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# Ultra-low power 256 channels optical phased-array based on low-doped carrier-depletion modulators

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**Abstract:** We report a 256 channels 1D optical phased-array (OPA) based on plasma-dispersion effect. This system exhibits ultra-low power consumption ( $\sim 1\text{mW}$ ) revealing the potential of carrier-depletion scheme at low doping dose for solid-state LiDARs applications. © 2022 The Author(s)

## 1. Introduction

Light Detection and Ranging (LiDAR) is a sensing technology based on the optical part of the electromagnetic spectrum. Its design in silicon photonics makes the LiDAR integrable at large scale with nonmechanical motion and enhanced performances. More specifically, the development of solid-state beam scanning technologies has attracted great attention for future mass-market deployment in automated driving, free-space optical datacommunications and widespread applications. Lately, the investigation on optical-phased arrays (OPA) as solid-state beam steering and beam shaping solutions gave promising perspectives and outcomes [1]. Today, most of the developed silicon OPAs use hundreds to thousands of thermo-optic (TO) phase-shifters with individual power consumption around 10mW which is not suitable for mobile applications. These require reducing the whole system consumption down to several hundreds of mW at the system level. In silicon, it is possible to induce a phase-shift by the mean of index manipulation through carrier-depletion effect, known as plasma-dispersion [2]. Devices based on this effect operate at high speed ( $>1\text{GHz}$ ) and with a lower power consumption ( $\sim CV^2.f$ ) at LiDAR scanning speeds ( $\sim 1\text{MHz}$ ).

In this work, we propose a 256 channels 1D OPA based on low-doped carrier-depletion modulators operating at a wavelength of  $1.55\mu\text{m}$  and integrated on a 300mm industrial platform. The power consumption, farfield pattern quality and steering performances are investigated to confirm the potential of such design.

## 2. Design and fabrication

We focused our research on the strategy of phase-control in the optical phased array. The phase modulators are designed on a 300nm SOI and based on a 250nm deep-etched access arms [3]. The detailed geometry is shown in Fig.1 and the default junction has been previously optimized in [3]. A first demonstration is done on a PN modulator using the optimal high doping (HD) of datacommunications ( $\sim 1\text{e}18\text{cm}^{-3}$ ). Nevertheless, in the case of OPA, this dose can be optimized, considering the overall OPA loss as the main criterion rather than bandwidth or OMA. This optimization is based on simulations [4] and shows the strong relation between the propagation losses, the optimal doping doses, and the position of the junction. For the designed asymmetric junction, lowering the doping levels down to  $1\text{ to }3\text{e}17\text{cm}^{-3}$  allows to reduce the OPA loss at its minimum. A reverse bias between 0 and 3V is then applied to extract associated losses, modulation efficiency and power consumption at 1MHz scanning frequency.

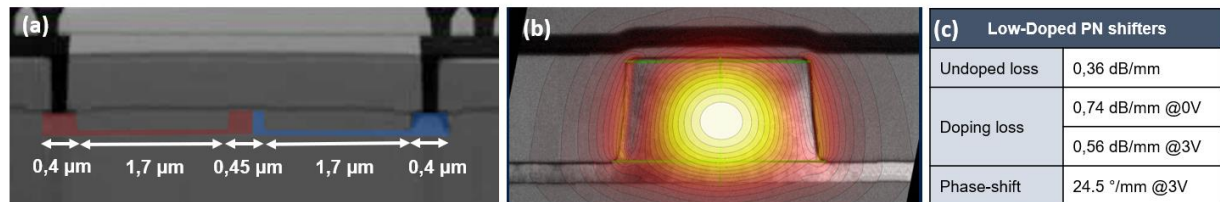


Fig. 1. Deep-etched PN phase-shifters (a) TEM cut with access arms and contacts (in red: P-doped region, in blue: N-doped region), (b) TEM cut of the doped waveguide and its optical mode, (c) Summary of performances of the low-doped PN shifters ( $\sim 1\text{-}3\text{e}17\text{cm}^{-3}$ )

### 3. Modulator characterization

The first results obtained with high doping (HD) doses, demonstrate efficient phase-modulation on the range of applied voltage (0 to 39.7°/mm). In counterpart, such doping level arises rather high losses (2 to 1.77dB/mm). Measurements confirmed that lower doping levels (LD) tend to reduce losses (0.74 to 0.56dB/mm) at the cost of weaker phase-shift efficiency (up to 24.5°/mm). Importantly, due to their capacitive behavior, the only consumption of PN comes from the change of applied voltage (0.28μW/mm for LD PN at 1MHz) unlike TO or PIN shifters that need continuous current injection in static regime.

Considering further integration of PN shifters in OPAs, the reduced efficiency of LD PN is a critical limitation for compactness. While a  $2\pi$ -phase-shift could be reached with 9mm-long HD PN, it is reached with 14mm-long LD PN. However, at these lengths, a HD PN loses 7dB more than a LD PN that would need to be compensated with a 20% increase of the input optical power which is not negligible looking at the consumption of a single modulator.

### 4. OPAs integration and characterisation

We fabricated a first 16 channels 1D OPA demonstrator with 9mm-long HD PN junctions to test the carrier-depletion scheme. In a second time, we implemented a 256 channels 1D OPA with 14mm-long LD PN junctions to confirm the potential of LD PN modulators (Fig.2a). Both OPA are operating at 1.55μm and use 400μm-long corrugated waveguides that act as antennas. Based on individual loss measurements of on-chip coupling, splitting and phase-modulation (but without antenna coupling efficiency), the 256CH LD OPA is expected to exhibit losses up to 12dB per channel against 19dB for the 16CH HD OPA.

The wafer level characterization is performed on a semi-automated prober, with fiber injection for on-chip coupling and electrical control ensured by a multiprobe. The farfield is collected on an IR camera combined with a genetic algorithm that pilots the set of modulators [5]. The low farfield spot divergence in both dimensions is found to be  $0.18^\circ \times 0.44^\circ$  for 256CH OPA (Fig.2d) and  $2.9^\circ \times 0.31^\circ$  for 16CH OPA, that is in good agreement with simulations. For both OPAs, a setup-limited steering range of  $\pm 25^\circ$  is realized in the array dimension by tuning the phase in each channel (Fig.2b) while the theoretical steering range is  $\pm 50^\circ$  thanks to a 2μm pitch (Fig.2e). Finally, for the 256CH OPA, the scanning in the second dimension is achieved through wavelength tuning with a dispersion efficiency of  $0.12^\circ/\text{nm}$  (Fig.2c). In the end, scanning between  $-20^\circ$  and  $20^\circ$  deflection angles with the 256CH OPA LD results in a total driving consumption of the system around 1mW at a scanning frequency of 1MHz (3.92μW per shifter) which confirms the potential of LD PN modulators for phase-controlled beam-steering.

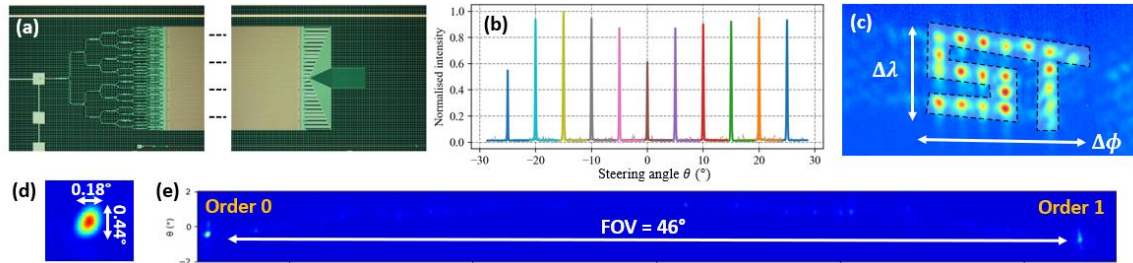


Fig. 2. 256CH OPA characterization (a) Microscope view (x5), (b) OPA field  $\pm 25^\circ$  scanning, (c) Superposition of farfield patterns after a 2D scanning with 100nm wavelength tuning, (d) Farfield pattern on the IR camera, (e) Panorama view of the farfield at  $-22^\circ$  deflection angle with side-lobe at  $24^\circ$ .

### 5. Conclusion

All in all, our work indicates that the low-doped carrier-depletion-based OPAs have great perspectives as ultra-low power solid-state LiDARs.

### 4. References

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