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Phased Array of Phased Arrays for Free Space Optical Communications[1,2]

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Abstract - An aperture composed of multiple small apertures has several advantages over a large continuous aperture when practical issues are included in the analysis. For example, a single bullet can easily produce a catastrophic failure of the laser communication link if all the optical gain for the transmitter (or receiver) is derived from a single large-diameter telescope. In addition to battlefield concerns, other naturally-occurring problems for large diameter optical systems exist such as turbulence and scintillation. A distributed aperture, composed of small segments (smaller than the coherence length along the beam path), provides a powerful means for mitigating turbulence effects, particularly if the sub-apertures are dynamic steering elements with independent phase adjustments. This type of capability is available using a phased array of phased arrays (PAPA) architecture, which also provides non-mechanical steering, single and multi-spot beam shaping, and high-power beam combining. This paper discusses some of the attributes and potential problems associated with the PAPA approach.

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1. INTRODUCTION

High-bandwidth laser communication links between moving platforms in a dynamic environment is a very challenging problem because of various competing requirements. An agile scanning system is needed to quickly acquire and continuously track the intended moving terminal. Accurate high-speed scanning is easier to achieve if the components are small and lightweight, but large optical apertures provide the needed loop sensitivity for high-bandwidth transfers. The physical difficulty in rapidly moving and accurately positioning massive optical components is only one problem with using large-diameter optics. Some other problems are: 1) interference with other platform functions such as maintaining a low radar cross section; 2) lack of continuous window area to provide an adequate field of regard with enough optical gain; 3) existence of single-point failure modes from debris or physical damage; and 4) susceptibility to performance degradation from environmental effects such as turbulence and scintillation.

These types of problems can be mitigated by combining several small apertures. The small apertures allow easier placement and less interference within the platform, since less continuous window area is needed. With several distributed aperture segments, physical damage to part of the aperture does not produce a catastrophic failure of the system. The received signal from each aperture contributes to the optical gain of the system. If each aperture segment is smaller than the spatial coherence length of the received signal, the optical gain at each element is not diminished by turbulence or scintillation. With proper phasing, each segment contributes coherently to the overall gain of the system. That is, the gain is directly proportional to aperture area which increases linearly with the number of segments. Without proper phasing, the effective gain increases by the square root of the number of segments within the array. Therefore, the optical gain is improved by using multiple aperture segments when turbulence limits the signal's coherence length to less than the receiver's effective aperture. By properly phasing the aperture segments in low turbulence situations, the segmented aperture does not greatly penalize performance if the array's fill factor is kept high.

As previously mentioned, a small aperture is easier to rapidly steer, since it has less mass. However, the need to accurately position and stabilize several apertures to act as

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one pointing mechanism is not a trivial problem. If mechanical steering mechanisms are employed for the task, each aperture segment requires a two-dimensional mechanical movement with actuators and positional feedback. Therefore, the electro-mechanical hardware needed per aperture limits the packing density (fill factor of the aperture) and greatly complicates beam control, which nullifies most of the advantage.

To realize the advantages provided by a distributed aperture, a beam control scheme is needed that does not add significantly to the size, weight, power or complexity of the system. This paper describes an architecture that uses several liquid crystal on silicon (LCoS) optical phased arrays (OPAs) to provide two-dimensional non-mechanical beam steering (refer to Figure 1).

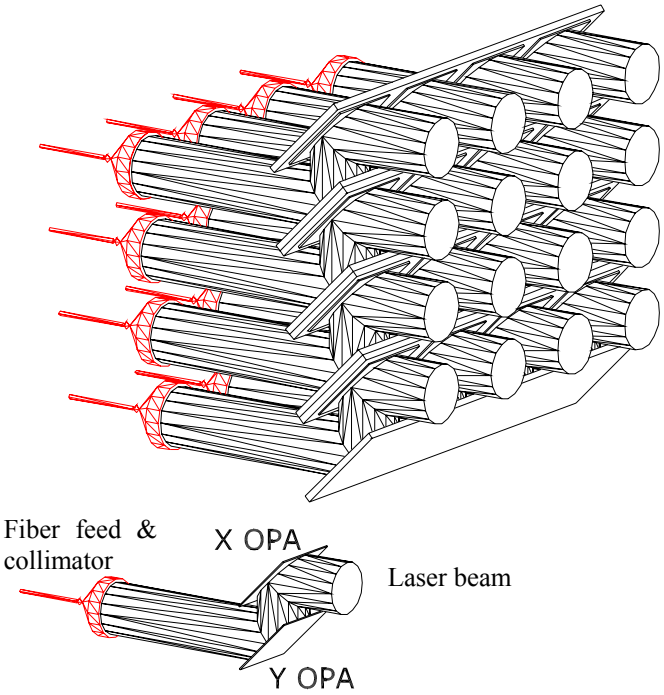


Figure 1. Conical-scanning phased array of phased arrays using liquid crystal on silicon optical phased arrays (LCoS OPAs).

The LCoS OPA technology offers several benefits for the PAPA architecture. The LCoS technology provides a means for manufacturing high-resolution backplanes capitalizing on 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, providing individual addressing of each pixel while minimizing interconnects to the OPA. By minimizing interconnects, the individual OPAs can be tightly packed to provide better aperture efficiency (better fill factor). Since each pixel is individually addressed, the phase modulation is not restricted to periodic phase ramps. This flexibility is useful, for example, for dynamically correcting phase distortion across the aperture. With the LCoS technology, each OPA requires less than a watt of electrical power and only adds a few grams of weight to the system. However, VLSI technology causes the OPA to operate in reflection. Reflection-mode operation complicates optical designs. The LCoS limitation imposed by reflection is addressed in this paper by presenting a novel PAPA architecture that allows in-line "transmissive" operation. That is, the beam fronts continue through the device in an on-axis direction.

"Transmissive" operation is achieved by coupling X and Y steering elements together to form a 2-D sub-aperture steerer for each beam. The PAPA resembles a set of Venetian blinds where the top of each louver contains the Y-steering elements and the corresponding X-steering elements are on the bottom of the next higher louver as shown in Figure 1. The on-axis propagation of the near-field beams allows compact implementation of the LCoS OPA technology for non-mechanical conical scanning in the PAPA architecture.

An OPA 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).

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

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[1]. If this technique is used to produce a spherical phase profile, then the device acts as a programmable lens (i.e. phase Fresnel lens) causing the beam to converge or diverge.

The phased-array approach eliminates mechanical inaccuracies such as overshoot and ringing from an underdamped control loop. As discussed above, the phase pattern written to the device accurately determines the steered angle with respect to the receiver's/transmitter's optical axis. These optical axes stay stationary with respect

to the platform. Therefore, there is no need for positional feedback from the steering mechanism to determine the beam's actual direction with respect to the platform. Thus, OPA beam control is expected to be less complicated and more reliable. Beam-control simplification is necessary for implementing the PAPA architecture, and it is beneficial for free space laser communications, where the transmit and receive apertures need to be rapidly and accurately aligned to complete the link.

2. CONSTRUCTION/OPERATION OF LCoS PAPA

A block diagram (side view) of a 3x3 "transmissive" PAPA unit using LCoS OPAs is shown in Figure 2. The design uses a fiber feed assembly that illuminates an array of 18 OPAs (nine Y and X steering elements). The fiber array consists of nine polarization-conserving, single-mode fibers designed for operation at 1.55 μm. At the end of each fiber is a lens which collimates the expanding beam emanating from the fiber core. These collimated beams illuminate the LCoS OPA array which steer the individual beams. An exit window covering the PAPA acts as a partial reflector. This partial reflector is used to sample small portions of the steered beams and reflect these samples back through the system into a lens where the light is focused onto an IR camera. The focal plane data detected by the camera provides a means for properly phasing the PAPA to act as a common aperture in the far field.

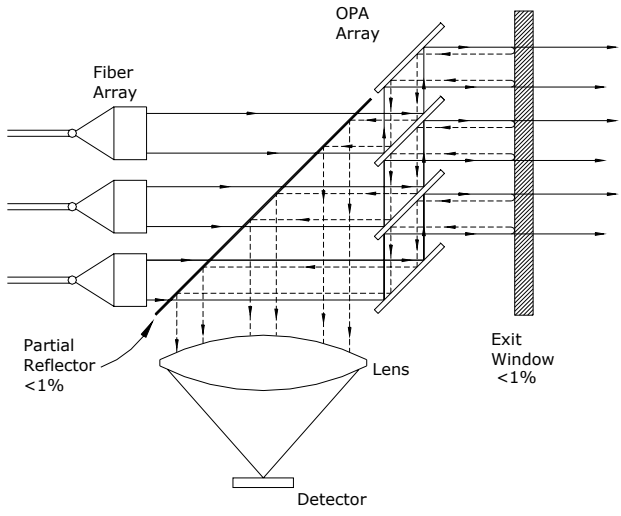


Figure 2. Side view of a 3x3 PAPA unit using a "transmissive" architecture.

The PAPA design shown in Figure 2 can be considered an adaptive optic system with the OPAs acting as segmented mirrors having two orthogonal axes of tilt combined with a piston movement. The tip and tilt comes from the X and Y steering stages and the piston action is derived from modulo-2π optical path differences that can be arbitrarily added, since each pixel and each OPA is individually addressed. This three-dimensional adjustment allows the system to act as a beam combiner forming one beam in the far field. That is, the output from several fiber amplifiers can be combined in the far field to form a high-power transmitter. For a receiver, the output from each segment can be spatially combined coherently or noncoherently depending on the environmental conditions.

For weak turbulence where the phase variations across the aperture are slowly varying, the different segments can be phased together to add coherently, maximizing the receiver's sensitivity. For this situation, the receiver's gain increases with aperture area. In strong turbulence, it may be very difficult to maintain proper phasing between segments. If the beam is not properly phased across the aperture, coherent combining by focusing the beam onto a detector causes communication drop outs (scintillation). To prevent spatial interference at the detector, active wavefront control requires detection and analysis of the distortion. This operation allows the system to determine the proper corrective action, but the detection and analysis requires time. This processing task slows the closed-loop response of the system to a fraction of the response time of the adaptive optics. Millisecond response times are of little help in ultra-high data rate systems unless communications are suspended while the adaptive optic corrections are being made. If the phase distortion is very dynamic, the response rate of the adaptive optic system may be insufficient to correct the disturbance. With a segmented aperture, however, each segment still substantially contributes to the gain of the receiver if the segment is smaller than the spatial coherence length of the signal. It has been shown that combining these multiple inputs noncoherently increases the signal-to-noise ratio (SNR) of the receiver and provides more gain than a single large aperture when the effective aperture is smaller than the receiver's aperture due to turbulence[2,3]. When noncoherently combining the segments, the SNR improvement is approximately equal to the square root of n, where n is the number of elements in the array.

To fabricate the 3x3 PAPA shown in Figure 2, six X and Y steering strips need to be stacked together to form the Venetian blind structure. Each OPA provides 1-D steering for a row of fiber feeds. To provide 2-D steering, separate X-steering and Y-steering strips are necessary, which requires different electrode layouts for the OPAs. These combined steering strips need to be thin to allow in-plane stacking with each strip tilted at 45° to the axis of propagation.

The LCoS technology provides a tremendous mechanical advantage for this configuration, since the VLSI backplane is 0.5 millimeters and the coverglass is ~1 millimeter thick. Therefore, a louver assembly that contains an X-steering stage on the bottom and Y-steering stage on top is approximately 3 millimeters thick. A thin assembly reduces occlusion by adjacent strips allowing a larger fill factor for the array.

Figures 3 and 4 are from a three-dimensional Solid Works model of a 3x3 PAPA assembly using existing LCoS OPAs that have a 6 mm x 7.4 mm active area. Figure 3 shows how the louvers consisting of both X and Y steering strips need to be configured to maximize packing density. Figure 4 shows the resulting PAPA footprint based on the active area available from the assembly. The OPAs active-area covers 59% of the total aperture. If there are no other losses, then this fill factor directly represents the PAPA's aperture efficiency. However, other parameters (such as OPA insertion loss) affect aperture efficiency, also.

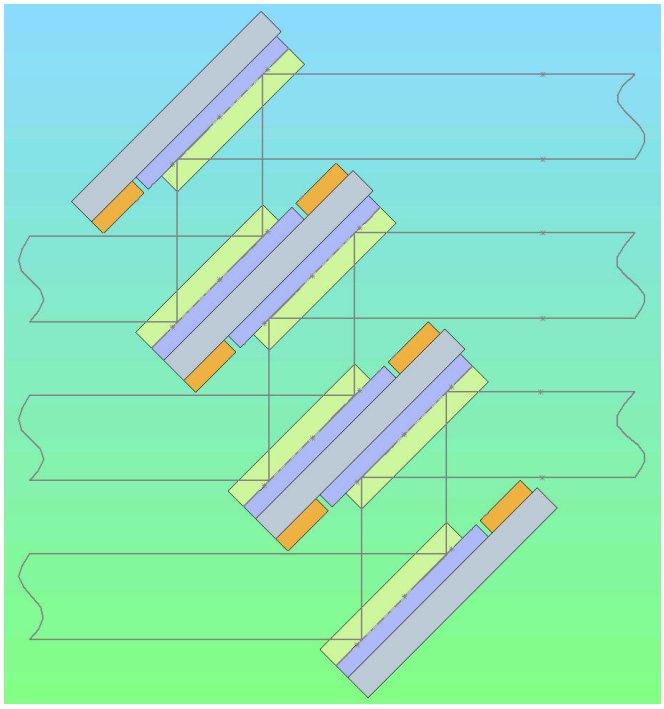


Figure 3. Mechanical model of PAPA stack using existing LCoS OPAs.

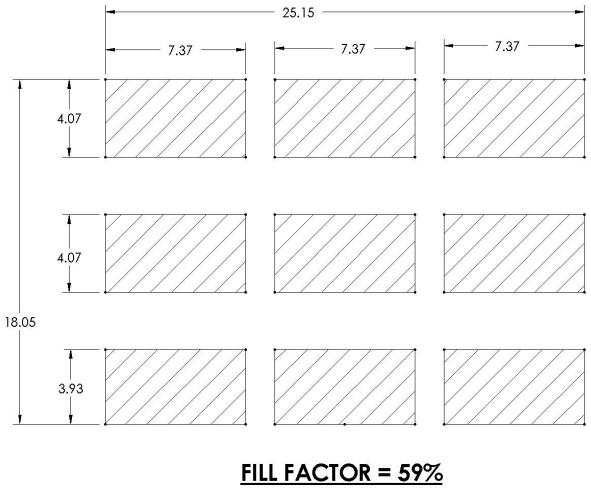


Figure 4. Active-area footprint of the PAPA stack shown in Figure 3.

To fabricate the louvers shown in Figure 3, one coverglass (yellow) is used with a row of OPA die (blue) which are cut from the wafer as one piece. The coverglass and die are gapped as a single cell and then filled with liquid crystal. By fabricating the steering strip as a single piece, the phase variation between die is kept to a fraction of a wavelength. After filling, the LCoS assembly is wire bonded to a flex circuit (orange) which provides the electrical feed for individually addressing the OPAs in the strip (refer to Figure 5).

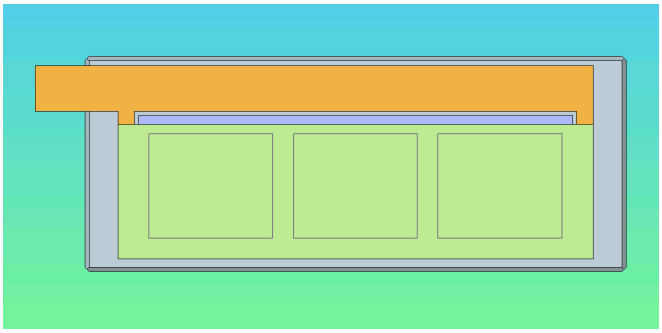


Figure 5. An X-steering strip with three OPA's and flex circuit mounted on a louver support.

By using rows of die cut directly from the wafer, the OPA spacing within the louver can be very tight (i.e. a few hundred microns). Unfortunately, the louver-to-louver spacing is more difficult to minimize, since area is needed for the flex circuit and to accommodate the thickness of the louver stacks shown in Figure 3. Since the louvers need to operate off-axis at 45 degrees, the active area of each OPA is reduced by a factor of 0.707 in the vertical direction, which has a large effect on fill factor when combined with the other factors that affect louver spacing. Even with these problems, the packing density of the PAPA is not limited by the OPA assembly. The actual restriction is the physical dimensions needed in the collimator assembly to provide tip/tilt adjustment which force the louvers to be separated by more distance than that required by the OPA assembly. When the constraints imposed by the fiber feed assembly are included in the mechanical model of the system, the array fill factor is reduced to approximately 50% (compare Figures 4 and 6).

The collimator produces a 4 mm diameter beam from the diverging beam emanating from the 8-micron fiber core. To collimate the light, an aspherical lens with a focal length of 18 mm is used. The outer diameter (OD) of the collimator assembly is approximately 8 mm. To accommodate the OD of the collimator housing and provide some adjustment for alignment, the minimum beam-to-beam spacing is increased to approximately 9 mm, producing the OPA active area footprint shown in Figure 6.

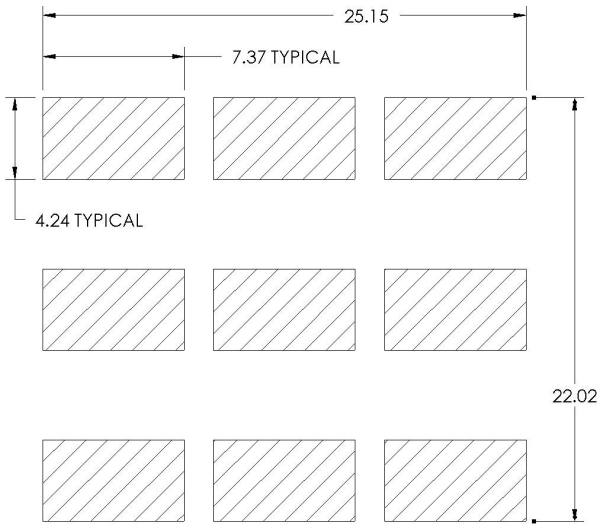


Figure 6. OPA active-area footprint of the PAPA stack after being modified to operate with the fiber array.

From the collimator's optical configuration, it is possible to calculate the PAPA's beam divergence and field-of-view angle. A Gaussian beam's angular spread, $\Delta\theta_t$, is equal to $\lambda/\pi\omega_o$ where ω_o is the beam's1/e radius at its waist. This beam width defines an envelope function in the far field for the PAPA. As beamlets from the different OPAs are coherently combined, the beam pattern defined by the envelope function separates into multiple beams (a main lobe and sidelobes). By properly combining more beams in the far field, the width of the different lobes become narrow, directing more energy into smaller angles, but the relative amplitudes of the different lobes, as defined by the envelope function, remain the same due to the diffraction caused by the thinned array. As a receiver, the field-of-view angle, $\Delta\theta_r$, defines the cone angle of light that is coupled into the fiber. This angle is directly related to the fiber core's diameter divided by the focal length of the collimator's lens. For the fiber feed assembly, the field-of-view angle is approximately 0.4 milliradians. In a symmetric design, its safe to rely on reciprocity and assume that $\Delta\theta_r = \Delta\theta_t$. Therefore, the divergence angle for the fiber assembly is 0.4 milliradians, also. As discussed above, the receiver's gain is increased by coherently or noncoherently combining the signals collected by the fiber array. In either case, the basic effect is that the receiver's aperture becomes a faster lens as more array elements are used to collect signal.

It is common practice in free space optical communications to defocus the telescope to increase beam divergence and widen the field-of-view angle to aid transmitter and receiver alignment[4]. The dynamics of the PAPA architecture offer some additional benefits in this regard. It has the ability to dynamically add distortion to widen the beam or create several beams (multispots) and then scan these "distorted" profiles to cover more area. The real benefit comes in the ability to systematically remove the distortion as the link becomes established. This function allows the system to quickly acquire a target terminal and maintain a link while the aperture reconfigures to maximize link margin for higher data transfers. This type of capability is not easily achieved using conventional scanning systems making link acquisition between moving platforms more difficult.

As shown in Figures 2 and 3, the LCoS OPAs are to be operated off-normal at 45°. The effect that the 45° angle of incidence has on the operation of the LCoS OPA is being investigated[5]. As part of this investigation, a Mach–Zehnder interferometer setup is used to measure phase-modulation depth as a function of angle of operation. By measuring fringe shifts when the device is operated on-axis and at 45° off normal, the results show that the modulation depth decreased by approximately 8.5%, which is slightly less than the theoretically predicted 9%. But, the two values are within measurement error. This data alleviates some concern as to whether the transmissive PAPA architecture as shown in Figure 2 is feasible.

3. LCoS PAPA Limitations/Improvements

The transient behavior of liquid crystal (LC) OPAs has become an area of concern for laser communication applications. When an OPA switches between two beam angles, several phase shifters across the array change to produce the new phase pattern. This transition produces a drop in intensity in the main lobe as the pattern switches. Some of the light is scattered over the field of regard of the OPA, but a significant amount is not steered producing a temporary zeroth-order sidelobe (i.e. on-axis component). The intensity drop in the main lobe is approximately 50% for small angles[6].

An OPA's transient response is not specifically related to the behavior of the liquid crystal modulator. The liquid crystal provides an analog change in path length as would a mechanical piston. With analog active-matrix backplanes that have addressing rates that exceed the response time of the LC, the phase shift at each pixel is fully controllable in an analog fashion. Therefore, the transient response is not due to uncontrollable changes in the liquid crystal modulator. Actually, it comes from limited modulation depth where periodic modulo-2π phase resets are used to form a pseudo-continuous phase slope. Because of limited modulation depth, the phase slope is normally adjusted by changing the spatial period of the phase ramps which requires most of the pixels to simultaneously change in phase (some increasing while others decrease). For a high-data-rate laser communication link between moving platforms, the beam needs to continuously scan through small angles without dropping significantly in intensity. Fortunately, the LC modulator can have more than 2π of phase and all the pixels in the array are individually addressed making it unnecessary to change all the pixels at

once. Under these assumptions, various methods for reducing the intensity variation as the beam scans in angle are being investigated.

One method, as suggested by Stigwall[6], uses a number of sub-patterns within the OPA array. The beam's location is shifted by changing the sub-patterns one at a time. With this technique, most of the pattern across the array remains in a static condition and only a small portion of the beam is lost due to transient switching. Unfortunately, this technique reduces the scan rate.

Another technique uses the PAPA architecture to form two (or more) beam lobes in the far field (e.g. two minimally resolvable beams). One lobe is on target and the other lobe leads the target. As the target platform moves from one beam into the other, the off-target beam (now lagging the target) is repositioned as the leading lobe by writing new patterns to only the PAPA segments that are controlling the lagging beam. This "inch-worm" tracking technique prevents dropouts due to pattern switching, but it reduces the power at the receiver also.

A third technique is to use modulators with more than 2π of phase modulation and adjust the phase slope to provide continuous small angle tracking. As discussed above, it is possible to perform slope adjustments in a continuous fashion with an analog backplane. However, some profile distortion occurs because the slope change at the resets is not exactly 2π. This distortion reduces the directivity of the main lobe, but a small loss in system sensitivity to maintain the link during data transfers is probably acceptable. Between data transfers or in sub-pattern stages, the distortion in the phase profile is removed to improve beam quality.

Array fill factor is currently limited by the fiber feed array. However, the additional area needed to accommodate fiber alignment becomes less of a factor as beam diameter grows. Therefore, the best method for greatly improving array fill factor is to develop OPA's with larger active areas. A new LCoS OPA, currently in development, is planned to have an active area of approximately 2 cm x 2 cm. This OPA development increases the effective aperture by nearly an order of magnitude over the current OPAs. For comparing fill-factor improvement with respect to the design shown in Figures 3 and 4, a 3x3 PAPA stack using the larger arrays and its associated active-area footprint are shown in Figures 7 and 8, respectively. The larger OPAs increase the array fill factor from 59% to 87%. A larger fill factor reduces sidelobe energy when transmitting and improves aperture efficiency when receiving.

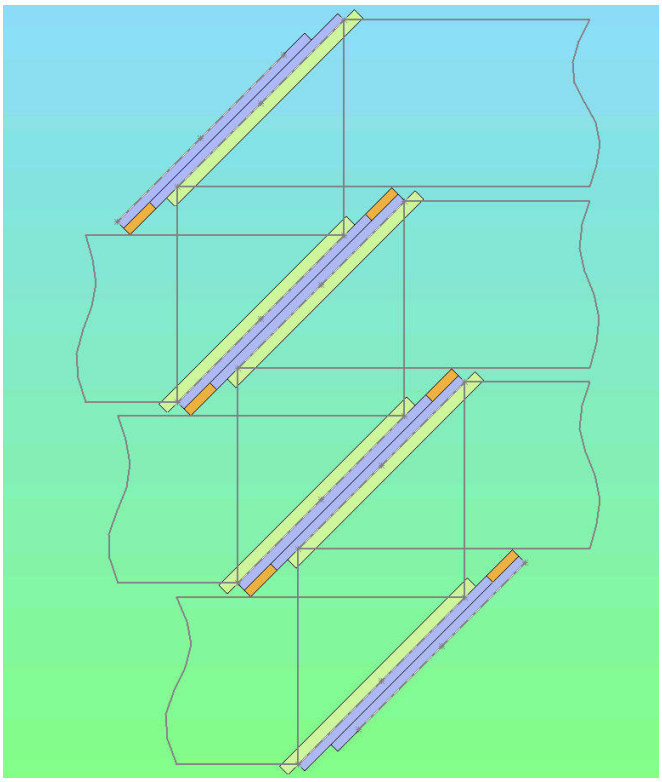


Figure 7. Mechanical model of PAPA stack using LCoS OPAs with approximately 2 cm x 2 cm active areas.

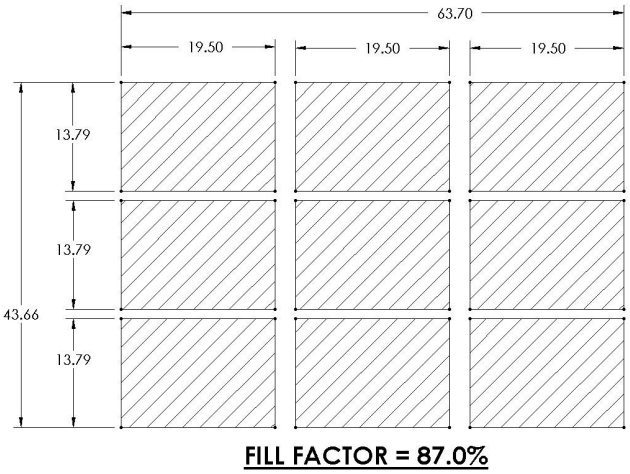


Figure 8. Active-area footprint of the PAPA stack shown in Figure 7.

In addition to increasing OPA's active area, the new OPA development increases the operating voltage from 5 to 13.2 volts. The voltage increase is essential for improving LC modulator response. With the current 5-volt device, the response time operating at 1.55 microns is approximately 35 milliseconds. This response time is greatly improved if the LCoS OPA uses dual-frequency nematic liquid crystal to reduce the modulator relaxation time. However, a dual-frequency LC modulator requires higher voltages. Also, it requires a more complicated drive scheme. These issues are resolvable as demonstrated by Figure 9 where the image is

from a high-voltage 256x256 spatial light modulator (SLM) filled with dual-frequency liquid crystal and operating at 1 kHz. When operated at 670nm, the SLM produces sub-millisecond, 2π phase modulation allowing the device's frame rate to exceed 1 kHz.

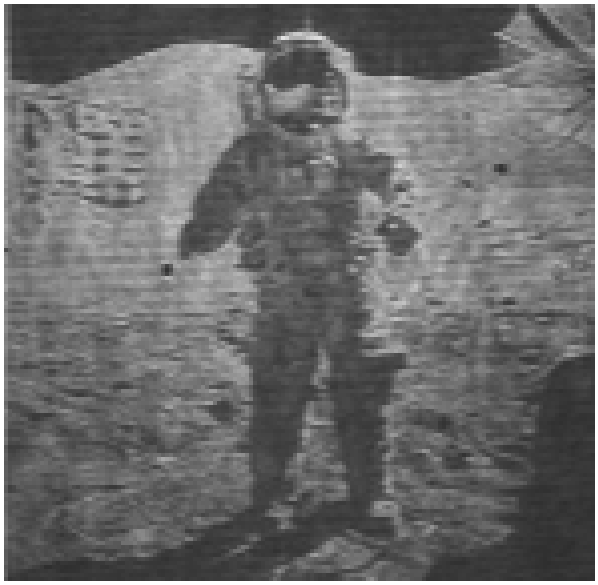


Figure 9. An image from a high-voltage 256x256 LCoS spatial light modulator using dual-frequency nematic liquid crystal and operating at 1 kHz.

Another limitation with the LCoS PAPA is its field of regard (FOR). This limitation comes from the OPA which performs best as a fine-angle steerer. The current OPA is capable of steering ±3° at 1.55 microns limited by efficiency (not backplane resolution). For angles beyond 3 degrees, the efficiency drops to less than 50%. The new OPA development is expected to increase the steer angle to ±10°. This improvement is to come mostly from the higher-voltage operation, which allows the LC modulator to be much thinner[7]. To increase the FOR further, there are at least two possibilities. One is to mate the system with coarse-angle steerers such as a digital beam deflector that cascades static wide-angle deflectors through a series of switches or a holographic optical element (HOE) that translates fine steer angles into wider angles. A second possibility is to develop the array as a spherical, cylindrical or conformal assembly. One row of a spherical assembly that provides full coverage over a 90° FOR is shown in Figure 10. This assembly is based on the steering capability of the new OPA development (±10°). The best technique depends on how current developments progress.

4. CONCLUSIONS

LCoS PAPA offers several advantages for free space laser communications between moving platforms such as the ability to change the beam profile to aid acquisition and tracking. However, there is a price to pay for this benefit. Several OPA limitations exist. The largest problem, limited field of regard, is being addressed through a variety of developments. If this issue is resolved in a reasonable fashion, the PAPA technology offers considerable potential for future laser communication applications.

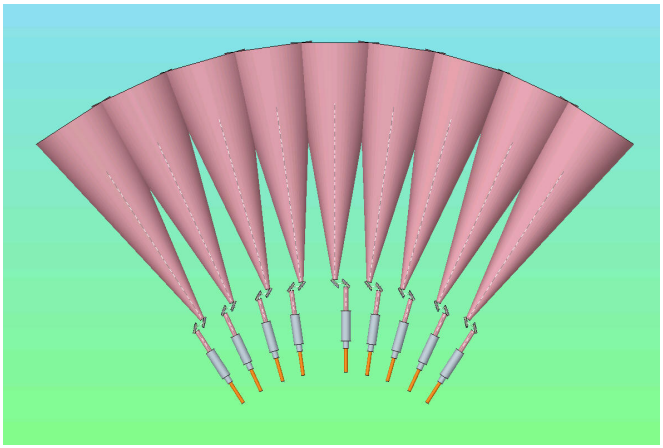


Figure 10. Spherical PAPA assembly for providing a 90° field of regard.

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