Large, Wafer-Thin Optical Apertures Leveraging Photonic Integrated Circuits to Replace Telescopes for Communications

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ABSTRACT

To aid in driving down the size, weight, and power (SWaP) of space-based optical communications terminals, we present a large-aperture telescope-replacement technology that reshapes a beam from a single-mode fiber to ~5 cm and larger apertures on a silicon wafer by using photonic integrated circuit (PIC) components. We achieve multi-centimeter apertures by sacrificing wide-angle steering in favor of good beam quality and manageable controls. Light from a single-mode fiber is coupled to a silicon chip consisting of low-loss silicon nitride waveguides for signal distribution to large phase-controlled emitters. Our demonstrations of beam phasing across a 1.8-cm-diameter, 16-emitter phased array show excellent agreement with simulations. We have designed and simulated a 4.7 cm, 64-emitter array and have begun fabrication as of 2023. This architecture removes the need for beam expansion optics, free-space propagation for beam expansion, and the support structure and housing used in traditional telescope assemblies. Its low size and weight make it compatible with current and future beam steering mechanisms, and its reduced loading provides added potential for size and weight reductions in those subsystems. We believe the architecture can eventually be expanded to larger apertures of 10 cm or more without significantly increasing thickness.

INTRODUCTION

Small-form-factor, cost-effective CubeSats and SmallSats are revolutionizing space exploration and commercialization by providing widespread access to space for researchers and companies. The increasing sophistication of the sensor technology that enables meaningful missions on these small platforms is driving a need for higher-bandwidth communications. While space-based optical communications terminals (OCTs) are now starting to be fielded in the hundreds and thousands by SpaceX and other companies and government agencies, the size, weight, and power (SWaP) of these systems are far from desirable for smaller satellite platforms. Lower-SWaP OCT options are needed to remove the communications bandwidth bottleneck from CubeSats and SmallSats while maximizing the amount of payload space for mission-enabling sensors.

In this work, SRI International (SRI) describes the demonstration of a photonic integrated circuit (PIC) that can replace the telescope subsystem of an OCT, as depicted in Figure 1. This PIC reshapes the beam from a single-mode fiber to a multi-centimeter-diameter output with good beam quality, all on the surface of a silicon wafer. By eliminating the need for free-space propagation, we have greatly reduced the size and inertial mass of the telescope subsystem, which enables further reductions in steering assembly SWaP. This foundry-compatible fabrication process will provide a very low-cost telescope alternative by eliminating the need for expensive optics and assembly and alignment touch labor.

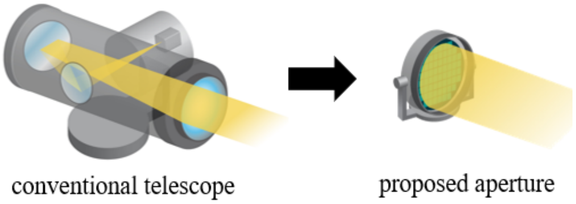


Figure 1: Telescope Replacement Concept

Our approach for beam shaping is an optical phased array (OPA) that prioritizes a large aperture, which maximizes the ‘fill factor’ or active area used to send and receive light. In transmit mode, the large aperture helps produce high-quality beams that minimize diffraction losses in propagation. In receive mode, the aperture maintains a large area to maximize the optical power collected.

In designing the OPA, we sought to maximize the size of individually addressable emitting elements to several square millimeters to both minimize control complexity and power consumption (by requiring only a few hundred phase controllers for a 5- to 10-cm aperture) and maximize the fill factor (by reducing the amount of space needed for the controls).

The OPA approach taken here is counter to much of the prevailing OPA PIC work that focuses instead on the ability to steer beams over wide angles, most prominently for use in automotive lidar. Wide-angle steering requires individually addressable micrometer-scale emitters, but these can be difficult to fabricate while maintaining a high fill factor, and millions of such emitters would be required for the multi-centimeter apertures needed for long-distance propagation. For example, 32,768 active elements were required for one-dimensional steering of a sub-cm array.[1] As well, steering is also accomplished by tuning the laser wavelength, which is not easily transferrable to optical communications systems, where narrowband filters are needed to reduce out-of-band noise. In addition, to be used as a receiver in a communications system, the angle of arrival and wavelength must be decoupled for practical implementation.

Our approach minimizes control complexity (and also steering range) by implementing large-area emitting elements. Each element's phase is independently controllable to compensate for static random phase fluctuations that occur from light propagating through the waveguides. In practice, the lengths at which these random phase fluctuations become important are on the order of a few square millimeters.[2] The element schematically depicted in Figure 2 consists of a thermal phase shifter followed by a beam expansion circuit comprising a splitter tree and waveguide tapers.

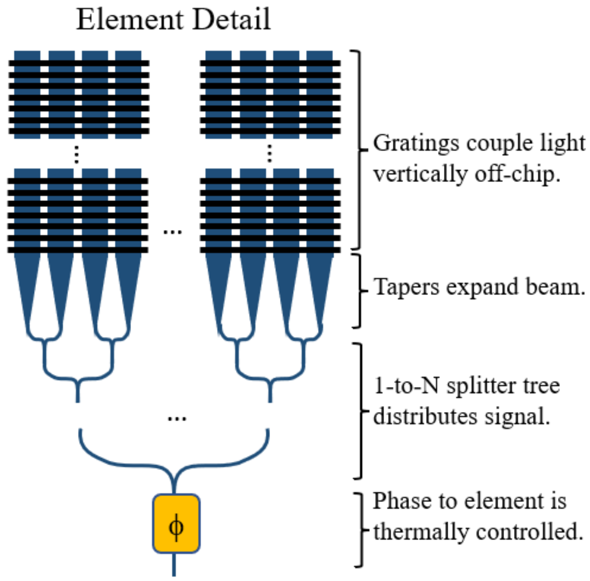


Figure 2: Emitter Element Detail

Within the few millimeters of the element, the phase of the light to each emitter is maintained constant from defining equal path lengths.[3]

PROOF-OF-CONCEPT DEMONSTRATION

We fabricated a 1.8 cm proof-of-concept aperture on SRI's in-house silicon nitride (SiN) waveguide PIC platform. The layout, shown in Figure 3, consists of a grating coupler input that is distributed to 16 identical 2-mm-wide elements, each consisting of 128 grating emitters. The layout was fabricated using an i-line (365 nm near-UV) stepper. To demonstrate scalability to larger apertures, we fabricated the device using two stepper masks with a stitched waveguide connecting the two fields. We thus demonstrated that future implementations of the concept are not restricted to the size of a single stepper field and are instead limited by the wafer size.

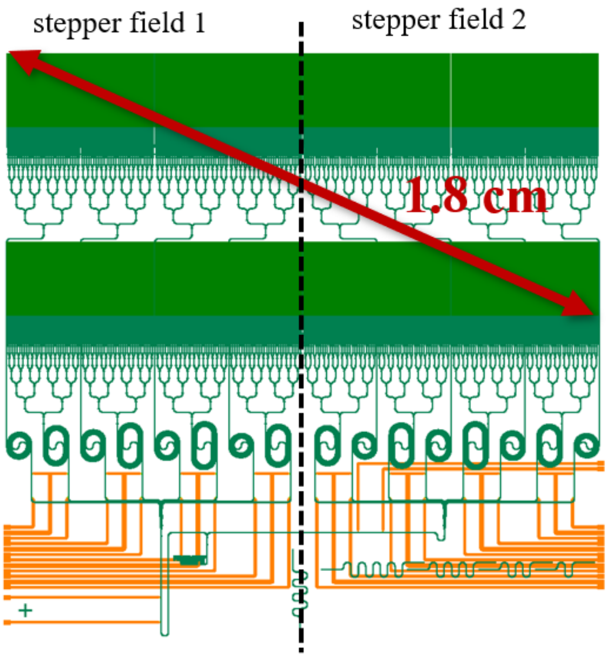


Figure 3: Layout of 1.8-cm Aperture

Thermo-optic phase shifters were included through the addition of resistive heaters at the input waveguide to each element. An image of the aperture under test is shown in Figure 4. A single cleaved SMF-28 fiber input launches the light into the single input grating and the PIC, then distributes the light to all the emitters. We used a pair of electrical probe arrays to thermally tune the aperture.

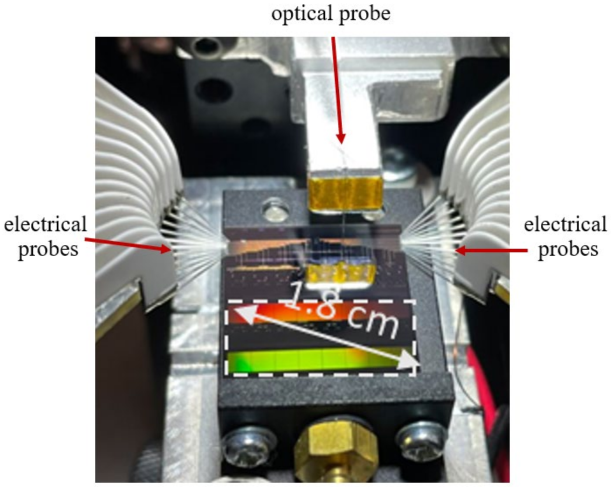
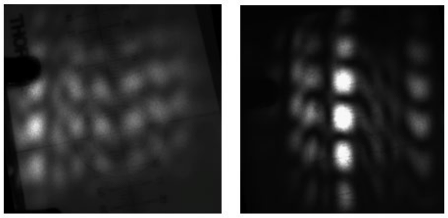


Figure 4: 1.8-cm Aperture Under Test

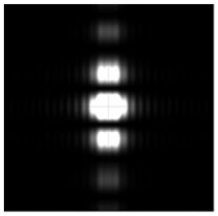
To phase up the far-field profile, the beam was propagated approximately 40 m, where it illuminated a small power meter. A beamforming algorithm[4] was then implemented with feedback from the reading on the power meter to optimize the power on detector. The resulting beam profiles (and comparison to simulation) are shown in Figure 5.

Experiment



Out-of-phase In-phase

Theory



Simulated

Figure 5: Far-field Beam Profiles of 1.8-cm Aperture

NEXT GENERATION APERTURE

A next generation implementation of this concept is currently in fabrication using the layout shown in Figure 6. This layout consists of 64 elements across four stepper fields for a total aperture diagonal of 4.7 cm. In addition to scaling up the total emission area, we also reduced the size. This size was chosen to support the required link budgets of pLEO crosslinks.

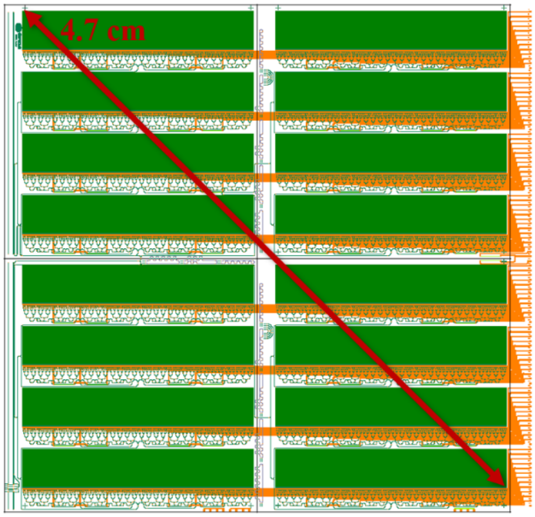


Figure 6: Layout of 4.7-cm Aperture in Fabrication (665 mm^2)

Figure 7 shows the simulated beam for out-of-phase and in-phase beam profiles. The ability to temporarily spoil the beam by controlling the multitude of phase controls is expected to be advantageous for implementing pointing, acquisition, and tracking algorithms during operation between multiple satellite vehicles.

Out-of-phase In-phase

Figure 7: Simulated Far-field Profiles for 4.7-cm Aperture

CONCLUSION

In summary, we have presented a novel optical phased array approach to replacing the bulky telescopes in spaced-based optical communication telescopes with a low-SWaP, wafer-thin aperture. Implementing the beam expansion and phase control on a photonic wafer achieves a significant SWaP savings and intrinsically supports additional functionalities such as beam spoiling and look-ahead. We experimentally demonstrated a 1.8-cm aperture and presented the design for a 4.7-cm aperture currently in fabrication.

ACKNOWLEDGMENTS

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