Subarray Design and Thermal Crosstalk Optimization for Power-Efficient Optical Phased Array

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BACKGROUND

A typical Optical Phased Array (OPA) transmitter takes a laser input, distributes the optical power through a distribution network and uses its optical antenna array to emit light into free space. By applying electrical phase control signals to each channel through a phase shifter, the relative phase between channels can be altered rapidly. The constructive and destructive interferences occur in the far field. the propagation direction of the emitted wavefront and energy hence can be focused (Beamforming) and steered (Beamsteering).

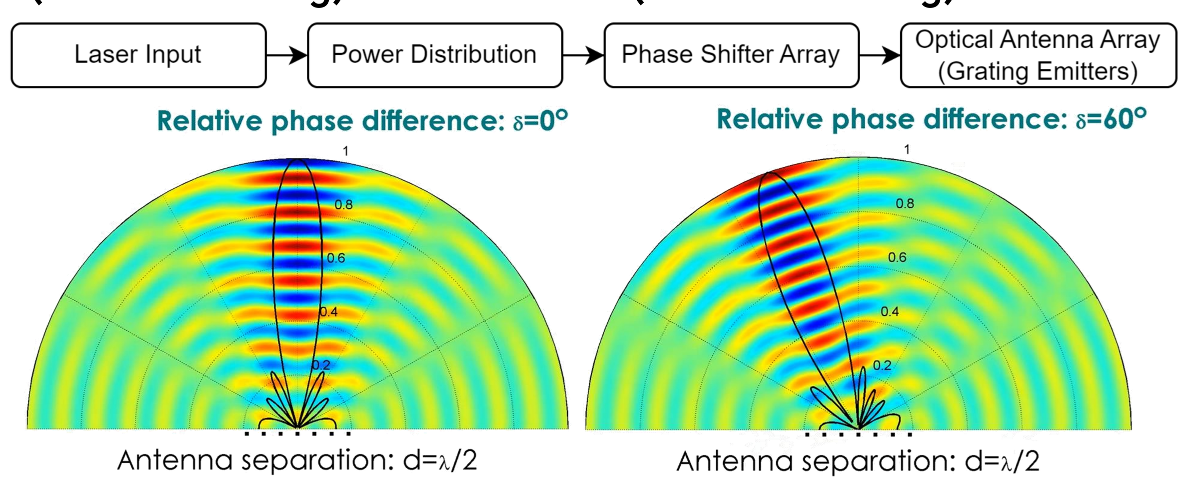


Figure 1. (a) OPA Components. (b) OPA operation, beamforming and steering illustrations.

Image: Mehmet E. Yavuz (2023). Beamforming by Phased Array Antennas. MATLAB Central File Exchange.

INTRODUCTION

Recently, large scale silicon photonic integrated OPAs with more than a thousand elements have been demonstrated [1] for potential applications such as solid-state LiDAR and free space optical communication.

Electro-optic (EO) and thermo-optic (TO) phase shifters are typically used in OPAs.

EO Phase Shifter	TO Phase Shifter
• Faster speed (>GHz). • Higher optical loss. • Large drive voltage. • Large footprint.	• Low speed (<200kHz). • Low optical loss. • Low drive voltage. • Small footprint.

The characteristics of the TO phase shifter are highly desirable for large-scale OPAs.

However, the large number of TO phase shifters in an OPA leads to thermal crosstalk, which results in not only non-ideal and inaccurate phase control but also an elevated temperature floor in the phase shifter array and the adjacent photonic circuits. Correspondingly, more heat and hence higher power consumption are needed to achieve the target phase shift profile.

To overcome this fundamental challenge, we propose a two-pronged approach:

- Spread phase shifts through the whole hierarchy in the optical signal path by adopting the subarray design for OPA.
- Globally optimize the phase shift profile in the OPA based on mapping of thermal crosstalk.

DESIGN AND MODELING

This 2-D OPA (4x4) subarray design:

- Implemented in a standard SOI photonic technology and operates at 1550nm.
- Uses Tungsten heaters which are 1µm above the 450×220nm Si strip waveguides.
- Spreads the phase shifts and generated heat to a broader region. reduces thermal crosstalk, especially within the phase shifter array region.
- Lower overall power consumption can be achieved in most cases.
- Small footprint of the design is maintained.

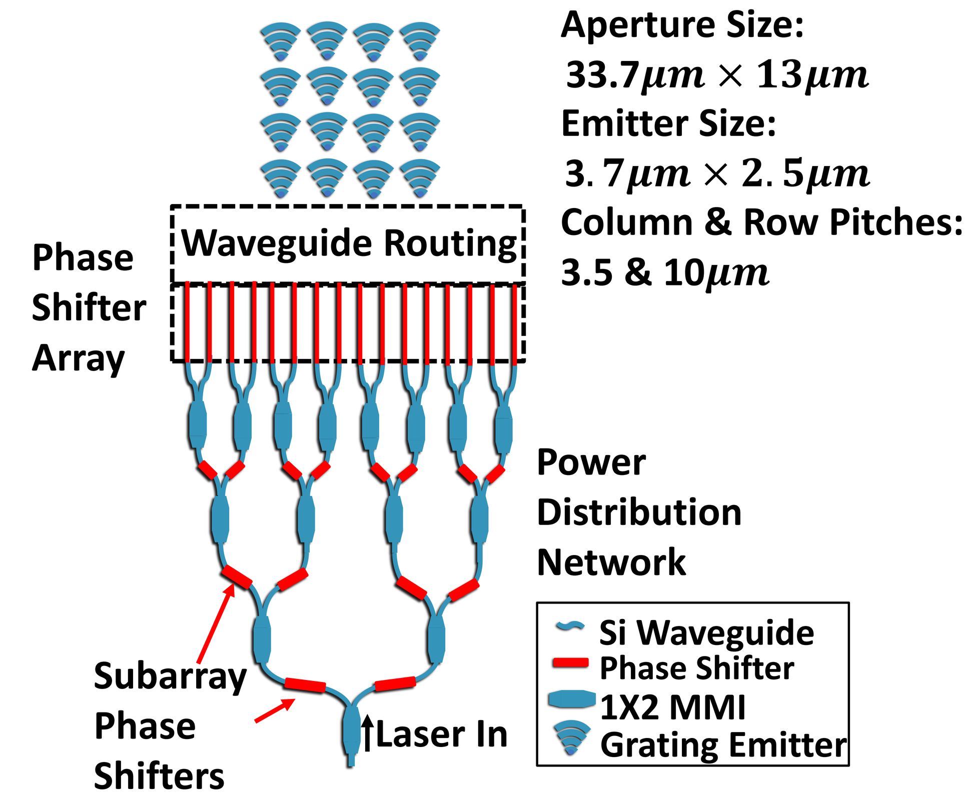


Figure 2. Subarray OPA design in the chip prototype.

- A 2-D finite-element thermal simulation is performed to model the phase shifting efficiency P_π and thermal crosstalk.
- P_π is also extracted from the peak intensity of the OPA's main lobe when sweeping the power of a phase shifter.
- The simulated and measured results show good agreement. Therefore, the thermal crosstalk can be estimated using the extrapolated model.

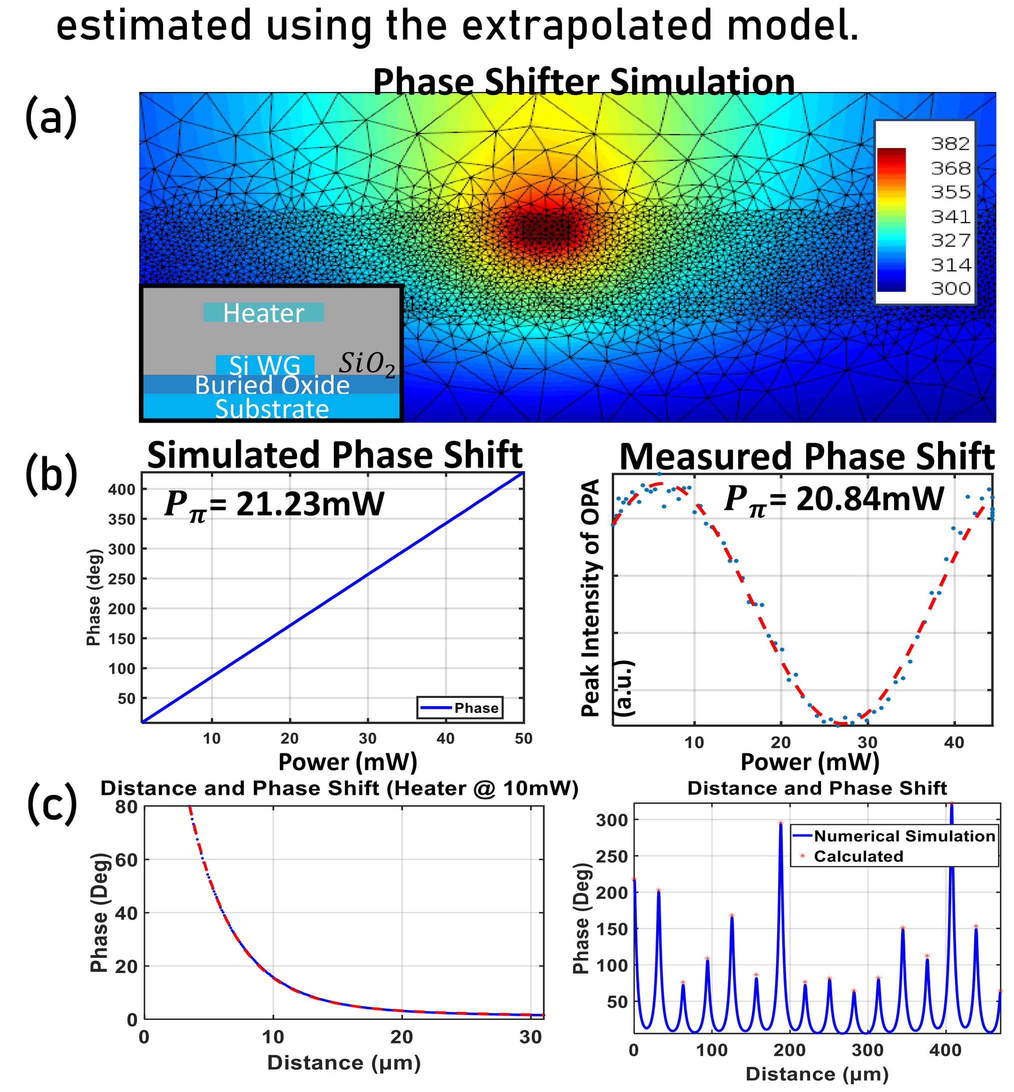


Figure 3. (a) 2-D thermal simulation of a TO phase shifter. (b) Phase shifting efficiency from simulation and extracted from measurement results. (c) Phase shift induced from a 150µm-long waveguide near the heater vs their distance. Extrapolated thermal crosstalk in the phase shifter array.

CONTROL METHOD

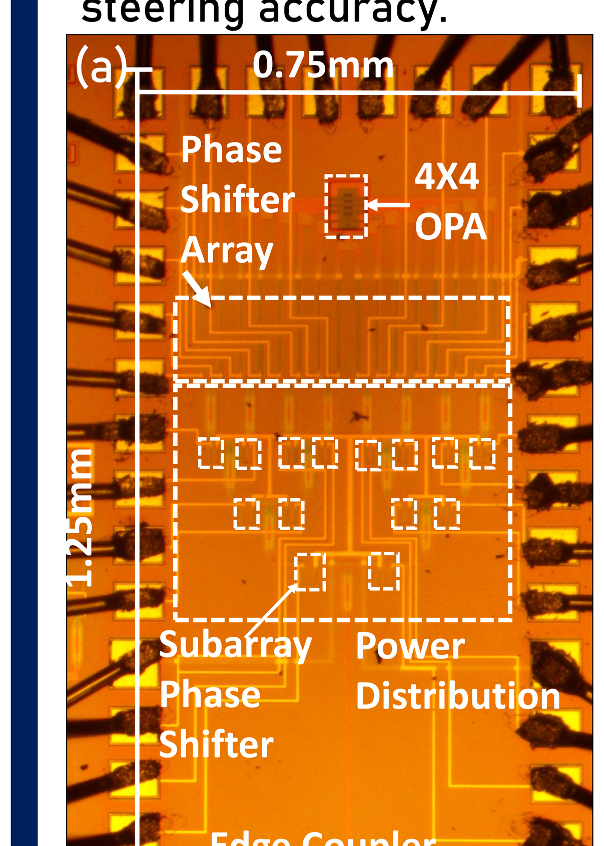
To compensate for thermal crosstalk between phase shifters, a phase coupling matrix model can be developed [2]: $\delta\tilde{\Phi} = \mathbf{T}\delta\Phi$, where vectors $\delta\tilde{\Phi}$ and $\delta\Phi$ are the phase shifts with and without crosstalk, and $\mathbf{T}$ is a $N \times N$ phase coupling matrix. Coupling coefficients T_{ij} between two phase shifters can be extracted from thermal simulations.

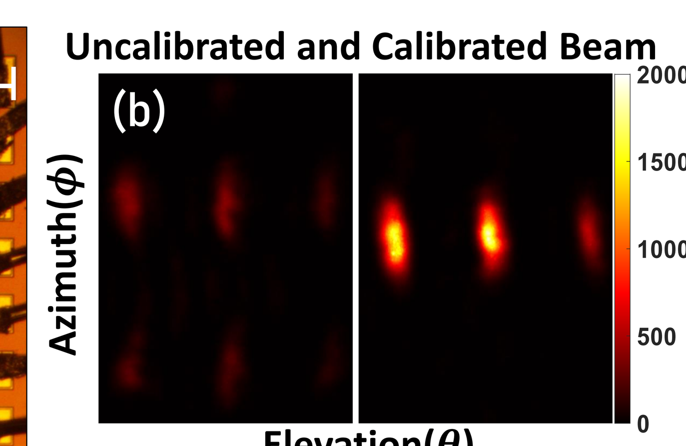
Using the array synthesis method [3], array steering vector Φ can be calculated based on the OPA's element and array factors. and array factors. Due to waveguide length differences and process variations, OPA also exhibits a static phase error Φ_0. The OPA's target phase shift profile is now: $\delta\tilde{\Phi} = \Phi - \Phi_0$. Therefore, the phase shifts generated without crosstalk should be $\delta\Phi = \mathbf{T}^{-1}\delta\tilde{\Phi}$, which is then converted to the currents applied to phase shifters.

We add the subarray phase shifts to the phase coupling matrix $\mathbf{T}$, making $\mathbf{T}$ a $N \times (N+M)$ matrix, where M is the number of subarray phase shifters. Subarray phase shifter's efficiency and crosstalk within the OPA need to be modeled. The number of target emitter phases is less than that of phase shifters, and hence the solution is not unique. By using linear programming and applying constraints on heater currents, we can minimize the total power consumption within the constraints.

EXPERIMENTAL RESULTS

The OPA beam pattern is captured and calibrated under the microscopic imaging system. Fast scannings of "U" and "R" pattern (451 points) are performed to verify steering accuracy.





- The patterns are obtained by synchronizing the camera exposure and patterns' beamsteering period.
- Each beamsteering point updates every ~350μs.

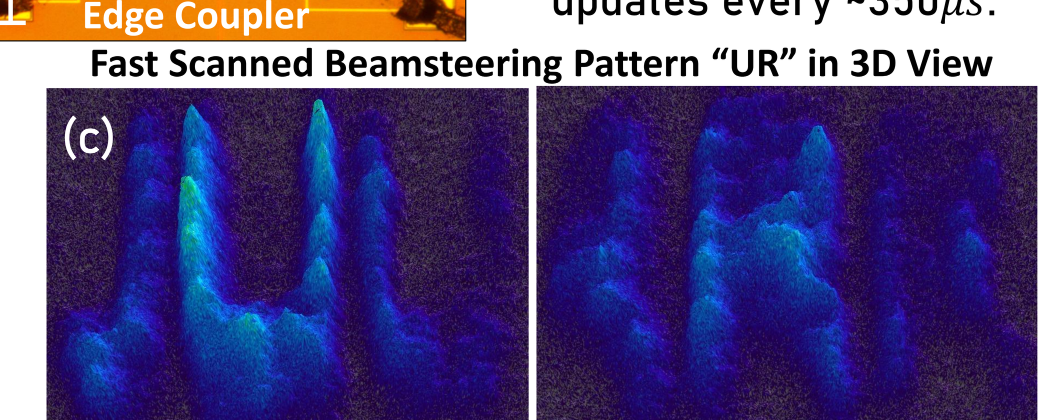
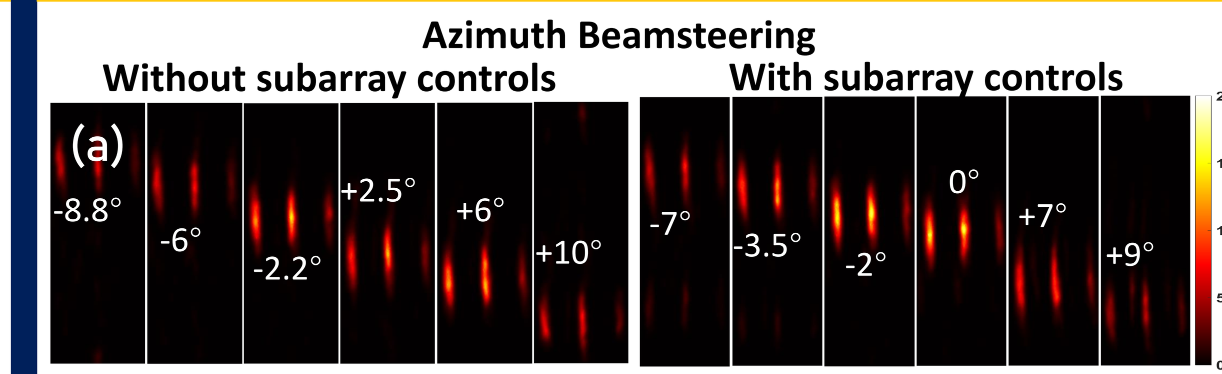


Figure 4. (a) Micrograph of the prototype OPA chip. (b) Uncalibrated and calibrated beam. (c) Beamsteering scan to show patterns of "U" and "R".

EXPERIMENTAL RESULTS



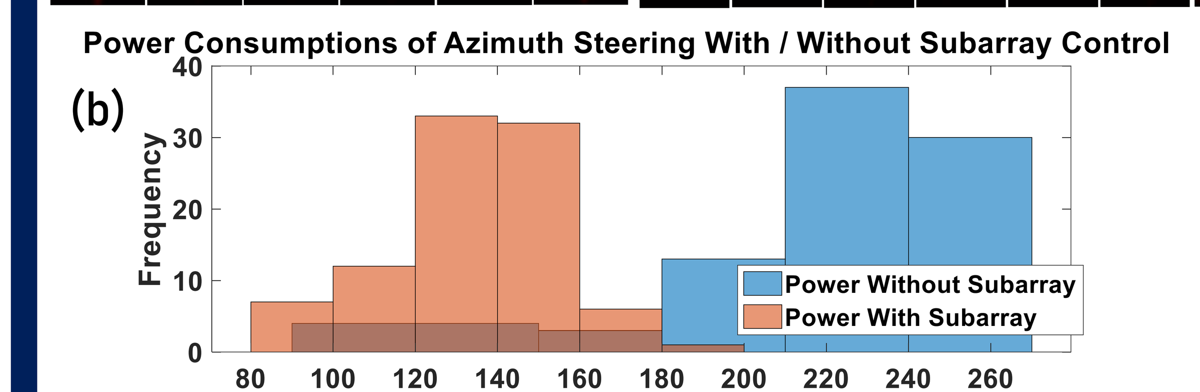


Figure 5. (a) Azimuth beamsteering (91 points) with and without subarray phase shift controls.(b) Histogram of total power consumption with and without subarray phase shift controls.

CONCLUSIONS

The power consumption histogram shows that the average power consumption with and without subarray controls are 135 and 220 mW respectively.

Therefore, applying subarray phase shifts effectively reduce the OPA total power consumption by ~38%.

Reference

[1] H. Abediasl and H. Hashemi, "Monolithic optical phased-array transceiver in a standard SOI CMOS process.," *Optics express*, vol. 23 5, pp. 6509–19, 2015.

[2] M. Milanizadeh, D. Aguiar, A. Melloni, and F. Morichetti, "Canceling Thermal Cross-Talk Effects in Photonic Integrated Circuits," *Journal of Lightwave Technology*, vol. 37, no. 4, pp. 1325–1332, Feb. 2019.

[3] F. Smith and H. Wu, "Photonic Phased Array Design by Synthesis," in *2018 IEEE 15th International Conference on Group IV Photonics (GFP)*, Aug. 2018.

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