Beam combining using a Phased Array of Phased Arrays (PAPA)[1]

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Abstract—Mobile free space optical (MFSO) networks introduce new challenges for laser communication terminals. Network capabilities, such as packet routing where different information packets are sent to different locations, require switchable links. Also, switchable links are needed to route an information packet through different channels to the same destination. For MFSO networks, the ability to route information through different channels greatly aids reliability because any one channel can be disrupted by weather conditions. To have the ability to route around obstructions, the mobile platforms have to act as hubs, communicating with a number of remote terminals. Since these terminals are all in motion, the challenge is to acquire and track multiple terminals from a single platform without requiring a full duplication of hardware for each link. To reduce hardware duplication, a significant improvement in scanning flexibility is needed. Improvement is being pursued through the development of non-mechanical optical phased arrays (OPAs). This paper discusses the ability to combine several OPAs to generate and independently control one or more beams from a common aperture.

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1. Introduction

For mobile laser communications, gimbals are generally the technology of choice for scanning a large effective aperture over a wide field of regard. When the application is one-to-one communications between two terminals, the performance attributes provided by gimbals allow longer-range operation, giving it a definite advantage over other technologies. Then again, the operation of future MFSO networks include terminal capabilities that are beyond those normally associated with one-to-one links. One highly desirable capability is multi-access communications where one terminal communicates with several other terminals. This type of operation is important for any terminal that is acting as a hub for other terminals. Also, multi-access operation is desirable for dynamic routing schemes where several terminals in the field maintain multiple links to route around obstructions. For multi-access operation, the inability of a mechanical system to move simultaneously in different directions is a definite limitation. To mechanically acquire and track several spatially separated terminals, multiple gimbaled apertures are needed, which may be impractical for platforms with limited power and space such as small unmanned vehicles or satellites.

Because the link configuration may constantly vary with regard to the number, direction and range of the links maintained by a multi-access terminal, it is desirable for the scanning system to use the full aperture to form beams as needed and independently control the angle and directivity of each beam. This capability maximizes efficiency for any combination of links. Also, acquisition and tracking is enhanced, if the scanning system generates beacons (beams with low directivity) to locate and track terminals. Then, beacons are converted to high-speed links by increasing beam directivity during data transfers. To provide this type of beam control, unconventional scanning techniques are needed.

Perhaps the most versatile possibility is full holographic beam formation where the phase profile over the full aperture is manipulated to realize any beam configuration. However, a holographic beam steerer is not a practical option. To provide this type of beam control, the phase profile needs to be controlled in two dimensions using element spacings of a half wavelength. For a 10-centimeter aperture, 18 Gigabytes per steer angle are needed to control the phase profile, assuming 8-bits of control for each phase element. For millisecond operation, a data rate of 18,000 Gigabytes per second is needed to control the aperture. Obviously, these data rates are beyond the bandwidth of current technology. However, a bigger problem is calculating the appropriate phase patterns in real time. Obviously, a compromise technique is needed.

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One compromise is to use an array of optical phased arrays (OPAs) to act as a common aperture by properly phasing the OPAs. Such a system is called a phased array of phased arrays (PAPA) architecture[1]. Each OPA is capable of changing the phase profile of a beam in one-dimension. By using two 1-D OPAs, two-dimensional (azimuth and elevation) beam steering is possible. Also, the OPAs are capable of adding arbitrary phase shifts to the linear phase profiles used to steer the beam. Therefore, a pair of OPAs is capable of providing tip, tilt and piston control.

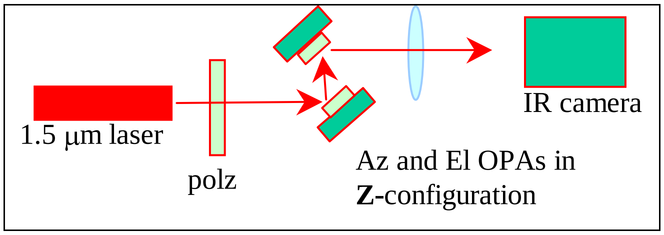


Figure 1. Two-dimensional steering using a pair of OPAs in a periscope (Z) configuration.

With an array of OPA pairs (as shown in Figure 2), the combination is capable of controlling multiple beams and coherently combining the beams to act as one beam. The beams from each subaperture are combined in the far field by properly phasing the array. If the effective aperture for one OPA pair is 2cm x 2cm, then an array of twenty-five pairs are needed to form a 10-centimeter PAPA aperture. To control the PAPA, 0.5 Megabytes is needed per steering pattern versus the 18 Gigabytes needed for a holographic beam former.

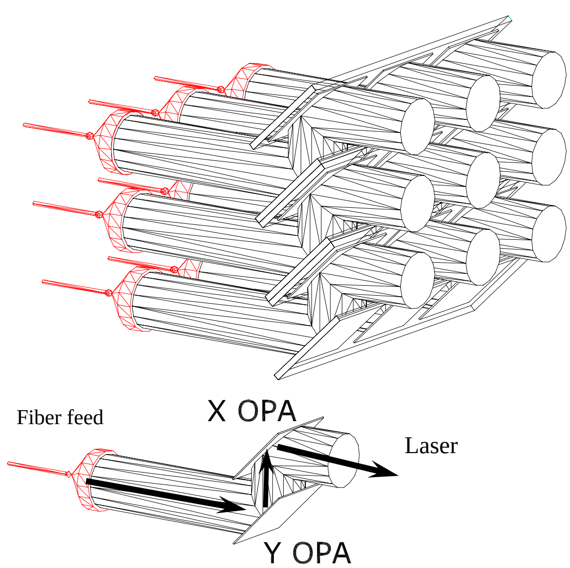


Figure 2. Conical-scanning PAPA using (LCoS OPAs).

In previous conference papers, the operation and performance of liquid crystal on silicon (LCoS) OPA technology was presented[2] and the ability to perform two-dimensional steering using LCoS OPA pairs arranged in a periscope configuration (as shown in Figure 1) was analyzed and demonstrated[3]. Also, the design and fabrication of a 3x3 PAPA aperture using LCoS OPAs was discussed[4]. The LCoS PAPA work was an aggressive 10-month development effort. This paper discusses the results of this short-term effort. The PAPA system performed well, demonstrating that individual beams can be non-mechanically steered and phased to form a coherent beam in the far field. However, the demonstration effort uncovered some problem areas, but all of the problems appear to be correctable by advancing proven techniques.

2. PAPA System Operation

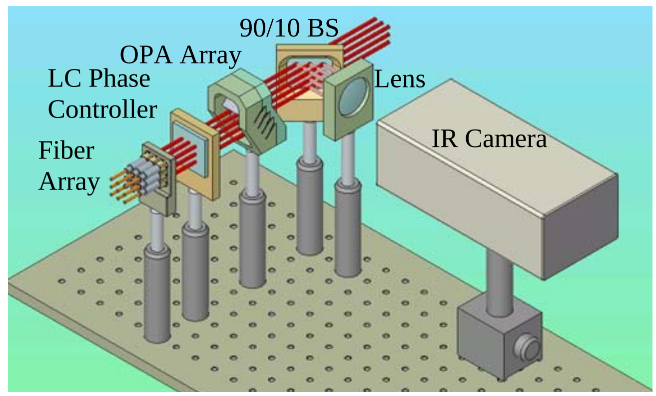


Figure 3. Model of 3x3 PAPA demonstration system.

Figure 3 is a representative drawing of the 3x3 PAPA demonstration hardware. As shown in the drawing, nine fiber sources, mounted in their mechanical holder, illuminate the PAPA array. First, the light from these sources travels through a 3x3 array of nematic LC retarders, which applies a relative phase shift to each of the 9 light sources. Then, the light from each fiber travels through the OPA array, where it is modulated with a linear phase ramp to steer the beam.

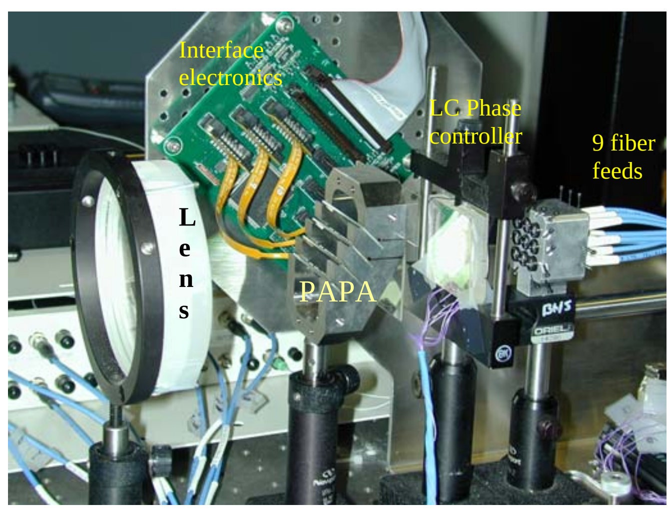


Figure 4. 3x3 PAPA demonstration hardware.

The above drawing shows the modulated beams passing through a sampling window, where a small amount of the light is redirected through a lens to the IR camera to provide feedback for controlling far-field beam pattern. In the actual demonstration system (shown in Figure 4), the sampling window was not used, since it was easier to use one IR camera than to provide separate far-field detectors for feedback and beam profile analysis.

For the PAPA concept to be successful, the individual subapertures have to operate as a common aperture. Therefore, wavefront error from the PAPA device has to be sensed, and the phase of the individual elements need to be adjusted to correct any error. With proper phasing, the individual beams coherently combine, forming the far field pattern shown in Figure 5. The combined beam is steered by applying a linear phase profile to the individual OPAs. To achieve this functionality, the PAPA controller has to sense and analyze the wavefront, apply correcting phase shifts to the nine beams and write appropriate phase profiles simultaneously to the OPAs.

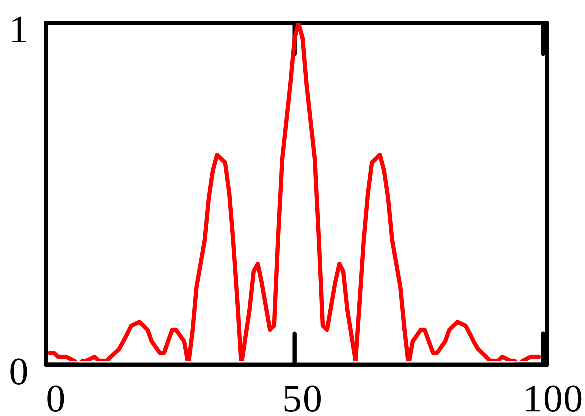


Figure 5. Expected far-field beam profile of a 3x3 array of 4-mm beams with 8.89 mm center-to-center spacing.

A LabView program is used to determine the appropriate phase profiles for controlling the PAPA aperture. The interface screen for this program is shown in Figure 6. This program allows the operator to adjust the phase profile at each OPA in the array (i.e. apply a unique phase profile to each OPA). One period of the phase pattern is first generated using the top left panel. This pattern is then repeated across a particular OPA modified by a phase correction (middle left panel). The resulting far-field beam pattern detected by an IR camera is displayed as an image (top right), profile plot of a single scan line (middle right) and 3-D intensity plot of the image (bottom right). This feedback is used to optimize the far field pattern. Optimization is aided by the bottom middle panel, which allows the user to add a phase shift to each beam. After calibrating a steer angle, the phase profiles being applied to the OPAs are saved as a single data file.

The data files representing calibrated steer angles are converted into scan patterns using a second LabView program. The interface screen for this program is shown in Figure 7. The upper left panel allows the user to add angle patterns to a sequence instruction file. By executing the sequence file, scan patterns are generated by the PAPA system. As with the calibration program, far field data detected by an IR camera provides feedback to the user (i.e. image - top right, profile plot of a single scan line – middle and 3-D intensity plot of the image - bottom right). In this program, the feedback is used to automatically calculate a Strehl ratio for the central peak as phase shifts are serially applied to the individual beams to maximize this Strehl ratio. The phase correction is needed to compensate for thermal drift in the fiber feeds. By maximizing the Strehl ratio, the beams coherently combine in the far field (refer to the profile plot). Due to video transfer rates and slow data processing, the simple hill-climbing algorithm being employed does not converge quickly. Therefore, the beams do not coherently combine if there is significant thermal drift.

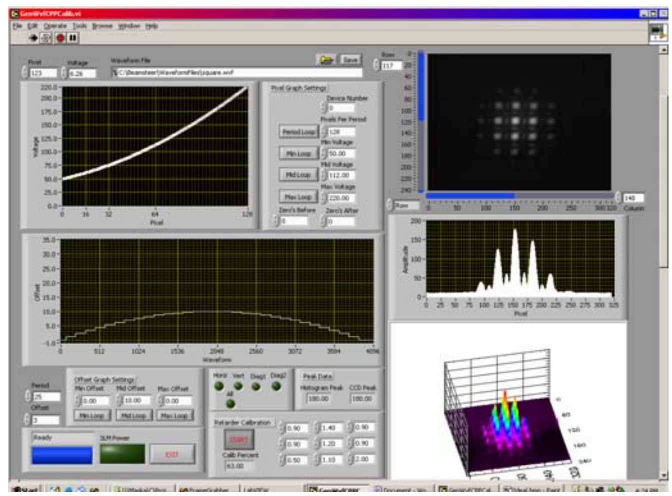


Figure 6. LabView interface screen for calibrating the PAPA system.

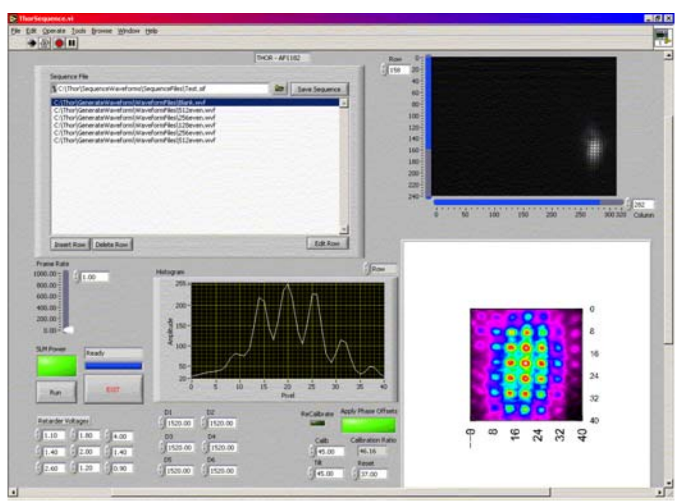
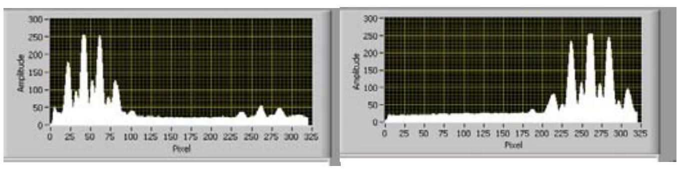


Figure 7. LabView interface screen for operating the PAPA system in scan mode.

3. Agile Far-field Beam Combining

After integration of the system, small-angle steering was investigated. The two far-field beam profiles shown in

Figure 8 demonstrated the ability of the PAPA array to steer and phase nine beams. The two profiles, from a steered and unsteered beam, strongly resemble the predicted pattern shown in Figure 5. However, there are a few minor problems with these results. One problem is that the beam energy skews to one side as the beam steers. Writing the same phase pattern to all the OPAs, which is incorrect since there is a gap between OPAs, causes this skew. Because of the gaps, the nine input beams are not properly phased to account for discontinuities in the phase ramps steering the beam. Therefore, some of the energy in the main lobe is redistributed to the side lobes as the beam steers off axis. By adding an offset to the phase profiles written to each OPA, the skew in the far-field patterns is reduced. This type of adjustment is added when the aperture is calibrated for a particular angle. A second problem is that the magnification causes larger angles to be out of the feedback cameras field of view.



512 ramp – 0.1° Unsteered - 0°

Figure 8. Steered and unsteered beam profiles and the expected profile based on modeling.

Fortunately, this magnification is not needed for operation, but it gives a better (more resolved) picture of the beam profile, allowing more direct comparison to the predicted profile. To achieve operation over larger angles, a set of small lenses in front of the camera were removed, and the camera was placed in the focal plane of the large lens shown in Figure 9. Without the smaller lenses, the output from the PAPA system was directly focused onto the camera by a 4-inch diameter lens with a focal length of 1300 mm (refer to Figure 9). The wider field of view reduced the optical magnification by a factor of three.

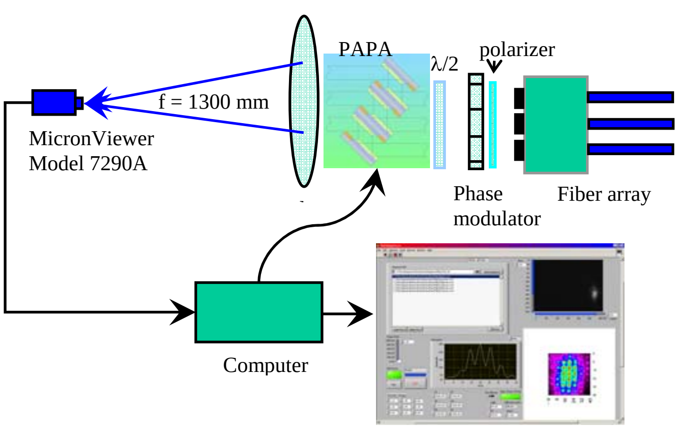
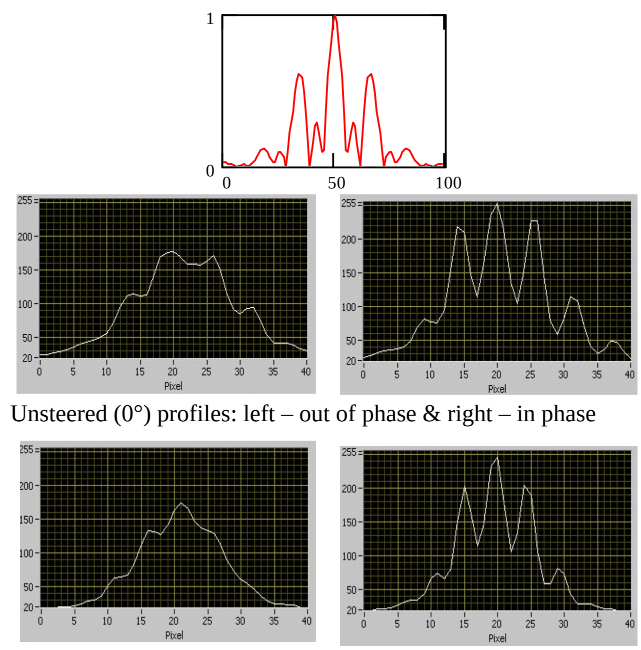


Figure 9. Operational schematic for wider-angle steering demonstrations.

The camera data was used by the adaptive-optics routine to determine the spatial coherence of the beam by calculating the Strehl ratio of the central order. This ratio was continuously calculated as the LC phase shifter was adjusted. A hill-climbing algorithm was used to maximize the Strehl ratio, which insures that the beams are coherently combining. As part of the user interface, the software displays the captured far-field pattern as a 2-D image, a 3-D graph and a line profile, and it stores the raw data to file when requested by the user.

Figure 10 is a collection of beam profiles showing the difference between incoherent summation (left profiles) and coherent combining (right profiles) in the far-field. The far-field pattern varies depending on the phase relationship of each beam. The overall envelope of the pattern corresponds to the spot size of the individual input beams. Within this envelope, the pattern will have peaks and valleys that shift depending on the different phase contributions from each beam. If there is little correlation in phase between the beams, then the far-field pattern is mostly smeared out over the spot envelope. Proper phasing forms a beam that resembles the predicted pattern with a high Strehl ratio based on the energy confined to the central peak. As predicted, this ratio approaches 0.5 for a coherent beam.

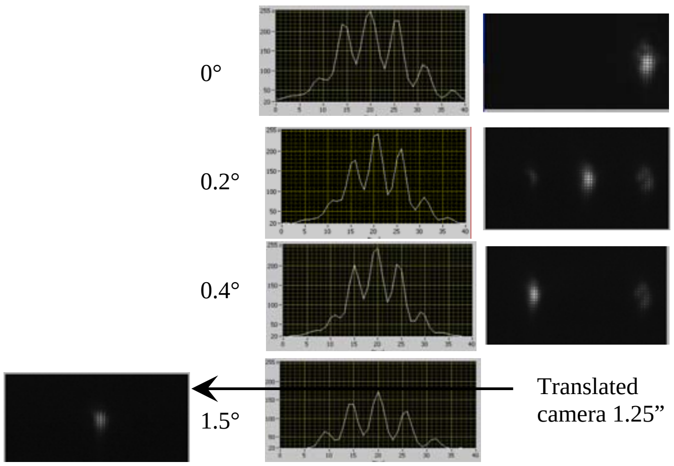


Unsteered (0°) profiles: left – out of phase & right – in phase

Steered (~ 0.4°) profiles: left – out of phase & right – in phase

Figure 10. Unsteered and steered far-field paterns with incoherent (left) and coherent (right) beam combining.

Figure 11 is a collection of beam patterns for a variety of steer angles along with a chart showing efficiency versus angle. A gamma correction of 0.7 is applied to the intensity values before the peak efficiencies are calculated. To capture the widest angle, the camera had to be laterally translated over an inch. Therefore, the spot locations within the figure are representative of their actual angular displacement with respect to each other.



Angle	Peak Intensity (Normalized)	Peak Efficiency (Normalized)
0°	1.0	0 dB
0.2°	0.91	-0.6 dB
0.4°	0.91	-0.6 dB
1.5°	0.63	-2.84 dB

Figure 11. Demonstration of agile beam combining using a PAPA aperture.

4. System Improvements

The PAPA development uncovered a variety of implementation problems. Minor problems, such as poor throughput at the polarizer due to collimator alignment, adversely affected the performance of the prototype system, but had a simple solution such as adding waveplates to decouple polarization and physical alignment of the fiber array. However, there are other performance issues that currently make the technology unattractive for most applications. The major issues are:

1) High sidelobes,
2) Slow switching,
3) Transient (versus continuous) scanning,
4) Slow coherent phasing,
5) Small scanning range.

A small array fill-factor causes large sidelobes. The envelope function for the combined beam is set by the divergence angle produced by each OPA section in the array. A small OPA section spreads the beam in the far field, producing a broad beam envelope. As the OPA size increases, the envelope functions narrows, having a steeper roll off. If the gap size remains the same and the OPA area is increased, the sidelobes are suppressed by the envelope roll off. This roll-off suppression is shown in Figure 12. The two PAPA beam profiles shown are based on arrays with 1x4096 OPAs (7.4mm x 4.2mm) and 1x12288 OPAs (19.5mm x 13.8mm), having nearly the same gap between beams. The difference in the far-field profiles is obvious. Another factor is the array gap. The gap between the array’s active area determines the angular distance between the sidelobes and the envelope’s peak. A smaller gap pushes the sidelobes further away from the peak. Whereas, a large gap causes the lobes to be relatively close to the peak of the envelope function. Therefore, further reduction in the sidelobes is possible by narrowing the beam spacing to increase the array fill factor. Other beam shaping techniques, such as the amplitude-weighting techniques used with RF phased arrays, offer a potential benefit, also.

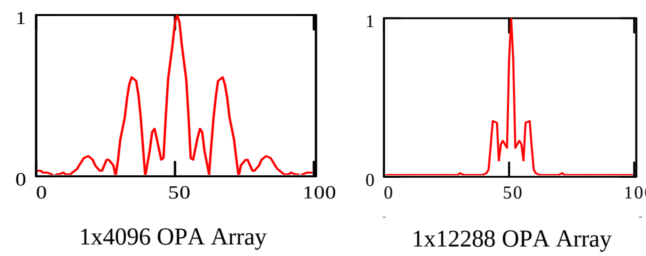


Figure 12. PAPA far-field profiles using OPAs of different size, showing the suppression of sidelobes from increasing the fill factor.

Slow switching response hinders the system’s acquisition and tracking. Also, it limits the bandwidth of the adaptive control. Most of the slow response associated with the LCoS technology is related to the voltage capability of the backplane. There are various liquid crystal modulators with good (sub-millisecond) response times provided that they are addressed with sufficient voltage. Possible modulator configurations include dual-frequency, ferroelectric with a quarter-half-quarter (QHQ) configuration, polymer-stabilized and surface-mode modulators. In general, these modulators have different performance characteristics, which may prevent some from being useful for the application. However, one common characteristic is that these modulators require more than 5 volts to operate at high speed. Therefore, a higher voltage backplane allows a variety of options for addressing the speed issue.

Recently, a high-voltage OPA was designed and fabricated (refer to Figure 13). This new OPA is a 1x12288 array with 1.6-micron pitch. It delivers 2.7 times more voltage than the 1x4096 device (13.5 volts versus 5 volts), increases the active area from 44 mm^2 to approximately 400 mm^2, and reduces the backplane curvature by a factor of three. These improvements are beneficial for reducing far-field sidelobes, improving wavefront quality and achieving sub-millisecond response. Sub-millisecond operation has not been demonstrated using a LCoS OPA, but it has been demonstrated using a LCoS SLM. By using a dual-frequency modulator and a high-voltage 256x256 LCoS backplane, the 2-D SLM provided sub-millisecond, phase-only modulation with more than a wave of stroke at 670nm. The new OPA backplane uses the same foundry process used by the 2-D SLM. The next step is to transition this sub-millisecond capability to the OPA and extend the phase stroke.

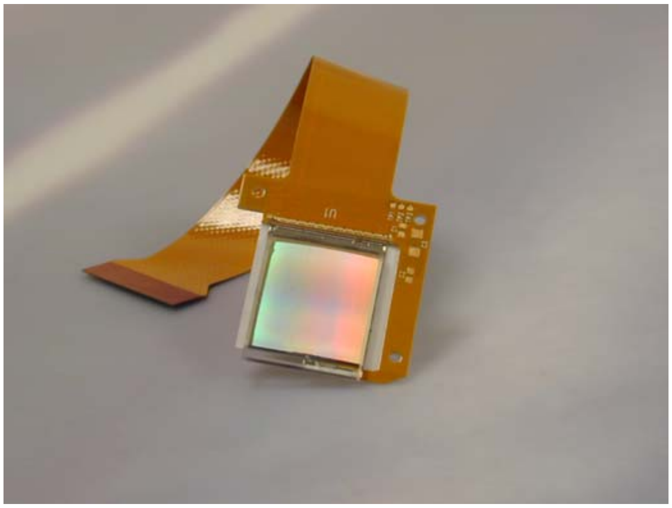


Figure 13. High-voltage 1x12288 optical phase array.

Some high-speed modulators do not provide continuous scans when normal addressing techniques are used. For example, a ferroelectric modulator needs to be DC-balanced, where the voltage signals are periodically inverted to prevent ion migration and stuck pixels. For a ferroelectric device, the modulation tracks the field, causing the phase profile to change for the inverted field. Therefore, DC-balancing causes tracking problems, since beam directions cannot be held indefinitely. With dual-frequency modulators, high-frequency resets, which are applied to quicken modulator response, force the whole array into a common state for a short period of time. A similar problem exists when changing beam patterns when all pixels within the array are written at once. Clever addressing techniques mitigate transient switching problems such as these. For example, the array values do not have to change simultaneously, since the active matrix backplane allows each pixel to change without affecting other pixels in the array. Therefore, the beam pattern is morphed into new scanning directions by modifying only a part of the OPA pattern at one time. After a portion of the beam changes to a new location, the remaining part of the pattern is modified to follow, allowing the pattern to continuously follow the target. This partial addressing technique is possible with a dual-frequency modulator, if the OPA addressing circuitry has enough flexibility. Also, the PAPA configuration is beneficial for this technique, using separate OPAs and inter-array phasing to help morph the beam pattern into a new location.

In addition to tracking and beam forming, fast inter-array phasing is useful for wavefront control. However, a considerable improvement in speed is needed to perform these tasks in a useful manner. The current method of using a hill-climbing algorithm based on Strehl ratio calculations is slow because of the video feedback, the image processing delay and the serial phase adjustment (i.e. one adjustment per measurement). A technique that co-phases each segment based on direct feedback from each element adds considerable parallelism and eliminates processing overhead. One co-phasing approach uses small lenses situated between the fiber feeds to sample portions of the elastic scatter coming back from each transmitted beam. This scatter is focused onto single-element detectors that detect the interference between sets of adjacent beams. If the beam portions are in phase, the spot intensity at each detector is maximized. Fast phase shifters, such as fiber stretchers or EO modulators, are used to adjust the phase of each fiber feed in response to the detector outputs. The array is co-phased in an orderly manner with one central beam acting as a reference, and each beam falls in sync with adjacent beams as they phase to the reference. This co-phasing technique is limited only by the speed of the phase shifters and the detector elements, which could operate in the nanosecond range if desired.

The PAPA approach is viewed as a fine angle steerer. OPA's have a steering range that is limited to a few degrees. Therefore, these agile apertures need to be integrated with coarse angle steerers to be practical for mobile free space optical communications. Most coarse steerers increase the operating range of a fine angle steerer by deflecting the beam to wider angles in discrete steps using angular deflection, introducing some implementation problems for PAPA systems. One problem is angular walkoff, which reduces the effective aperture of the steering stage. Since the effective aperture is smaller than the physical aperture, PAPA fill-factor is reduced producing sidelobe loss. Another problem is steering independence. If the coarse steerer selects the general beam direction for all PAPA segments, then the PAPA array loses its ability to spatially track multiple terminals that are widely separated.

The spatial agility of the non-mechanical aperture is greatly aided by a novel non-mechanical coarse steerer, which fully complements the fine-angle LCoS PAPA. That is, the coarse steerer is composed of individual compact elements that provide independent 2D wide-angle scanning for each element in the PAPA. The coarse steering stage discretely controls the launch position of a beam in the focal plane of a fast lens[5]. A fine-angle steering section, composed of X and Y optical phased arrays (OPAs), feeds each coarse-steering element. These fine-angle sections provide zone fill and adaptive wavefront control. Unlike other beamsteering techniques, the operation of the fine and coarse steerers are decoupled through an intermediate Fourier transformation (i.e. fine stage modifies angle and coarse stage alters position). This combination greatly reduces the walkoff problem, and it allows each PAPA section to operate independently over the full field of regard of the non-mechanical beamsteerer.

5. Conclusions

It is obvious that the PAPA approach requires further development before it will be a viable approach for lasercom terminals. However, the unique capability it provides for multi-access, scalable terminals is an important asset not currently available. Therefore, the development required to implement the solutions discussed above is a worthwhile effort. If these issues are resolved in a reasonable fashion, the PAPA technology offers considerable potential for future laser communication applications.

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Anna Linnenberger *received her B.S. in Computer Engineering in 2001 from the University of Denver. Prior to graduation Ms. Linnenberger was employed a Ball Aerospace and Technology where she wrote software for the Space Infrared Telescope Facility. Upon graduation she joined BNS in 2001. At BNS she has worked on the development and support of Windows and Labview based software for the 128x128 SLM, the 256x256 SLM, the 512x512 SLM, and the 1x4096 SLM products. In addition to her work on commercial products, she has developed software for production testing, modeling of optical tunable filters performance, optical correlators and phased-array of phased-array beamsteering systems.*