AFRL-ML-WP-TP-2006-466

FAST MULTI-SPECTRAL LIQUID-CRYSTAL-ON SILICON SPATIAL LIGHT MODULATORS (PREPRINT)

John R. McNeil, Michael J. O'Callaghan, Mark A. Handschy, Guoqiang Zhang, Anatoliy Glushchenko, John L. West, Kerry Lane and Stephen D. Gaalema

SEPTEMBER 2006

MATERIALS AND MANUFACTURING DIRECTORATE
AIR FORCE RESEARCH LABORATORY
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REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

1. REPORT DATE ***(DD-MM-YY)***	**2. REPORT TYPE**	**3. DATES COVERED** ***(From - To)***
September 2006	Conference Paper Preprint	10/01/2002 – 12/01/2005

4. TITLE AND SUBTITLE
FAST MULTI-SPECTRAL LIQUID-CRYSTAL-ON SILICON SPATIAL LIGHT MODULATORS (PREPRINT)

5a. CONTRACT NUMBER FA88650-04-M-5443
5b. GRANT NUMBER
5c. PROGRAM ELEMENT NUMBER 62102F

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5d. PROJECT NUMBER M08R
5e. TASK NUMBER 10
5f. WORK UNIT NUMBER 00

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Materials and Manufacturing Directorate
Air Force Research Laboratory
Air Force Materiel Command
Wright-Patterson AFB, OH 45433-7750

10. SPONSORING/MONITORING AGENCY ACRONYM(S)
AFRL-ML-WP

11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S)
AFRL-ML-WP-TP-2006-466

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
This conference paper has been submitted to SPIE for publication in the 2006 Proceedings of the Defense & Security Symposium.

This work is a result in whole or in part from Department of the Air Force contract number FA88650-04-M-5443.

This paper contains color. PAO Case Number: AFRL/WS 06-0351, 9 Feb 2006.

14. ABSTRACT
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15. SUBJECT TERMS
sheared liquid crystal, liquid crystal on silicon (LCOS), infrared scene projection, beam steering

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT:**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** (Monitor)
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Aaron M. Klosterman
Unclassified	Unclassified	Unclassified	SAR	14	**19b. TELEPHONE NUMBER** *(Include Area Code)* N/A

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18

Fast multi-spectral liquid-crystal-on-silicon spatial light modulators

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ABSTRACT

The stressed liquid-crystal (SLC) electro-optic effect promises fast electro-optic response times even for design wavelengths in the infrared (IR). Here we report characteristics of SLC devices appropriate for use as liquid-crystal-on-silicon (LCOS) spatial light modulators (SLMs) in the near (λ = 1.8–2.5 μm), mid (3–5.5 μm) and far (8–14 μm) IR bands. For these three bands we fabricated SLC devices with 5, 10, and 20 μm thicknesses; at drive voltages of 25, 50, and 125 V respectively these devices gave half-wave modulation with response speeds in the 1.3–1.6 ms range. Visible-light measurements on a 20-μm-thick SLC device between crossed polarizers gave a contrast ratio of 360:1 which improved to nearly 18,000:1 with a Babinet-Soleil compensator offsetting residual SLC retardance. The drive voltages for near- and mid-IR devices enable fabrication of SLCOS devices using high-voltage transistors options in standard CMOS processes; improvement of SLC materials by modest increase of birefringence Δn and dielectric anisotropy Δε would further bring far-IR devices within the standard CMOS drive voltage range. High-voltage CMOS transistor design rules permit pixel pitches less than 24 μm, making 1000 × 1000 SLMs feasible.

Keywords: sheared liquid crystal, liquid crystal on silicon, LCOS, infrared scene projection, beam steering

1. INTRODUCTION

Liquid-crystal-on-silicon (LCOS) devices have emerged as the preeminent spatial light modulator (SLM) technology. These devices utilize a light-modulating layer of liquid crystal material placed directly on a CMOS integrated circuit to give a compact, inexpensive, easy-to-use SLM with millions of gray-scale pixels electrically addressable at thousands of frames per second. LCOS SLMs have found widespread commercial application as electronic viewfinders (EVF) for camcorders and digital still cameras, and as the image-generating element in rear-projection high-definition televisions (HDTV). Their commercial success sustains an infrastructure geared towards short product-development cycles and low-cost mass manufacturing.

Liquid crystal devices (including LCOS SLMs), though, have found only limited application in the infrared. The principal barrier to widespread acceptance has been slow response speed. For most liquid crystal (LC) optical modulation modes, the response time increases quadratically with design wavelength λ. The thicker liquid-crystal layer needed to modulate the longer infrared wavelengths then results in slow response. For example, a liquid-crystal effect with fast millisecond response for visible wavelengths (λ = 0.5 μm) would have a slow 100 ms response at λ = 5 μm in the mid IR. So-called sheared liquid crystal (SLC) devices with a novel liquid-crystal/polymer composite aligned by shear stress promise to overcome this limitation and deliver electro-optic modulators with high speeds at IR wavelengths.[1]

2. PROTOTYPE IR SLC DEVICES

2.1. Intensity modulation

An SLC device functions as a variable retarder to modulate light. It produces efficient intensity modulation when oriented between crossed polarizers with its shearing axis aligned at 45° to the polarizers. The spectral dependence of the modulation for a *reflective* device is given by:

	CALCULATED			MEASURED					
OPERATING BAND	λ_C (µm)	Δnd (µm)	I_E/I_0	d (µm)	shear (µm)	Δnd (µm)	V_{MAX} (V)	τ_{OFF} (ms)	τ_{ON} (ms)
NIR (1.8–2.5 µm)	2.12	0.53	0.94	5	50	0.57	25	0.1	1.3
MWIR (3–5.5 µm)	4.06	1.02	0.84	10	80	1.2	50	0.1	1.3
LWIR (8–14 µm)	10.6	2.65	0.86	20	100	2.4	125	0.1	1.6

Table 1. Optimal and measured SLC properties for each wavelength band. Calculated: center wavelength λ_C, SLC retardance Δnd, and throughput I_E at band-edges. Measured for indicated cell thickness d: undriven retardance Δnd, saturation voltage V_{MAX}, and 10/90% optical phase-shift response times.

$$I = I_0 \sin^2(2\pi \Delta nd/\lambda). \qquad (1)$$

Optical throughput of unity is obtained when the SLC layer thickness d is chosen so that $\Delta nd = \lambda/4$, where Δn is the SLC birefringence. The throughput function of equation (1) varies slowly around its maximum, indicating that a single modulator can serve over a broad wavelength band. In fact, for $0.7\lambda_C < \lambda < 1.3\lambda_C$, throughput I/I_0 will be greater than 80% (where center wavelength $\lambda_C \equiv 4\Delta nd$). Table 1 shows, for the IR wavelength bands of interest, the center wavelength λ_C, the minimum needed SLC retardance Δnd, and the throughput I_E/I_0 at the edges of the band for ideal SLC modulators absent absorption or dispersion of birefringence.

IR absorption. We fabricated SLC cells of thickness 5, 10, and 20 µm targeted for the near, mid, and far IR wavelength bands respectively. The cells were made from a mixture of 10% NOA-65 UV-cure adhesive (Norland Products) in the single-component nematic liquid crystal 5CB. The cells were fabricated as previously described,[1] using spacers sized to give the target cell thicknesses, and shearing the cells by the amounts indicated in Table 1. We also performed IR absorption measurements on transmissive SLC cells of various thicknesses made from NaCl substrates, as shown in Figure 1. A reflective SLC SLMs of thickness d would have IR absorption equal to that of a transmissive cell of thickness $2d$; thus, a 5 µm thick SLC SLM operating in the near-IR would have a total optical absorption corresponding to that shown for the 10 µm thick cell in Figure 1, and so on.

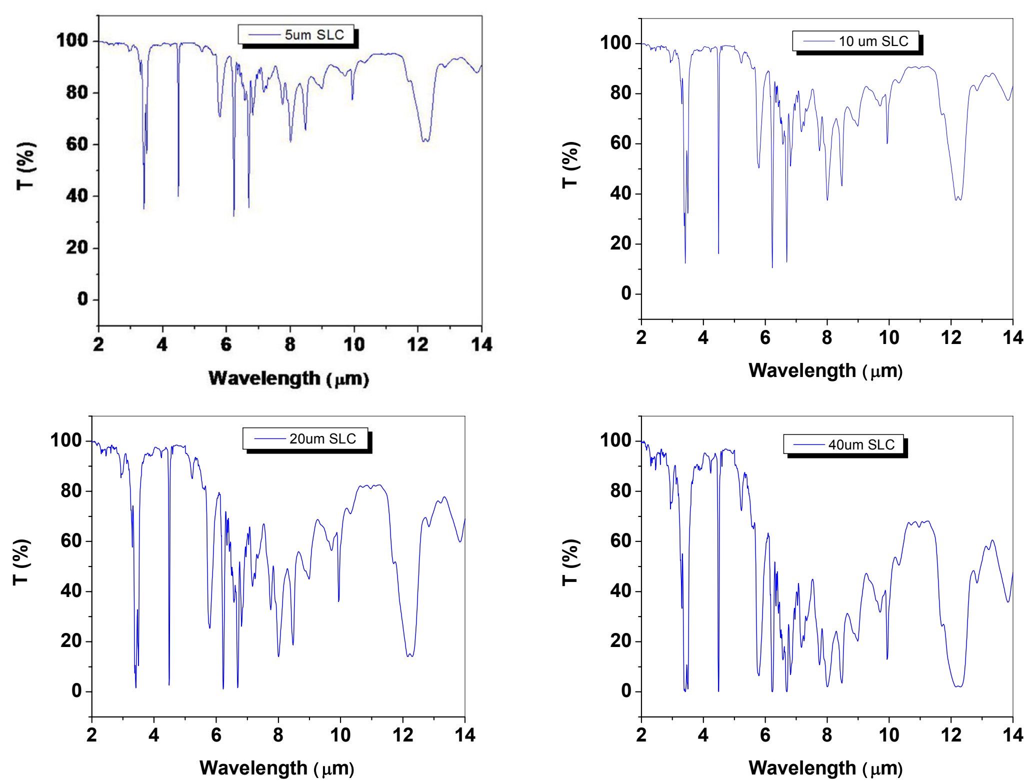


Figure 1. IR transmission spectra of 5CB-SLC cells of 5, 10, 20 and 40 µm thickness.

Response speed. Figure 2 and Figure 3 show the electro-optic characteristics of these cells measured at λ = 633 nm when driven with a 1 kHz square wave. We first measured transmitted intensity vs. drive voltage (peak), as shown in Figure 2(a). We then converted these measurements to retardance vs. voltage by inverting equation (1), with the results shown in Figure 2(b). Next, we chose for each cell thickness a drive voltage amplitude sufficient to nearly saturate its response (i.e. to reduce its retardance nearly to zero), and measured the dynamic response of the cell to application and removal of this drive voltage, with the results shown in Figure 3 (measured intensity has been converted to retardance). Table 1 summarizes the results. The retardances at 0 V come close to the needed minimum values derived in Table 1 for each of the three wavelength bands, since the IR birefringence of 5CB in fact differs little from it value in the visible. Response times in Table 1 are stated as 10–90% and 90–10% values for phase shift response. The fast response and its independence from cell thickness demonstrate the value of the SLC effect for IR modulation.

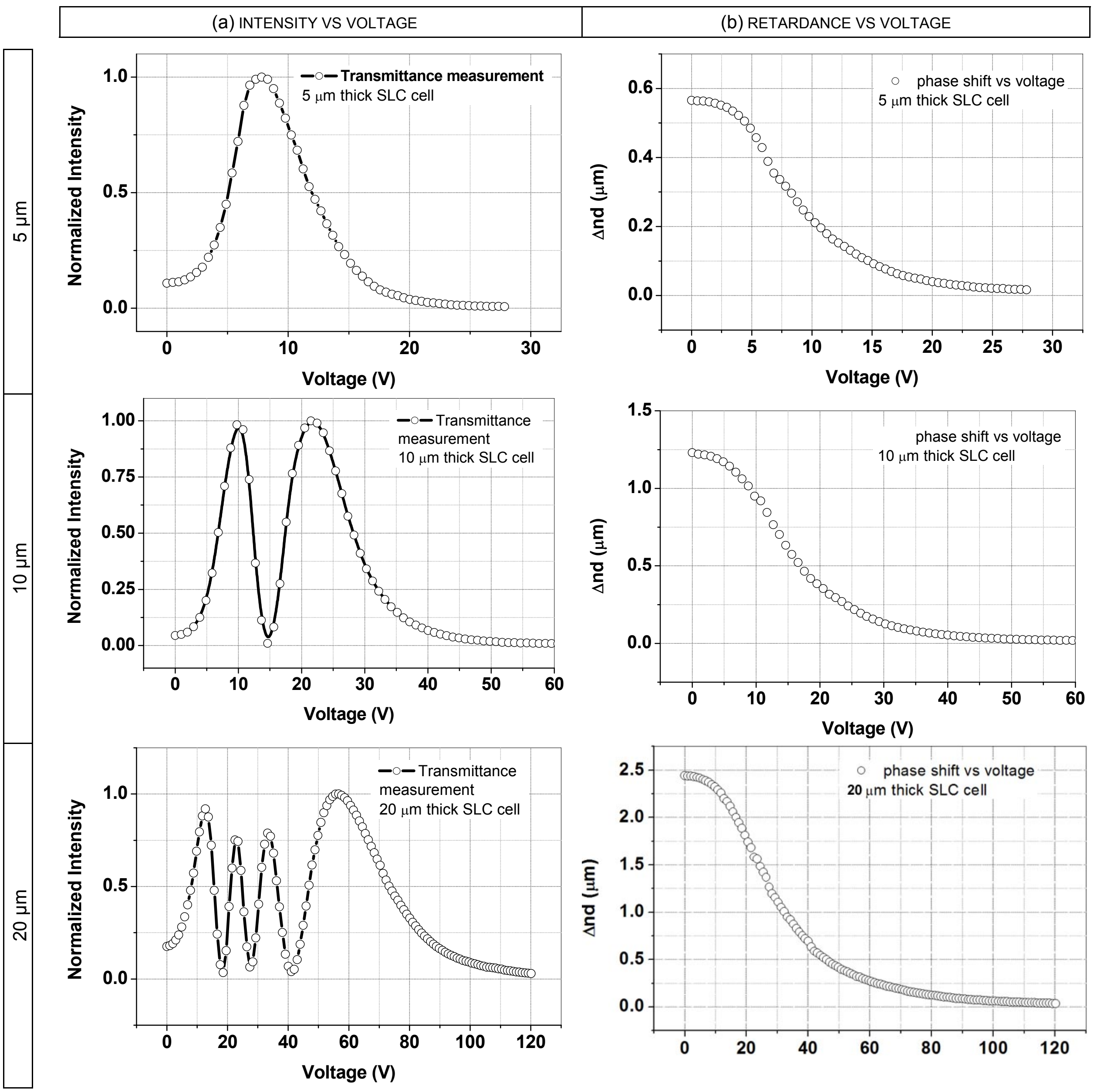


Figure 2. Electro-optic modulation vs. drive voltage for 5 μm, 10 μm, and 20 μm SLC cells.

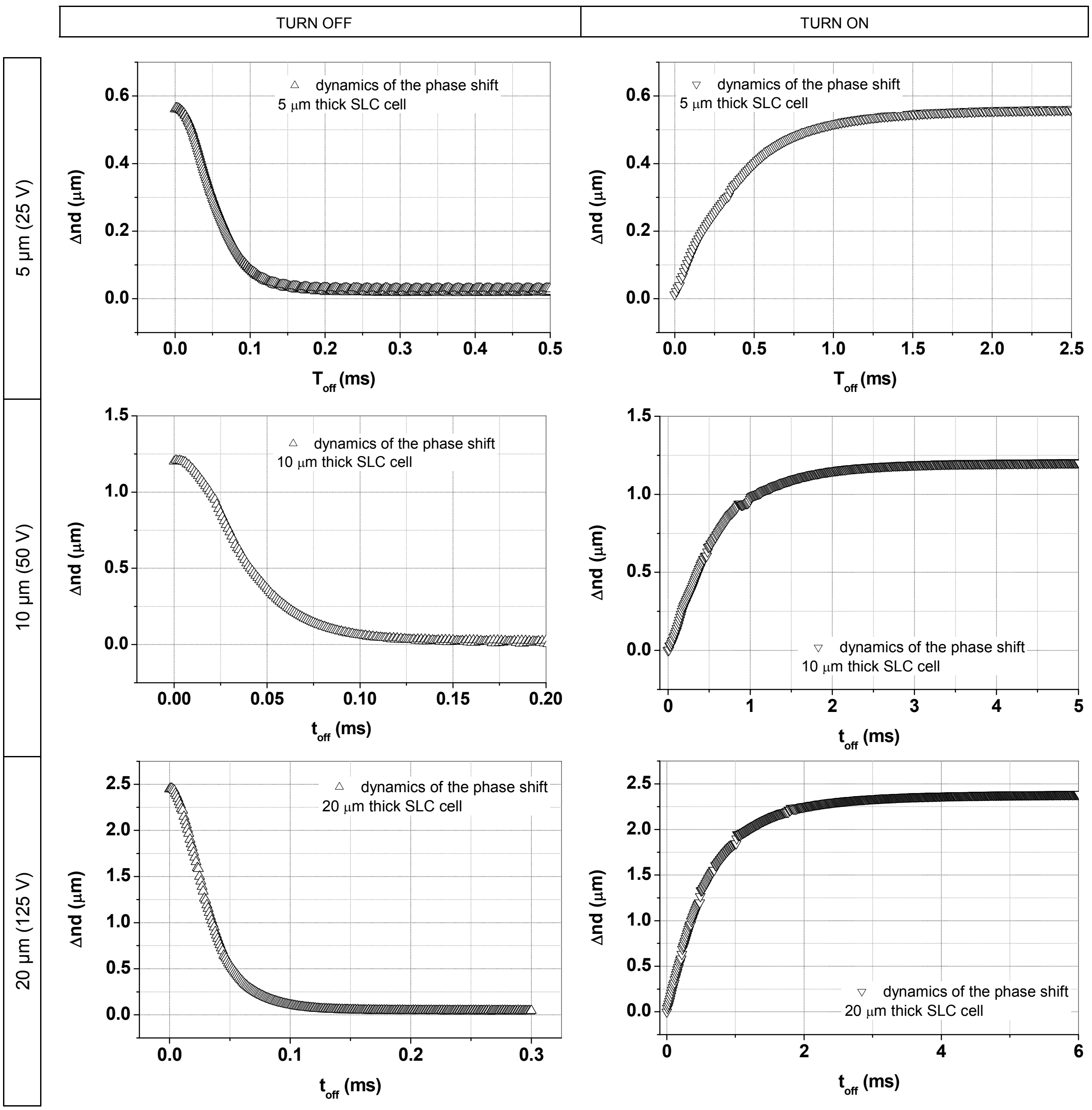
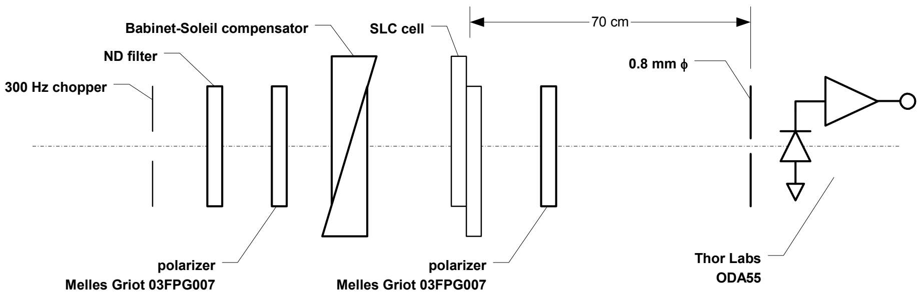


Figure 3. SLC electro-optic response dynamics in 5 µm, 10 µm, and 20 µm cells.

Contrast ratio. We made visible-light contrast measurements to begin gaining an understanding of achievable SLC dynamic range. Using an unexpanded 633 nm HeNe laser beam in the set-up shown in Figure 4 we characterized a 20 µm-thick SLC cell by driving it first to the highest-voltage throughput maximum (see Figure 2(a)) and then to a lower voltage throughput minimum. With nothing between the crossed polarizer and analyzer we obtained detector readings below 0.6 µV using a lock-in amplifier to reject noise (set-up dynamic range > 100,000). With just a 20 µm-thick SLC cell between the polarizers we obtained a contrast ratio of about 360:1. By using a Babinet-Soleil compensator (Karl Lambrecht) to offset residual birefringence at the throughput minimum of the SLC device, we were able to improve the contrast ratio to about 18,000:1. Maximum contrast was obtained with a compensation retardance of slightly more than a quarter-wave.



state	detector (mV)	contrast ratio
without compensator		
max.	65	
min.	0.18	**360**
with compensator		
max.	53.5	
min.	0.003	**18 000**

Figure 4. SLC contrast measurement set up and results.

2.2. Phase modulation

The variable retardance of the SLC effect functions equally well as a phase modulator. To demonstrate this illuminated a Michelson interferometer with linearly-polarized light from a diode laser with wavelength $\lambda = 1.55\,\mu m$, and placed a 22 μm-thick SLC device in one arm, with its shear direction aligned along the polarization. Figure 5 shows the output light intensity of the interferometer vs. the voltage applied to the SLC. Its variation from bright at 0 V, to bright at about 25 V, and to almost fully bright again at 40 V shows that the phase varies by almost two full waves. For this test the cell was driven with a 10 kHz square wave amplitude modulated by a slow 2 Hz triangle wave.

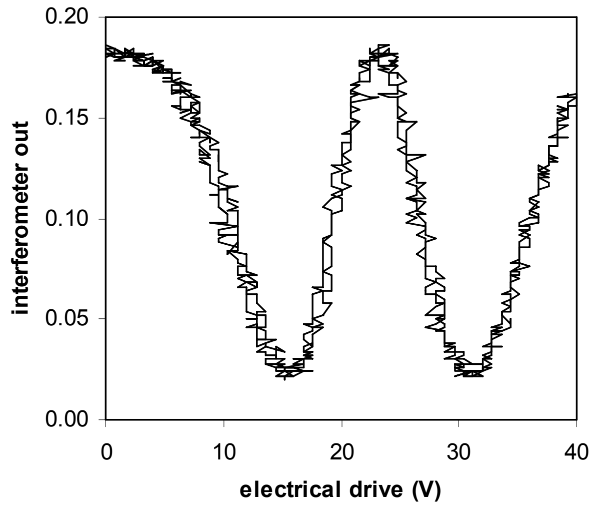


Figure 5. Interferometer output vs. SLC drive voltage (peak).

Figure 6 shows interferometer output (solid lines) obtained when driving a 22 μm-thick SLC cell with a 10 kHz amplitude-modulated square wave (hatched line shows peak drive amplitude). For amplitude A the drive voltage alternates between $+A$ and $-A$ at the 10 kHz rate. In Figure 6(a) and (b) the drive is stepped to change the SLC optical phase delay by approximately one wave between two states giving constructive interference—the width of the minimum indicates the response speed. Figure 6(a) and (b) differ in their starting (high) amplitude, and it is seen that the SLC is slightly faster at the higher voltage. Figure 6(c) shows the speed for a phase change of approximately 1.5 waves.

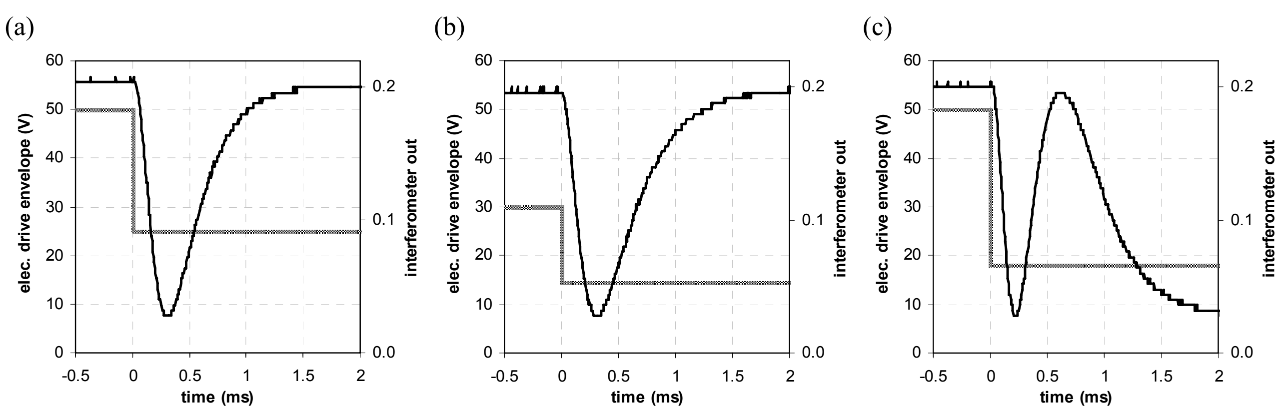


Figure 6. Interferometer output (solid) for SLC cell driven with 10 kHz square wave of modulated amplitude (hatched).

3. LCOS PIXEL DRIVE CIRCUITS

As shown in Table 1, SLC devices benefit from higher drive voltages for longer IR wavelengths. For a pulse-width-modulation (PWM) digital gray scale scheme, a simple boost circuit like that shown in Figure 7 can be used to drive the pixel electrode in an LCOS device to a suitable voltage level. The pixel's gray-scale circuitry (not shown) generates a train of low-voltage pulses with duty cycle proportional to desired drive level. This pulse train provides the input to the circuit of Figure 7. The p-channel transistor is biased to source a few nanoamps of current that charges the pixel electrode to the HV rail when the logic-level input is low—otherwise the n-channel transistor pulls the pixel electrode to ground. We analyzed the design rules for several 0.25 μm high-voltage (HV) CMOS processes to evaluate the tradeoff between drive voltage and achievable pixel pitch. The most efficient layouts are obtained with the HV boost transistors segregated into rows where the HV transistors are shoulder-to-shoulder, as shown in Figure 8. This layout shows the eighteen 32-V transistors needed for a block of nine pixels; nine p-channel transistors form the row across the top of the block and nine n-channel transistors form the row across the bottom. The spacing of the p-channel transistors determines the minimum pixel pitch of this layout at 23.5 μm—the space in the interior of the block is reserved for low-voltage gray-scale circuitry to serve the nine pixels.

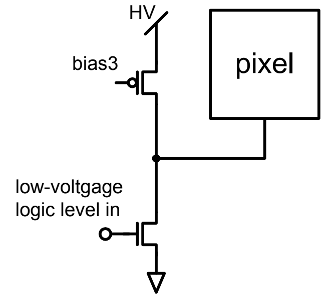


Figure 7. High-voltage pixel boost drive circuit.

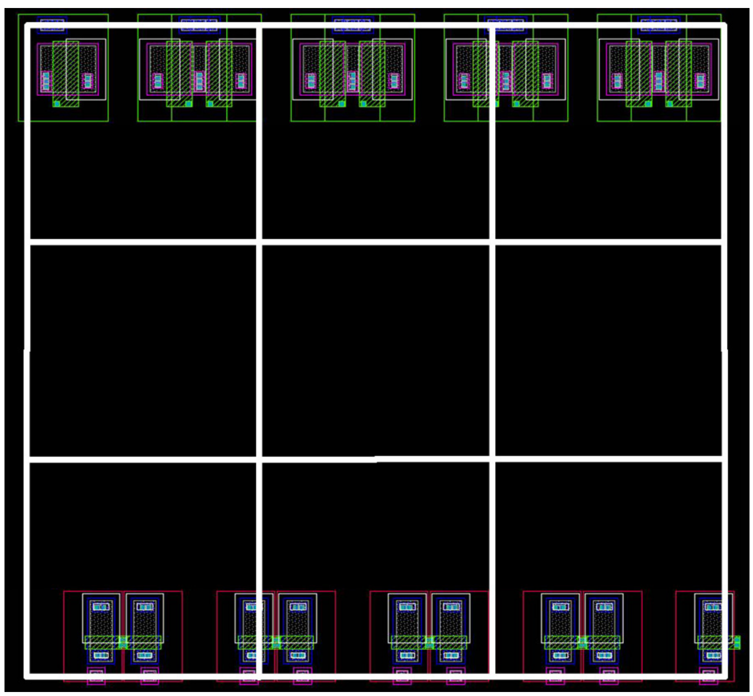


Figure 8. Layout of HV transistors for 3 × 3 block of 23.5 μm-pitch pixels.

4. IMPROVED IR LIQUID CRYSTAL MATERIALS

Based on the results shown in Figure 1, SLM optical throughput will initially be dominated by SLC optical absorption, at least in the mid and far-IR bands. Further, while CMOS drive voltage capability seems adequate for the characteristics of current near-IR and mid-IR SLC devices, improved far-IR operation could be obtained if drive voltages for that band could be reduced. A direct way to improve throughput and reduce needed drive voltage is to reduce liquid-crystal layer thickness by increasing liquid-crystal birefringence. Figure 9 shows an example of results obtained by this way. The lower curve is the spectrum of a standard Displaytech ferroelectric liquid crystal (FLC) material with thickness

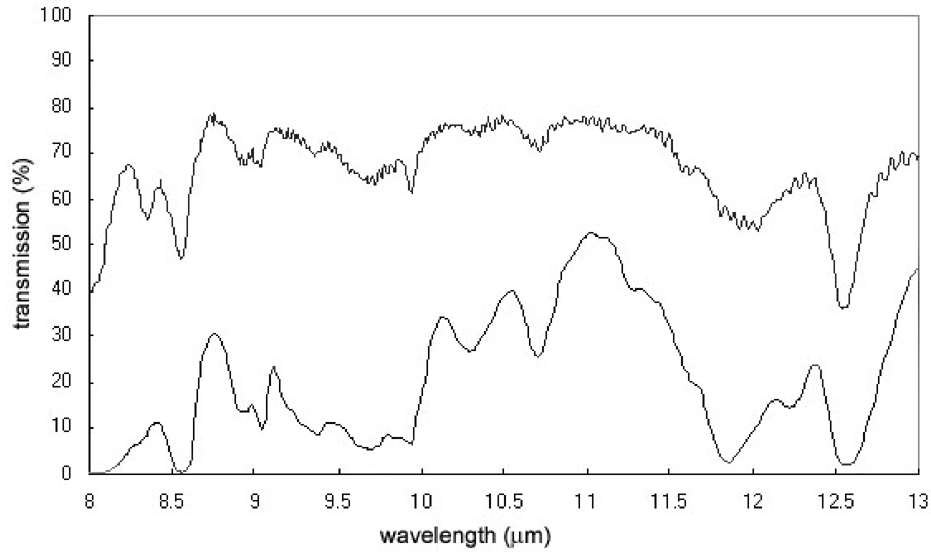


Figure 9. IR transmission spectra of standard (bottom) and optimized (top) LC materials.

chosen to give half-wave retardation in the far infrared, the same as for the SLC in Figure 1(d). Principally by increasing liquid crystal birefringence we developed an improved FLC material that yielded a thinner half-wave sample with absorption shown by the upper spectrum. We believe similar advantages should accrue with modest development effort to SLC devices. Choosing high $\Delta\varepsilon$ liquid-crystals would further reduce needed drive voltages. Given that fringing fields limit the smallest SLC region that can deliver full modulation to a size comparable to the SLC thickness, SLC materials with high birefringence also offer important resolution advantages at longer wavelengths.

5. CONCLUSIONS AND RECOMMENDATIONS

The results above demonstrate the feasibility of making fast IR SLMs using the SLC effect. Such devices would have response times in the 1.3–1.6 ms range, even in devices thick enough to modulate far-IR wavelengths. Simple high-voltage CMOS boost circuits enable SLM pixels smaller than 24 μm that can deliver drive voltages up to 64 V peak-to-peak. Reducing SLC film thickness through the use of high-birefringence liquid crystal materials is also the most direct way to reduce absorption in the mid and far-IR devices.

REFERENCES

[1] John L. West, Guoqiang Zhang, Anatoliy Glushchenko, and Yurii Reznikov, "Fast birefringent mode stressed liquid crystal," Appl. Phys. Lett. **86**, 031111 (2005).