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Advances in Optical Phased Array Technology

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ABSTRACT

Commercially available Liquid Crystal on Silicon (LCoS) Optical Phase Arrays (OPA) are capable of non-mechanically beamsteering up to ± 3 degrees at 1550 nm. While the existing technology is useful for many applications such as laser communications and pulse-shaping, it is desirable to increase the steer angle and decrease the response time of the OPA. This was accomplished through a research effort funded by Langley Research Center at NASA. Under this research effort Boulder Nonlinear Systems (BNS) designed a new 1x12288 pixel OPA. In the new backplane design the pixel pitch was decreased from 1.8 μm to 1.6 μm , the backplane voltage was increased from 5 volts to 13 volts, and the aperture was increased from 7.4 x 6.0 mm to 19.66 x 19.66 mm. The OPA, when built with new liquid crystals and calibrated with new automated calibration procedures demonstrated a greater than 2x improvement in steer angle. The OPA that was tested, which was built for operation at 1550 nm, demonstrated the ability to steer to ± 6.95 degrees. Additionally the relaxation time of the OPA was improved to 24.8 ms. This paper discusses the benefits of the new backplane design, the liquid crystal (LC) properties that are most desirable for beamsteering, the implementation of the automated calibration procedures, and the results.

Keywords: Beamsteering, Liquid Crystal Optical Phase Arrays, High Figure of Merit Liquid Crystal, Fringing Fields

1 INTRODUCTION

An OPA steers light by phase modulating the light. By applying a linear phase ramp across the beam's wavefront as it leaves the system, the light propagating along the system's optical axis is steered to an off-axis angle, as shown in Figure 1. An OPA typically has a modulation depth of 1-2 waves ($2\pi - 4\pi$ of phase shift). This makes a large phase ramp, distributed over the entire aperture, impractical. However, due to the cyclic nature of phase modulation, it is possible to increase or decrease the phase shift by 2π , and still maintain the slope of the phase profile. Figure 1(b) illustrates how a linear phase ramp can be periodically decreased by 2π , producing a saw tooth phase profile which behaves in the same manner as a continuously increasing phase ramp, without requiring large phase shifts from the modulator.

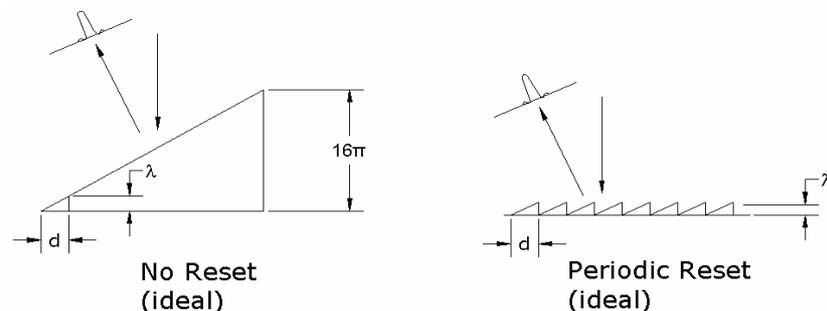


Figure 1. Operation of a LCoS OPA.

The primary benefits of the 1x12288 OPA are: a decreased pixel pitch, an increased backplane voltage, and a 3x increase in pixel count. As is shown in Figure 1, the angle to which the input light is steered is determined through the following equation:

$$\sin(\theta) = \lambda/d \quad \text{Equation 1}$$

Where Lambda is the wavelength of the input light, and d is the width of the ramp which is calculated by multiplying the pixel pitch by the number of pixels in the ramp. Thus by decreasing the pixel pitch in the new backplane design the number of resolvable spots that the device can steer to increased.

One of the drawbacks to a small pixel pitch is an increase in inter-pixel cross talk. When the pixel pitch is large, such as in our 2D arrays, the fringing fields between pixels are minimal in comparison to the field across the LC layer. Thus it is quite easy to drive every other pixel between a 0 and π phase shift without seeing notable fringing fields. However, as the pixel pitch decreases the fields between the pixels begin to exceed the fields across the LC layer. The result is that voltages that would normally result in a linear phase ramp are smoothed into a more sinusoidal waveform. This effect is shown in Figure 2. The smoothing isn't significant as long as the voltage difference between neighboring pixels is minimal, such as along the phase ramp. However, in the 2π resets the inter pixel cross talk can become a more serious problem. We have found that minimizing the cross talk in the 2π resets is one of the most important factors in achieving a wide steer angle. The solution to this problem in the new OPA is two-fold. First the backplane voltage of the OPA was redesigned to operate at 13 volts as opposed to 5 volts in the 1x4096 OPA. This allows the user to apply a stronger field across the LC layer in order to overcome the fringing fields. Additionally, the thickness of the LC layer in the OPA can be adjusted such that the OPA produces greater than 1 wave of modulation depth. This allows for the user to allocate extra modulation depth to over-driving the 2π resets. This procedure is discussed in greater detail in Section 4.3.

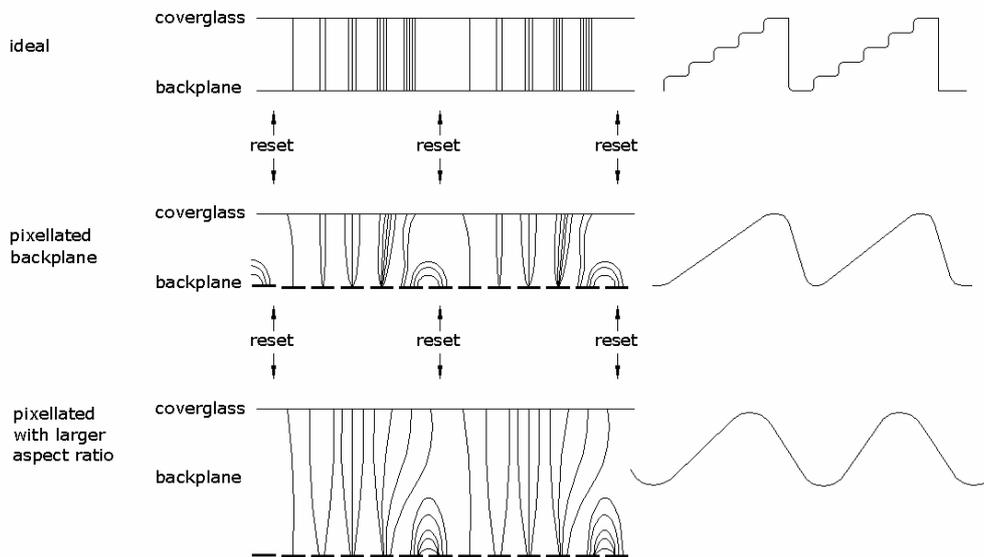


Figure 2. Inter- pixel influence

2 LC Testing

In order to minimize the effects of inter-pixel cross talk it is desirable to use a liquid crystal with a high threshold voltage. Figure 3 shows a sample response curve of nematic LC to voltage. It is possible to operate anywhere on this curve as long as the difference in phase shift is at least one wave. In order to minimize cross talk it is desirable to operate at the bottom of this curve. In this case the fringing fields at the 2π resets would have to be quite significant to overcome the threshold voltage. The drawback of this is that once the threshold is overcome small changes in voltage result in large differences in phase shift. The result is that the OPA will not have as many discrete phase steps as the OPA would if it were built with a LC that produced a more linear phase response. Thus there is a trade off between minimizing cross talk through use of a high threshold LC and retaining linear phase levels.

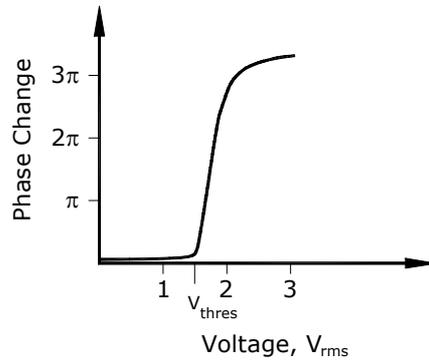


Figure 3 Phase response of the liquid crystal

Another method of minimizing cross talk is the use an LC with a high figure of merit. The Figure of Merit describes the relationship between birefringence and the visco-elastic constant of the LC. Equation 2 describes Figure of Merit, where Δn is birefringence of the liquid crystal, γ is the viscosity of the liquid crystal, and K_{11} is the elastic constant of the liquid crystal. Thus, from this equation, it is desirable to find a LC that offers high birefringence while minimizing the visco-elastic constant.

$$FoM = \frac{K_{11}(\Delta n)^2}{\gamma} \quad \text{Equation 2}$$

By selecting a LC with a high birefringence the thickness of the LC layer is minimized. This is important because as the thickness of the LC layer increases it becomes more difficult to get the full field across the LC layer, which results in an increase in cross talk. Equation 3 describes the relationship between modulation depth δ , LC layer thickness d , birefringence Δn , and wavelength λ . From this equation it is shown that a LC with a high birefringence will decrease the thickness of the LC gap, which results in a minimization of inter pixel cross talk.

$$\delta = d\Delta n / \lambda \quad \text{Equation 3}$$

The importance of minimizing the thickness of the LC gap is further supported by the interferograms of Figure 4. Figure 4a shows an interferogram of an OPA built for operation at 633 nm. In this picture a stripe pattern is written to the OPA showing a π phase shift. In this picture the cross talk is so minimal that an almost a perfect “checkerboard” pattern is shown. Because the cross talk is so minimal in this OPA it would be pointless to show a 2π phase shift, as it would be impossible to see the resets. Figure 4b shows an interferogram of an OPA built for operation at 1550 nm. Because of the difference in operating wavelength, an OPA built with the

same LC must have a significantly thicker LC layer in order to produce the same modulation depth as the 633 nm OPA. The effects of the increased thickness are clearly shown. In the interferogram of Figure 4b the cross talk is so significant that it is possible to show a 2π phase shift and easily see the 2π resets. This demonstrates how sensitive the OPA is to the thickness of the LC layer. In this example a 3x increase in the LC layer gap resulted in an increase in cross talk from a nearly negligible number to ~ 17 pixels.

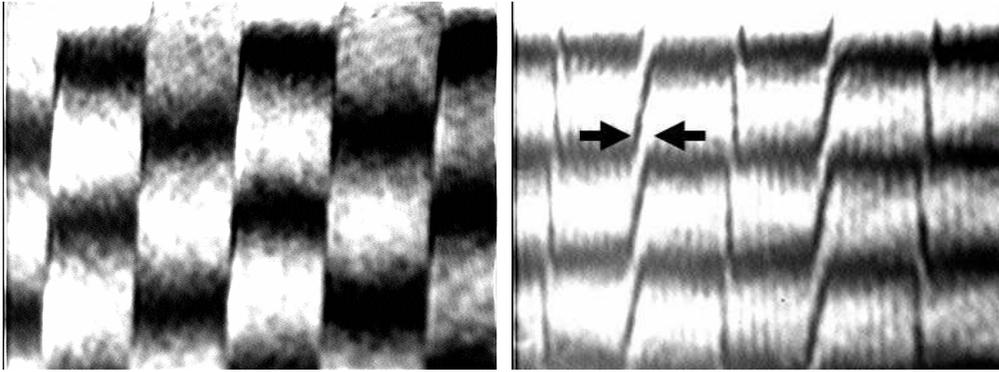


Figure 4 (a) interferogram of an OPA built for operation at 633 nm. An alternating 0, and π phase shift stripe pattern is written to the OPA, showing that the OPA is producing little to no cross talk. (b) the same OPA design is used, but the LC gap is increased by a factor of 3 such that the OPA will produce greater than 1 wave of modulation at 1550 nm. This OPA shows significant cross talk as a result of the increased LC gap.

Minimizing the thickness of the LC gap also has an effect on the relaxation time of the OPA as is shown in Equation 4. Additionally, minimizing the visco-elastic constant (γ/K_{11}) of the LC will decrease the relaxation time of the OPA. Equation 4 describes the relationship between the relaxation time of the LC τ_{relax} , the thickness of the LC layer d , the viscosity of the LC γ , and the elastic constant K_{11} . Thus by choosing a LC with a high figure of merit, the visco-elastic constant is minimized, and the LC gap is minimized. This combined affect has a significant impact on the relaxation time of the OPA.

$$\tau_{decay} = \frac{\gamma_1 d^2}{K_{11} \pi^2}$$

Equation 4

This concept is further supported by the response time testing shown in Figure 5. The high figure of merit OPAs shown in Figure 4 were tested for response time. The relaxation time of the LC is of particular interest, as the LC cannot be driven into its relaxed state, making relaxation time the limiting factor in determining how fast the OPA can be driven. The OPA built for operation at 633 nm demonstrated a relaxation time of 4.8 ms, and the OPA built for operation at 1550 nm demonstrated a relaxation time of 24.8 ms. The same LC was used in both OPAs, so the difference in relaxation time was strictly due to the increased thickness of the 1550 nm OPA. For contrast similar OPAs were built using a commercially available LC, and the relaxation time was measured. Because the commercially available LC did not have the same birefringence as the high figure of merit LC, the thickness of the LC gap was not the same for the two sets of OPAs. However, it still made for an interesting comparison of relaxation time. The 633 nm OPA built with a commercially available LC demonstrated a relaxation time of 16.2 ms, and the 1550 nm OPA built with a commercially available LC demonstrated a relaxation time of 56.4 ms. This demonstrates how significantly a high figure of merit LC impacts the response time of the OPA.

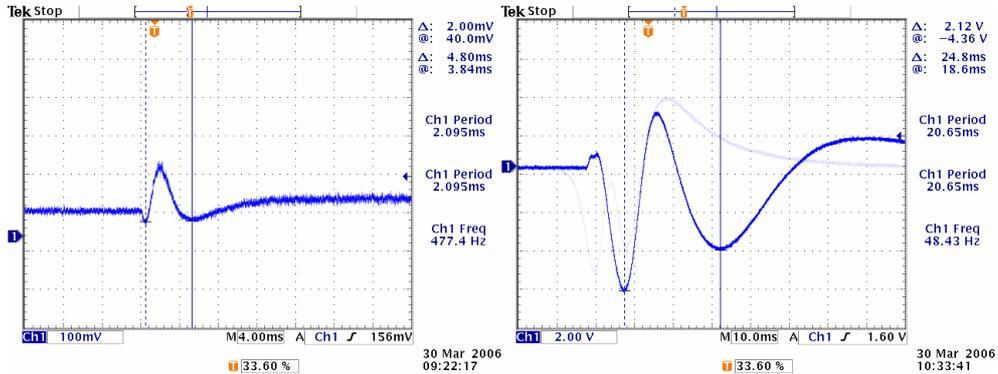


Figure 5 Plots of the LC relaxation time for an OPA built for operation at (a) 633 nm, and (b) 1550 nm, both using a high figure of merit LC. The 633 nm OPA demonstrated a relaxation time of ~4.8 ms, and the 1550 nm OPA demonstrated a relaxation time of 24.8 ms.

Thus, by using a high figure of merit LC it is possible to not only decrease the thickness of the LC gap which minimizes cross talk, but it is also possible to decrease the response time of the OPA. The result of this is a fast phase modulator with minimal inter-pixel cross talk.

3 Automated Calibration Procedures

Through the use of automated calibration procedures BNS has been able to better characterize, and optimize the OPA. The calibration procedures are broken into three steps. The first step is to generate a look up table, or LUT file to linearize the phase response of the LC. The second step is to generate a backplane calibration file that minimizes distortions introduced by the OPA. The last step is to clean up the cross talk regions. For the shorter wavelengths cross talk is minimal because the LC layer is so thin. However, at longer wavelengths, or in highly reflective OPAs, it is necessary to address cross talk.

3.1 LUT Calibration

The first step in the calibration procedure is to generate a LUT file. This file is used to linearize the phase response of the liquid crystal. The LUT takes in grayscale values from 0 to 255 and re-maps them to a new set of grayscale values that result in a linear 0 to 2π phase shift. If the mapping is correct, then the following table will hold true.

Input Grayscale Value:	0	64	127	192	255
Output Phase Shift:	0	$\pi/2$	π	$3\pi/2$	2π

In order to generate a LUT, the OPA is placed in an interferometer. The tilt of the OPA is adjusted such that horizontal fringes can be seen. Next the calibration software enters a loop where a series of stripe patterns are written to the OPA. The grayscale value of one stripe is held constant as a reference, and the grayscale value of the other stripe is varied. With each applied pattern a picture is taken of the resulting fringe shift. Through this process a relationship is established between input grayscale value and resulting fringe shift with respect to a reference. From this relationship it is possible to determine how the LUT file should re-map the 0 – 255 data such that a linear 0 to 2π phase shift is achieved.

3.2 Backplane Calibration

The second step in the calibration is to clean up any distortions introduced by the OPA. Typically there is slight curvature across the OPA, making the OPA look slightly domed. With our 2D array it is possible to completely characterize and calibrate out these distortions. However, with the 1D array it is only possible to correct in one dimension. Thus when the phase calibration is applied to

the 1D OPA the result is curvature from top to bottom, but little curvature across the array. Using standard fringe analysis tools problems were encountered in accurately characterizing a 1D device. Thus, it was necessary to generate our own calibration software. To do this BNS wrote a program that traces fringes, and then calculates a compensation file using a Least Squares algorithm. The program outputs a backplane calibration file, and before and after Peak to Valley and RMS error measurements. Figure 6 is a screen capture showing results of the fringe analysis software. The fringes are traced with red dots, and an ideal fringe is traced using blue dots. In this figure, the P-V error before calibration was 0.98 waves, and after calibration the error was 0.17 waves. The RMS error before calibration was 0.34 waves, and after calibration the error was 0.068 waves. This shows a typical improvement in wavefront distortion for the OPAs that have been measured thus far.

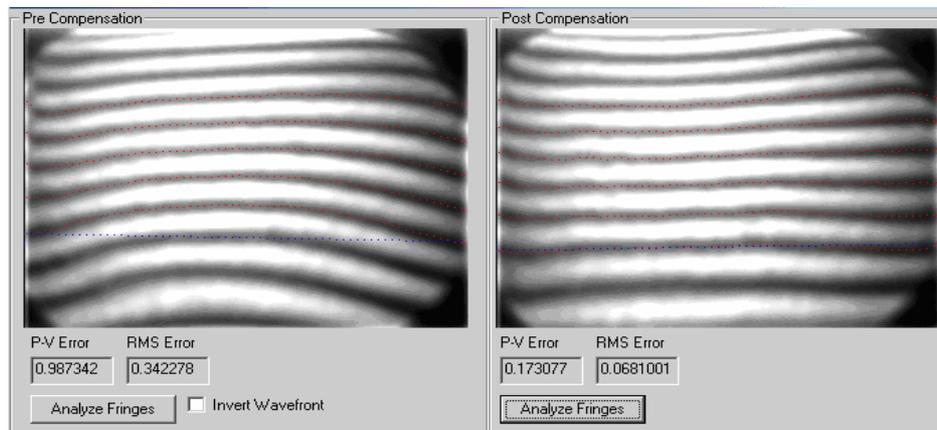


Figure 6 Fringe Analysis software showing interferograms before and after calibration.

3.3 Cross Talk Calibration

The LUT file is a useful as a starting point in defining the shape of a phase ramp. However, because in this calibration a wide group of pixels are ganged up when the measurements are made, this calibration does not take into account inter-pixel cross talk. There are two techniques that can be used to clean up cross talk.

3.3.1 Overdriving the 2π Resets

Cross talk can be cleaned up by shifting down on the phase response curve such that there are regions of grayscale values above 2π and below 0 that can be used to over-drive the resets. The top portion of Figure 7 shows a typical phase ramp that is generated using the LUT calibration only. The bottom portion of Figure 7 shows how this ramp was adjusted to over-drive the resets. In order for this strategy to work it is necessary to build the OPA with approximately 2 waves of modulation depth such that $\frac{1}{2}$ of a wave above and below the linear phase ramp are allocated to over-driving the 2π resets. It is only necessary to allocate a few pixels of the phase ramp to over-driving the resets in order to see a significant decrease in cross talk. In the interferograms shown in Figure 8 only 5 pixels were allocated to over-driving the resets. For this OPA if more pixels were allocated to over-driving the resets then the phase ramps would start to lose linearity, and if fewer pixels were allocated the gap in the 2π reset would increase.

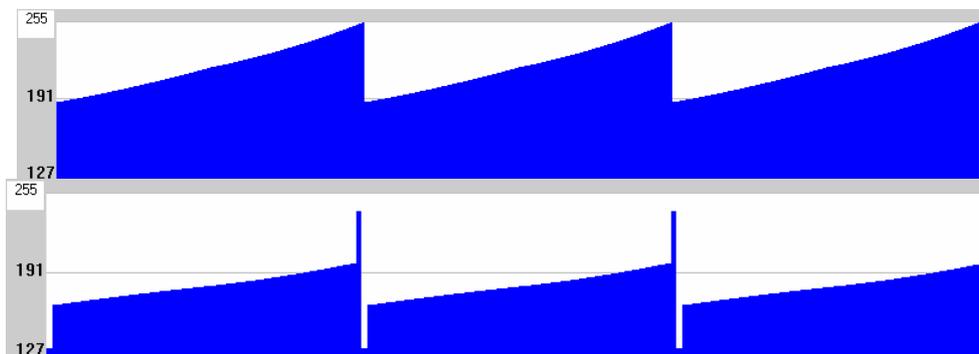


Figure 7 (top) Typical phase ramp generated using the LUT calibration only
(bottom) Over-driving the 2π reset to minimize cross talk

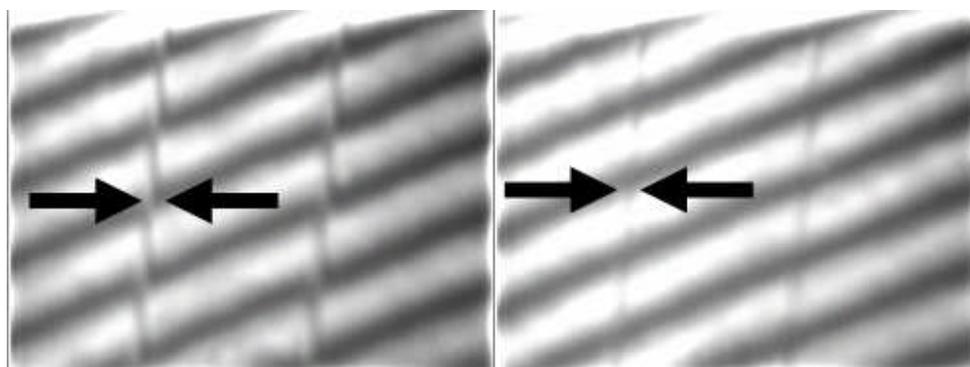


Figure 8 (a) generating linear phase ramps directly using the LUT file, (b) over-driving the 2π resets to minimize cross talk

As is shown this method is quite effective for cleaning up the 2π resets. However, it is not always an option to build an OPA to have greater than 1 wave of modulation depth. For example, in a highly reflective OPA a dielectric stack must be added to the backplane. As the reflectivity of the dielectric stack increases the thickness of the stack likewise increases. In this case the LC layer must remain as thin as possible to compensate for the added thickness of the dielectric stack. Thus, it is not reasonable to build the OPA to have extra modulation depth, so an alternate means must be used to decrease cross talk.

3.3.2 *Toggleing the Phase Ramp*

One of the benefits of working with nematic LC is that the LC responds only to the strength of the electric field, not the sign. In our current driving scheme the coverglass of the OPA is held at a constant voltage that is half of the full field. For example, in the 13 volt electronics of the 1x12288 OPA the coverglass is held constant at 6.5 volts. This means that the field applied to the LC is ± 6.5 volts with respect to coverglass. Because the response of the LC does not respond to the sign of the field, the phase shift is symmetric about a 0 field. A typical nematic response curve is shown in Figure 9. Usually the user opts to operate on one side of the response curve, or the other. However, aside from minimizing the complexity of the downloaded data it is not necessary to limit use to one side of the response curve. In fact, it is desirable to alternate between the two sides when trying to minimize cross talk. For example, if the user is writing a phase ramp to the SLM, then one ramp can use a positive field, and the next ramp can be mirrored around a grayscale value of 127 to make use of a negative field. The result is an increase in voltage difference between the phase ramps while maintaining a linear phase response. Figure 10 demonstrates the concept. The top portion of the Figure 10 shows typical data used to generate a

linear phase ramp. In the bottom portion of Figure 10 it is demonstrated how the data is mirrored around a grayscale value of 127 after each 2π reset. Thus the software is actively using both sides of the LC response curve. Figure 11 shows interferograms an OPA showing significant cross talk due to a very thick modulator design. The first part of this figure shows cross talk without toggling the data, and the second part of the figure shows the improvement in cross talk when the data is toggled.

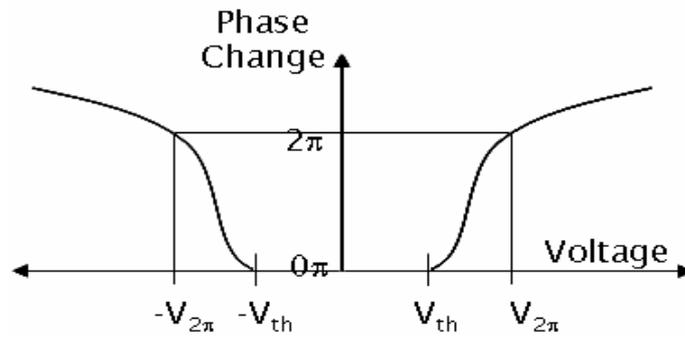


Figure 9 Plot of Phase Shift versus voltage for Nematic LC

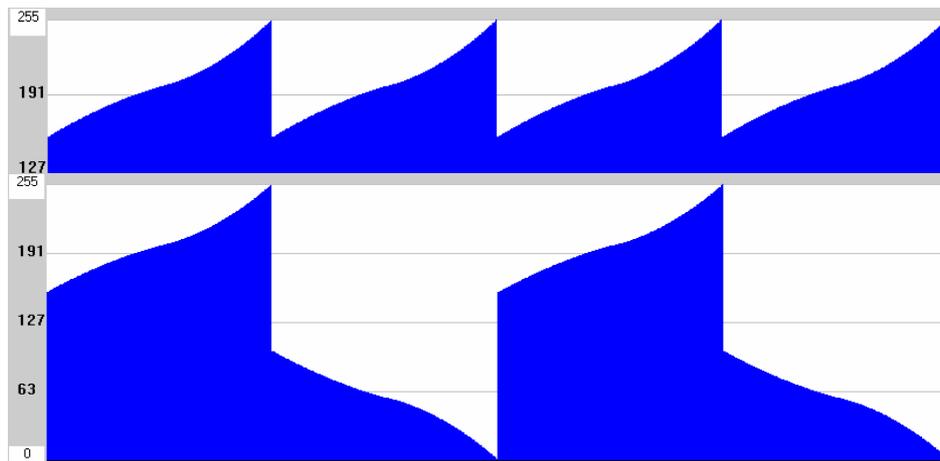


Figure 10 (top) Automatically generated phase ramp (bottom) Toggling the data to make use of the symmetric nature of the LC response

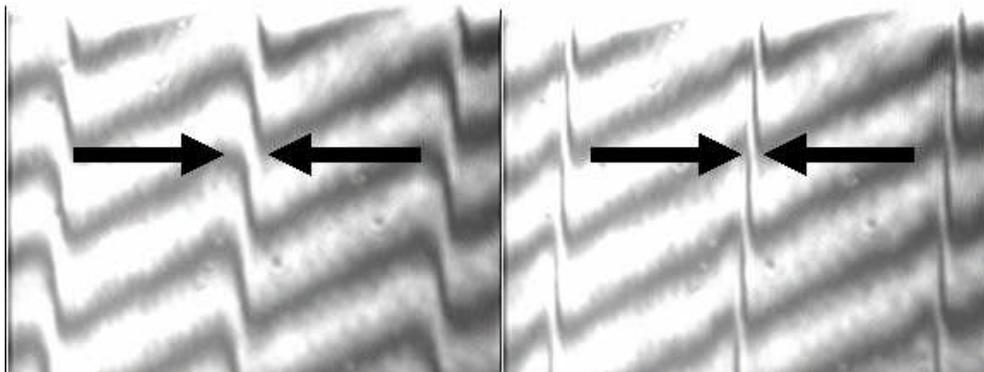


Figure 11 (a) linear phase ramps applied to a very thick OPA showing significant inter pixel cross talk. (b) toggling the data to clean up the 2π resets

In this example the cross talk was decreased by a factor of 2, while the modulation depth of the OPA remained at only slightly over one wave. This technique has been shown to be quite effective. It adds a level of complexity in generating the data to download to the OPA, but the new software that BNS has developed allows the user to individually plot each step of the applied profile. In this case the phase profile consists of the desired data (a ramp) added to the backplane calibration that is then processed through the LUT (used to linearize the phase response of the LC), which is then toggled at each 2π reset. By seeing each step individually, and the result of each step combined it is possible for the user to understand what is being downloaded to the OPA and why.

4 Conclusions

During the research effort funded by NASA BNS significantly improved steer angle and response time over that of our existing commercially available 1x4096 pixel OPA. This was accomplished by designing a new OPA backplane with a decreased pixel pitch, an increased backplane voltage, and a larger OPA aperture. Additionally BNS developed automated calibration procedures to: linearize the phase response of the LC, minimize distortions introduced by the OPA, and minimize inter pixel cross talk. The result was that the maximum steer angle was more than doubled, and the response time was significantly decreased.

The following table summarizes the current specifications for the 1x12288 pixel OPA built for operation at 633nm and at 1550 nm. Where applicable these specifications are compared to that of the 1x4096 pixel OPA. A value for the calibrated OPA distortion of the 1x4096 OPA is not reported because the recent development efforts have not yet been applied to the 1x4096 OPA. Likewise, a value is not reported for the relaxation time of the 1x4096 OPA due to the difference in operating voltage of the two backplanes.

This chart show significant progress in the new OPA design. Through this research effort the steer angle of the OPA more doubled to ± 6.95 degrees, and the response time was decreased to 24.8 ms. This is a particularly important milestone, with significant impact in the fields of beamsteering, wave front correction, and optical processing.

	1x4096 OPA		1x12288 OPA	
	633 nm	1550 nm	633 nm	1550 nm
Steer Angle	1.5°	3.08°	4.53°	6.95°
Ramp Period	32 pixels	16 pixels	5 pixels	8 pixels
OPA Distortion	2 waves P-V	2 waves P-V	< 1 wave P-V	< 1 wave P-V
Calibrated OPA Distortion			< 0.1 waves RMS	< 0.1 waves RMS
LC Relaxation Time			4.8 ms	24.8 ms

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