Cascaded One-Dimensional Liquid Crystal OPAs for 2-D Beam Steering

Jay Stockley and Steve Serati
Boulder Nonlinear Systems, Inc.
450 Courtney Way #107
Lafayette CO. 80026
303-604-0077
jstockley@bnonlinear.com

Abstract— Beam steering in two dimensions can be achieved using a reflection-mode liquid crystal optical phased array (OPA) with a backplane that has a two-dimensional pixel structure. However, current lithographic constraints require a relatively large pixel pitch, limiting two-dimensional OPAs to steering only to milliradian angles. Moderate to large angle two-dimensional steering can also be readily achieved by placing two one-dimensional OPAs in series.

After a brief introduction to liquid crystal beam steering, we discuss the coupled wave analysis, with which the modulation depth can be determined from the wave vector components along the direction of propagation. It can be shown that the minimum off-axis effects occur when the orientation of the liquid crystal extraordinary axis is perpendicular to the plane of incidence. This is followed by experimental demonstration of the change in phase modulation depth for the cases of normal incidence and a 45 degree angle of incidence. Two-dimensional beam steering using two one-dimensional reflective liquid crystal electrode arrays is reported on for the first time. The paper ends with conclusions drawn from this research.

TABLE OF CONTENTS

1. INTRODUCTION

Two-dimensional beam steering, by cascading two one-dimensional beam steerers has been successfully demonstrated before [1]. Reference 1 specifically describes two geometries for cascading two one-dimensional transmission mode OPAs to achieve two-dimensional beam steering. However, the state of the art for addressing transmissive liquid crystal OPAs is such that groups of pixels must be ganged together, which decreases the number of resolvable spots, and limits the ability to correct for phase distortions. Reflection-mode devices implemented using very large scale integrated circuit (VLSI) addressing provide the ability to individually address each pixel which maximizes the number of resolvable spots and allows for phase correction. While reflection-mode beam steerers show potential for superior performance, a transmission-mode device may allow more design flexibility for the optical systems designer.

An alternative geometry for a two-dimensional beam steering optical subsystem is to use two one-dimensional, reflection-mode VLSI beam steerers in an in-line configuration. This then mimics a transmissive element, reducing the complexity of the overall optical system design. There are several in-line configurations possible ranging from on-axis designs resembling a Cassegrainian telescope to off-axis designs where the light reflects off of one OPA at an oblique angle, illuminates a second orthogonally oriented OPA and proceeds forward.

We report on the theory and experimental implementation of two one-dimensional reflection-mode beam steerers placed in series to achieve two-dimensional steering. For the in-line geometry considered here, polarized light is incident on a first beam steerer at a 45 degree angle. This light is steered in azimuth then reflected at a 45 degree angle onto an off-set, second beam steerer that steers elevation. The beam steerers employ planar aligned nematic liquid crystal and are tuned by a variation in the extraordinary index via an applied electric field. The polarization of the incident light is vibrating along the extraordinary axis of the liquid crystal and as the electric field is applied, the incident light encounters a varying optical path. The remainder of this paper discusses the implementation and its results for a two-dimensional beam steering subsystem based on two one-dimensional OPAs.

2. THEORY OF OFF-NORMAL INCIDENCE

From coupled wave analysis, the modulation depth can be determined from the wave vector components along the direction of propagation (taken here as z) [2]. The modulation depth, Δ, is given by

0-7803-7651-X/03/$17.00 © 2003 IEEE

$$\Delta = (k_{ez} - k_{oz})\, d \,. \quad (1)$$

Where k_{ez} is the z component of the extraordinary wave vector, k_{oz} is the z component of the ordinary wave vector, and d is the physical thickness of the liquid crystal layer.

For pure phase tuning such that a change in the extraordinary index modulates the optical path, we are interested in the change in the z component of the extraordinary wave vector:

$$k_{ez} = -\frac{k_0}{2}\left(n_e^2 - n_o^2\right)\left[\frac{n_e(\psi)}{n_e n_o}\right]^2 \sin(\theta)\sin(2\psi)\cos(\phi) + k_0\, n_e(\psi)\sqrt{1-\sin^2(\theta)\left[\frac{n_e(\psi)}{n_e n_o}\right]^2\left[1-\cos^2(\psi)\sin^2(\phi)\left(1-\left[\frac{n_o}{n_e}\right]^2\right)\right]} \quad (2)$$

where k_0 is the vacuum wave number, n_e is the maximum extraordinary index, n_o is the ordinary refractive index and $n_e(\psi)$ is the variable extraordinary index which changes as a function of the tilt angle ψ. $n_e(\psi)$ has a maximum value of n_e at ψ = 0 and a minimum value of n_o at ψ = 90. θ is the angle of incidence, and the angle ϕ is the rotational orientation of the optic axis with respect to the plane of incidence. ϕ resides in the plane transverse to the direction of propagation. So in a right-handed coordinate system, ϕ = 0 and ϕ = 90 are along the x and (-)y axes, respectively.

Because this is phase only modulation, there are only two orientations of ϕ that apply, 0 and 90 degrees. Now, the LC tilt varies from 0 to 90 degrees, so the phase modulation depth is described by the difference in optical path from the condition for ψ = 0 degrees to ψ = 90 degrees.

For normal incidence, regardless of whether ϕ = 0 or ϕ = 90, the change in the z component of the extraordinary wave vector is

$$\begin{aligned} &k_{ez}(\theta = 0, \psi = 0, \phi = 0{,}90) \\ &- k_{ez}(\theta = 0, \psi = 90, \phi = 0{,}90)\ , \\ &= k_0 n_e - k_0 n_o \end{aligned} \quad (3)$$

that is, it reduces to k_{ez}-k_{oz} .

Taking θ = 45 degrees, then for ϕ = 0 degrees, the maximum optical path (ψ = 0) gives:

$$k_{ez} = k_0\, n_e \sqrt{1-\frac{1}{2n_o^2}}\ , \quad (4)$$

and for ψ = 90 degrees, θ = 45 degrees, ϕ = 0 degrees:

$$k_{ez} = k_0\, n_o \sqrt{1-\frac{1}{2n_e^2} + \frac{k_o\left(n_e^2 - n_o^2\right)}{2\sqrt{2}}\left(\frac{1}{n_e}\right)^2}\ . \quad (5)$$

Then taking the case for ϕ = 90 degrees, we have for ψ = 0:

$$k_{ez} = k_0\, n_e \sqrt{1-\frac{1}{2n_e^2}}\ , \quad (6)$$

and for ϕ = 90, ψ = 90:

$$k_{ez} = k_0\, n_o \sqrt{1-\frac{1}{2n_e^2}}\ . \quad (7)$$

Assuming all variables are positive valued (which is physically the case) and that $n_e > n_o$, (i.e. a positive birefringent liquid crystal), one sees that:

$$\begin{aligned} &k_{ez}(\psi = 0, \phi = 90) - k_{ez}(\psi = 90, \phi = 90) \\ &> k_{ez}(\psi = 0, \phi = 0) - k_{ez}(\psi = 90, \phi = 0) \end{aligned} \quad (8)$$

and it is closer in value to k_{ez}-k_{oz}.

It has been shown that the minimum off-axis effects occur when the orientation of the liquid crystal extraordinary axis is perpendicular to the plane of incidence. Moreover, for an orientation of the liquid crystal extraordinary axis perpendicular to the plane of incidence, the modulation depth is decreased with increasing angle of incidence, θ, by a factor of

$$\sqrt{1-\sin^2\theta\left(\frac{1}{n_e}\right)^2}\ . \quad (9)$$

3. PHASE MODULATION DEPTH MEASUREMENT

To measure the change in phase modulation depth between normal and oblique incidence, two interferometers were set-up. Each interferometer included a liquid crystal OPA in one of the arms. A schematic of the first interferometer as shown in Figure 1 demonstrates its Michelson geometry. The linearly polarized laser light from the source is split by a non-polarizing beam cube. The light traveling down one arm goes through a polarizer (to ensure polarization purity) and illuminates the beam steerer. It is reflected and recombined with light from the reference arm at the input to a microscope objective which expands the interference pattern for easy evaluation on a screen in the far field.

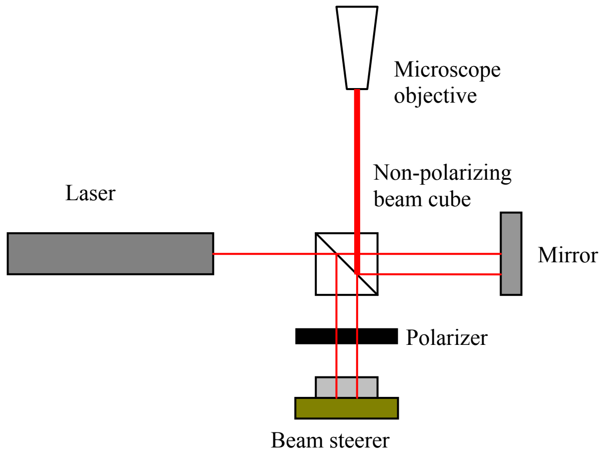

Figure 1. Schematic of the Michelson interferometer set-up used to measure phase modulation depth for normal incidence.

To measure the phase modulation depth for oblique incidence a Mach-Zehnder interferometer was used as shown in the schematic of Figure 2. The incident laser light is split by a non-polarizing beam splitter. Half the light travels down the sample arm. It goes through a polarizer then reflects off the beam steerers at a 45 degree angle proceeds to a mirror were it is again obliquely reflected back to a second beam splitter which recombines this light with that from the reference path. Again a microscope objective was used to expand the interference pattern on the screen in the far field.

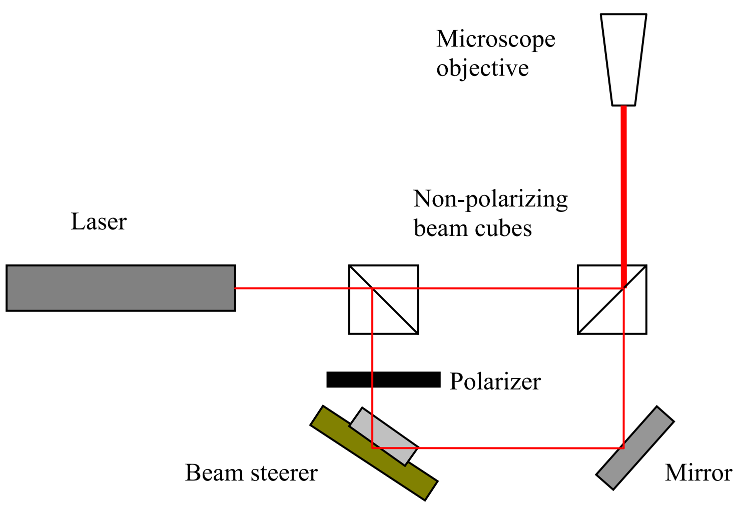

Figure 2. Schematic of the Mach-Zehnder interferometer used to measure the phase modulation depth for oblique incidence.

For both normal incidence and a 45 degree angle of incidence, the interference pattern was projected from the microscope objective onto a screen on the wall. The fringe period was measured to determine the extent of 360 degrees of phase. Next the beam steerer was addressed with a 2 kHz amplitude modulated signal as a single pixel with an increasing voltage up to the maximum 5V, then returning to zero. The distance that the fringes shifted was marked and measured. This number gave the modulation depth. For 633 nm wavelength laser light incident the modulation depth for normal incidence measured using the Michelson interferometer was 806.4 degrees. For the light at a 45 degree angle of incidence the Mach-Zehnder interferometer was used to measure a phase depth of 738 degrees. This is a decrease in the modulation depth of 8.48 %. The theoretical decrease is 8.96 %. This discrepancy can easily be accounted for by the error in the measurement of the fringes or in the angle of incidence for the oblique case being slightly less than 45 degrees, some deviation can probably be attributed to both.

4. TWO-DIMENSIONAL BEAM STEERING

To achieve two-dimensional beam steering, using two one-dimensional OPAS, the set-up shown in Figure 3 was constructed. A 1.5 micron diode laser is the source. The laser light is linearly polarized and impinges on the first beam steerer at an angle of 45 degrees. The light then passes through a half-wave plate to rotate the polarization 90 degrees for steering in the orthogonal dimension by the second, offset beam steerers. The light exits through a second polarizer, it is converted to the far field by a lens then the diffraction pattern gets recorded by an IR camera.

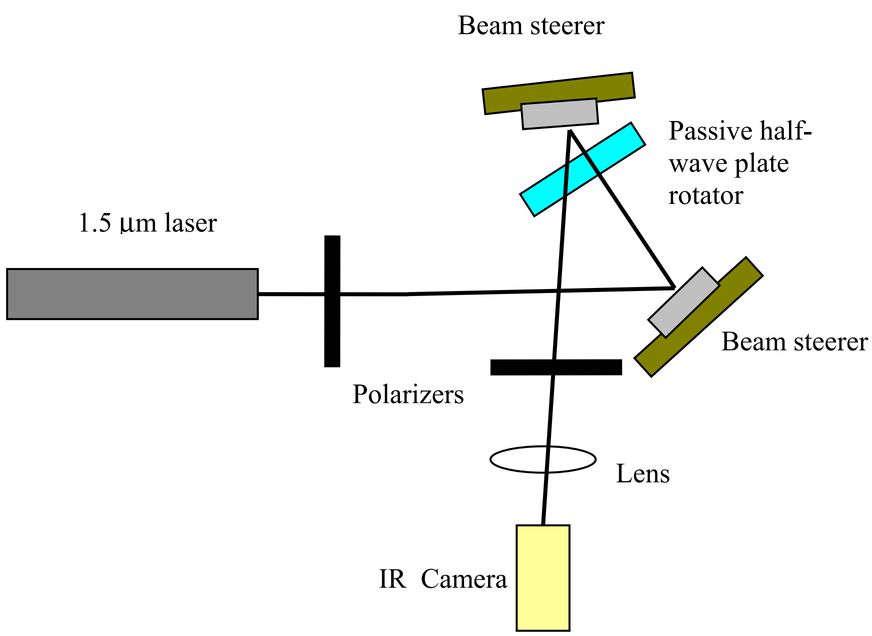

Figure 3. A schematic showing the set-up used for the two-dimensional beam steering demonstration.

The three dimensional plots shown in Figure 4 are the recorded far field diffraction patterns obtained from a frame grabber to which the IR camera output its signal. The diffraction patterns are a result of the following: pattern (a) is the zero order (neither beam steerer is addressed). Patterns (b) and (c) are for a 128 electrode grating period written to the first beam steerer and a 64 electrode grating period written to the second beam steerer, respectively. Pattern (d) is the result of both beam steerers being addressed simultaneously.

For these beam steerers and at this wavelength a 128 electrode grating corresponds to a steer angle of 0.375 degrees and a 64 electrode period to 0.75 degrees. As expected, the efficiency decreases as the light is steered away from the zero order. To minimize the zero order some initial adjustment of the orientation of the polarizers and half-wave plate were required, but once set, these passive components remained fixed.

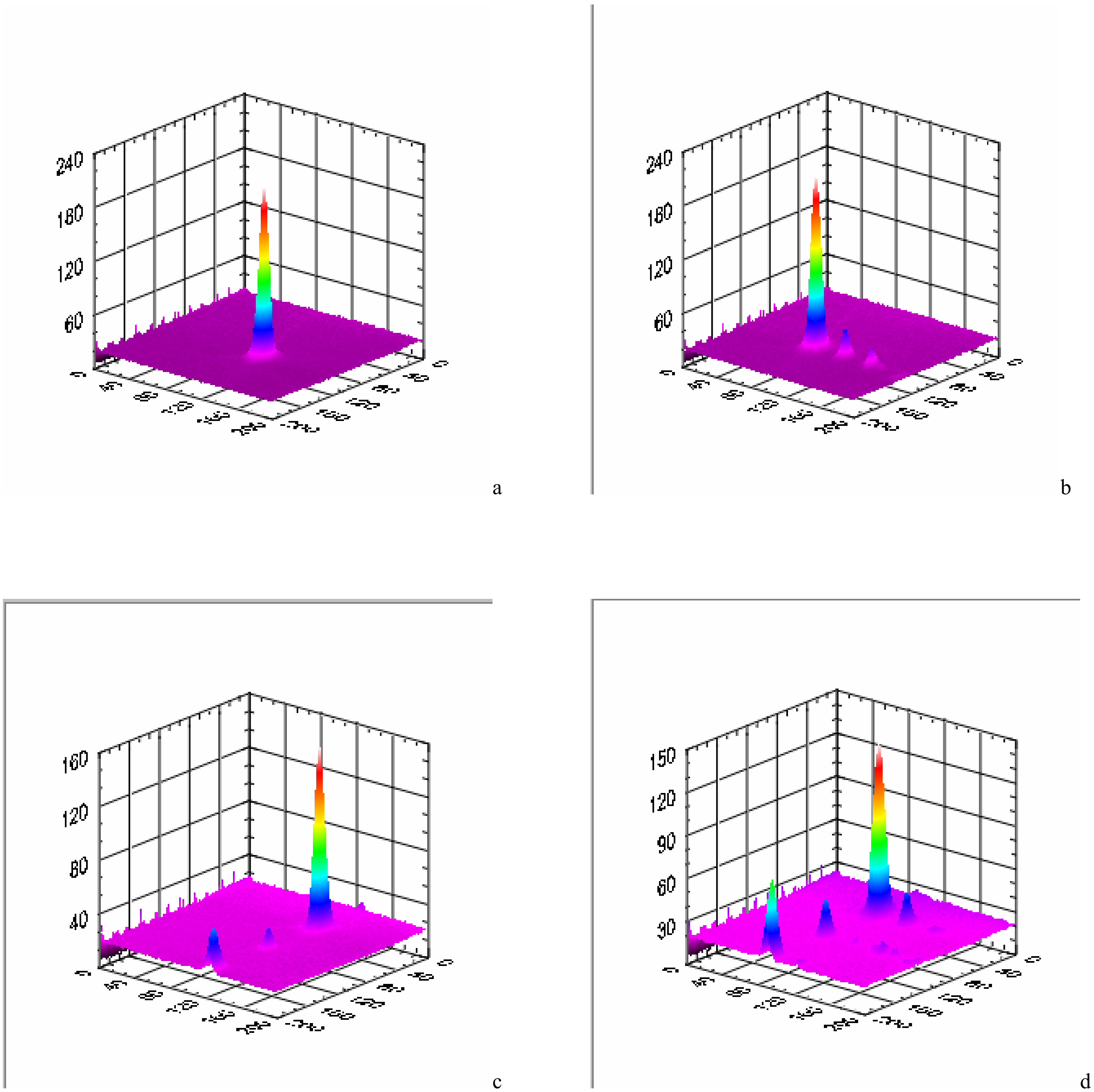

Figure 4. Far field diffraction patterns captured by the IR camera and frame grabber.
(a) zero order, (b) 0.375 degrees left, (c) 0.75 degrees up (d) 0.375 degrees left and 0.75 degrees up.

5. CONCLUSIONS

Based on the above results, it is apparent that liquid crystal OPAs can be used at oblique incidence and in series. The off-normal incidence does require special calibration, but that is not an obstacle to operation.

There is a decrease in phase modulation depth for off-normal incidence, but that can readily be compensated for by gapping the device to produce more than one wave of phase shift.

For an OPA addressed at a relatively large oblique angle there remains an unmodulated component of the light that manifests itself in the zero order. This can be overcome by appropriate choice of the incident polarization. In that this unmodulated component did not readily show up in the interferometric phase modulation depth investigation, we are attributing it to the resets of the OPA grating structure at this time. Further investigation of this phenomenon is warranted.

The far field patterns obtained in the experimental investigation of the two-dimensional steering do not exhibit any noticeable conical diffraction. It may be that the steer angles investigated are not large enough for significant deviation from linear diffraction.

In that these devices can be used at large angels and in series, they are well suited to transmission-like geometries such as can ease optical design requirements [3].

REFERENCES

[1] P. F. McManamon, T. A. Dorschner, D. L. Corkum, L. J. Friedman, D. S. Hobbs, M. Holtz, S. Liberman, H. Q. Nguyen, D. P. Resler, R, C, Sharp, and E. A. Watson. "Optical Phased Array Technology," Proceedings of the IEEE, Vol. 84, No. 2, Feb. 1996.

[2] A. Yariv and P. Yeh, **Optical Waves in Crystals**, Wiley, (1984).

[3] S. Serati and J. Stockley, "A Phased Array of Phased Arrays (PAPA) Architecture for Improving the Performance of Free Space Optical Communications," Submitted to 2003 IEEE Aerospace Conference (this conference).

ACKNOWLEDGEMENTS

This work is supported by the DARPA Tera-Hertz Operational Reach back (THOR) program. The authors are grateful to Scott Harris of AFRL SNJ for technical feedback and conversion of software, and to Anna Linenberger of BNS for the data capture and driving software.

Jay Stockley *is a Research Scientist at Boulder Nonlinear Systems Incorporated (BNS). At BNS, he contributes to liquid crystal modulator development and beam steering related research. He is currently responsible for administration of, and technical contributions to, two beam steering research subcontracts funded through the DARPA STAB program, an Air Force Phase II SBIR for optical filter development, a Missile Defense Agency Phase II STTR on multispot beam steering and technical contributions to a DARPA THOR contract. He earned his Ph. D. in Electrical Engineering from the University of Colorado in 1996. He received his B.S. in Electrical Engineering with a minor in Mathematics from Colorado State University in 1986 and the degree of Master of Science in Electrical Engineering, also from Colorado State, in 1991. He is an author on 29 technical papers or presentations, 10 invention disclosures and 1 patent. Dr. Stockley has been an R&D engineer or scientist since 1987. His former employers include Ophir Corporation, Colorlink, and the University of Colorado.*

Steve Serati *is founder and Chief Technical Officer of Boulder Nonlinear Systems Incorporated (BNS). He has a B.S. and M.S. in Electrical Engineering from Montana State University. Before starting BNS in 1988, he was a design engineer at Honeywell's Avionics Division for five years, design engineer and project manager with OPHIR Corporation for three years and a system engineer and project manager with Tycho Technology Incorporated for two years. In addition to his duties as BNS' CTO, Mr. Serati is the Principal Investigator for a multi-aperture Beam steering effort under the DARPA THOR program. He is also leading efforts on developing novel SLM technologies for optical processing and active-diffractive optics applications, and he is responsible for developing large-aperture adaptive optics for atmospheric correction. (A photograph is not available.)*