Advances in liquid crystal beam steering

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ABSTRACT

A space platform for optical communications could benefit from nonmechanical beam steering in which no inertia is used to redirect the laser communications link. This benefit is to come in the form of compact, low-power, light-weight optical phased arrays that provide greater flexibility in their steering capability. Non-mechanical beam steering eliminates the need for massive optomechanical components to steer the field of view of optical systems. A phased array approach also allows for random access beam steering. This paper discusses nonmechanical beam steering based on liquid crystal on silicon optical phased array technology. Limitations of the current technology and improvements are presented.

Keywords: Liquid Crystal Optical Phased Arrays Beam Steering

1. INTRODUCTION

A non-mechanical approach to beam steering eliminates the need to apply mechanical force to move massive reflectors and consequently the need to counterbalance these forces. Therefore, non-mechanical beam steering is beneficial in applications where the optical axis of the instrument needs to be rapidly 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.

There are several means to implement nonmechanical beam steering including liquid crystal optical phased arrays (OPAs), solid crystal based electro-optic modulators, acousto-optic modulators, and micro-electromechanical (MEMs) actuators. These nonmechanical beam steering technologies have the potential to exceed pointing capability offered by gimbals while greatly reducing the weight, power and size of optical assemblies making them very attractive for orbiting-platform implementations.

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 wave front as it leaves the system, the light propagating along the system's optical axis is steered to an off-axis angle[1]. The angle of propagation is a function (the arcsine) of the ratio of the light's wavelength to the distance over which a phase shift of 2π occurs. Therefore, a higher occurrence of 2π phase shifts across the wave front increases the steer angle (i.e. higher spatial frequency increases the deflection angle). 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 that represents modulo-2π phase shifts at a particular spatial frequency. This spatial frequency pattern is phase conjugated by the frequency-matching phase shifts applied by the OPA causing the incoming light from a particular angel to propagate along the system's optical axis.

Boulder Nonlinear Systems (BNS) uses very large scale integration (VLSI) to address an array of liquid crystal modulators to implement a nonmechanical beam steering device. The VLSI addressing allows for true multiplexing to achieve individually addressable pixels across the entire optical aperture. This flexibility results in a random access beam deflector with the potential for phase correction.

The 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 as shown in Figure 1. The VLSI backplane receives analog voltage signals through input lines and routes signals to each phase shifter element using a multiplexer arrangement. Each array element has a storage capacitor to hold an analog voltage level on the LC addressing electrode as other array elements are

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loaded with data. The ability to individually control every electrode of a large array is achieved with a minimum number of electrical interconnects, maximizing the number of addressable spots and versatility of the device[2].

In order to modulate the phase of incident light, the 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).

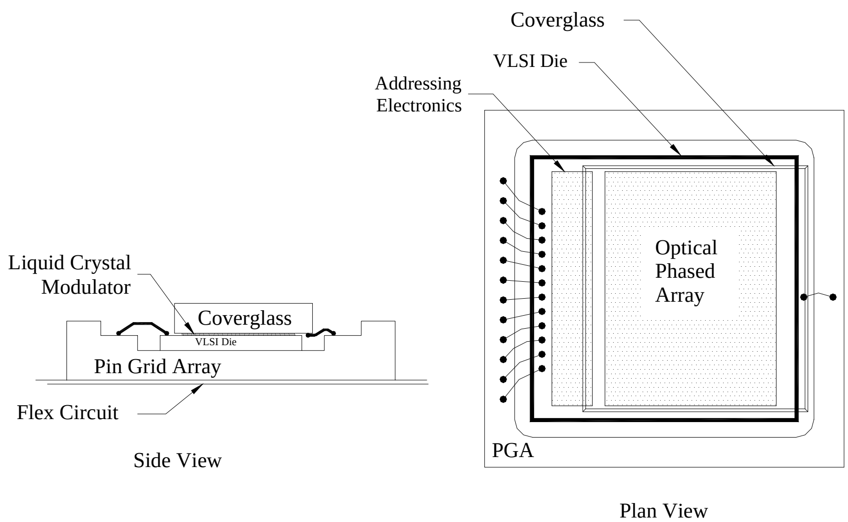

Figure 1. Layout of a liquid crystal on silicon OPA optical head

The deflection angle for an OPA, θ_m, is given by

$$\theta_m = \sin^{-1}\left(\frac{m\lambda}{d}\right) \quad .$$

Here m is the diffracted order (usually only the first order is considered), λ is the vacuum wavelength and d is the (variable) grating period. Note that due to the nature of diffractive devices, steering is, in general, not continuous. However, techniques can be used to make the steering appear continuous. A major advantage of diffractive devices is that the addressable angles can be randomly accessed.

In this paper, we discuss the performance of our liquid crystal optical phased-array technology and improvements currently under development.

2. OPTICAL PHASED ARRAY BEAM STEERING PERFORMANCE

The electro-optic performance of an OPA designed for 1550 nm operation is discussed in this section. For this particular device, the passivated OPA backplane with a 5 layer dielectric stack was gapped using 6 micron glass spheres to an AR coated cover glass. The assembled cell was filled with nematic liquid crystal, BL066, formerly available from Merck.

To investigate the device's steering characteristics, vertically polarized light from a 1.55 μm laser source was directed onto the OPA via a nonpolarizing beam splitter. The light diffracted from the OPA was then focused onto an IR camera. A frame grabber was used to record the intensity level of the beam as it was steered. A MathCAD program was used to convert the digital data of the frame grabber into plots of the intensity. Figures 2, 3 and 4 show the relative intensity for three different angles: 0.046^o, 1.5^o and 3^o.respectively.

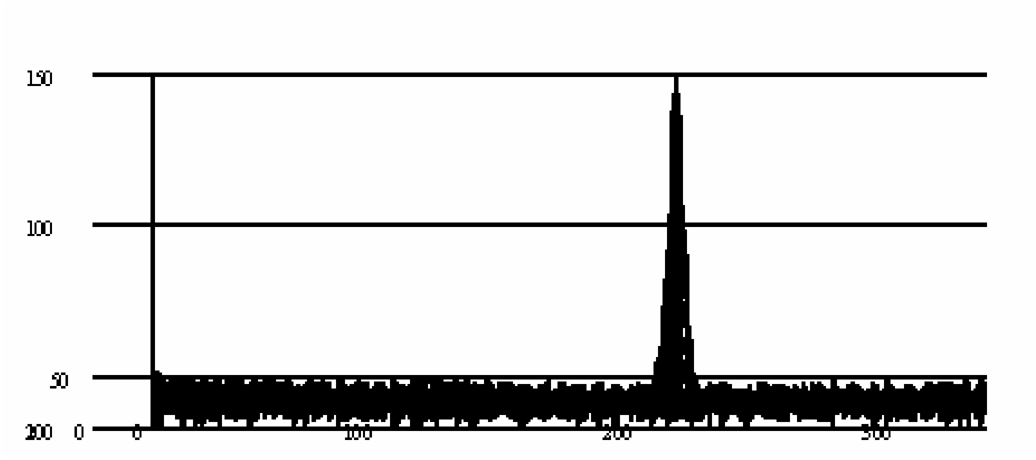

Figure 2. Plot of far field intensity of diffracted beam for 4 wedges written across the aperture. The grating period is 1024 electrodes or 1,843 µm. The deflection angle is 0.046^o.

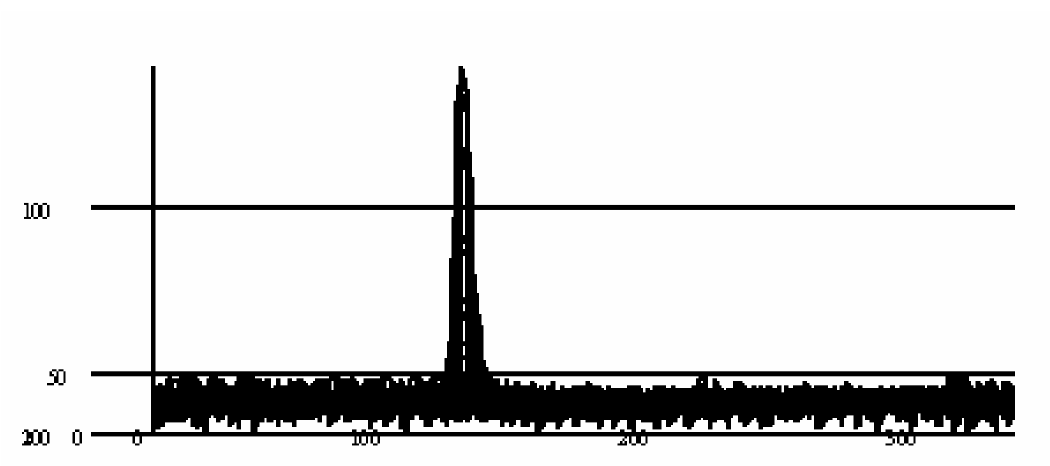

Figure 3**.** Plot of far field intensity of diffracted beam for 128 wedges written across the aperture. The grating period is 32 electrodes or 57.6 µm. The deflection angle is 1.5^o**.**

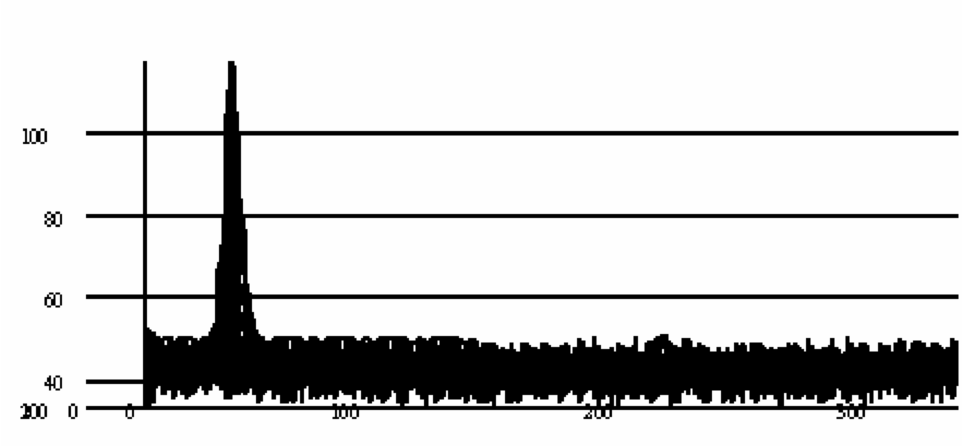

Figure 4. Plot of far field intensity of diffracted beam for 256 wedges written across the aperture. The grating period is 16 electrodes or 28.8 μm. The deflection angle is 3°.

The intensity patterns of Figures 2, 3, and 4 have no side lobes that are distinguishable from the noise floor. Based on previous measurements it is estimated that the next highest side-lobe is on the order of –11 dB from the peak where a dB is defined as 10 Log {power ratio}.

Using data obtained from the diffraction efficiency measurements, the relative diffraction efficiency of selected steer angles is plotted in Figure 5. Here the measured intensity is normalized to the light reflected from the device when it has not been addressed. There is also an additional 10% to 20 % insertion loss to these devices. That is, the specular reflection into the zero order is 80% to 90% depending on the device. The insertion loss is due to the imperfect dielectric mirror, index mismatches between the mirror and LC and diffraction from the underlying metal electrodes. Note that these figures are based on the incident light being linearly polarized at the proper orientation.

The efficiency decreases with increasing angle as expected. The fringing fields between electrodes have both positive and negative effects. The fringing fields smooth the phase profile[3]. This improves the fill factor, but it also creates what has been termed a flyback region at the reset. This flyback region is manifested by a phase reset that is not normal with respect to the backplane, but is instead sloped with an opposite blaze. The flyback region is a function of the aspect ratio. That is, the distance between the electrodes and the cover glass in proportion to the distance between the electrodes themselves controls the extent of the fringing fields as illustrated in Figure 6. For a given device thickness, the flyback region remains relatively constant. When the grating period is decreased to steer to larger angles the amount of a grating period that is steering light in the proper direction is proportionally smaller because the extent of the flyback region is unchanged for a given geometry. This results in a decrease in the efficiency.

This decrease in efficiency for large angles limits the maximum steer angle to less than the ideal maximum possible. For the device discussed here, the minimum useable grating period was 14 electrodes or 25.2 μm. This translated to a maximum steer angle of 3.4 degrees. The flyback region observed under a microscope was on the order of 4-6 electrodes(or 7.2-10.8 μm). This is too large a fraction of a period for any of the gratings that produce angles much beyond 3 degrees to exhibit high efficiency. So the aspect ratio between the distances from the electrodes on the backplane to the transparent conducting oxide on the coverglass with respect to the size of the period governs the efficiency of the steering angle.

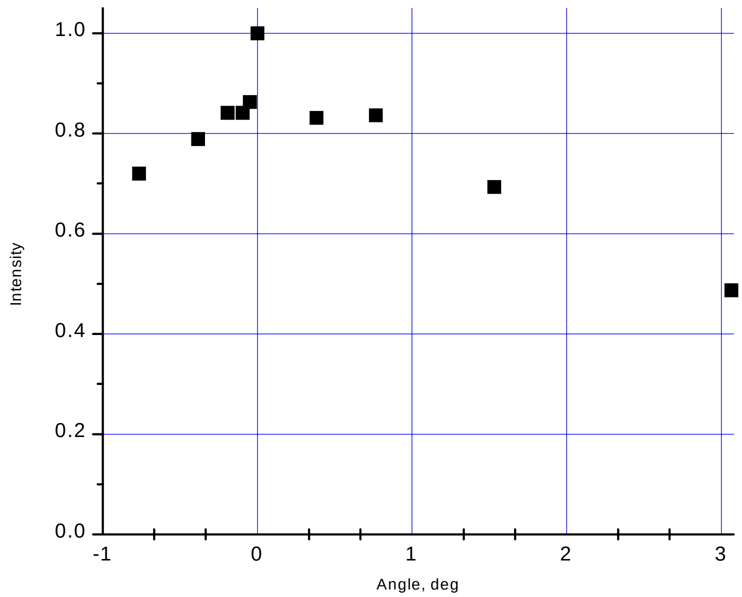

Figure 5. Measured diffraction efficiency relative to unsteered light.

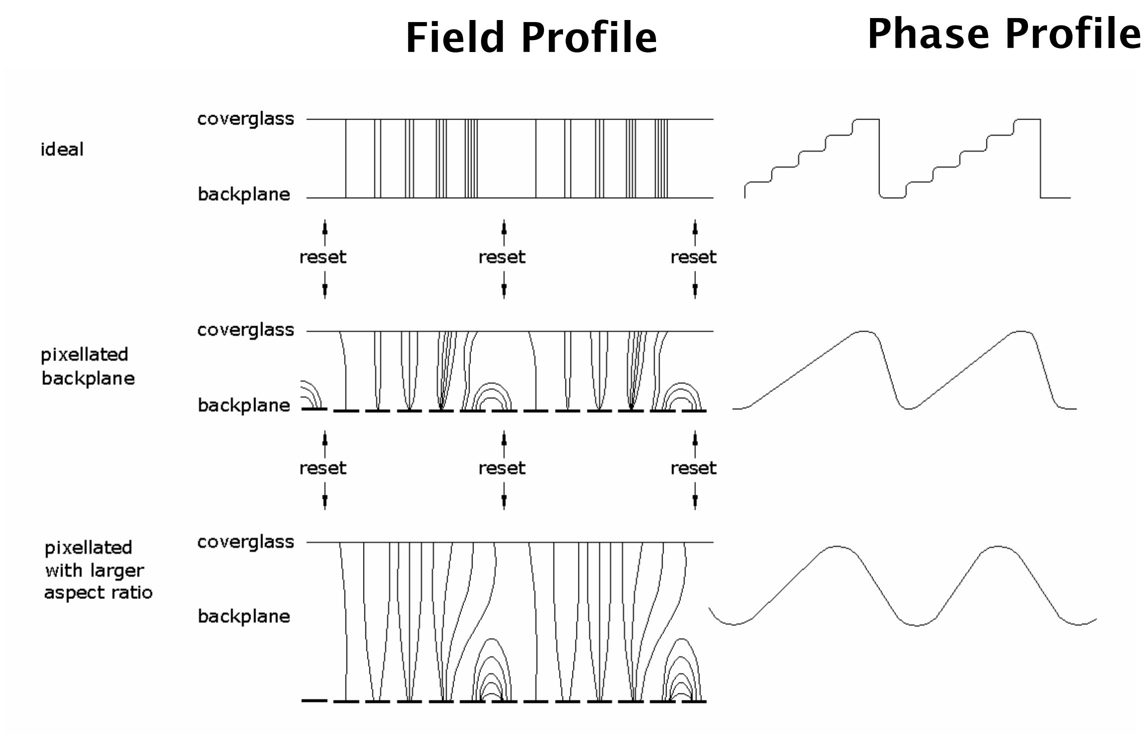

Figure 6. Illustration of fringing fields and their affect the Phase profile for a liquid crystal OPA.

3. OPTICAL PHASED ARRAY IMPROVEMENTS

Boulder Nonlinear Systems' approach to improving optical phased array technology is to improve the liquid crystal on silicon phase modulating component. Different liquid crystal materials are being examined and a new backplane has been developed.

3.1 Liquid crystal materials

The amount of voltage needed to switch a nematic liquid crystal modulator is a function of the specific material used, cell thickness and alignment. The 1x4096 backplane used to obtain the results above is limited to 5 V. It is possible to vary some parameters to achieve improved low voltage operation, but there is always a performance price to pay. For example, it takes less voltage to get an equivalent change in retardance from a thick cell than from a thin cell. The performance cost, however, is a slower response time

As discussed above, the aspect ratio has a profound effect on the ability to convert addressing resolution into steering capability. At the fly-back region where the 2π resets occur, the abrupt change in voltage causes a portion of the light to be deflected in the wrong direction, producing loss of energy in the main lobe. Reduction of the fly back region is possible using different types of LC. 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. Unlike the birefringence, other LC properties useful for reducing the fly back region, such as the threshold voltage of the material, produce voltage dependent effects and may not be usable due to backplane voltage limitations.

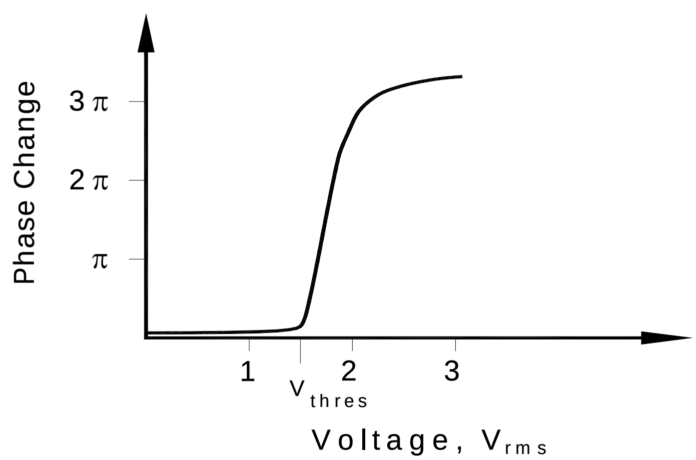

Figure 1. Response curve for a nematic parallel-aligned liquid crystal cell.

The nonlinear voltage response at threshold increases the sharpness of the modulator. At threshold as shown in Figure 1, a small change in voltage produces a relatively large change in phase modulation. This nonlinear response counteracts electrical smoothing and reduces the fly-back region. Fringing field effects are reduced by using high threshold materials with sharp response. For the 1x4096 OPA the threshold voltage techniques can not be used because the 5 V limit of the backplane forces the use of low threshold materials.

Switching speed is also voltage dependent. Most commonly used nematic LC materials exhibit a positive dielectric anisotropy. This means that they can be rapidly driven on (an optically thick state to an optically thin state). However, switching off requires time for the LC molecules to relax. Fast relaxation requires operation at voltage levels that are large compared to the threshold voltage. High-speed operation, therefore, is contrary to using sharper switching materials as described above for reducing the fly back region. One solution is to use dual frequency liquid crystal materials in which the dielectric anisotropy changes sign depending on the addressing frequency, allowing the molecules to be driven back to an optically thick state[4]. However dual frequency materials also require a higher voltage backplane.

3.2 Backplane Improvements

While using a high birefringence material can improve the modulator aspect ratio, a higher addressing voltage can also significantly enhance beam steering performance in terms of increased addressing angle and speed. BNS has developed a 1x12288 electrode backplane capable of addressing liquid crystal materials with voltages up to +- 26 V. Figure 8 shows the 1x4096 optical head and new 1x12288 electrode OPA.

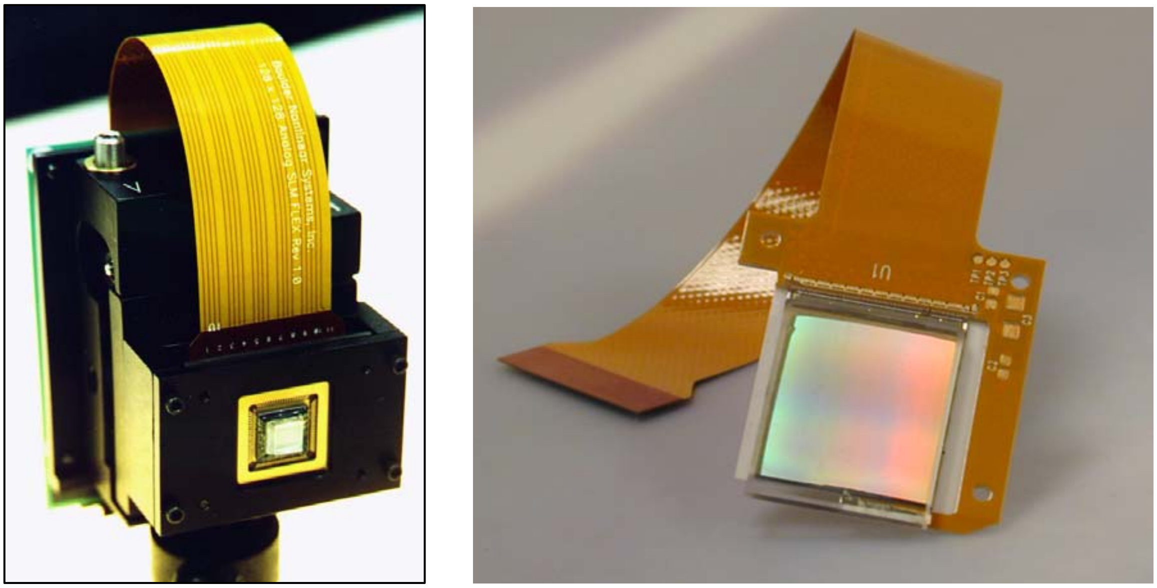

Figure 8. A 1 x 4096 OPA (left) and a 1 x 12288 OPA (right).

The torque on the liquid crystal molecules is linear with respect to applied field. The increased backplane voltage of the 1x12288 OPA should result in an increase in the maximum addressable angle by a factor of 2.5 over that achieved by a 1x4096 OPA for a given wavelength and assuming the same liquid crystal material. In addition, the higher voltage will allow use of dual frequency materials which have previously been used by BNS to demonstrate phase modulators with 1 kHz response times[5]. Moreover, this new 1x12288 backplane represents an increase in aperture over that of the 1x4096 from 6 mm x 7 mm to 19 mm x 19 mm

3.3 The importance of increasing the aperture

Angular deflection is a function of electrode spacing, but the ability to resolve angles is a function of the entire 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 constant, which is another way of defining the optical invariant. A larger active area provides more electrodes, increasing the number of addressable angles, and narrowing beam width, however, the active area of a LCoS device is restricted by the VLSI process. If the process uses one-to-one contact printing, then the VLSI die can be as large as a wafer. However, this type of lithography is used for larger geometry processes (2 to 5 μm) which limits device resolution. For sub-micron processes. The die size is limited by the reticule size of the pattern stepper to 2 cm x 2 cm or less. A further increase in aperture is possible with a Phased Array of Phased Arrays (PAPA) approach[6,7,8].

4. CONCLUSIONS

The present liquid crystal grating technology is limited by slow materials and non-ideal grating profiles. Recent advances in VLSI foundry processes have made possible high-resolution, light-efficient backplanes capable of driving electro-optic modulators with high-voltage signals. The high-voltage signals provide the excitation to achieve sub-millisecond response times with a wave of phase modulation. By combining high-speed phase modulators with high-voltage VLSI backplanes, compact optical phased arrays become available for applications that could benefit from optical beam steering without generating inertia.

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