Spatial light modulator considerations for beam control in optical manipulation applications

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ABSTRACT

Holographic beam forming to generate and control multiple optical traps has proved successful using high-resolution spatial light modulators (SLMs). This type of beam control allows a multitude of traps to be independently controlled in three dimensions. Also, exotic beam shapes and profiles can be generated, which gives the optical trapping system even greater flexibility.[1] Until recently, the generation of high resolution phase patterns has limited the speed of dynamic holographic optical trapping (HOT) systems. Today, video rate operation controlling hundreds of traps using 512x512 phase masks is possible and significantly faster operation is possible with fewer traps using less phase resolution. Therefore, phase-only liquid crystal modulator response is becoming the bottleneck. This paper discusses recent advances in SLM developments which address this issue.

Holographic beam control, spatial light modulators, phase-only modulation, liquid crystal, multi-spot beam steering, pulse shaping

1. INTRODUCTION

The use of holograms to generate three-dimensional spot patterns from a single input beam is finding new applications in the fields of optical trapping,[2,3,4] laser radar[5,6,7] and optical communications.[8,9] This interest comes from the evolving ability to dynamically generate holographic masks in real time. Each application has its own set of requirements for this type of volumetric beam control, but the need to accurately control size, intensity, shape and position of all the spots within the sample volume without introducing significant loss or scatter is always important. Highly efficient pattern generation, containing hundreds of independently moving spots, has been demonstrated using high-resolution, phase-only spatial light modulators (SLM). These SLMs use nematic liquid crystal materials that are properly aligned to provide a pure optical path delay (OPD). As research in this area continues, it is being found that the dynamic behavior of the liquid crystal OPD modulator has a profound effect on the performance of these multi-beam systems. This paper discusses some of the dynamic issues and techniques for controlling their effects to allow accurate real-time phase mask generation.

The control of LC through an active matrix backplane greatly simplifies the addressing hardware, but it introduces performance tradeoffs especially for generating phase-only holograms in real time. To control hundreds of thousands of elements using a reasonable number of interconnects, data needs to be time-sequentially multiplexed into the active matrix backplane. Typically, active-matrix displays use a small number of analog drive signals (2 to 4) or several binary drive signals (16 to 32). These display drive schemes provide multi-level addressing of the LC modulator at video rates using a minimal set of drive electronics. For display, the device does not have to present complete images to the eye even for a short period of time, since the eye does not rely on spatial coherence and uses the average intensity received over several milliseconds to form an image. On the other hand, beam forming techniques used in holographic optical trapping (HOT) systems rely on the phase patterns produced by the SLM to be spatially complete and temporally static for a period of time to correctly steer the incident light into the desired spot pattern. Therefore, the amount of light effectively forming traps versus stray light is strongly related to the time the phase profile remains static over the frame period (i.e. the time devoted to one spot pattern). In a typical display, the frame period is 16.7 milliseconds and the time to fully load an image is 16.7 milliseconds. Even with a very fast LC modulator (much faster than a frame period), a complete image pattern is not present across the whole array unless multiple frame periods are used for each image. To maximize trapping effectiveness and not compromise the speed of the dynamic trapping system, a fast LC modulator is desired. However, this paper will show that the frame period needs to be several times faster than the response of the LC modulator to effectively form static patterns. Thus, video frame rate addressing greatly limits phase-only SLM operation. Also, this paper demonstrates that an effective solution is to use sub-millisecond load rates to eliminate data-dependent phase droop/ripple especially when using high figure of merit LC materials to provide fast SLM response.

2. HIGH FIGURE OF MERIT LC MODULATORS

A zero-twist (i.e. Electrically Controlled Birefringence - ECB) mode nematic liquid crystal (LC) modulator provides pure phase-only modulation without adding data-dependent amplitude variations, as occurs with twisted-nematic modulators such as those used in liquid-crystal displays. Pure phase modulation with a full wave (2π) of modulation depth provided at each pixel for the design wavelength is required for efficiently creating and controlling multiple optical traps using high-resolution holographic masks. Due to the variation in modulator thickness for the different design wavelengths Boulder Nonlinear Systems (BNS) offers over the 532 nm to 1064 nm band, the response times of the nematic LC SLMs range from 30 to 15 frames per second, respectively, when using commercially available LC materials that have a birefringence of approximately 0.2. To substantially improve performance, a high-birefingent LC material with a low viscosity to elastic constant ratio (i.e. low viscoelastic coefficient - γ_1 / K_{11}) was developed.

The cell gap (*d*) needed to provide a wave of modulation at the design wavelength (λ_d) is proportional to the LC's birefringence (Δn) as shown below

$$d \propto \frac{\lambda_d}{\Delta n} \; . \tag{1}$$

This thickness directly affects the response time of the LC modulator, which is dominated by the free relaxation time (τ_o) given by

$$\tau_o = \frac{\gamma_1 d^2}{K_{11}\pi^2} \; . \tag{2}$$

By using the relationships given in Equations 1 and 2, a figure of merit (FoM) for modulator response expressed in terms of LC material properties has been introduced to compare various LC materials:[10]

$$FoM = \frac{K_{11}(\Delta n)^2}{\gamma_1} \; . \tag{3}$$

As shown in Equation 3, this figure of merit is independent of cell gap thickness, and it points out the importance of LC birefringence to modulator response. Note that the FoM is indirectly wavelength and temperature dependent, because LC properties are affected by these parameters.

A high FoM LC material was developed for use in BNS' SLMs. This material has a very high birefringence as compared to most commercial materials (Δn=0.38 and 0.42 at λ= 632.8 nm and 532 nm, respectively). The mixture shows an impressively high FoM at room temperature (14.4 μm^2/s). Under the same circumstance, the FoM of Merck TL-216 is ~2.4 μm^2/s.[11] The birefringence of Merck TL-216 was measured to be 0.20 at λ=633 nm and T=22°C. Thus, the new material shows ~6X higher FoM than popular commercial high birefringence LC mixtures.

Chemical and ion purity is an important concern for active-matrix applications such as liquid crystal on silicon (LCoS) SLMs because it affects the voltage holding ratio. For an active matrix SLM that uses a slow load/refresh rate (several milliseconds), the phase pattern does not hold steady (i.e. phase modulation drops) if the LC has a low resistivity. High chemical and ion purity also elongates the lifetime of the LC devices. The long-term chemical stability can be greatly improved by eliminating the organic side-products as well as inorganic agents involved in the processing. The compounds used in our experiment were synthesized according to the state-of-the-art procedures with final chemical purity in the range of 99.5-99.9 wt %. Both of the high birefringence mixtures were purified using ion exchange resins in multiple-step processes. After only three steps of ion purification, the resistivity of the high FoM material improved to 10^{13} Ohm-cm.

With the high FoM material, it will be possible to greatly increase the operating speed of the phase-only SLM. To date the response time of the SLM has not been a significant

problem, since the operating speed of HOT systems has been restricted by other component and application issues. For example, it takes considerable processing power to calculate trap locations from a user input and convert this information into a series of holographic phase masks to dynamically move the traps. Only recently have efficient algorithms been implemented with the appropriate computer hardware to allow hundreds of optical traps to be individually controlled at video rates using 512x512 phase masks. With the current trend in computing capability doubling every few years and as the need for autonomous manipulation of optical traps develops, a video-rate SLM will soon become a significant limitation to these HOT systems. Even today, there are developing nano-factory applications where faster manipulation of fewer traps appears to be the best approach. This type of application allows the resolution of the phase mask to be reduced (i.e. a 256x256 hologram being sufficient) which in turn reduces the processing overhead, allowing the system to operate faster. For the 256x256 case, it is necessary for SLM operation to increase by a factor of four (>100 frames per second) to fully support a lower-resolution HOT system capability, which is possible with the high FoM material.

3. ECB MODULATORS WITH VIDEO RATE ADDRESSING

Various papers and books (e.g. Ref. 10) discuss the dynamic behavior of ECB liquid crystal modulators. This literature describes the components (viscosity, elastic constants, dielectric anisotropy, etc.) of the various competing forces within the cell that control the LC material's response to an applied field. However, the multiplexing drive scheme used to control the voltage at each pixel of an active matrix backplane significantly adds to the dynamic behavior of the LC modulator which complicates the issue. Therefore, this paper uses the results from a few experiments to demonstrate the temporal and spatial effects that reduce pattern integrity. For this paper pattern integrity refers to the ability to accurately form the phase hologram and maintain the pattern.

In this paper, we use results from both transmissive and reflective ECB devices, since we needed different backplane designs to implement the different addressing schemes. Figure 1 schematically shows the SLM test setup used to evaluate the temporal response of the reflective ECB devices. The configuration, through the operation of the polarizing beam splitter and waveplate, places the reflective SLM between crossed polarizers. The incident light is aligned at 45° degrees to the optic axis of the LC modulator, which causes the ECB modulator to vary the polarization angle of the reflected light. As the ECB transitions from one state to another, the crossed-polarizer configuration converts the polarization rotation into an intensity profile at the fast detector. The detected intensity profiles are captured using a digital oscilloscope. The same basic approach is used for the transmissive devices except an in-line configuration with two separate polarizers is used. For the following experiments, the active-matrix backplane is loaded with one gray scale value across the whole array during a frame period. The monotone pattern is then held constant for several frames.
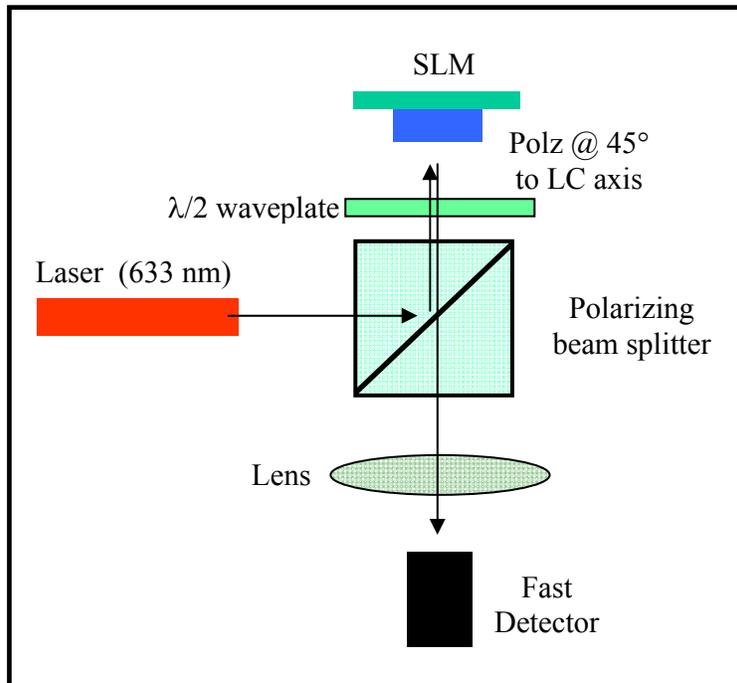
Figure 1: Optical test setup for analyzing ECB modulator response.

Figure 2 shows the response of a transmissive ECB modulator that uses a LC material with a FoM of 2.4 μm^2/s. The SLM is addressed at video rate - 60 frames per second (fps). The gray scale values change from 0 (high field) to 255 (low field) during the trace capture. For a full 2π transition, the resulting trace should complete a full cycle (i.e. from peak to peak, valley to valley, etc). From the trace shown in Figure 2, it is uncertain if the modulator produces a full 2π transition at 633 nm. When a high FoM material (FoM = 14.4 μm^2/s) is used in the same design, the phase transition clearly exceeds a full 2π (refer to Figure 4). In addition to the large effect caused by the 0 to 255 transition in Figure 2, there is other obvious structure in the waveform. The small periodic variations are synchronous with the frame period (60 Hz ripple). This ripple is very consistent from period to period, but its amplitude and temporal variation is data dependent as shown in Figure 3. Because of this data dependency, there is virtually no time that the hologram is truly static. The phase variation due to the ripple is generally less than a tenth of a wave for the lower FoM materials. Unfortunately, the problem becomes significantly worse as the relaxation time for the LC modulator becomes shorter (i.e. for higher FoM LC materials). Figure 4 shows the relaxation response of a high FoM device (FoM = 14.4 μm^2/s). With the higher birefringence, the SLM clearly demonstrates more than 2π of modulation depth (i.e. a clear peak-to-peak transition). Also, this LC modulator has a significant 60 Hz data-dependent ripple, as shown in Figure 5. Figure 6 compares the 60 Hz peak-to-peak ripple for the different FoM materials discussed. It is obvious from Figure 6 that the higher FoM material adds considerably to phase error when addressed at video rates.
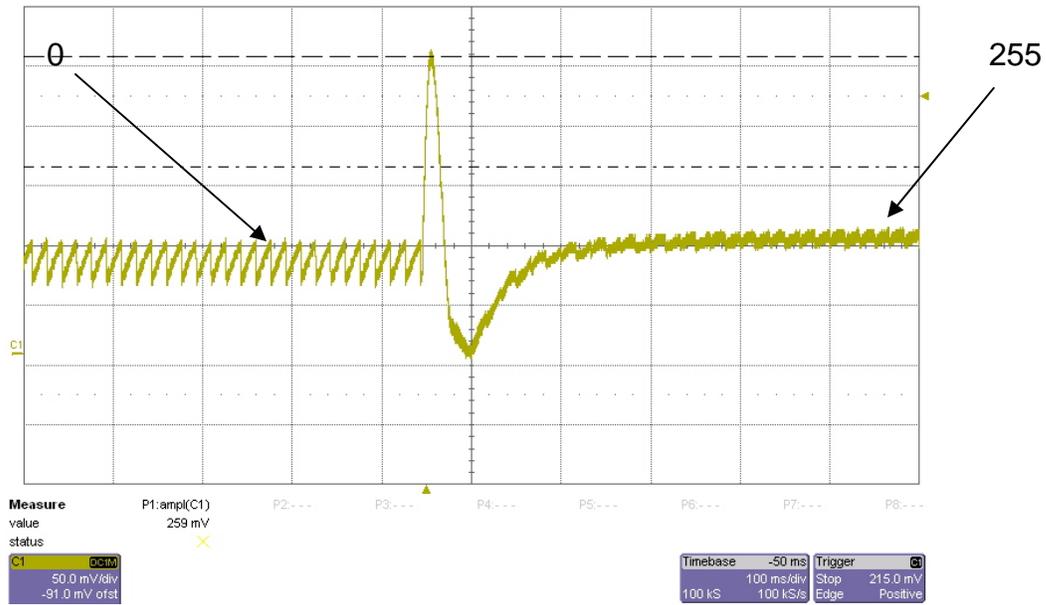
Figure 2: Relaxation response (0=high field, 255=low field) of transmissive SLM (FoM = 2.4 μm^2/s).
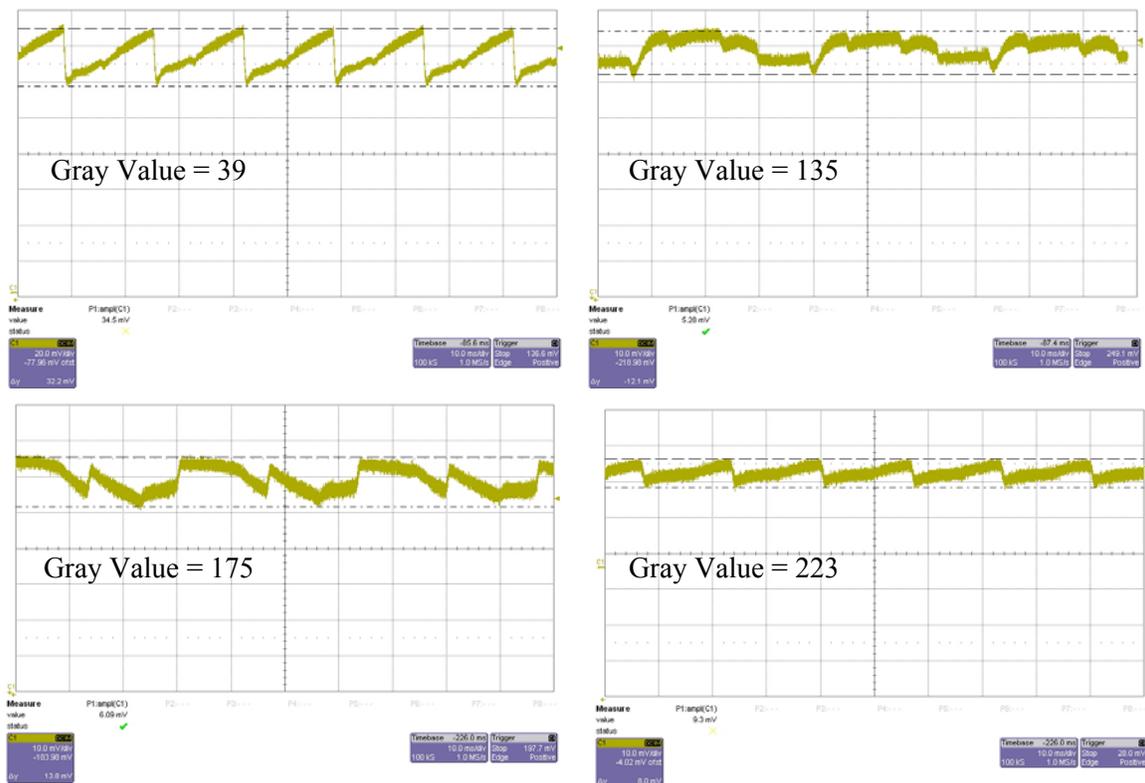

Figure 3: Data dependent ripple due to 60 fps addressing. Gray level values of 39, 135, 175 and 223 are represented in the different plots (transmissive SLM with FoM = 2.4 μm^2/s).

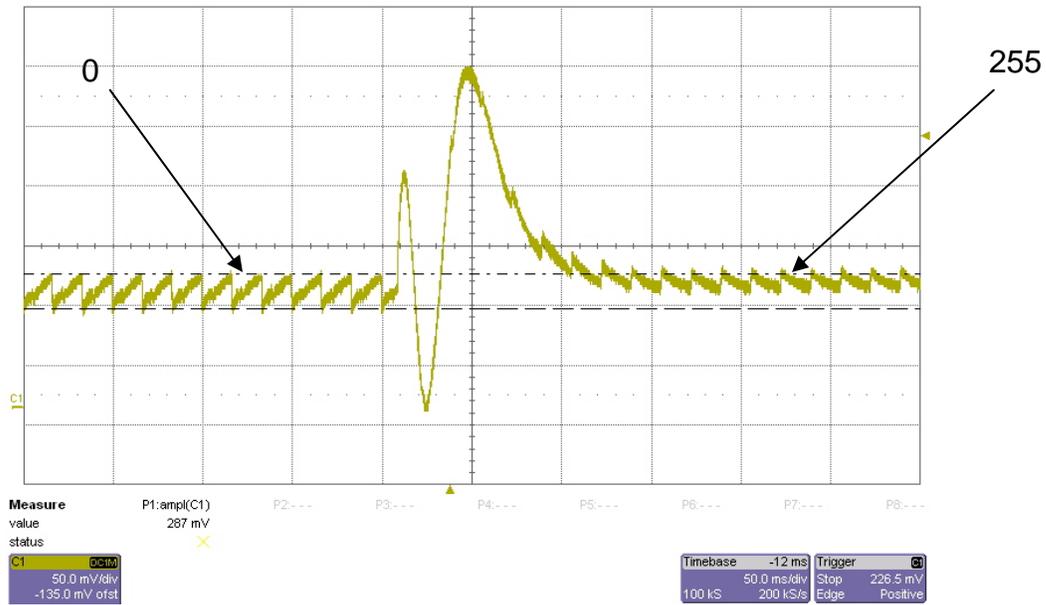**Figure 4:** Relaxation response (0=high field, 255=low field) of transmissive SLM (FoM = 14.4 μm^2/s).
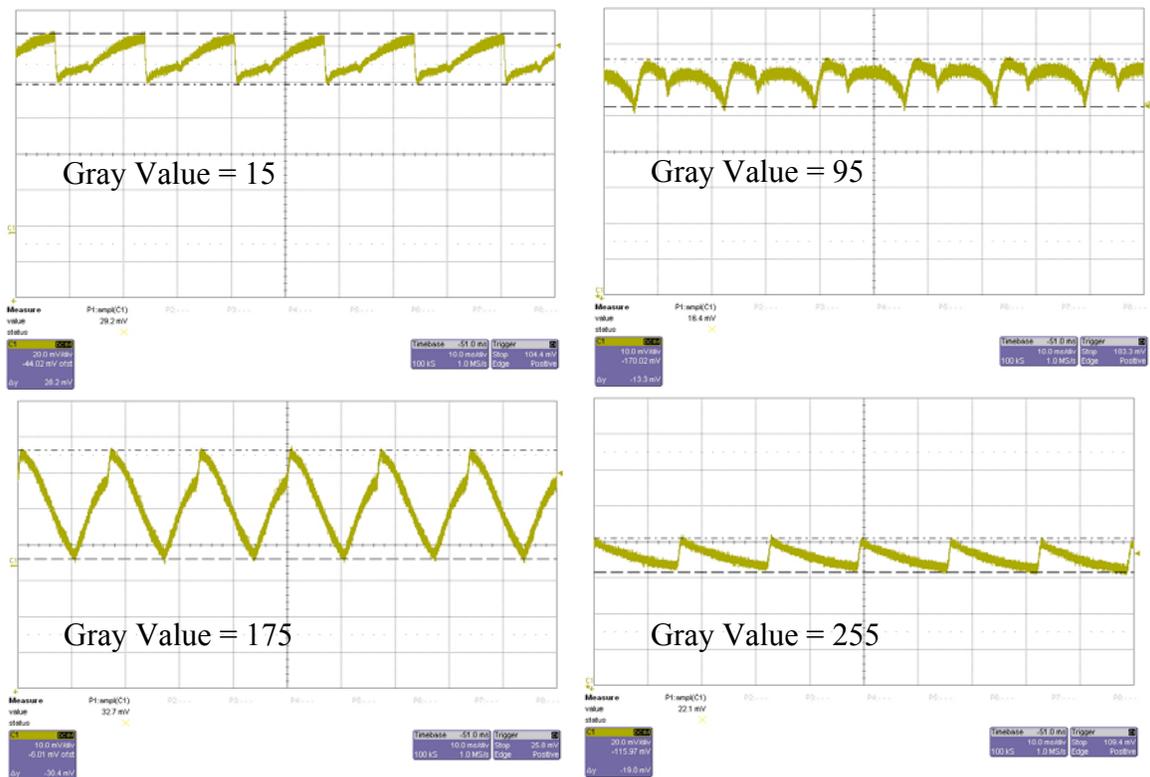

Figure 5: Data dependent ripple due to 60 fps addressing. Gray level values of 15, 95, 175 and 255 are represented in the different plots (transmissive SLM with FoM = 14.4 μm^2/s).
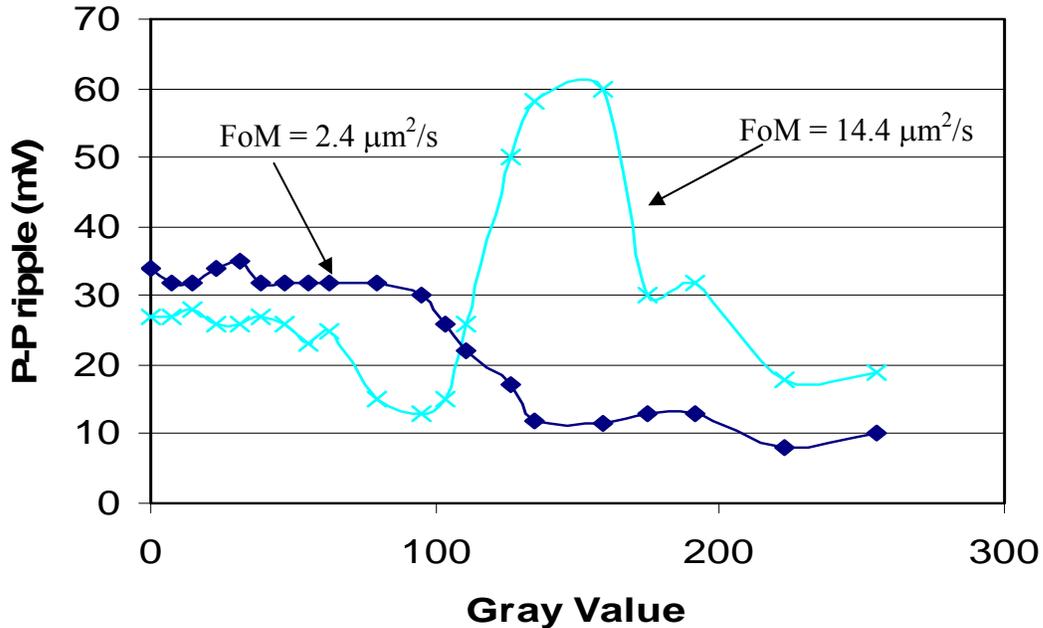
Figure 6: Plot of 60 Hz peak-to-peak ripple versus gray scale for LC materials having different figures of merit (load rate = 60 Hz, toggle rate = 30 Hz).

4. DRIVING TECHNIQUE FOR REDUCING ADDRESSING RIPPLE

The previous section shows the result of driving ECB modulators at video rates. In the test cases shown above, the transmissive active-matrix backplane was addressed at a 60 Hz rate. That is, a whole frame of data was loaded in 16.7 milliseconds. Each time a new frame of data was loaded with the same gray scale values, a voltage level was stored at the pixel that reversed the field across LC modulator (i.e. the field had the same amplitude but opposite polarity). Therefore, the field was inverted (toggled) at 30 Hz (33.3 milliseconds per cycle). If the toggle period is compared with the free relaxation time of the two transmissive ECB modulators (refer to Equation 2), we find that the relaxation period for the lower FoM modulator is longer (42 milliseconds) and the higher of FoM modulator is shorter (25 milliseconds) than the toggle period. However, both relaxation times are close to the toggle period, which explains why both have considerable ripple. Also, the two examples indicate that the toggle period needs to be significantly shorter than the relaxation time to reduce the ripple.

The overall goal is to achieve fast response with minimum ripple. The high FoM transmissive ECB modulator is easily capable of supporting 30 fps operation with a full wave of modulation at 633 nm. It is desirable to greatly increase the operating speed of the device. By moving to a reflective configuration for the SLM, it is possible to halve the modulator thickness and still maintain the full modulation depth. By reducing the

modulator thickness by a factor of two, the operating speed of the SLM increases by approximately a factor of four (refer to Equation 2), which allows the SLM to run at over 100 fps. However, the faster response requires the toggle rate to be significantly higher than 100 Hz to prevent ripple. Fortunately, the 512x512 reflective SLM backplanes developed by BNS accept 32 analog inputs at 50 MHz, allowing a 6 KHz load rate. The drive electronics invert the data after a user-specified number of SLM load cycles. With the number set to three, the device drives the LC modulator with a 1 KHz toggle rate. By using these design and operating parameters, a high FoM reflective device was fabricated and tested.

Figure 7 shows the relaxation response of a reflective ECB modulator that uses a LC material with a FoM of 14.4 μm^2/s. As discussed above, the SLM is loaded at 6 KHz frames per second and the field polarity is toggled at 1 KHz. The gray scale values change from 0 (high field) to 255 (low field) during the trace capture. This device produces a full 2π transition at 633 nm in less than 10 milliseconds, allowing the SLM to operate at 100 fps. There are no visible periodic variations that are synchronous with the frame or toggle period (6 KHz or 1 KHz ripple).
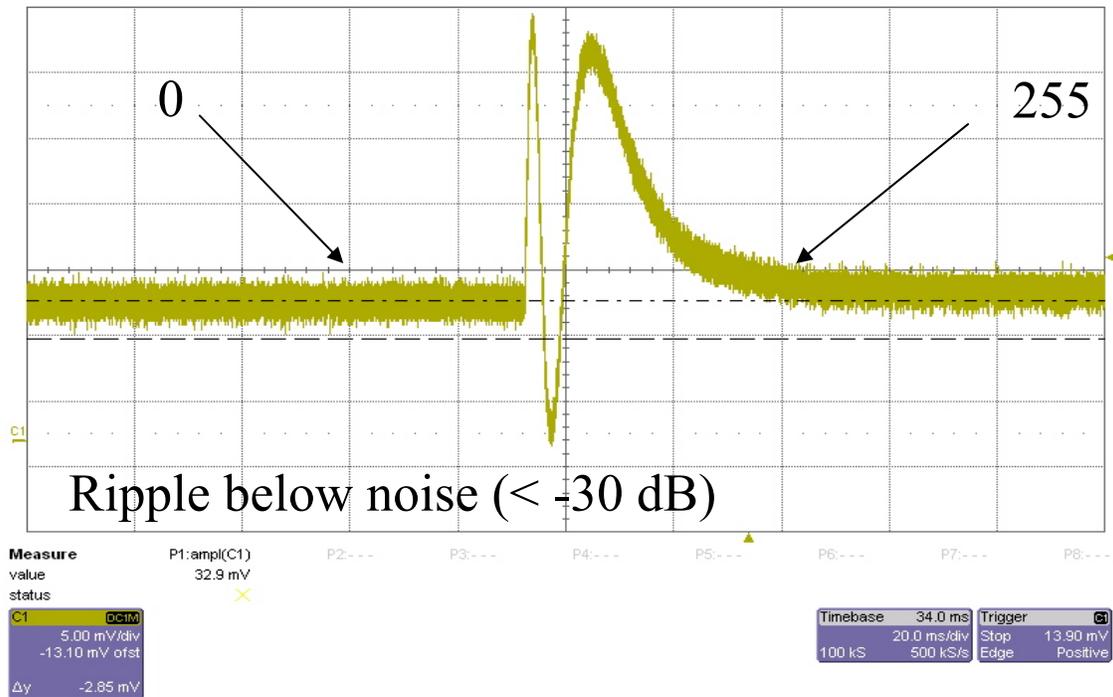

Figure 7: Relaxation response (0=high field, 255=low field) of reflective SLM (FoM = 14.4μm^2/s).

5. CONCLUSIONS

The use of high birefringent, high figure of merit liquid crystal materials for ECB modulators was investigated. These materials allow a thinner cell gap to be used for the modulator, which greatly improves SLM response times. At 633 nm, reflective SLMs capable of operating at 100 fps were demonstrated using room temperature conditions. By heating the SLMs and using higher voltage addressing, we believe operation at several hundred fames per second is possible.

These speed improvements however place additional requirements on the active matrix backplane and addressing electronics. As shown in Figure 8, there is significant data-dependent ripple caused by slowly addressing the modulator (plot on left). That is, the rate used to toggle the field driving the ECB modulator is slower than its relaxation response. To eliminate the ripple, the toggle rate needs to be several times faster than the modulator's response (right plot). This requires active matrix backplanes and drive electronics capable of sub-millisecond load rates.

Toggle rate = 30 Hz
Refresh rate = 60 Hz

Addressing Ripple < -30 dB

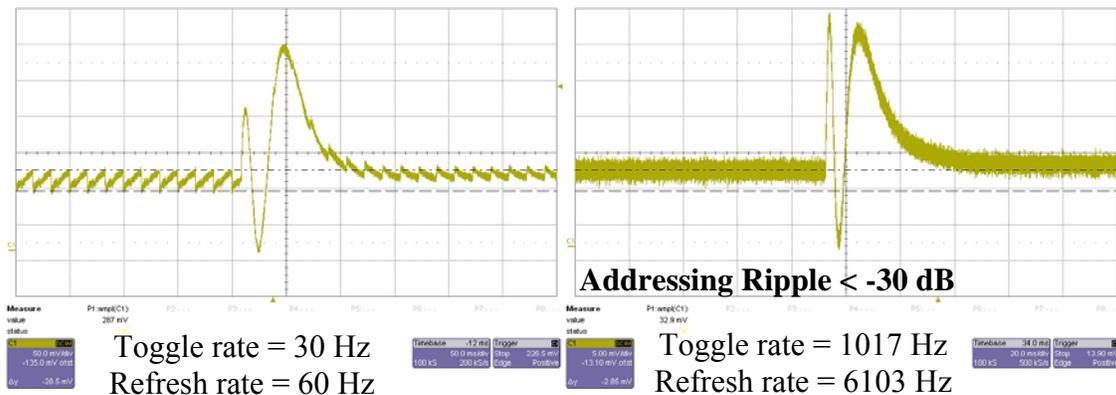Toggle rate = 1017 Hz
Refresh rate = 6103 Hz

Figure 8: High figure of merit ECB modulators addressed at different rates. The left plot shows a strong data-dependent ripple that is synchronous with the video rate addressing period.

ACKNOWLEDGEMENTS

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