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14. ABSTRACT Laser communications offer increased bandwidth and security over radio frequency. These advantages have made laser communications a key technology for future communication systems. The operation of transformational lasercom networks include terminal capabilities that are beyond those normally associated with one-to-one links. One requisite capability is multi-access communication 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. Thus multiple optical communication links mimic broadcast communications in a more secure format. Also, multi-access operation is desirable for dynamic routing schemes where several terminals in the field maintain multiple links to route around obstructions. A multi-access laser terminal offers potential savings in size, cost, and power, and is considered an enabling technology for the Transformational Satellite Communications System (TSAT).

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 can be realized by compact, low-power, light-weight optical phased arrays. 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.

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Multi-access Laser Terminal Using Liquid Crystal Beam Steering [1,2]

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Abstract—Laser communications offer increased bandwidth and security over radio frequency. These advantages have made laser communications a key technology for future communication systems. The operation of transformational lasercom networks include terminal capabilities that are beyond those normally associated with one-to-one links. One requisite capability is multi-access communication 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. Thus multiple optical communication links mimic broadcast communications in a more secure format. Also, multi-access operation is desirable for dynamic routing schemes where several terminals in the field maintain multiple links to route around obstructions. A multi-access laser terminal offers potential savings in size, cost, and power, and is considered an enabling technology for the Transformational Satellite Communications System (TSAT).

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 can be realized by compact, low-power, light-weight optical phased arrays. 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.

After a brief introduction to satellite-based laser terminal concepts, liquid crystal beam steering and how it might be used to implement a multi-access laser terminal is discussed. The paper ends with a summary.

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1. INTRODUCTION

Multi-access lasercom and lasercom crosslinks have been identified as key elements for the MILSATCOM access network that will form the backbone of the Transformational Communications Architecture. The operation of transformational lasercom networks include terminal capabilities that are beyond those normally associated with one-to-one links. One requisite capability is multi-access communications where one terminal communicates with several other terminals, for example, a satellite downlink to multiple platforms in a battlefield arena. However, 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. A multi-access laser terminal offers potential savings in size, cost, and power, and is considered an enabling technology for Transformational Communications.

While traditional gimbals offer performance advantages for one-to-one links, 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.

In the following section satellite laser terminal architecture is discussed. The laser terminal is looked at based on physical constraints, communication multiplexing approaches and beam control. Following this, optical phased arrays are introduced. Section 4 considers a specific example of a satellite laser terminal beam control system

[1] 0-7803-8870-4/05/$20.00© 2005 IEEE
[2] IEEEAC paper #1386, Version 3, Updated December 16, 2004

based on optical phased array technology. The paper ends with conclusions in which it is pointed out where nonmechnical beam steering components might contribute.

2. SATELLITE LASER TERMINALS

A satellite based multi-access lasercom terminal is a complex subsystem[1]. The problem can be made more tractable by considering some of the primary constraints and functional requirements individually at first, then bringing the whole together. One needs to consider three principle areas: first, the physical requirements, for example, size, weight and power constraints and the environmental factors. Another major area to investigate is the actual implementation in an optical communication system. For example, what are the most efficient encoding schemes for this technology, is direct detection or coherent detection most promising, what are the best ways to implement the transmit and receive functions? Also what is the best multiplexing scheme? Possibilities include time division, wavelength division and spatial multiplexing. Thirdly, what is the acquisition and tracking capability of the terminal design. The constraints here are the number of independent beams that need to be controlled by each terminal and also how far and how fast the beams need to be steered. In addition, to simply redirecting the beam, the ability to shape the beams and the overall beam quality need to be considered.

Beginning with the physical requirements, obviously one wants to minimize size weight and power (SWaP). In addition one needs to consider the space environment (vacuum, extreme temperatures, and cosmic radiation). Also, there is reliability. How long is the terminal expected to operate? Are component lifetimes consistent with expected mission duration? Is there a soft failure mode? Does the terminal exhibit graceful degradation?

For the multiplexing scheme, temporal multiplexing of high data rates to different directions may place unrealistic requirements on the beam handling subsystem. A wavelength division multiplexing (WDM) approach has a proven track record for telecom, but WDM architectures are generally highly sensitive to angle and consequently difficult to implement with nonmechanical beam steering. Spatial multiplexing naturally lends itself to a nonmechanical beam steering approach based on diffraction.

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. Moreover, acquisition and tracking is enhanced, if the scanning system generates beacons (beams with low directivity) to locate and track terminals. Then, on acquisition, the 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. Optical Phased Array (OPA) technology offers many advantages over existing technologies while still maintaining reasonable constraints on cost, size, and power consumption.

3. LIQUID CRYSTAL BEAM STEERING

An optical phased array (OPA) steers light by phase modulating the light. By applying a linear phase ramp 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, as shown in Figure 1. 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).

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

An OPA typically has a modulation depth of 1-2 waves (2π - 4π of phase shift). This makes a large phase ramp, distributed over the entire aperture, as shown on the top of Figure 1, impractical. However, due to the cyclic nature of phase modulation, it is possible to increase or decrease the phase shift by 2π, and still maintain the slope of the phase profile [2]. The linear phase ramp can be periodically decreased by 2π, producing a saw tooth phase profile which behaves in the same manner as a continuously increasing phase ramp without requiring large phase shifts from the modulator. A higher number of 2π phase shifts across the wave front (small *d*) increases the steer angle. This is a diffractive steering approach and it is typical of nonmechanical beam steering technologies including, acousto-optic gratings, MEMs arrays and liquid crystal on silicon optical phased arrays. Grating dispersion is inherent in these technologies, but it can be compensated for [3].

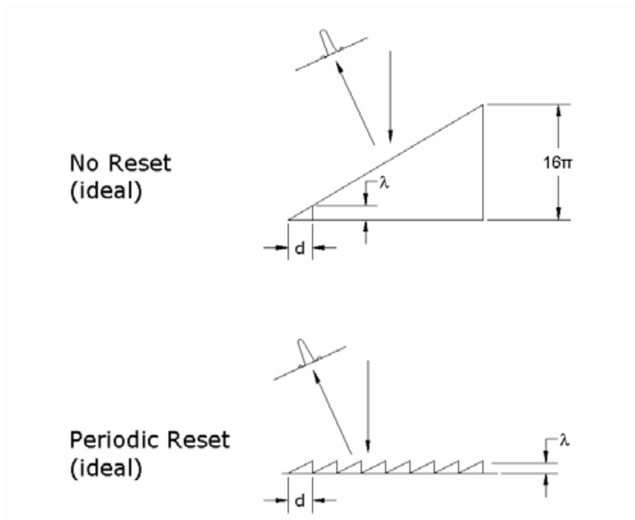

Figure 1. Optical phased array concept.

Efficient optical phased arrays with large angle-aperture products must provide a means for controlling thousands of phase shifting elements that are spaced within a wavelength of each other. The difficulty of this problem is greatly mitigated by using liquid crystal (LC) materials to provide the phase shift and VLSI backplane structures to control the LC modulators.

This liquid crystal on silicon (LCoS) approach demonstrates several advantages over transmissive direct drive implementations. First, unlike a direct drive device, for a LCoS device, every pixel is controllable, this leads to flexibility in improving angular resolution, applying wave front correction, or applying focus and defocus to aid acquisition and tracking. In addition, the number of electrical interconnects (a potentially reliability issue) are fewer for the LCoS implementation. Finally, temperature sensing and control is easier to achieve for the LCoS devices than it is for large aperture transmissive OPAs.

Liquid crystals are frequently used as optical modulators. LC 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 birefringence is used. That is, the index of refraction of a liquid crystal cell changes with applied field. 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. An application of electric field causes the molecules to tilt in a direction parallel with the direction of propagation of the optical field. The incident light then encounters 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 to the ordinary index.

As shown in Figure 2, the OPA head consists of a layer of LC sandwiched between a cover glass and a VLSI backplane in a pin grid array package. 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 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 [4].

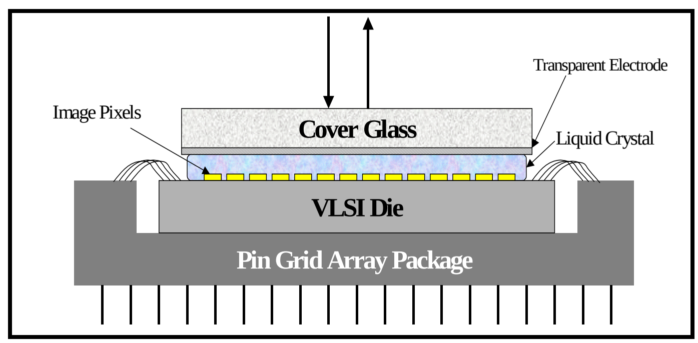

Figure 2. Layout of the OPA optical head. For purposes of illustration, this schematic is not to scale, e.g. liquid crystal layer is less than 10 microns, cover glass thickness is 1 mm.

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. Hiding the electrodes under a reflective dielectric coating that is deposited over the array minimizes diffraction from the electrode elements.

This LCoS optical phased array is a robust technology. The basic components are similar to that of a liquid crystal display. Typical LC display life times are 15 years. Moreover, Boulder Nonlinear Systems' liquid crystal cells and OPAs have been tested to over 200 kRad total dose of gamma radiation, equivalent to 14 years at geosynchronous orbit [5].

The OPA electrode structure inherently deflects the beam in one dimension, however, by cascading two one-dimensional OPAs with their grating axes crossed, one can achieve two dimensional steering out to a few degrees. BNS has identified a compact geometry that can use two OPAs to produce two-dimensional steering and an in-line optical path so that the module can be placed in an optical train as if it were transmissive [6]. This composite OPA unit, shown in Figure 3, forms an essential building block for potential laser terminal design candidates.

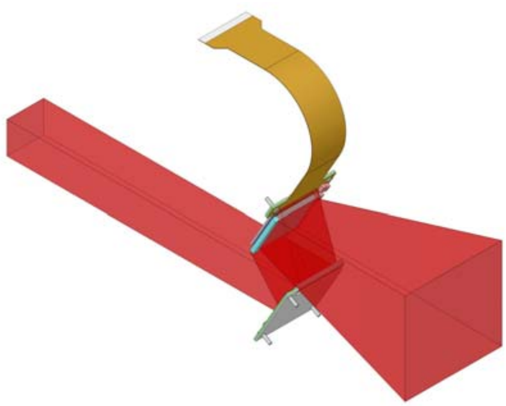

Figure 3. Two-dimensional steering using a pair of OPAs in a periscope (Z) configuration.

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 unless experimental stitching techniques are employed. A further increase in aperture is possible with the Phased Array of Phased Arrays (PAPA) approach discussed below.

4. A SPECIFIC BEAM CONTROL SYSTEM EXAMPLE

As one example of a laser terminal concept based on optical phased array technology, consider the Phased-Array of Phased Arrays (PAPA) configuration [7]. BNS recently completed development of a PAPA transmitter for laser communication links as part of the TeraHertz Operational Reachback (THOR) Program sponsored by the Defense Advanced Research Projects Agency, Advanced Technology Office (DARPA/ATO). In this scheme, multiple OPA devices are packaged closely together so they can serve as a common aperture. An OPA is capable of controlling multiple beams [8] and, with an array of OPAs as shown in Figure 4, coherently combining the beams to act as one beam [9]. The beams from each subaperture are combined in the far field by properly phasing the array. As an example, if the effective aperture for one OPA pair is 2cm x 2cm, then a 5x5 array of twenty-five pairs are needed to form a 10-centimeter PAPA aperture.

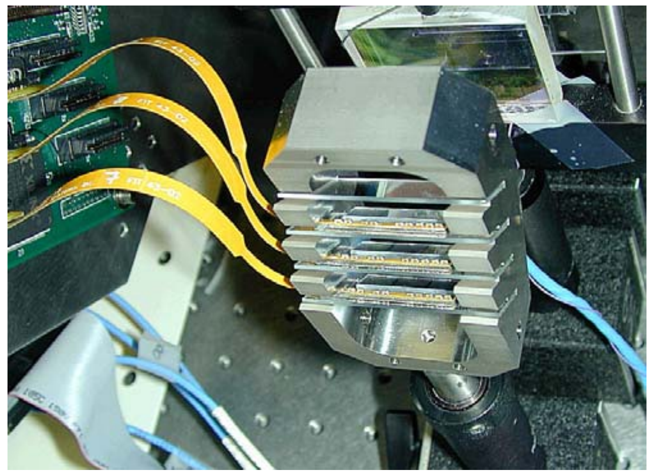

Figure 4. Photograph of 3x3 liquid crystal on silicon optical phased array of phased arrays in housing.

Combining several small apertures enhances platform compatibility, robustness and platform jitter rejection. 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 (r_o) of the received signal, the optical gain at each element is not diminished by turbulence or scintillation. With proper phasing, the effective aperture of 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. If the wave front controller is not able to properly phase the segments due to severe platform jitter, the effective gain increases by the square root of the number of segments within the array. Therefore, the optical gain is still improved by using multiple aperture segments when platform jitter limits the signal's coherence length to less than the receiver's effective aperture. By properly phasing the aperture components, the segmented aperture does not greatly penalize performance if the array's fill factor is kept high.

To maintain a high fill factor (i.e. aperture efficiency), a compact technique for controlling the beam at each aperture segment is needed. It is important that the beam control scheme does not add significantly to the size, weight, power or complexity of the system. LCoS-OPA technology provides two-dimensional non-mechanical beam steering along with tip, tilt and piston adjustment for each beam in a extremely compact package. These adjustments allow the beams from the separated apertures to be steered and phased to act as a common aperture (i.e. a phased array of phased arrays or PAPA).

Figure 5 illustrates an example of a possible multi-access terminal design. To use the PAPA configuration to control the terminal, the fine-angle LCoS PAPA is integrated with a unique coarse steerer and a true-time-delay fiber phasing technique. The agile aperture is combined with a transceiver that uses spatial and temporal diversity to form and maintain multiple links from a common aperture. The transceiver is composed of a single-channel differential-phase-shift-keyed (DPSK) receiver, a single-mode CW laser and external high-speed electro-optic (EO) phase modulators on each fiber feed. By properly phase modulating the fiber feeds (temporally) and the PAPA segments (spatially), the flexibility to acquire, track and communicate at high data rates with multiple terminals is achieved using simple heterodyne techniques [10]. Because of the optical heterodyne's ability to channel hop at GigaHertz rates, only one receiver is needed to service multiple channels spatially tracked by the PAPA configuration.

This adaptable configuration allows the system to have a large dynamic range where the loop sensitivity is scalable to meet the requirements of a particular link. As partitioned, the transceiver is very modular and easy to scale by increasing the number of PAPA segments. To provide adequate isolation, separate PAPA elements within the aperture are used for transmit and receive, and circular polarization is used to eliminate polarization dependence on platform orientation.

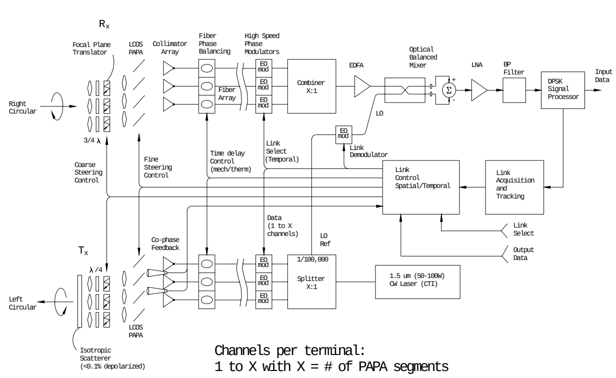

Figure 5. Scalable multi-access transceiver example.

The PAPA approach demonstrates a unique dynamic aperture design that offers high-power beam combining, platform movement mitigation and multi-beam control using agile, non-mechanical steering techniques. However, performance issues such as: high side lobes, slow switching, transient (versus continuous) scanning, slow coherent phasing, and small scanning range, need to be addressed in future PAPA developments. Solutions for these issues have been identified and the problems are correctable using available technology.

The laser terminal concept based on a phased array of phased arrays discussed above is just one example of how OPAs can be implemented in a multi-access terminal design.

5. CONCLUSIONS

A typical concept for a laser satellite terminal contains many beam control elements [1]. These can include, a point ahead mechanism, a fast steering mirror, and a coarse pointing mirror. Each of these components has the potential to be implemented using nonmechanical beam steering technology. Whether this happens, and which components are used, depends on how the nonmechnical steering technologies mature.

One example discussed above is the phased array of phased arrays approach in which the entire aperture can be dynamically reconfigurable. This has the potential for significantly increasing the flexibility of the beam control subsystem for the laser terminal. This added capability should be attainable within reasonable size weight and power constraints.

There are several potential improvements to the phased array of phased arrays architecture discussed above as one example of a multi-access terminal based on OPA technology. These include increasing the array fill factor, using dual frequency liquid crystal materials, parallel feedback for co-phasing and integration with a coarse steerer.

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BIOGRAPHY

Jay Stockley is a Research Scientist at Boulder Nonlinear Systems Incorporated (BNS). At BNS, he contributes to liquid crystal modulator development and beam steering related research. He earned his Ph. D. in Electrical Engineering from the University of Colorado in 1996. He received his B.S. in Electrical Engineering with a minor in Mathematics from Colorado State University in 1986 and the degree of Master of Science in Electrical Engineering, also from Colorado State, in 1991. Jay has been an R&D engineer or scientist since 1987. His former employers include OPHIR Corporation, Colorlink, and the University of Colorado. He has been an employee of BNS since 1995.

Steve Serati is founder and Chief Technical Officer of Boulder Nonlinear Systems Incorporated (BNS). He has a B.S. and M.S. in Electrical Engineering from Montana State University. Before starting BNS in 1988, he was a design engineer at Honeywell's Avionics Division for five years, design engineer and project manager with OPHIR Corporation for three years and a system engineer and project manager with Tycho Technology Incorporated for two years. In addition to his duties as BNS' CTO, Steve is also leading efforts on developing novel SLM technologies for optical processing and active-diffractive optics applications, and he is responsible for developing large-aperture adaptive optics for atmospheric correction. (A photograph is not available.)