enters the display linearly polarized, travels through the cover glass, through the LC layer, is reflected off the pixels and returns back through the LC layer and cover glass. An exit polarizer is used to analyze the voltage induced polarization changes – thereby converting pixel by pixel polarizations into black, white or gray pixels.

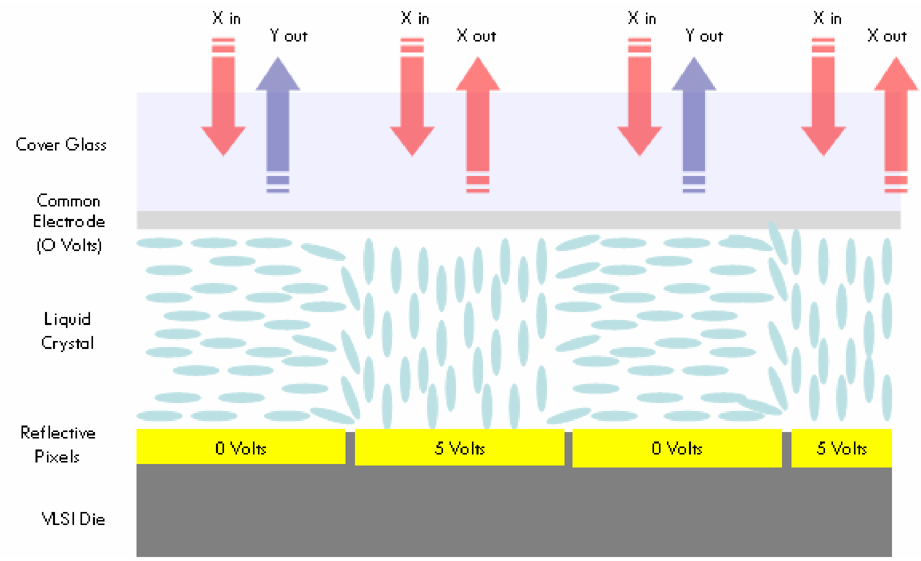


Figure 1. Side view of a LCOS display.

3. TRANSITIONING LCOS TO THE IR

Liquid crystal on silicon is an attractive candidate for IR scene projection. In order to transition the LCOS devices from the visible to the infrared, however, several obstacles must be overcome. First, the materials commonly used to fabricate visible LCOS displays are not appropriate for the infrared. Secondly, the response time of existing visible LCOS displays are insufficient for the IR scene projector application

3.1. IR Absorption

Minimizing absorption in the LCOS display is important for two reasons. First, it is important to maximize the optical efficiency of the device. Second, absorption leads to local heating. This adds noise to the IR system, and can change the optical properties of the liquid crystal layer. By examining Figure 1, one can determine where in the light path one might encounter optical loss. At the air to cover glass interface, there will be Fresnel reflection due to the refractive index mismatch. This can reduced through the use of a suitable anti-reflection coating. The cover glass itself can be the source of absorption. In the visible, a fused silica cover glass is commonly used. However, fused silica absorbs in the infrared, therefore an alternative material must be found. An ideal candidate would not only be optically transparent in the IR, but would be transparent enough in the visible to facilitate fabrication and testing. In addition, the substrate material must be durable enough to withstand cleaning and the application of alignment layers and coatings. Hygroscopic (water-absorbing) materials are difficult to work with and are not appropriate for field deployable units. Compatibility of the substrates with transparent conductor films is another important consideration. After surveying available IR substrates, we found zinc selenide (ZnSe) to be the best candidate in the MWIR.

To successfully transition LCOS displays to the MWIR and LWIR, an IR compatible transparent conductive film must be found to serve as the common electrode. Transparent Conductive Oxides (TCO) are a class of thin film semiconductor ceramics used in a variety of applications, including liquid crystal displays, anti-static films, anti-fog windows, and solar cells. These films are normally optimized for visible operation, but can be customized for IR applications[3]. Film optimization focuses on optimizing the optical and electrical properties of the materials. The optical properties of interest include the transmission, reflectivity, and absorption of the film at a given IR wavelength (if used with an IR laser) or IR wavelength band (if used with a broadband radiator). The optical properties are primarily a factor of the base oxides used, and the film thickness. Of equal importance are the electrical properties, such as the conductivity and sheet resistance, which determines the switching dynamics of the common electrode. Low sheet resistances can be achieved by modify the film deposition processes or by reducing the film thickness, but ultimately one is limited by the mobility of the material itself. In addition, in a scene projection application, the spatial uniformity of these films must be insured as pixel-to-pixel variances cannot be tolerated. In practice, the availability, toxicity, reproducibility, and cost of the coating must also be considered.

In the MWIR, we have found a number of candidate TCO materials including In(Ti)O and In(Mo)O that have good mobility and can result in films with absorptions of less than 1%. In the LWIR, however, the outlook is not as promising. Most TCO films have absorption of more than 8% in this region. One material, CdO has very high mobility and low absorption in the LWIR, but is a highly toxic material. An interesting alternative to a TCO in the long wave is to use a semiconductor as both the substrate and the common electrode. Both silicon and germanium are transparent in the LWIR and are electrical semi-conductors that can be doped to change their electrical properties. These materials could be used as both coverglass substrate and common electrode.

The liquid crystal materials also have some absorption in the infrared[4]. For example, in the MWIR, absorption in the 3.4-3.6 μm range can be observed, due to molecular vibrations of CH, CH_2, and CH_3. There is also a strong absorption band, due to CN absorption, at 4.45 μm. In addition, there are several absorption bands in the 8-12 μm region. One solution is to shift the absorption bands out of the region of interest by modifying the molecular composition of the LC material[5]. The effect of absorption bands can also be avoided altogether through the use of passive spectral filters or through the use of narrow-band laser illumination.

3.2. Response Time

Response time is the greatest concern when considering a liquid crystal based solution to the IR scene projection problem. Although the response time of commercially available nematic LC materials is adequate for visible operation, IR operation requires a thicker LC layer, which greatly reduces the switching speed of the material. Response time of liquid crystal based devices is also a function of drive voltage. This can make high-speed operation with a standard VLSI 5V backplane difficult. Therefore, a successful device for the IR will require both a high-voltage backplane and high speed materials.

The most conventional liquid crystal display architecture is a homogenously aligned nematic liquid crystal display. The minimum thickness of the LC layer required for such a reflective LCOS device is a quarter wavelength thick, resulting in a half wavelength of phase modulation in the double pass through the device. The required thickness, *d*, can be determined by the equation:

$$d = \frac{\lambda}{4\Delta n}$$

Where λ is the wavelength of the incident light and Δn is the birefringence of the liquid crystal. The speed of a given device is highly dependent on the LC layer thickness, *d*, and on material dependent properties, such as the threshold voltage (Vth), the rotational viscosity (γ_1) and the elastic constant (K)[6]. Typically, the rise time (~1ms) is much faster than the decay time, and so in a display application, it is the decay time that is of concern. Maintaining a thin LC layer is very desirable as the resulting switching speed decreases as the square of the thickness. A high speed LC material would therefore need both low viscosity and a high birefringence to minimize LC layer thickness.

Two promising alternative LC materials are ferroelectric LC and dual-frequency nematic LCs. In conventional nematic LC materials, the molecules can be switched in one direction with the application of an electric, but relax back to their original configuration once the field is removed. Ferroelectric liquid crystal materials have permanent dipoles perpendicular to the long axis of the molecules. This causes the material to exhibit a spontaneous polarization when subjected to an electric field. Unlike nematic LC materials, the molecules can be driven in both directions, resulting in much faster switching speeds. Dual-frequency liquid crystal materials have a dielectric anisotropy that changes direction at a relatively low frequency. All nematic LC materials exhibit this type of behavior. However, the frequency and temperature where the cross over occurs is material dependent. Therefore, special mixtures have been developed to have a low frequency (around 10 KHz) cross-over point. These materials can likewise be driven in both directions, resulting in a rapid electro-optic response.

4. MWIR PROTOTYPE RESULTS

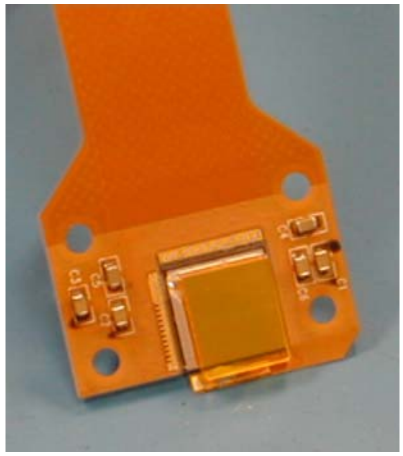


Figure 2. 256x256 FLC MWIR display.

To demonstrate the feasibility of a liquid crystal on silicon approach for IRSP applications, we fabricated three separate displays using a silicon backplane from BNS' existing stock[7]. The backplane utilized is an array of 256x256 pixels, with a center to center pixel spacing of 24 microns. The backplane was fabricated using a custom high-voltage process, and can support a voltage of 13V at each pixel. Because of the thicker LC layers required for IR operation, a higher pixel voltage is a necessity. All three displays were then evaluated in the MWIR at Infrared Systems Laboratory at the University of Central Florida (CREOL).

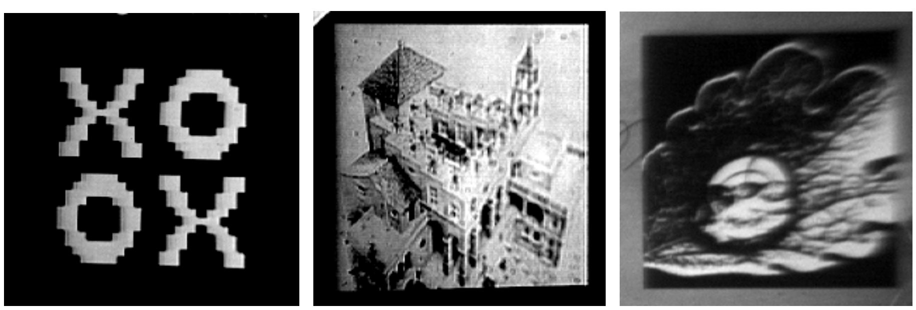


Figure 3. MWIR images from LCOS displays (blackbody source).

The first display was manufactured with a commercial nematic LC (Merck E44) with a homogenous alignment. The cover glass was CaF2 with an ITO coating. The display was limited to the 13 V available on the VLSI backplane. This display had a measured response time of 92 ms, an order of magnitude slower than desired for the IRSP application. Therefore, an alternate strategy had to be found.

The University of Central Florida's College of Optics has been developing innovative high speed materials to enable LC beamsteering devices[8]. These materials exhibit both high birefringence and low viscosity. A sample of high birefringence material was provided by UCF, and was incorporated into the second MWIR display. This material showed impressive improvement over the commercial material, with a switching time of 38 ms.

4.1. MTF Measurements

The modulation transfer function (MTF) of the UCF nematic display was measured. Modulation transfer function (MTF) is a convenient figure of merit used to measure system image quality. To test MTF, a series of vertical bar targets of increasing spatial frequency are used. This provides a good visual comparison of the desired driving image for the display and the result when viewed in the mid-wave (3-5) μm band. We used an input data set of square-wave bar targets and a frame-grabber to take a series of digital pictures of the resulting images on the display as shown in Table 1. On the left side of the table are arrayed pictures of input images to the display. On the right are shown corresponding results when viewed with the mid-wave IR camera looking into the LCOS display. At low spatial frequencies the wide vertical bars are reproduced quite well; there are some aliasing effects however at the transitions between adjacent bright and dark vertical bars. One can see quite clearly see progressive degradation of the images at higher spatial frequencies.

The LCOS device has 256x256 pixels with a pixel pitch of 24 μm. This puts a theoretical limit on the spatial frequency of 21 cycles/mm which could be displayed. It's actually slightly less than this number because of the fill factor.

A line-by-line series of horizontal slices were extracted from images like those show above. The absolute value of the Fourier transform of each line scan was taken and averaged. This procedure is then repeated for each spatial frequency of interest. To avoid nonlinearity in the camera response the square-wave data sets used were at 40% modulation depth at the display input which is why the vertical bars show intermediate gray levels rather than hard black-to-white transitions. This technique reduces aliasing effects in the output image.

Modulation transfer function (MTF) is defined as the modulus of the complex optical transfer function (OTF) and is a convenient figure of merit used to measure system image quality. It may also be defined as the absolute value of the Fourier transform of the point spread function (PSF),

$$MTF = \left|\mathcal{F}(PSF)\right| .$$

The advantage of the MTF approach is that the total system MTF is simply expressed as the product of each of the subsystem MTFs:

$$MTF_{System} = \prod_{i=1}^{n} MTF_i \ .$$

This property allows for the MTF of each subsystem to be studied independently. For higher spatial frequencies we determined MTF as the magnitude of the fundamental component of the Fourier transform. This avoids the necessity of a series correction to convert square-wave to sine-wave data. As an alternative interpretation, for low spatial frequencies modulation transfer function may be approximated by the modulation depth:

$$M = \frac{A_{MAX} - A_{MIN}}{A_{MAX} + A_{MIN}} .$$

Measurements were performed on the 256x256 display filled with the UCF material. The figure below shows MTF as a function of spatial frequency for our prototype display.

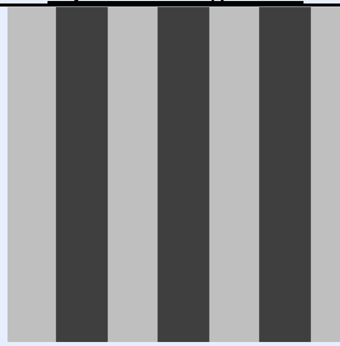
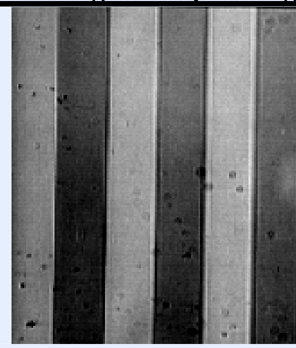
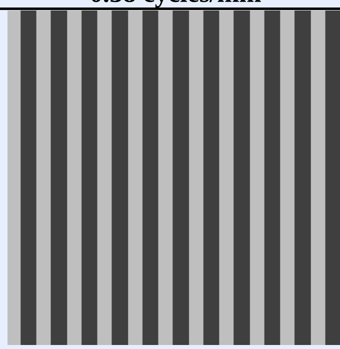
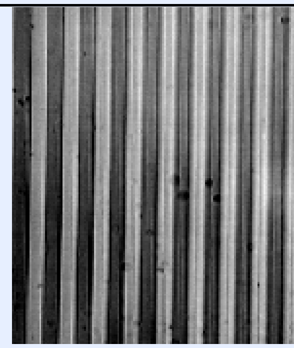
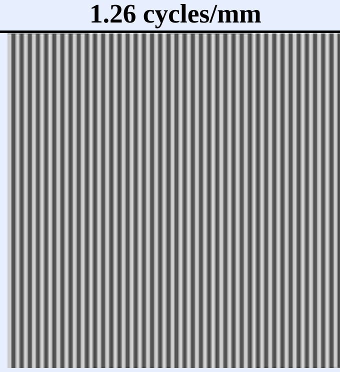
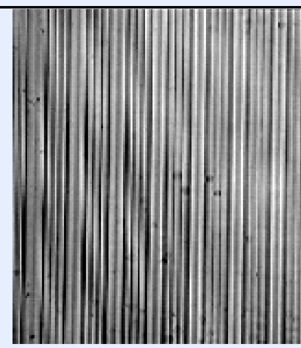
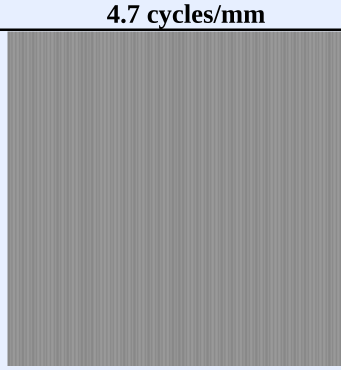
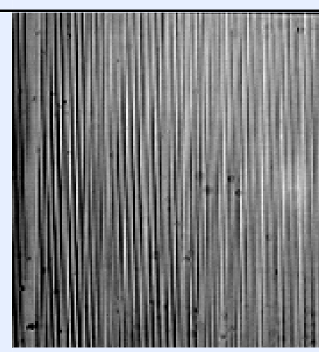
Input Bar Target File:	Resulting IR Output Image:
 0.38 cycles/mm	
 1.26 cycles/mm	
 4.7 cycles/mm	
 18.8 cycles/mm	

Table 1. Input bar-target images used to drive the display, and their resulting images as seen through the mid-wave IR camera.

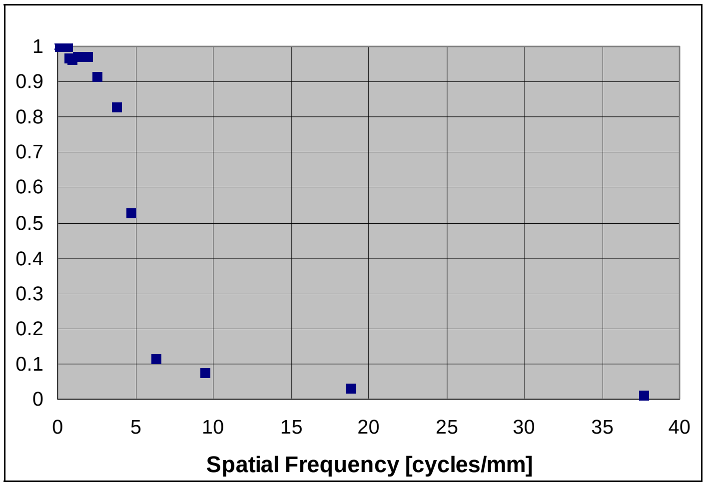


Figure 4. **Measured MTF of the UCF nematic display.**

One can see that the image quality begins to dramatically drop off near a spatial frequency of 5 cycles/mm. This represents a period of about 4 pixels. We observe the sharp knee and fall-off of the MTF curve specifically because this is a pixilated system. It is what one would expect rather than the gentler drop in MTF often seen in imaging system level such as microscopes or cameras. At small spatial distances less than a few pixels the ability of the system to properly image input information drops off sharply. Note that in Figure 4 the data point on the far right is beyond the limit of the device yet its MTF is reported as greater than zero. This represents the error in our measurement and computation method.

In summary, the main MTF limitations of our device are pixel pitch, fill factor and diffraction effects. Increasing device resolution and changing the design configuration for on-axis illumination/viewing should improve device performance.

4.2. High-Speed Material Investigation

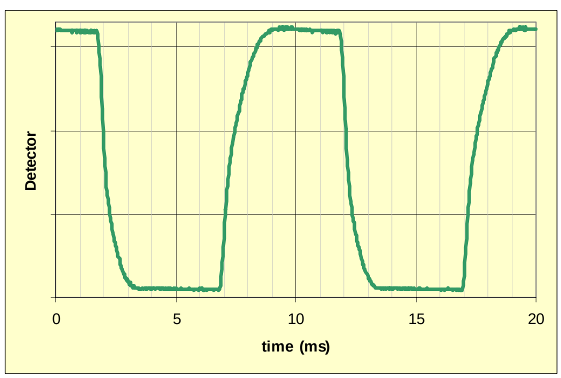


Figure 5. **Switching response of the MWIR FLC cell.**

The IRSP application demands high speed operation. To achieve 200 Hz frame rates, an alternative to a standard nematic approach must be found. Both ferroelectric LC materials and dual-frequency materials are considered viable candidate to meet this demand. As part of our material investigation, we fabricated two MWIR test cells with high speed mixtures; one with a ferroelectric LC compound and a second with dual frequency LC material. Both cells were fabricated with CaF_2 substrates with a thin ITO layer used as the transparent conductor. The ferroelectric cell required a thickness of 7 microns, a result of the relatively low MWIR birefringence of the material. However, the switching time was impressive, (see Figure 5) with a 2 ms activation time and a 1.5 ms deactivation time when subjected to a 13V field. The absorption of the FLC cell was measured by the University of Central Florida using a FITR spectrometer.

Those results are shown in Figure 6. Note the strong absorption at 3.4-3.6 µm, as is also seen in the nematic LC materials.

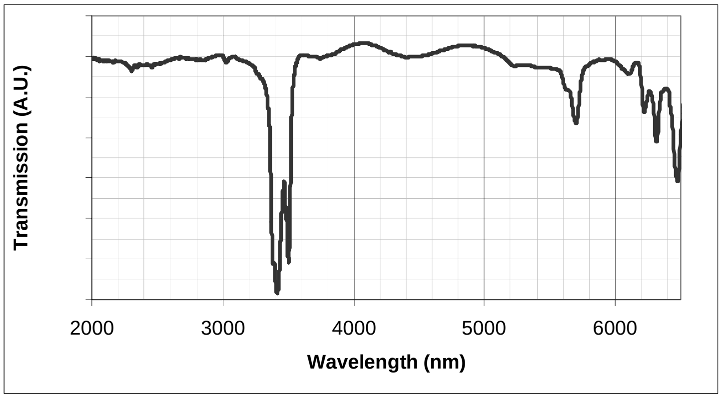


Figure 6. Transmission spectrum of the FLC cell.

The dual-frequency nematic cell was driven with a pulsed square toggling between 2 kHz and 40 kHz. The change in frequency changes the sign of the dielectric anisotropy of the material, causing the material to be driven in both directions. Initial measurement were made with a National Instrument card with a voltage limit of 20 V (see Figure 7). Even with this limited voltage, the material exhibited an activation time of 4ms and a deactivation time of 4 ms. Subsequent tests with a standalone function generator at 60V produced a deactivation time of 2 ms.

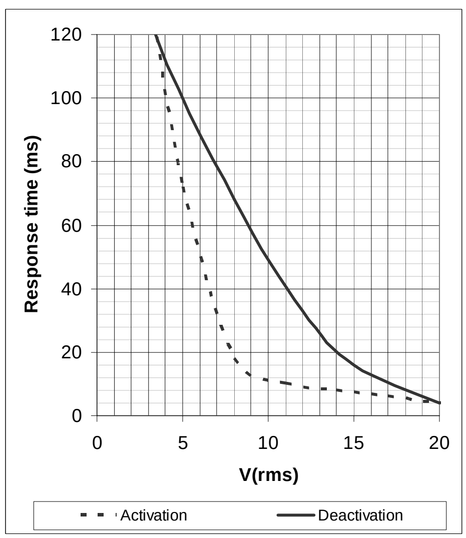


Figure 7. Response time of the MWIR Dual-Frequency nematic cell.

Consequently, a third display was filled with the FLC mixture. The display also exhibited a 2 ms response time. However the display exhibited poor spatial uniformity due to poor alignment. In addition, the display exhibited a very limited grayscale response. Future efforts will concentrate on fabrication improvements and enhancing the grayscale response.

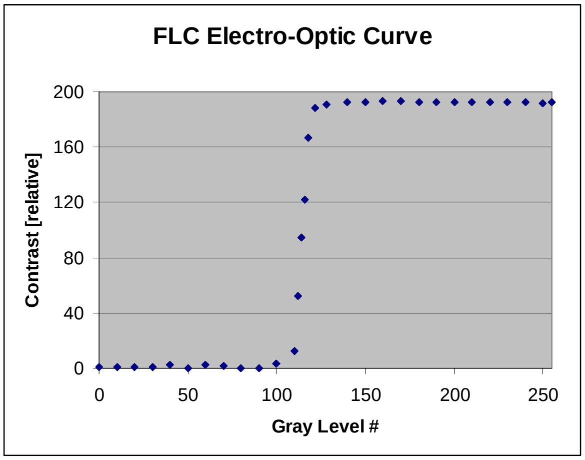


Figure 8. **Grayscale response of the FLC display.**

5. CONCLUSIONS

It has been demonstrated that liquid crystal on silicon devices can be transitioned to both the mid-wave and long-wave infrared bands. IR appropriate substrate materials, transparent conductive films and liquid crystals address absorption concerns. However, it is clear that a unique LC configuration will need to be pursued to meet the desired response time.

Future efforts will focus high-speed LC materials and on the fabrication of a high resolution, high-voltage silicon backplane. This backplane is an essential component, irregardless of the LC architecture pursued. The complicated drive scheme required to support dual-frequency LC materials will also be developed. Additional goals are to increase the contrast ratio of the LCOS display, pursue IR transparent conductive films, develop high voltage drive electronics and pursue high temperature displays.

An interesting benefit from this research is the application of the devices as programmable phase modulators. With minor modifications, the IR displays can be configured to be IR programmable lenses, wavefront correctors[9] and/or non-mechanical beamsteering devices[10]. This could greatly enhance the capability of current IR sensor arrays, or could provide a solid-state option to mechanically scanned mirrors.

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REFERENCES

[1] S. Solomon, “Adventures in High-Temperature Resistive Emitter Physics”, Proc. SPIE, **5092,** pp. 52-60 (2003).

[2] S.T. Wu, U. Efron, J. Grinberg, L. Hess and M. Welkowsky, “Infrared liquid crystal light valve,” *SPIE Proc.*, **572**, pp. 94-101, (1985).

[3] J. Perkins, C. Teplin, M. Van Hest, C. Warmsingh, D. Ginley and S. Harris,”Optimization of Transparent Conducting Oxides for Liquid Crystal Based Optical Phased Arrays”, *Proc. IEEE Aerospace Conference 2003,* **5.0801**, p. 4-1823, (2003).

[4] S.T. Wu, “Infrared Properties of Nematic Liquid Crystals: an Overview,” *Opt. Eng.*, **26**, 2, pp. 120-128, (1987).

[5] S.T. Wu, Q.H. Wang, M. Kempe and J. Kornfield, “Perdeuterated cyanobiphenyl liquid crystals for infrared applications”, *J. Appl. Phys.,* **92**, 12, (2002).

[6] S.T. Wu and D.K. Yang, Reflective Liquid Crystal Displays, John Wiley & Sons, 2001, pp 270-271.

[7] S. Serati, X. Xia, O. Mughal, A. Linnenberger, “High-resolution phase-only spatial light modulators with sub-millisecond response,” *Proc. SPIE*, **5106**, pp. 138-145, (2003).

[8] S. Gauza, H. Wang, C. H. Wen, S. T. Wu, A. Seed, and R. Dabrowski, “High birefringence isothiocyanato tolane liquid crystals,” Jpn. J. Applied Physics, Part I 42, 3463-66 (June, 2003).

[9] S. Serati, T. Ewing, and J. Stockley, “ New developments in high-resolution liquid-crystal spatial light modulators for wavefront control,” **4825**, pp. 46-55 (2002).

[10] S. Serati, and J. Stockley, “Advanced liquid crystal on silicon optical phased arrays,” *Proc. IEEE Aerospace Conference 2002,* **5.0301** (2002).