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Advanced Liquid Crystal on Silicon Optical Phased Arrays¹

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Abstract - Non-mechanical beamsteering eliminates the need for massive optomechanical components to steer the field of view of optical systems. This benefit is to come in the form of compact, low-power, light-weight optical phased arrays (OPAs) that provide better control with greater flexibility in their steering capability than their mechanical counterparts. Due to such benefits, there is a need to develop technologies that provide this capability without greatly sacrificing other parameters such as aperture size, efficiency, and scanning range. One technology being explored for OPA implementation is liquid crystal on silicon (LCoS). The LCoS technology provides a means for manufacturing high-resolution backplanes using high-volume semiconductor processes commonly used for very large scale integrated (VLSI) circuits. VLSI production minimizes the cost of backplane fabrication and allows integration of electronic circuits into the backplane structure to provide individual addressing of each pixel while minimizing interconnects to the OPA. Since each pixel is individually addressed, the phase modulation is not restricted to phase ramps but provides any type of phase profile. This capability is useful for dynamic correction of phase distortions across the aperture due to heating effects, for example. Also, it allows the reset period to be randomized to minimize sidelobe amplitudes. However, VLSI technology has its own set of limitations that have slowed the development of high-speed, high-resolution, non-mechanical beamsteerers having good optical efficiency and a large scanning range. This paper discusses the benefits and limitations of the LCoS approach and methods for improving the state-of-the-art.

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1. Introduction

An optical phased array steers light by phase modulating the light entering or exiting the optical system. By applying a linear phase shift 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. The angle of propagation, θ , is a function (the arcsine) of the ratio of the light's wavelength, λ , to the distance, d , over which a phase shift of 2π occurs (as shown in Equation 1).

$$\theta = \sin^{-1}(\lambda/d) \quad (1)$$

Due to reciprocity, monochromatic light entering the system from a particular angle has a linear phase shift with respect to the system's optical axis. By conjugating the linear phase shift, incoming light from a particular angle propagates along the system's optical axis. Fortunately, the phase shift applied by the OPA does not have to be continuously increasing or decreasing which would require phase shifters with large modulation depth. Due to the cyclic nature of phase modulation, it is possible to increase or decrease the phase shift by 2π and maintain the relative slope of the phase profile. Therefore, the linear phase ramp can be periodically decreased by 2π , producing a sawtooth phase profile which acts to shift a monochromatic beam in the same manner as a continuously increasing phase ramp but without requiring large phase shifts from the modulator. The sawtooth profile is commonly viewed as modulo- 2π phase shifts at a particular spatial frequency. A higher occurrence (higher frequency) of 2π phase shifts across the wave front increases the steer angle. This effect is true for coherent laser beams and monochromatic images.

For an imaging system, the field of view of the optics, which determines resolution and sensitivity, is usually limited to optimize system performance. If a system is detecting spectrally narrow (monochromatic) images, an OPA is useful for changing the view angle without affecting system performance by phase conjugating the higher spatial frequencies associated with angular displacement. However, the lower spatial frequency content that forms the image passes through the system intact. This operation steers the field of view of the optics to provide a larger angle of regard for the imaging system.

The phased-array approach^{1,2} to optical beamsteering eliminates the need to apply mechanical force to move massive objects such as telescopes and consequently the need to counterbalance these forces to prevent the platform's orientation from being affected. Non-mechanical beamsteering is beneficial in applications where the optical

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axis of the instrument needs to be rapidly and accurately redirected to random locations or where the platform is relatively small and mechanical stabilization during scanning is a difficult problem. Due to such benefits, there is a need to develop technologies that provide this capability without greatly sacrificing other parameters such as aperture size, efficiency, and scanning range.

2. Construction/Operation of LCoS OPAs

For efficient optical phased arrays with large angle-aperture products, the technology has to provide a means for controlling thousands of phase shifting elements that are spaced within a wavelength of each other. One approach is to use liquid crystal (LC) materials to provide the phase shift and VLSI backplane structures for controlling the LC modulators. Liquid crystals are frequently used as optical modulators. These materials offer several advantages including large modulation depth, solid state operation, low power dissipation, sub-millisecond switching, potential for large aperture operation, and low cost. For the OPA application, an LC modulator having an electronically controllable retardance is used. That is, the index of refraction of a liquid crystal cell changes with applied field. Normally, this index change is polarization dependent so that the light needs to be properly polarized for phase-only operation.

In order to modulate only the phase of incident light, a nematic liquid crystal is aligned in a planar conformation. Here the liquid crystal director (i.e. long axis of the molecule) is oriented parallel to the polarization of the incident light. Most materials exhibit a positive dielectric anisotropy and, 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). The voltage is provided by addressing electrodes spaced a few microns apart and several millimeters long.

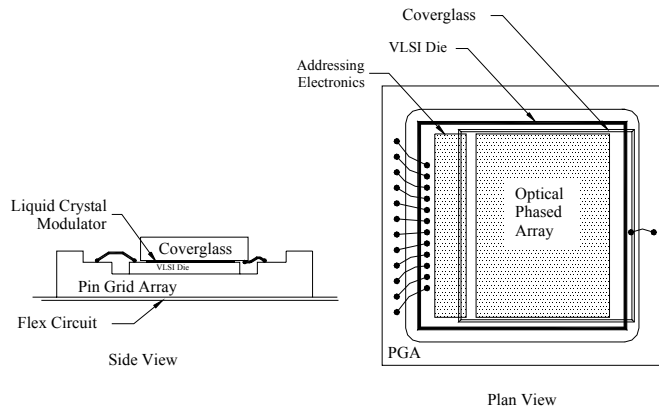


Figure 1. Layout of OPA optical head

As shown in Figure 1, the OPA optical head consists of a layer of liquid crystal sandwiched between a cover glass and a VLSI backplane in a PGA (pin grid array) package. The VLSI backplane receives analog voltage signals through a limited number of input lines and routes the signals to the appropriate phase shifter element using a multiplexer arrangement (refer to Figure 2). Each array element has a storage capacitor for holding the analog voltage level on the LC addressing electrode as the other array elements are loaded or refreshed with data. Therefore, the voltage across the LC layer remains constant until new data is loaded into the array. The load rate for the whole array is faster than the response of the LC producing a static phase pattern across the device. With this type of operation, the ability to individually control every electrode of a large array is achieved with a minimum number of electrical interconnects. The ability to individually control every electrode maximizes the number of addressable spots and versatility of the device.

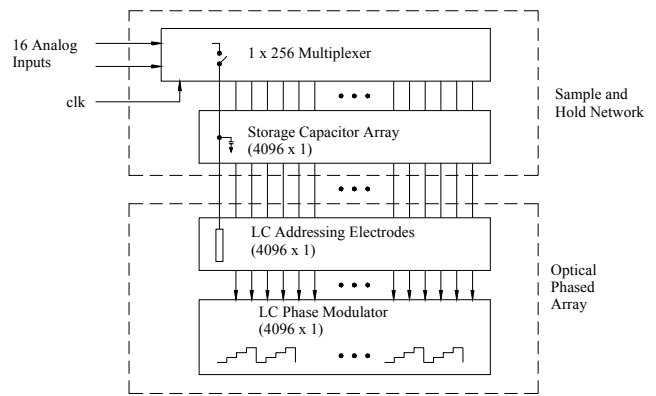


Figure 2. Functional block diagram for a 4096x1 OPA head

The actual electrodes are thin metal wires that run the length of the active area and are spaced approximately one optical wavelength from each other. This metal wire grid is a diffractive reflector since the space between wires is approximately equal to the width of the wire. Diffraction from the electrode elements is minimized by hiding the electrodes under a reflective dielectric stack that is deposited over a planarized surface covering the metal electrodes (refer to Figure 3).

The electric field used to control the LC phase shifter is created between the electrode wires and the single transparent indium tin oxide (ITO) electrode on the coverglass as shown in Figure 3. The distance from the ITO electrode with respect to the width of the backplane electrodes has a large effect on LC addressing. A large aspect ratio of modulator thickness to backplane electrode width causes the electric field to be smeared spatially across the LC layer, smoothing the resulting phase profile produced by the LC. The electric field applied across the LC modulator and dielectric stack is affected also by the voltage levels at the adjacent electrodes. A potential difference

between adjacent backplane electrodes causes field coupling (i.e. fringing fields) to exist. Strong fringing fields between electrodes cause the LC molecules to rotate in plane instead of perpendicular to the electrode plane, thus producing complex amplitude modulation instead of pure phase modulation. The strength of the fringing field is determined by the relative voltage between electrodes where the greatest difference occurs at the modulo- 2π reset of the phase ramp. At the reset, the fringing fields generally cause in-plane switching over the area of several electrodes. This effect reduces efficiency as the spatial period decreases, causing the loss of the largest steering angles.

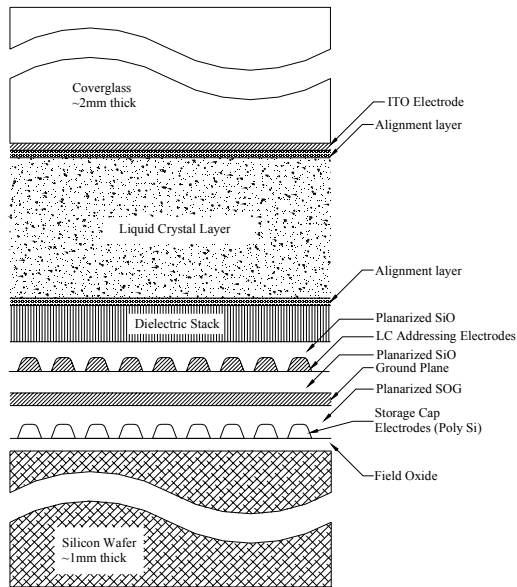


Figure 3. Cross section of LCoS OPA head

Figure 3 shows the modulator-electrode aspect ratio of an existing LCoS OPA. For this device, the electrodes are spaced 1.8 microns apart and the width of each electrode is one micron. Foundry planarization techniques, such as chemical mechanical polishing (CMP) of the oxide layers and spin on glass (SOG), are employed in the VLSI fabrication process to remove underlying topography that causes diffraction. Above the VLSI structure resides the dielectric stack and LC modulator. The complete modulator stack is approximately 10 microns resulting in a ten-to-one aspect ratio. If one were to calculate the steer angle based only on backplane resolution, the device would be capable of steering 1.55 micron light through an angle of ± 16.68 degrees with better than 50% efficiency (three phase levels per ramp). Unfortunately, a large aspect ratio keeps this theoretical range from being realized.

Figure 4 shows IR camera images of the far-field diffraction patterns arising from an LCoS OPA having an electrode spacing of 1.8 microns and steering 1.55 micron light. For no voltage applied to the grating (0°), 87% of the incident light is in the zero order (specularly reflected). After addressing the device, a majority of the incident light is diffracted to the desired angle, but the beam intensity falls to approximately 50% of its zero-order value at $\pm 3^\circ$. Therefore,

the actual steering range of the device is approximately a factor of five less than what is possible from the backplane. This disparity is physically attributable to a large aspect ratio. However, the large aspect ratio is partially due to factors imposed by VLSI backplane limitations. These limitations are discussed in the next section.

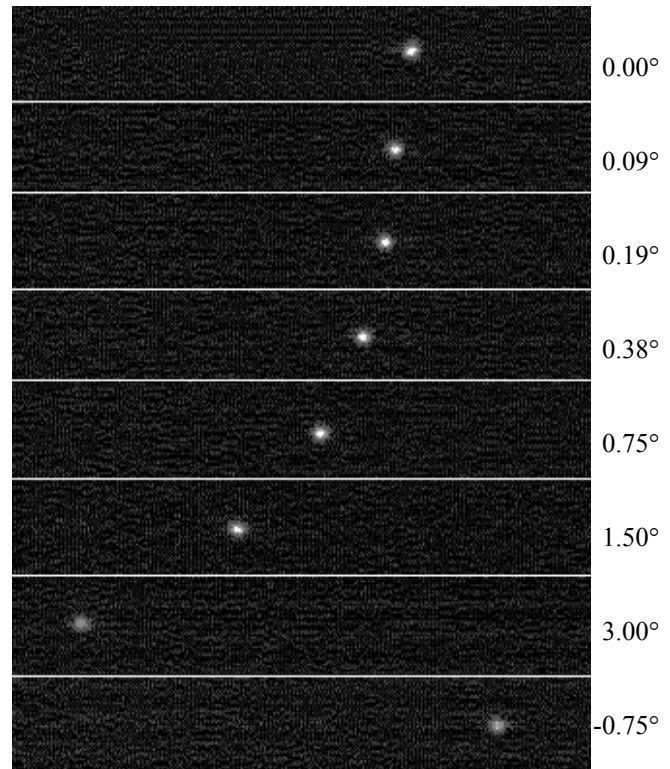


Figure 4. Diffraction patterns imaged by an IR camera produced by a 4096-electrode LCoS OPA steering 1.55 micron light.

3. LCoS Limitations/Improvements

Most semiconductor foundries are moving to smaller geometry processes (i.e. higher resolution lithography). The smaller geometries allow greater circuit integration and provide faster circuitry with less power consumption. Today, semiconductor foundries commercially offer process sizes ranging from a few microns to a couple tenths of a micron. As the process size decreases, smoother (shinier) metals are used and layer thicknesses are made more uniform by planarization techniques such as chemical-mechanical polishing (CMP). These process changes are meant to improve electrical yield, but they greatly contribute to the optical quality of the silicon backplane by eliminating topography that scatters light. Higher resolution lithography allows the electrode pitch to be reduced at the cost of reduced operating voltage, since higher voltages require larger gate structures. In the higher resolution processes, an optical reduction is used when the patterns are transferred from the mask to the wafer. These patterns are then repeated across the wafer by stepping the pattern to different locations on the wafer. The pattern's projection onto the wafer is

limited by the reticle of the stepper which ultimately limits the size of the VLSI die. Therefore, the general trend in semiconductor fabrication offers significant advantages for producing LCoS OPAs, but it is not all beneficial.

The reduction in voltage with increased resolution is arguably the greatest limitation to the technology. To produce OPA's with large angle-aperture products, high resolution addressing is needed to provide three or more phase levels in the distance of a few wavelengths. For visible and near IR applications, this spacing requires sub-micron foundry processes with design rules that allow the addressing circuits to be as tightly packed as the electrode structure. These spatial requirements limit the operating voltage of the device. As an example, the device described in the previous section operates at five volts. At the time of its design, it used one of the highest voltage sub-micron processes available that had favorable design rules for the gate structures.

Voltage provides the field that switches the LC modulator. The amount of voltage needed for a particular LC modulator is a function of the LC material, cell thickness and LC alignment. It is possible to vary some of the parameters to achieve low voltage operation, but there is always a performance price to pay. For example, the voltage needed to switch LC molecules at the center of the cell is considerably less than the voltage needed to switch molecules near the cell's alignment layer that are strongly affected by surface forces. It takes less voltage to get an equivalent change in retardance from a thick parallel-aligned cell than from a thin cell. The performance cost is that thicker cells have slower response

As discussed above, the modulator-electrode aspect ratio has a profound effect on the ability to convert addressing resolution into steering capability. The electric field smoothing acts as a low pass filter causing discrete steps at each element to be smeared out spatially over a larger area. At the 2π resets, the abrupt change in voltage produces a more noticeable effect which is sometimes referred to as the fly back region. The loss of energy in the main lobe as the period decreases is usually contributed to the fly back region which causes a portion of the light from each sawtooth to be deflected in the wrong direction. The net effect due to smoothing and fly back is a fast fall off in the intensity of the main lobe as the steer angle increases.

Reduction of the fly back region is possible by using different material properties of liquid crystal. An obvious property that helps in this effort is the birefringence of the material. A highly birefringent material reduces the LC layer thickness needed to achieve 2π of phase modulation. Fortunately, there is very little down side to using the highest birefringence material available that meets device requirements. Unlike the birefringence, other LC properties useful for reducing the fly back region, such as the elastic and electrical parameters of the material, produce voltage dependent effects and may not be usable due to backplane

limitations. One such effect is the threshold voltage of the material.

For a parallel-aligned cell, the threshold voltage, V_{th} , is a function of the elastic constant, k_{11} , that keeps the molecules aligned parallel to the cell's surface and the difference, $\Delta\epsilon$, in the perpendicular and parallel dielectric constants of the LC material as given by³

$$V_{th} = \pi \sqrt{k_{11} / \epsilon_0 \Delta\epsilon}, \quad (2)$$

where ϵ_0 is the permittivity of free space.

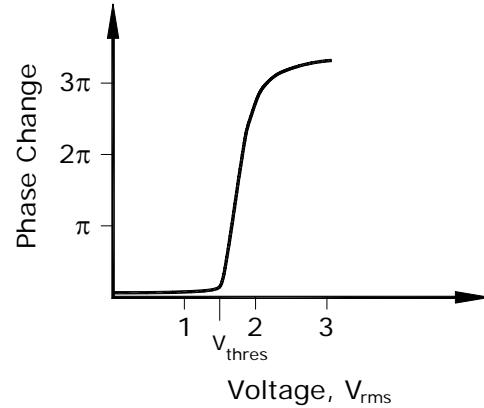


Figure 5. Response curve for a nematic parallel-aligned liquid crystal cell

The nonlinear voltage response at threshold increases the sharpness of the modulator. At threshold as shown in Figure 5, a small change in voltage produces a relatively large change in phase modulation. Sharpness is aided by using an alignment with no pre-tilt of the molecules. That is, all the long axes of the molecules are parallel with the surfaces of the cell. This arrangement reduces coupling to the field, keeping the molecules from rotating until the threshold voltage is exceeded. After it is exceeded, the bulk of the molecules rotate into the field producing a large change in retardance. This nonlinear optical response tends to counteract electrical smoothing and reduce the fly back region.

Fringing field effects are reduced by using high threshold materials with sharp response to prevent the voltage difference between the backplane electrodes from exceeding the voltage difference between the backplane and ITO. If, for example, the modulator has a threshold voltage of three volts and provides a full wave of phase modulation in two volts, then the two volt fringing field between adjacent electrodes is less of a problem, since this voltage difference is below threshold. Thus, in-plane switching is prevented.

For the steering results shown in Figure 4, the threshold voltage techniques discussed above were not employed. The loss of voltage across the dielectric stack forced the use of low threshold materials and non-zero pre-tilt alignments to achieve sufficient modulation depth with the five-volt

backplane. This is one reason that the fly back effect extended over the distance of several electrode elements causing the large reduction in steer angle. The ability to write cleaner phase profiles for all possible periods would greatly increase angle coverage and the number of resolvable spots produced by the OPA.

The fly back problem is not only a matter of efficiency. The periodicity of the fly back region produces sidelobes. Fortunately, the LCoS OPA provides a flexible addressing structure. With the ability to spatially and temporally vary the drive signals to the LC modulator at each electrode, it is possible to greatly reduce sidelobes without eliminating fly back. For example, it is possible to use a modulator that has more than 2π of modulation to randomly distribute the phase resets instead of having them occur periodically. This random distribution causes the stray light due to fly back distortion to be distributed across the field of view preventing strong grating lobes from causing interference.

The use of random 2π resets to mitigate fly back effects was simulated and compared to phase profiles with periodic resets. At each random or periodic reset, a fly back distortion was introduced where the 2π phase resets were distributed linearly across a set number of pixels. Table 1 shows the results of this simulation effort where the power levels of the main lobes and highest sidelobe are given for different phase slopes (steer angles). The phase slope is given in the number of electrodes in which a change of 2π occurs. The power levels of the lobes are given as a percentage of the total power. The results shown are for a fly back region of four electrodes at each reset.

Table 1. Normalized Far-field Intensities for Periodic versus Random Resets (fly back = 4)

Ramp Period	Periodic Mainlobe	Periodic Sidelobe	Random Mainlobe	Random Sidelobe
8	28.1	32.3	36.8	15.5
16	56.3	8.7	64.7	4.2
32	76.4	2.2	81.3	1.1
64	87.8	0.5	90.4	0.3
128	93.8	0.1	95.5	0.1

As shown in the above table, a factor of two reduction in sidelobe intensity is achieved. To implement this ability, each electrode must be fully programmable which is possible using the LCoS OPA design discussed in the previous section.

Another voltage dependent performance issue is speed. Most commonly used nematic liquid crystals exhibit a positive dielectric anisotropy. This means that they can be rapidly driven from an optically thick state to an optically thin state as the dipole moment couples to an applied field. However, for conventional materials, going from an optically thin state to an optically thick state requires time for the molecules to relax to the next voltage state, V_b . The time constant for relaxation, τ_{relax} is³

$$\tau_{relax} = \frac{\gamma_1 t^2}{k_{11} \pi^2} \frac{1}{\left| \left(\frac{V_b}{V_{th}} \right)^2 - 1 \right|}, \quad (3)$$

where γ_1 is the material viscosity and t is the cell thickness. Equation 3 shows that fast relaxation requires operation at voltage levels that are large compared to the threshold voltage. The higher voltage operation in this case makes use of the tightly bound molecules near the surface of the cell. These surface molecules have a fast relaxation, but the phase change versus voltage has a shallow slope as shown in Figure 5. This type of operation, therefore, is contrary to that described above for reducing the fly back region.

Instead of relying on relaxation, it is possible to drive the molecules into a high-retardance state if the dielectric anisotropy of the nematic LC changes sign (i.e. ϵ -perpendicular becomes greater than ϵ -parallel). The value of ϵ -parallel is frequency dependent where as ϵ -perpendicular is not. Therefore, the sign of the dielectric anisotropy is frequency dependent and it changes sign at relatively low frequencies in certain types of materials. These materials are called dual frequency materials. An investigation of some of these materials indicates that sub-millisecond response time is possible if large drive voltages are used (~12 volts produces a 0.5 millisecond response). This type of modulator also requires an addressing technique that provides a high frequency excitation (about 40 kHz) to produce the sign-changing drive signal. Fortunately, the high frequency signal is only needed to reset the LC modulator before a new pattern is written to the grating. By applying a high-frequency drive signal to the common coverglass electrode, the LC modulator is quickly reset to its high birefringence state, allowing new data written to the VLSI backplane to be displayed within a millisecond if the VLSI backplane has sufficient voltage.

High speed liquid crystal materials require addressing at considerably higher voltage levels than the standard 3.3 - 5 volt capability available from most sub-micron semiconductor processes. Fortunately, a few different foundries are developing higher voltage processes. There are now 12 to 40 volt processes using sub-micron lithography. However, the gate sizes required by these processes limit the spatial resolution of the backplane. Therefore, there is still a voltage-versus-resolution tradeoff that has to be addressed in the backplane design. Higher voltage backplanes allow higher threshold materials and dual-frequency nematic materials to be employed, which would improve steering range and response time of the device.

Angular deflection is a function of backplane resolution, but the ability to resolve angles is a function of aperture size. This is one reason that angle-aperture product is the quantity of interest to system developers. It is always possible to use reducing optics to increase the deflection angle of an OPA at the expense of reducing its effective aperture. However, the

number of resolvable spots remains the same which is sometimes referred to as the optical invariant.⁴ A larger active area provides more programmable electrodes increasing the number of addressable angles, and it narrows the beam width, providing better far-field resolution. However, the active area of a LCoS device is restricted by the processes used in VLSI fabrication. If the VLSI process uses one-to-one contact printing, then the VLSI die can be as large as a wafer. However, this type of lithography process is usually used for larger geometry processes (2 to 5 microns) which limit device resolution (i.e. electrode spacing). For sub-micron processes, the wafer is patterned using a stepper to project a reduced pattern onto the wafer. Therefore, the die size is usually limited by the reticle size of the pattern stepper. For most small geometry processes, the reticle size is approximately 2 cm x 2 cm or less.

At an electrode spacing of two microns, a 2 cm x 2cm OPA has 10,000 individually addressable lines. If this device is used to steer 1.55 microns, then the backplane resolution allows ± 15 degrees of steering range with at least three phase levels per ramp and the aperture provides a 0.0044 degree half-power beam width. Therefore, the maximum number of resolvable spots is 6756 based only on aperture size and Rayleigh criterion. Unfortunately, the actual number is considerably less if one alters the steer angle by changing the phase ramp period in electrode width increments.⁵ In this case, there are large angular jumps at the large steer angles (small number of electrodes per period). At small angles (hundreds of electrodes per period), the beam does not move a full beam width for each electrode width added to the period. Because of the set electrode width, the number of unique spots addressable in this fashion is roughly an order of magnitude less than the value given above for resolvable spots based on aperture size.

Most of the loss of angular resolution comes at the large steer angles. When the number of phase levels per ramp is increased from eight to nine using a two-micron electrode spacing, the steer angle at 1.55 microns changes from 5.6° to 4.9°. A jump of 0.7 degrees occurs which is the loss of 157 resolvable angles. Of course, modulator-electrode aspect ratio is the primary limitation to angular coverage at this spatial resolution, but the angular jump due to electrode width soon becomes the dominant factor as the period increases. Fortunately, some of this problem is correctable by using a LC modulator capable of supplying more than 2π . For example, a modulation depth of 2.25π allows the phase slope to be varied to cover the range from 4.9 to 5.6 degrees without changing the number of phase levels from nine to eight. If the 2.25π phase shift is linearly divided into 256 levels (8 bits), an 8-bit addressing scheme allows 28 angles (out of the 157 available) to be addressed between 4.9 and 5.6 degrees. The LCoS backplane stores analog voltages. In theory, it has the ability to address all angles within its highest spatial resolution if the LC modulator has sufficient depth.

If optical throughput and not angular resolution is the primary concern, then die size limitations due to pattern

stepping does not prevent the aperture from being considerable larger. By having the ability to phase together several LCoS OPAs to operate as a single aperture (refer to Figure 6), the optical throughput of the system is increased by the number of OPAs in the array. Likewise, the power handling capability of the system is increased by the number of backplanes in the array. An individual LCoS OPA backplane is capable of handling considerable power since the semiconductor layer which is photo sensitive is well shielded using a metal ground plane (refer to Figure 3). The actual power limitation is expected to be from heating due to absorption in the various layers.

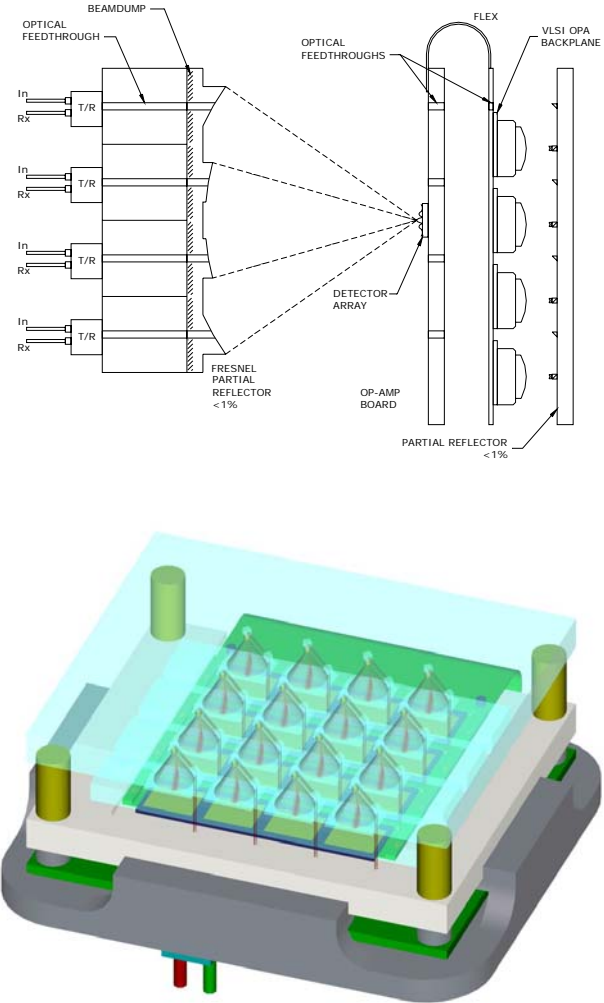


Figure 6. Phased array of phased arrays using LCoS OPAs

A conceptual phased array of phased arrays assembly using LCoS OPAs is shown in Figure 6. The design shown uses a fiber feed network that illuminates the array of 16 OPAs through 6-to-1 expanders (refer to Figure 7). The expanders allow the reflective array to operate on axis without blocking much of the aperture (approximately 2%). After expansion, there is roughly a 50% fill factor across the array. Another 2-to-1 expansion can be added to improve the fill factor at the expense of losing some angular coverage. The back reflection off of the top window covering the array is detected after being Fourier transformed by a Fresnel partial

reflector and this information is used for spatially phasing the individual OPAs. One coverglass is used for four OPA die which are cut from the waver as one piece. With one coverglass, the phase variation between the die is kept to a fraction of a wave. The die are wire bonded to a flex circuit which provides the electrical feed for addressing all 16 OPAs. Four coverglasses are attached to an optically flat mount which minimizes phase variations between the rows of OPAs.

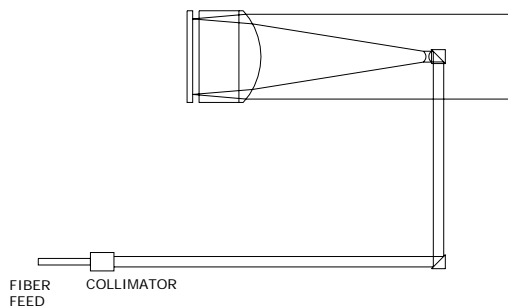


Figure 7. Fiber to reflective OPA feed

4. Conclusions

LCoS offers several advantages for implementing optical phased arrays such as the ability to use the same inexpensive high volume manufacturing techniques now being used for low-cost microdisplays. However, there is some price to pay for this benefit. Several LCoS OPA limitations exist. The largest problem (the modulator-electrode aspect ratio) is not specifically related to the LCoS technology, but other problems resulting from the high-resolution foundry processes used in the fabrication of the silicon backplane add to its severity and affect other performance parameters as well. These problems and some possible solutions are listed below.

Modulator-electrode aspect ratio:

A large ratio reduces the steering range of the device by increasing the fly back region. A method for correcting this problem is to use a LC material with high birefringence, sharp response and high voltage threshold. This solution requires a high voltage backplane. The sidelobes produced by the fly back region are reduced using phase patterns with random resets.

Voltage-resolution tradeoff:

High voltage operation reduces the addressing resolution of the backplane. Due to other limitations, the full addressing capability of the backplane is not realized in practice. Therefore, some loss of resolution for a substantial gain in operating voltage is a good tradeoff. With higher voltage, a decrease in the fly back region, an increase in LC response

and the ability to use more modulation depth to steer between the angles set by electrode spacing are possibilities. These improvements are likely to compensate for any loss in addressing resolution.

Limited die size:

Aperture size determines the beam width and hence the number of resolvable spots over the steering range. As with addressing resolution, the aperture size is not, in practice, the real limit. However, a large aperture is important for optical gain and power handling. Fortunately, these system parameters are satisfied by using multiple OPAs.

With improvements to the state of the art as discussed in this paper, the LCoS approach promises to be a viable technique for OPA implementation.

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