Liquid crystal spatial light modulator for multispot beam steering

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ABSTRACT

The advantages of laser communications including high bandwidth, resistance to jamming and secure links have made it a key technology for current and future C4ISR capabilities. Laser Communications between space/air/ground/sea-based assets may require multiple links. One advantage of this redundancy is that the signal is more likely to reach the intended receiver even if the environmental conditions are poor for laser transmission. In addition, multiple links provide simultaneous receipt of information to various assets engaged in activities that may need to be coordinated. That is, multibeam laser communication mimics the "broadcast" advantage of RF communications but with less likelihood of jamming or intercept. Liquid Crystal spatial light modulators are a versatile optical head that can be used for multispot beam steering applications. One advantage of the liquid crystal approach to multibeam laser communication is that the device is a modulator in addition to a mirror, so that one could conceivably send different signal amplitudes to different locations simultaneously. This paper discusses recent improvements to a 512x512 spatial light modulator that is specifically implemented as a multispot beamsteerer. This will include characterization of the device, analysis of its performance, and what improvements should be incorporated into the next generation device.

Keywords: Liquid Crystal Spatial Light Modulator Multispot Beam Steering

1.0 INTRODUCTION

The large bandwidth made possible by free space optical communications allows for the potential of sending or receiving images. Moreover, since it is a line of sight technology, the communication is more secure than broadcasted radio waves. However, because it operates on line of sight, there are also disadvantages, for example it can be obstructed and it also tends to have a limited number of recipients. By using multiple laser spots emanating from a single transmitter, one can overcome some of the disadvantages of line of sight operation. Using multiple spots one can assure that there is enough redundancy in the transmitted signal to overcome obstacles in the transmit path. Further, multiple spots allow for the possibility of recipients at different locations obtaining the same information. This then provides broadcast coverage with less risk of interception. If the multispot generator is also a modulator, then recipients at different locations could receive different messages simultaneously. One such means to obtain multiple independent spots is by using a liquid crystal spatial light modulator (SLM) to steer the beams[1].

Liquid crystal based SLMs offer several advantages including large modulation depth, no moving parts, low power dissipation, potential for large aperture operation, and low cost. In order to modulate the phase of incident light, a nematic liquid crystal modulator is aligned in a planar conformation. Here the liquid crystal director (i.e. long axis of the molecules) is oriented parallel to the polarization of the incident light. Upon application of a voltage, the molecules tilt in a direction parallel with the direction of propagation of the optical field. This causes the incident light to encounter a reduced refractive index. The change in refractive index translates directly to a change in the optical path, and consequently a phase shift for the incident light. If enough voltage is applied, the variation in refractive index ranges from the extraordinary index (for no applied voltage) to the ordinary index (maximum tilt of the molecules). A typical change in the refractive index for maximum applied voltage is 0.2.

The SLMs considered here use very large scale integration (VLSI) to address an array of liquid crystal modulators. The VLSI addressing allows for true multiplexing to achieve individually addressable pixels across the entire optical aperture. This flexibility results in a randomly addressable phase mask that can act as an optical phased array with the potential for phase correction. The optical head and mount board for the liquid crystal on silicon (VLSI-addressed) beam steering device offered by BNS is shown in Figure 1. The optical head consists of a layer of liquid crystal sandwiched

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between a cover glass and a VLSI backplane in a PGA (pin grid array) package. For the research reported here, variations of the VLSI backplane pixel configurations include a 128x128, a 256x256 and a 512x512 pixel modulator. For the multispot beam steering communications application considered here, the more pixels, the better the signal to noise ratio. This is an artifact of the encoding used to obtain independent multiple beams.

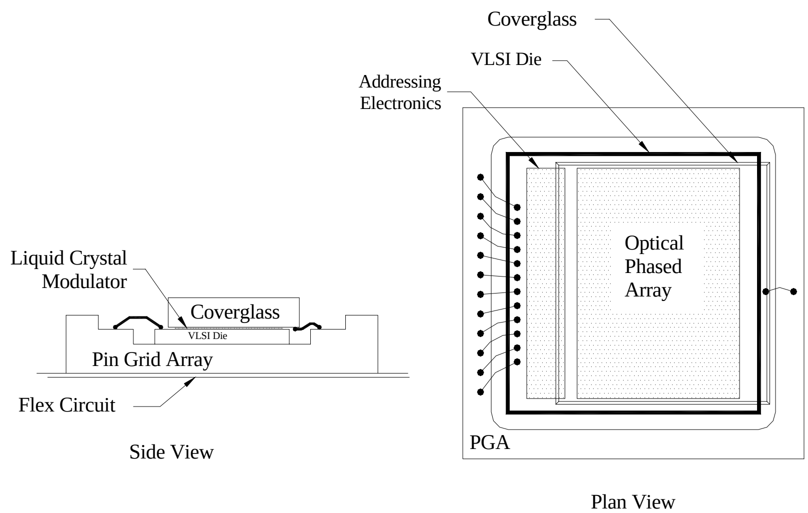

Figure 1. *Schematic of an optical head for a liquid crystal on silicon spatial light modulator*.

The generation of multiple steered beams as a result of an arbitrary diffraction pattern in the far field can be accomplished with a complex amplitude phase mask. However, SLMs do not provide arbitrary access to the complex plane without resulting to a potentially expensive multiple modulator system. In practical terms the diffraction pattern must be generated using values readily available from the modulator. Producing a diffraction pattern subject to modulator constraints is called encoding.

Pseudorandom encoding (PRE) is a statistically based encoding method introduced in 1994 by Cohn and Liang[2]. For PRE a desired complex value, $\mathbf{a}_c$, is related to the actual modulator value, $\mathbf{a}$, according to

$$\mathbf{a}_c = \int \mathbf{a}\, p(\mathbf{a})\, d\mathbf{a} \ ,$$

where $p(\mathbf{a})$ is the probability density function of $\mathbf{a}$. Once an appropriate density function has been determined, the desired complex value $\mathbf{a}_c$ is encoded by drawing a single value of $\mathbf{a}$ from a random distribution having the density function $p(\mathbf{a})$.

This pseudorandom encoding process is applied to each pixel in sequence to encode the desired spatially varying complex modulation. The resulting diffraction pattern approximates the desired diffraction pattern in an average sense. The expected intensity consists of two terms. The first term is the desired diffraction pattern. The second term corresponds to the average level of background noise that is generated as a result of the randomness of the modulation. By spreading the energy over the entire diffraction plane, the peak noise can be low. High signal to noise ratios can be achieved for signals that have moderate diffraction efficiency and moderate bandwidth.

The versatility of multispot beam steering using a liquid crystal spatial light modulator has been made evident by demonstrating the following system capabilities[3]:

arbitrary scanning
sidelobe reduction
pattern translation
continuous scanning
replicated parallel scans
variable resolution scanning time-averaged scanning
broad area illumination,
and , more recently, tracking[4].

The remainder of this paper discusses improvements to a 512x512 spatial light modulator that is specifically implemented as a multispot beamsteerer. Section 2 discusses the addition of a dielectric mirror to the VLSI backplane. Section 3 includes characterization of the device, and a comparison to a device without a dielectric mirror on the backplane. Section 4 concludes the paper with a brief discussion of the results presented here and improvements that will be incorporated into the liquid crystal spatial light modulator beam steering technology.

2.0 SPATIAL LIGHT MODULATOR BACK PLANE IMPROVEMENT

One approach for improving the optical performance of a liquid crystal SLM basically involves deposition of a dielectric mirror onto the backplane prior to gapping and filling the SLM. The idea is that the mirror deposition over a polished surface would improve optical flatness and enhance the diffraction efficiency. A 512x512 backplane with a special 2 micron thick passivation layer was back-polished approximately 1 micron. This has been tried both by hand and on a mechanical polisher. The manual polishing appears to provide a more aesthetic polish, while the mechanical polishing is more repeatable. Next a dielectric stack of alternating high index and low index quarter-wave layers was deposited onto the backplane. A cross section of this modulator is shown schematically in Figure 2.

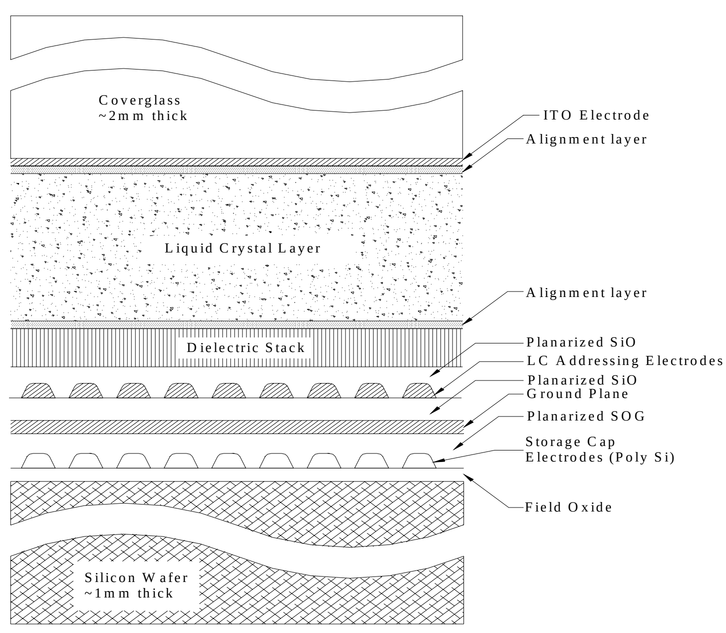

Figure 2. *Modulator cross section showing a liquid crystal SLM with a backplane that has a deposited dielectric stack.*

There are some technical issues with depositing a dielectric stack onto an SLM backplane. First, adding the layers to the backplane increases the voltage requirement. This is because the liquid crystal is switched by the electric field across it, and when a significant portion of the electric field is dropped across the dielectric stack, the overall voltage needed to achieve switching increases. One method to increase the voltage level available to switch the liquid crystal is to also address the cover glass with a signal that is of the same amplitude and frequency but 180 degrees out of phase (electrically). This results in a potential of up to twice the maximum addressable backplane voltage.

The mirror design is a 9 layer stack designed for 532 nm. This stack consists of 5 high index (TiO_2) quarter-wave layers each approximately 665 Angstroms thick, 4 low index (SiO_2) quarter-wave layers each approximately 875 Angstroms thick. The approximate total thickness is 6,825 Angstroms and the approximate reflectivity at 532 nm is 84%.

A spectrometer scan of the reflection from the dielectric stack is shown in Figure 3.

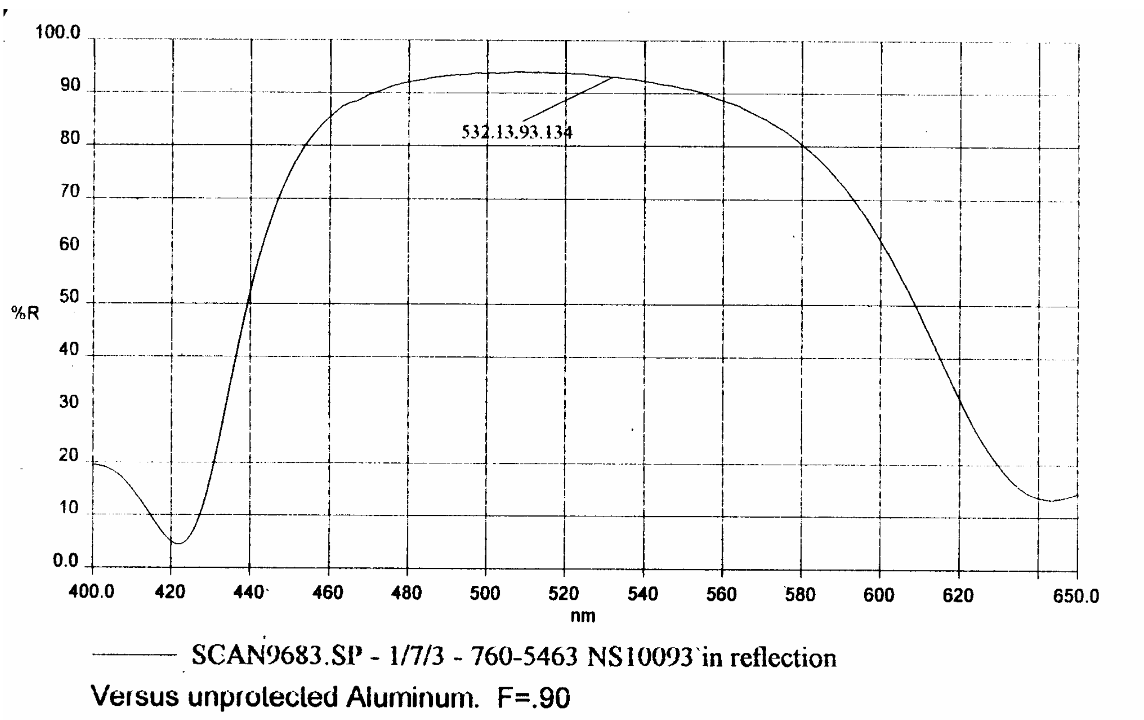

Figure 3. *Scan of dielectric stack. Note the reflection is normalized to 0.9 so the 93.134% reflectivity at 532 nm is actually 84% of the incident light.*

3.0 SPATIAL LIGHT MODULATOR CHARACTERIZATION

The SLM with the dielectric stack was gapped to a cover glass using 4 micron spacers and filled with BL087 a commercial nematic liquid crystal available from E.M Industries, Hawthorne New York. The device was first tested for adequate modulation depth using the imaging set-up illustrated in Figure 4. Linearly polarized laser light is routed through a polarizing beam cube and rotated to be 45 degrees with respect to the liquid crystal optical axis by a half-wave plate. The rotated light is then set such that the SLM will provide an amplitude response that correlates to the retardation of the liquid crystal layer which will provide information on whether the device has an adequate modulation depth.

Figure 5. is an image of the optical response of the spatial light modulator in amplitude mode. A voltage wedge was written to the device and the response should be a corresponding wedge of alternating light and dark bands. Here we see that the response has a curve or skew at the bottom of the device. This is due to the addressing signal. By using cover

glass flipping as discussed above, not all of the array is addressed before the next cycle is written. To improve this response, the cover glass was off-set in timing by one-half load cycle in relation to the signal that addressed the pixels. The improved response is shown in Figure 6. Upon examination of Figure 6, one sees a progression of stripes from light to dark to light then into dark again. One complete period represents a wave of modulation depth so this device has between 1 and 2 waves of modulation depth which is adequate for modulo 2π phase-only modulation with some additional throw to allow for a choice of the best liquid crystal response range (i.e. the relative maximum phase shift needs to be 1 wave and having a device with more modulation depth allows you to choose the extremes of the modulation for optimal response).

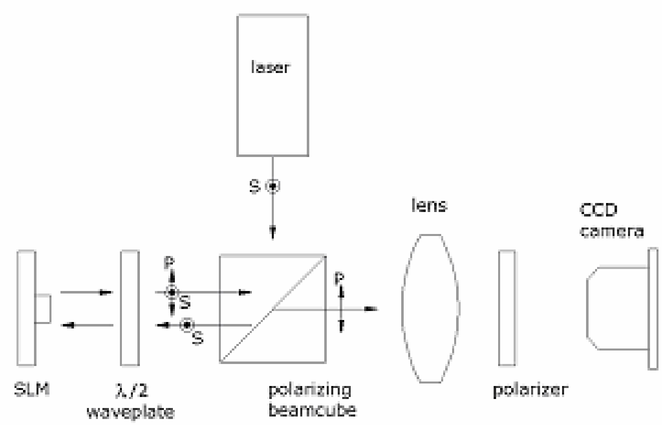

Figure 4. *Test set-up for imaging the spatial light modulator.*

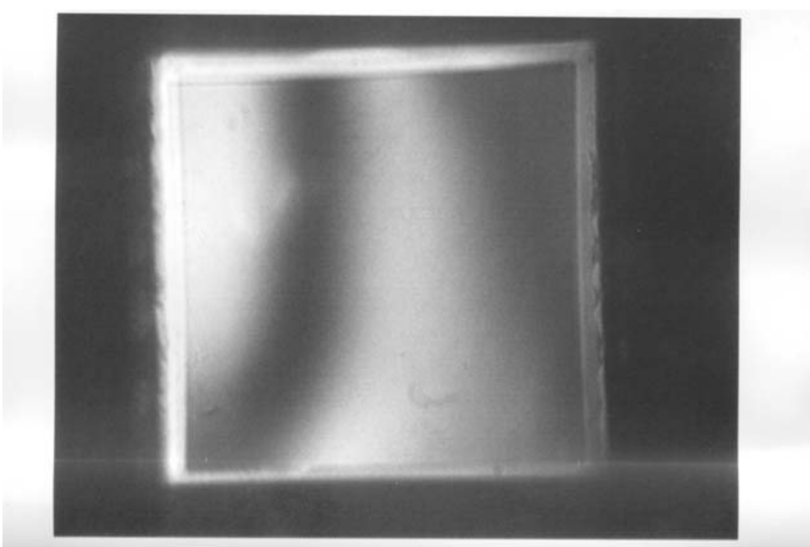

Figure 5. *Optical amplitude response due to a wedge written to the SLM prior to shifting the cover glass signal.*

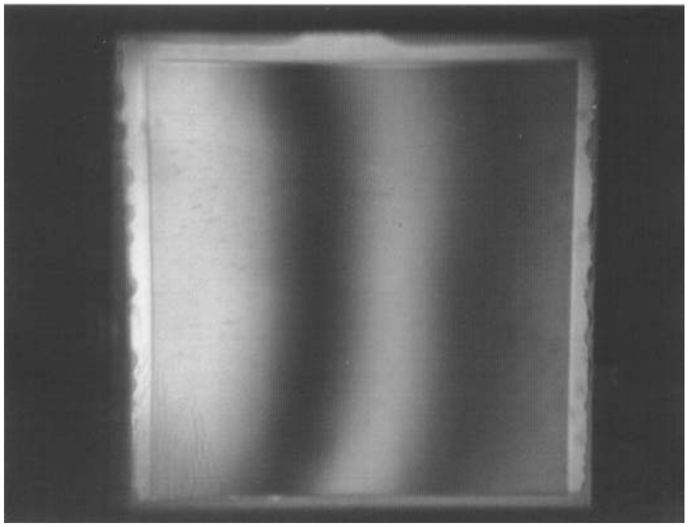

Figure 6. *Optical amplitude response due to a wedge written to the SLM after shifting the cover glass signal.*

To examine how the addition of a mirror to the backplane improved the diffraction efficiency, two SLMs (one without a mirror and one with a mirror on the backplane) were placed in the set-up shown in Figure 7. Here linearly polarized laser light is routed through a non-polarizing beam cube and oriented by the wave plate such that the polarization is coincident with the extraordinary optical axis of the liquid crystal. When the applied electric field switches the liquid crystal, this produces phase-only modulation due to a change in the optical path encountered by the incident light. Rather than imaging the SLM, here the camera is viewing the far-field diffraction pattern produced on the output screen.

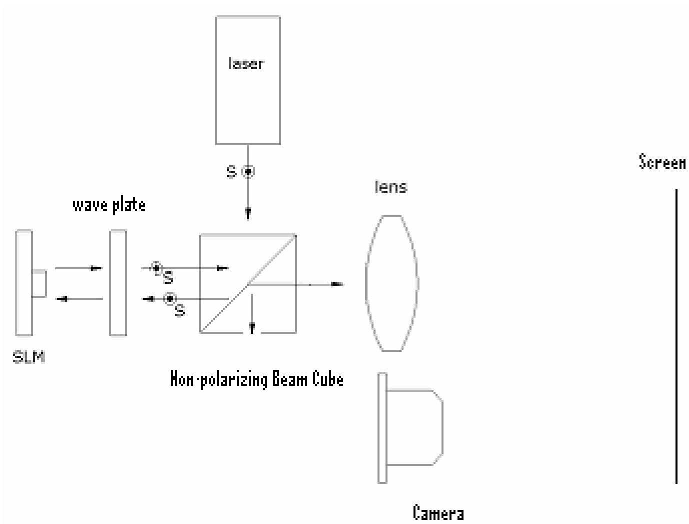

Figure 7. *Schematic of optical set-up to examine multispot beam steering.*

The diffraction pattern obtained when the non-mirrored SLM is addressed to produce a 9x9 array of spots is shown in Figure 8. The central spot is the zero-order return and the array of 81 spots in the upper right hand quadrant (+1, +1 diffraction order) is the desired steered multispot pattern. Figure 9 shows the diffraction pattern when the SLM with the dielectric mirror is addressed to produce the same pattern. The intensity of the desired 9x9 diffraction pattern of the mirrored SLM was measured using a power meter and determined to be 2.74 times greater than the intensity of the pattern obtained using the device without a dielectric mirror. This is a significant improvement in the diffraction efficiency of the SLM. The principle difference is that the mirrored device scatters less light to higher orders.

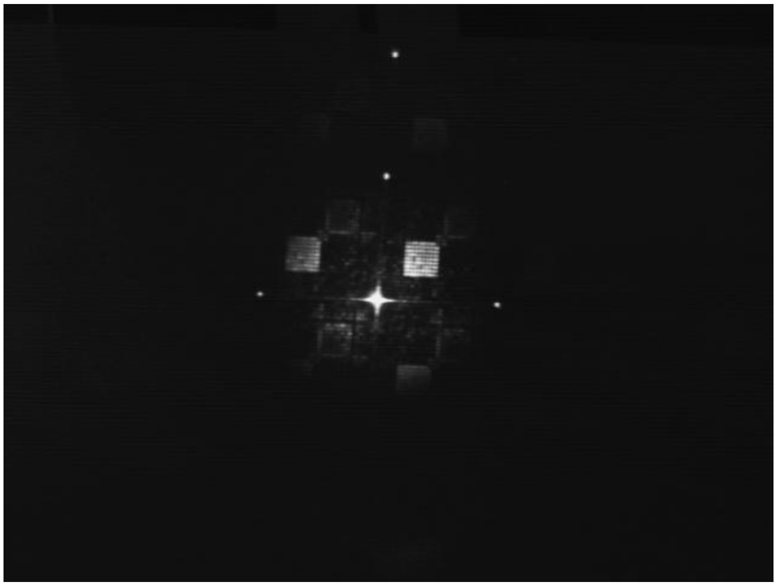

Figure 8. *Diffraction pattern from a non-mirrored SLM addressed to produce a 9x9 array of spots in the +1, +1 order.*

Figure 9. *Diffraction pattern from an SLM with a dielectric mirror on its backplane addressed to produce a 9x9 array of spots in the +1, +1 order.*

4.0 CONCLUSIONS AND FUTURE IMPROVEMENTS

The optical performance of a phase only SLM has been improved by post-processing steps taken on the backplane. The backplane was polished then a 9 layer quarter-wave stack dielectric mirror was deposited onto it. The mirrored backplane exhibited only marginal improvement in optical flatness, but the diffraction efficiency was significantly improved. Other steps for improving the performance of liquid crystal SLMs for multispot beam steering applications include using the liquid crystal to correct for backplane curvature and trying other liquid crystals such as dual frequency materials to increase the response time. The former can be done using the existing backplanes and a feedback loop where the strehl ratio of the diffraction pattern for a steered beam is maximized. The latter improvement will require higher voltage backplanes.

ACKNOWLEDGEMENTS

The authors are grateful to Jamie Gorden of Boulder Nonlinear Systems, Inc. for modification to the SLM driver board to reduce the data skew.

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