Dual-Mode, Subarray Design for Optical Phased Array With Electro-Optic Phase Shifters

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ABSTRACT

We propose a new design optimization method for integrated optical phased arrays (OPA) with subarrays. The new design enables a low-loss mode for subarrayed OPA operation that offers better trade-offs between power consumption, optical loss, and chip area.

BACKGROUND

- Applications: LiDAR, Free-space communication
  - Demand: high scan rates, fine resolution, long range, and low power consumption, lower costs.
- Integrated OPA technology enables
  - Rapid beamsteering
    - Electro-Optic Phase Shifter (EOPS)
      - High modulation speed, low power consumption
      - More area, large drive voltage, high optical loss
    - Advanced, high-speed electronics
  - Narrow beamwidth
    - Large array aperture and dense spaced elements
      - Large number of elements
        - More area for power splitting
        - Higher power consumption
  - Monolithic Electronic & Photonic Integrated Circuit (EPIC)
    - Photonic filter, modulators, detectors, etc.
    - Advanced CMOS electronics

Extensive studies have been conducted to enhance the performance of OPAs at the EOPS device level.
Can we overcome the limitations of OPAs at the circuit level?

ELECTRO-OPTIC PHASE SHIFTER

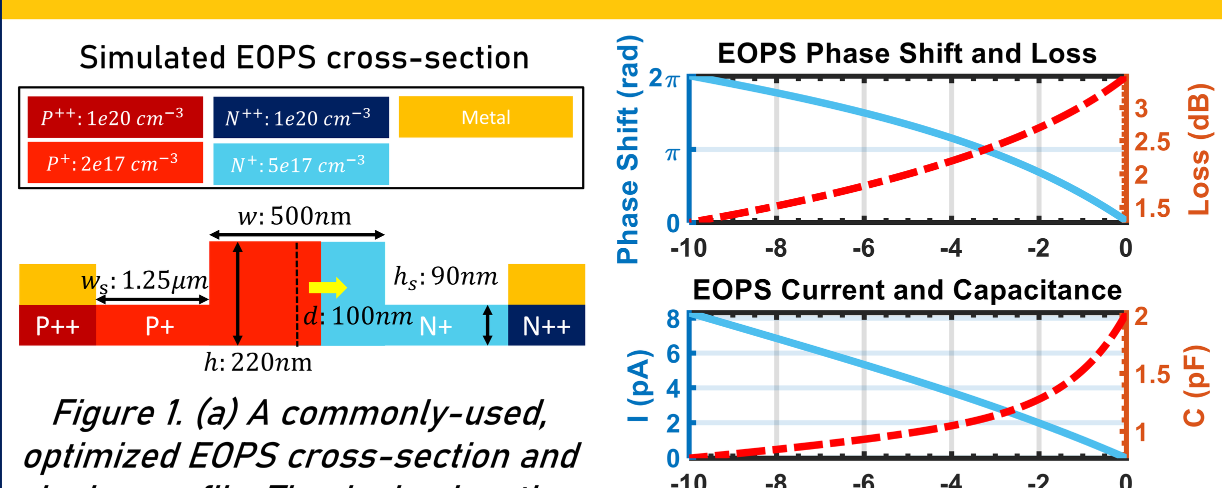

Figure 1. (a) A commonly-used, optimized EOPS cross-section and doping profile. The doping junction is shifted toward n-type region by 100 nm; the p-type doping concentration is slightly reduced to optimize the optical mode region and achieve lower optical loss. *(b) The simulated characteristics of the EOPS under reverse bias or carrier depletion (length = 5.875mm, designed to achieve a 2π phase shift within -10V).*

BEAMSTEERING AND COMMON PHASE

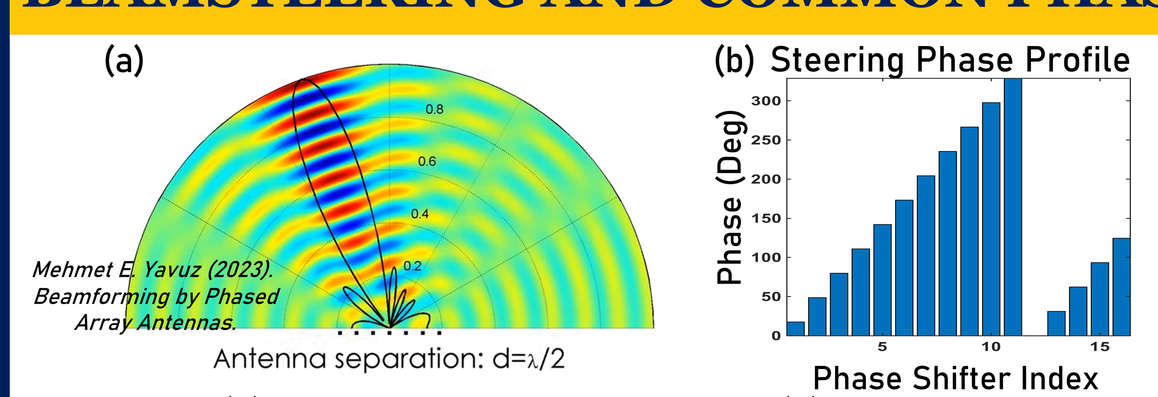

Figure 2. (a) Beamsteering field illustration. (b) Relative phase profile for beamsteering in a 16-element phase shifter array.

- For 1-D OPA, the relative phase profile at the phase shifter array
  - Follows a periodic sawtooth pattern.
  - Its slope and number of period ∝ steering angle.
  - Common phases exist between OPA antennas.

How can we leverage the common phases?

CASCADED SUBARRAY DESIGN

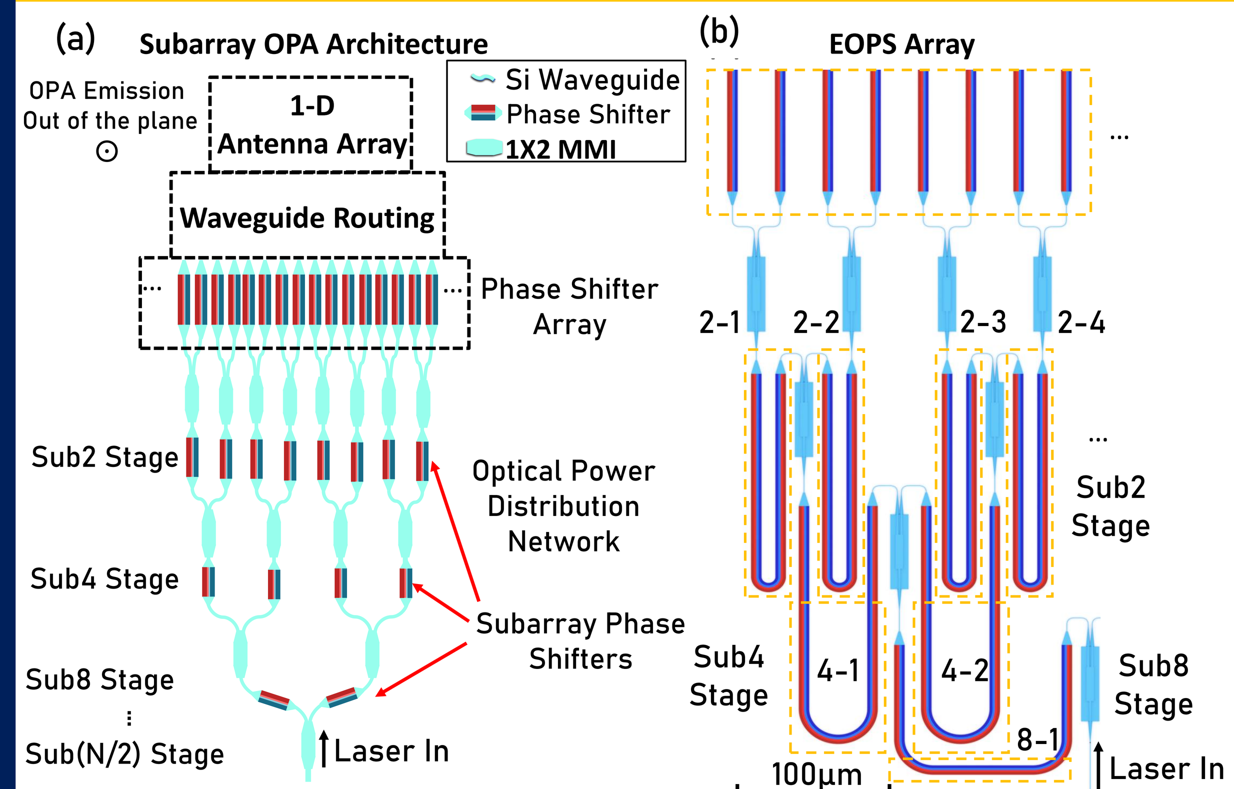

Figure 3. (a) Cascaded subarray design. (b) An example layout of a partial subarray design in the OPDN. Folded and interleaved layouts are possible.

- The phase of light accumulates along its propagation path.
- A subarray phase shifter introduces a common phase shift to grouped antennas before power splitting occurs.
- Advanced CMOS process/packaging technologies available.
- Introduce additional subarray controls to OPA's optical power distribution network (OPDN).
  - Common phases are controlled via subarrays.
  - Higher degrees of freedom allow non-unique solutions.
  - Folded and interleaved layouts are possible.
  - Various subarray configurations can be implemented.

COMMON PHASE REDISTRIBUTION

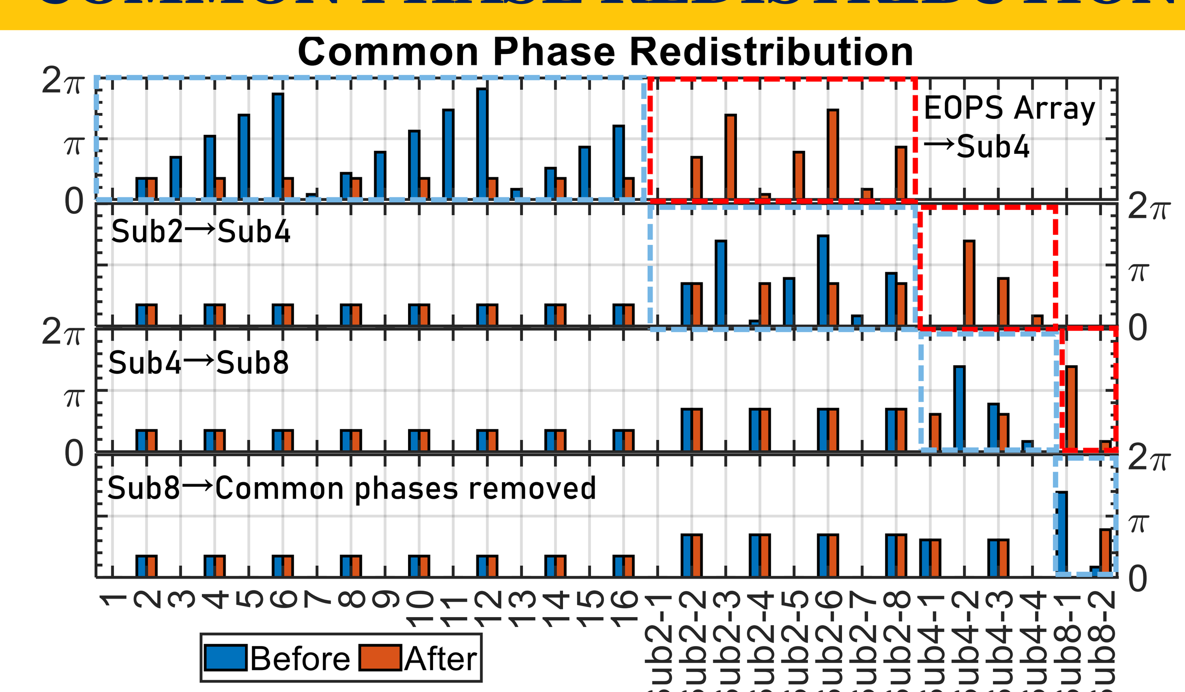

Figure 4. Common phase redistribution process: the common phases are propagated to the subarray and eventually exit the system. The final phase shift from each phase shifter is now below π.

- OPA steering vectors for the cascaded subarray:
  - Obtained from nonlinear programming optimization[ref:3]
    - Slower and require more computation resources.
  - Obtained from common phase redistribution algorithm.
    - A simpler and faster method.

- The common phase redistribution algorithm:
  1. Start with the original steering vector at the EOPS array.
  2. Identify & remove the common phases at the current stage.
  3. Transfer the common phases to the next subarray stage.
  4. Realign relative phases at the current stage to minimize the total power.
  5. Repeat Step 2,3,4 until the final common phase is removed from the system.

POWER REDUCTION

- The dynamic power is obtained through EOPS's time-domain simulation at 20MHz.
- Under subarray controls, EOPSs have smaller magnitudes of bias voltages and changes, leading to significantly reduction of static and dynamic power consumptions.
- However, the optical loss is increased due to the common loss introduced by the extra lengths of subarray EOPSs.
- To reduce the loss, additional common phases can be added to each subarray stage and EOPS array based on the available headroom of the reverse bias limit.

Low Power Consumption Mode

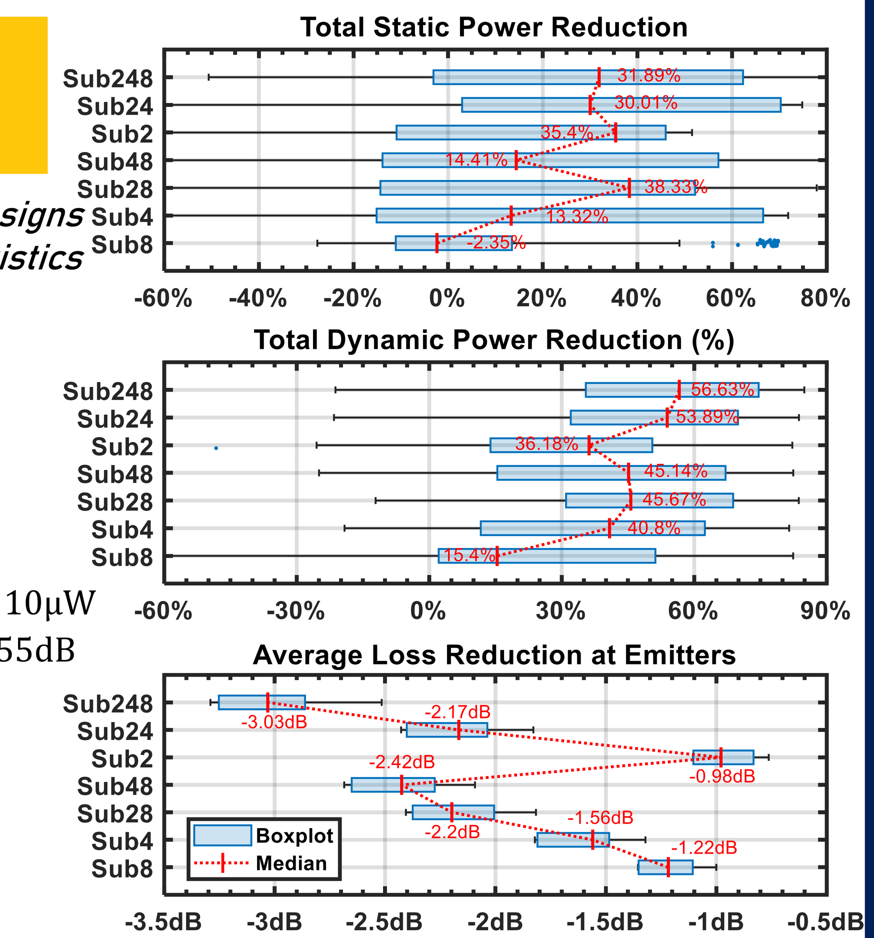

Figure 5. Subarray designs and performance statistics under low power consumption mode.

The reference design (without subarray) Est. performance:

- $P_{max,static}$: 0.3nW
- $P_{max,dynamic(20MHz)}$: 10μW
- $Loss_{ave@antenna}$: −2.55dB

LAYOUT AREA REDUCTION

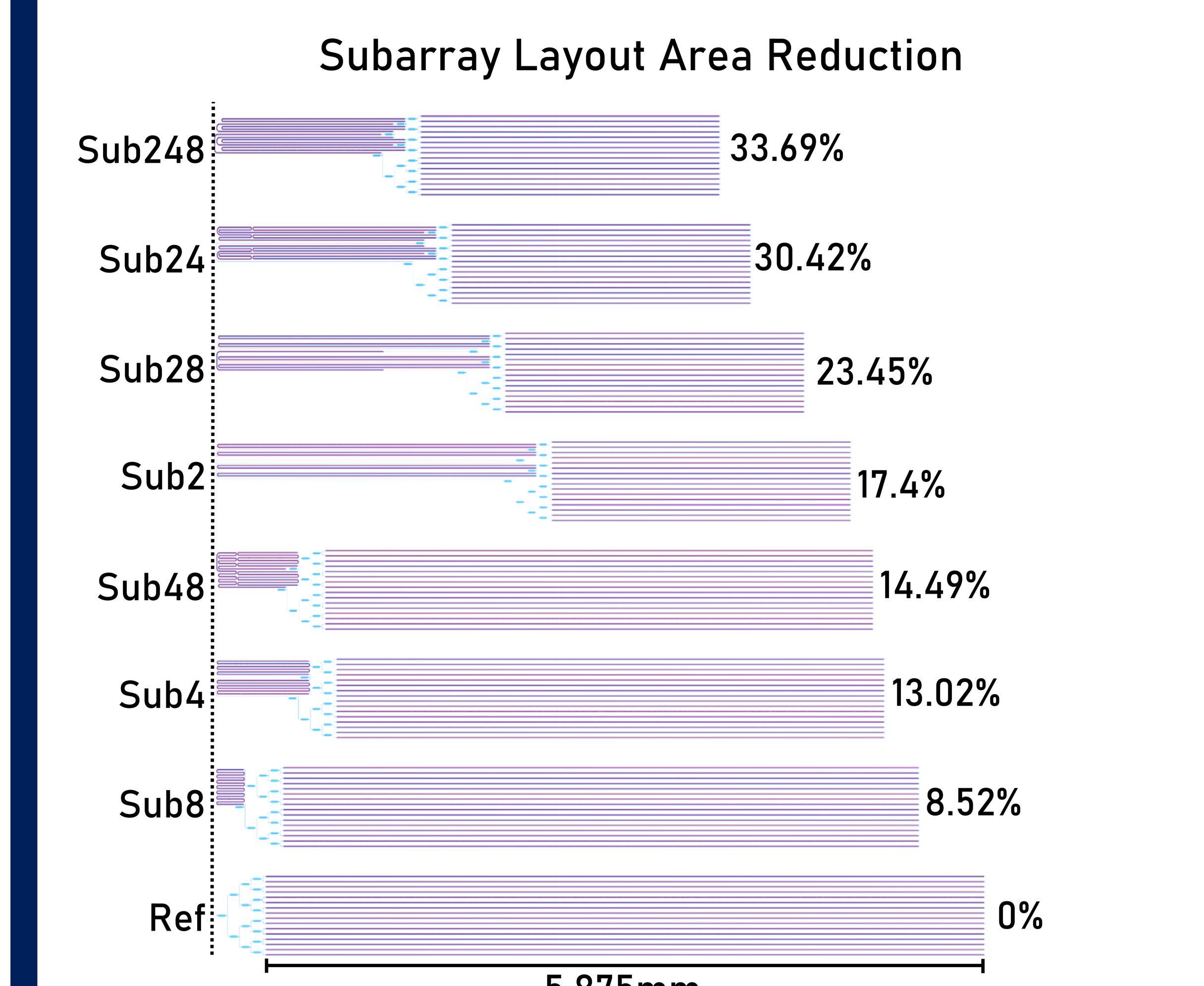

Figure 6. Layouts of different subarray configurations. Each configuration enables a different level of area reduction. All layouts have the same height. (half of each subarray layout is implemented to show the differences).

- OPA layout area reduction is achievable with subarrays.
- Use the developed algorithm to optimize all steering vector.
- Take statistics and get required phase range of each EOPS.
- Determine the required EOPS length of each subarray stage.
- Apply folding and interleaving methods to subarray stages.

LOW-LOSS MODE OPERATION

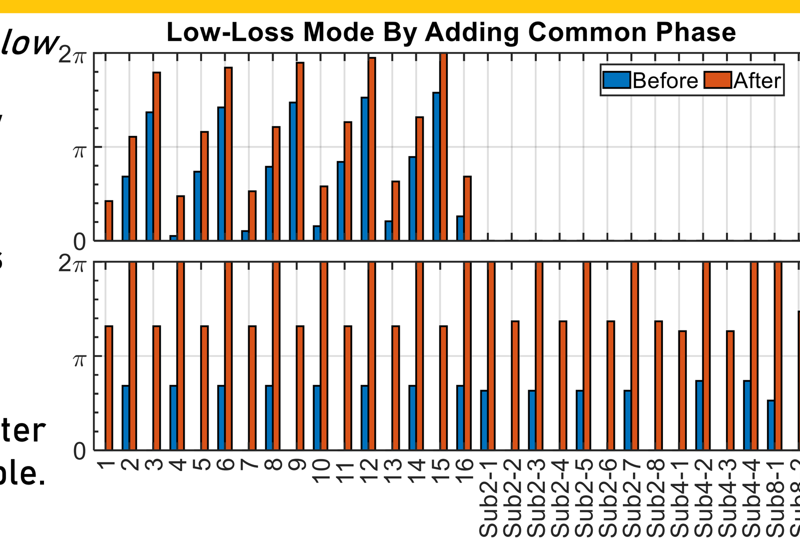

Figure 7. Operation in low loss mode by adding common phases to all stages.

- Without subarray: limited headroom is available for adding additional common phases.
- With subarray: greater headroom is available.

Low Optical Loss Mode

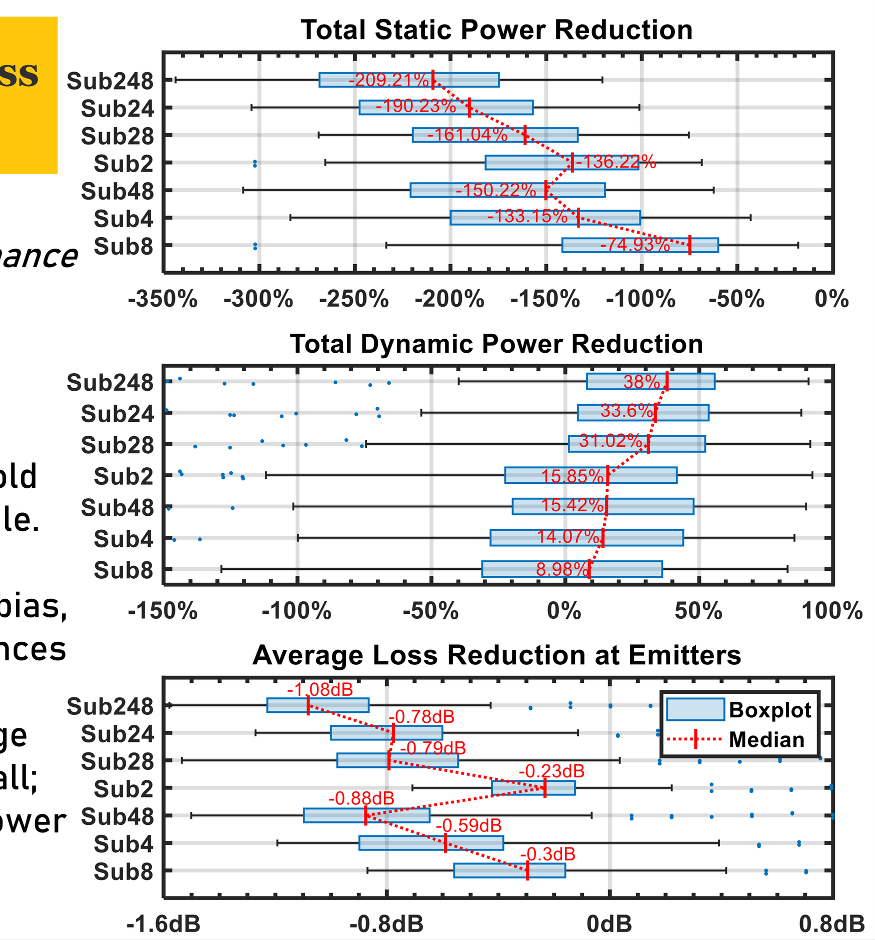

Figure 8. Subarray designs and performance statistics under low optical loss mode.

The static power increases several-fold but remains negligible.

Under high reverse bias, the EOPSs' capacitances are lower, and the magnitudes of voltage changes remain small; thus, the dynamic power consumption is still reduced.

CONCLUSIONS

The subarray design for OPA with reverse-biased EOPSs offers a trade-off between the number of controls and optical loss for a more compact footprint and reduced power consumption.

REFERENCE

[1] Poulton, C. V. et al. "Coherent LiDAR With an 8,192-Element Optical Phased Array and Driving Laser." IEEE Journal of Selected Topics in Quantum Electronics 28, 1–8 (2022).
[2] Zhang, Z. et al. "High-Speed and Low-Power Silicon Optical Phased Array Based on the Carrier-Depletion Mechanism." IEEE Photonics Technology Letters 34, 271–274 (2022).
[3] Wang, W. et al. "Cascaded subarray design and control method for power efficient, thermal crosstalk optimized optical phased array." Opt. Express, OE 31, 37381–37394 (2023).

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