8192-Element Optical Phased Array with 100° Steering Range and Flip-Chip CMOS

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Abstract: We present an optical phased array with a record 8192 individually-addressed elements driven by flip-chip CMOS spanning a $100^{\circ} \times 17^{\circ}$ field of view. The reticle-sized PIC+CMOS beam steering engine enables near cm-scale apertures for long-range applications.

OCIS codes: (130.3120) Integrated optics devices; (250.5300) Photonic integrated circuits; (280.3640) LIDAR.

1. Introduction

Optical phased arrays (OPAs) are a differentiating technology in beam steering applications such as light detection and ranging (LiDAR) and free-space optical communication [1–6]. As element pitches decrease towards $\lambda/2$ to maximize steering range, increased element counts are crucial to form large apertures supporting small diffraction angles and adequate receiver areas. Many thousands of tightly-pitched elements, ideally individually controlled, are necessary for centimeter-scale TX/RX apertures required in long-range applications. Previous demonstrations include 1024 elements at a 2 µm pitch (~45° phase-controlled steering), achieved with monolithic CMOS photonics [5], and 512 elements at a 1.3 µm pitch (~70°), which utilized wirebonding to external DACs [6]. Additionally, tightly-pitched 1D-steerable "end-fire" arrays have been realized, but are limited in element count and require external collimation lenses [1]. To date, no demonstration has simultaneously achieved large element counts, steering range, and aperture size.

In this work, we present an 8192-element OPA driven by flip-chip CMOS electronics. Eight CMOS DAC banks are flipped directly onto the photonic integrated circuit (PIC) forming a chip-scale PIC + CMOS beam steering engine which consumes 2.5 W (300 µW/DAC). Optical elements (phase shifters and vertically-emitting antennas) are placed at a 1 µm pitch, facilitating 2D beam steering with a 100° phase-controlled horizontal axis and 17° λ-controlled vertical axis. A yield of >95% was measured for the 8192 elements. With an 8 mm × 5 mm aperture, this demonstration meets the metrics demanded by challenging applications and brings a new era for state-of-the-art OPA technology.

2. OPA Demonstrator Overview

A block diagram and photograph of the demonstrated system are shown in Figs. 1(a-b). The 2.8 cm × 2.5 cm PIC contains a one-dimensional 8192-element optical phased array (Fig. 1(c)). Outside of the 8 mm × 5 mm emission aperture, eight identical custom ASICs are flip-chip attached to the PIC. Each ASIC controls 1024 voltage-mode DAC outputs, and the multi-layered electrical traces on the PIC route each DAC output from its pad grid to a respective optical phase shifter (8×1024, 8192 total). Furthermore, CMOS power rails and digital inputs are routed from the ASIC, through the PIC traces, to wirebond pads on the PIC perimeter, similar to an interposer. The assembled PIC + CMOS is die-attached to a PCB and wirebonded. Laser light is input through an epoxied PM fiber and 2D beam steering is achieved by altering the phase shifters and input wavelength (no phase shifter changes are necessary when varying wavelength). A µController board, soldered to the back side of the PCB, parses USB serial commands and drives the ASIC digital inputs to simultaneously control the 8192 DACs. Finally, the housing has a $13\times13\times5\,\text{cm}^3$ size.

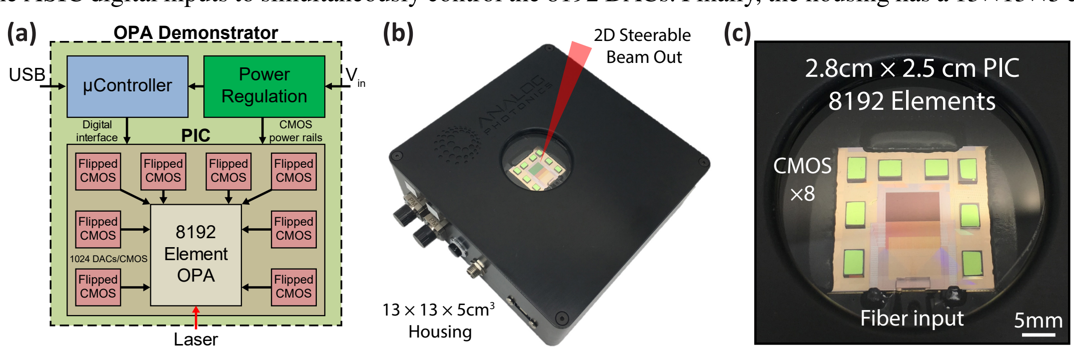
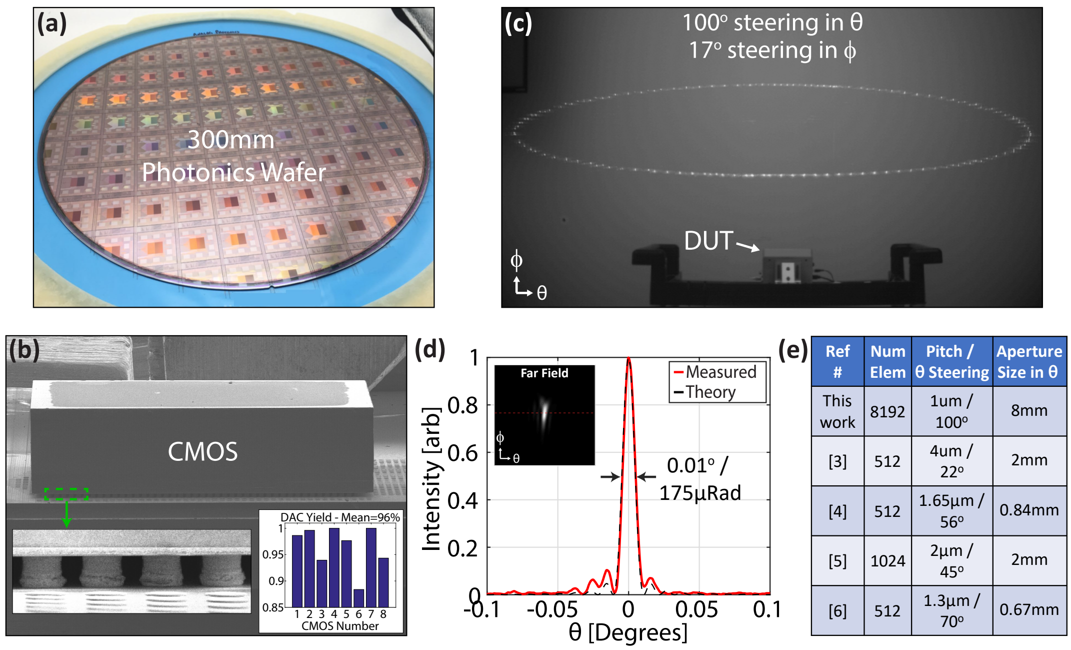


Fig. 1. (a) Block diagram of 8192-element optical phased array demonstrator containing OPA, flip-chip CMOS, and driving µController. (b) Photograph of demonstrator. (c) Zoom-in to wirebonded and fiber-attached OPA.

3. OPA Demonstrator Integration and Results

Figure 2(a) shows a 300 mm photonics wafer containing an 8192-element optical phased array per reticle. Wafer-level processing is performed for compatibility to receive flip-chip bonding. In addition, CMOS wafers are copper pillar bumped on the wafer-level. The CMOS chips are singulated through dicing, and flip-chip attach occurs by aligning and reflowing eight CMOS die onto the PIC. Figure 2(b) is an SEM of an attached CMOS die with a zoom-in showing high-fidelity connections to the PIC pads. Operational success of the individual OPA elements was observed by actuating its respective DAC during calibration. The measured yield was >95%, which includes flip-chip/wirebond connections and CMOS/PIC components. Figure 2(c) is an IR camera image of summed spots on a wall formed while performing 2D beam steering with the phase shifters and input wavelength (1515 nm to 1635 nm). The element pitch of 1 μm (both phase shifters and waveguide grating antennas) enabled 100° steering in the horizontal axis with phase shifter control (θ), and a λ sensitivity of 0.14°/nm produced 17° vertical steering (ϕ). A FWHM diffraction angle of 0.01°×0.039° was observed in the far field with 10 dB side-lobe suppression (Fig. 2(d)). Finally, the measured power of an individual ASIC was 300 mW (300 μW/DAC), corresponding to a PIC + CMOS engine power consumption of 2.5 W to drive the 8192 elements. The optical phase shifters themselves consume single microwatt-level powers [4].



Ref #	Num Elem	Pitch / θ Steering	Aperture Size in θ
This work	8192	1um / 100°	8mm
[3]	512	4um / 22°	2mm
[4]	512	1.65μm / 56°	0.84mm
[5]	1024	2μm / 45°	2mm
[6]	512	1.3μm / 70°	0.67mm

Fig. 2. (a) 300 mm photonics wafer with 8192-element OPAs. (b) SEM image of CMOS flipped onto PIC with insets of zoomed-in bump connections and DAC yield. (c) Sum of spots on wall showing 2D beam steering. (d) Cross-section of far field in the θ dimension. (e) Table of state-of-the-art OPA demonstrations.

In conclusion, we have demonstrated an 8192-element OPA driven by flip-chip CMOS electronics. The PIC + CMOS beam steering engine had a power consumption of 2.5 W (300 μW/DAC) with a measured yield of >95%. A 1 μm inline element pitch enabled 2D beam steering with a 100° horizontal axis (17° vertical axis) for the first time. Figure 2(e) shows a performance table of recent state-of-the-art OPA demonstrations. This work establishes a new benchmark for optical phased arrays in element count, steering range, and aperture size, and meets the metrics for demanding applications such as automotive LiDAR, all within a chip-scale package. As one of the most complex PICs ever realized, this demonstration pushes the boundaries of integrated photonics technology.

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References

1. C. T. Phare, *et al.*, “Silicon Optical Phased Array with High-Efficiency Beam Formation over...,” arXiv:1802.04624 (2018).
2. D.N. Hutchison, *et al.*, “High-resolution aliasing-free optical beam steering,” Optica **3**, 887 (2016).
3. C. V. Poulton, *et al.*, “High-Performance Integrated Optical Phased Arrays for Chip...,” in CLEO 2018, paper ATu3R.2.
4. C. V. Poulton, *et al.*, “Long-Range LiDAR and Free-Space Data Communication With...,” JSTQE **25**, 7700108 (2019).
5. S. Chung, *et al.*, “A Monolithically Integrated Large-Scale Optical Phased Array...,” IEEE JSSC **53**, 275 (2018).
6. S. A. Miller, *et al.*, “Large-scale optical phased array using a low-power multi-pass silicon photonic platform,” Optica **7**, 3 (2020).