High-Performance Integrated Optical Phased Arrays for Chip-Scale Beam Steering and LiDAR

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Abstract: We present high-performance integrated optical phased arrays and LiDAR on diffusive targets for the first time at 25 m with velocity extraction. This work shows the promise for optical phased arrays in solid-state LiDARs.

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1. Introduction

Light detection and ranging (LiDAR) is becoming a crucial ranging technology for autonomous vehicles. With a recent emphasis on low-form-factor solid-state LiDARs, integrated photonics has taken the spotlight in miniaturizing systems with on-chip beam steerers and photodetectors. Integrated optical phased arrays (OPA) have been proposed for on-chip beam steering [1–5] but technical issues such as high loss have limited OPAs in LIDAR systems, and ranging on diffusive targets has yet to be shown [1]. In order to achieve centimeter-scale apertures, thousands of elements are required. Commonly used thermo-optic phase shifters have power consumptions on the order of 15 mW/π [1–3] and injection-based phase shifters require 10 mA/π [4, 5], limiting the number of elements and driving electronics. Furthermore, due to limitations in reticle size and the desire for multiple systems per reticle, matched phase shifter and antenna pitches (inline phase shifters) are crucial for scalable inexpensive arrays with equal-path-length elements.

In this work, we present record-performance optical phased arrays with low-loss and low-power components such as inline <2µW power optical phase shifters with an average loss of only 2.4 dB and >90% directional antennas over a ∼200nm band. 2D beam steering is demonstrated with 13 dB side lobe suppression and less than 20 dB noise floor. Using OPAs as transmitter and receiver apertures, LiDAR with table-top detectors is demonstrated at 25 m on diffusive targets with velocity extraction for the first time.

2. Optical Phased Array Component Results

A schematic of a one-dimensional OPA is shown in Fig. 1(a) which includes a power distribution network, optical phase shifters, and waveguide grating antennas. Cascaded 1×2 splitters are utilized for their high element count scalability and inherent path length matching. The splitters used have a –0.04 dB transmission at 1550 nm and within –0.08 dB from 1475 nm to 1625 nm, allowing for broadband operation. In order to reach thousands of elements, low-power phase shifters are essential. Fig. 1(b) shows the loss and power response of the reverse-biased electro-optic phase shifters used. A phase shift of 2π is achieved with a maximum power of only 2 µW, and an average loss of 2.4 dB when applying modulo 2π across the elements. The 10%-90% time constant was measured to be less than 10 ns, enabling a fast scanning rate. Finally, a long unidirectional waveguide grating antenna design is employed to allow maximum efficiency and minimize light interaction with the silicon substrate. The emission pattern (element factor) is designed to minimize power in any grating lobes. Fig. 1(c) shows a sum of element factors while sweeping wavelength showing minimal substrate reflections and indicating greater than 90% directionality from 1450 nm to 1640 nm.

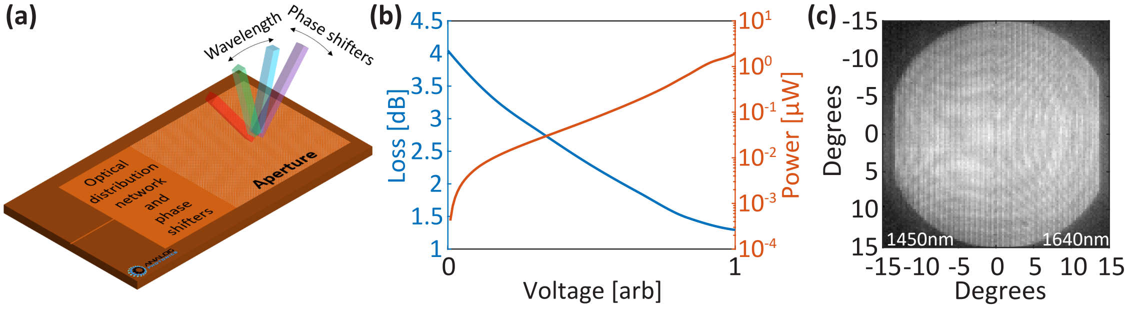

Fig. 1. (a) Schematic of a one-dimensional OPA. (b) Phase shifter loss and power as a function of voltage. (c) Sum of element factors while sweeping wavelength of unidirectional waveguide grating antennas.

3. Optical Phased Array Experimental Results

An inline uniform pitch 512 element OPA was fabricated without large-footprint pitch-converting "S" bends or waveguide fan-outs/ins and driven with an FPGA with custom DAC boards and a tunable laser. Fig. 2(a) shows far field intensity cuts when beam steering with the optical phase shifters in a 20° field of view. The look-up-table (LUT) for phase shifter beam steering was generated with feedback from an InGaAs IR camera. Fig. 2(b) plots the intensity cuts of a beam showing a 13 dB side lobe suppression, and less than –20 dB noise floor (limited by the InGaAs IR camera used). Fig. 2(c) is the sum of various normalized single far field spots when performing 2D beam steering with the phase shifters and input wavelength. Note that no adjustment to the element phase values is needed when steering with wavelength due to the inherent path length matching and broadband phase shifter design, allowing for a look-up-table (LUT) with minimal memory requirements. Fig. 2(d) shows an IR camera image of a beam on a wall 25 m away emitted from a large-scale passive OPA. A LiDAR system was created with OPA transmitter and receiver apertures and table-top detectors. 1D scanning LIDAR was achieved with wavelength steering up to 25 m as shown in Fig. 2(e) scanning objects such as a wall and couch. The coherent LiDAR detection method used also allows for velocity measurements [6] as shown in Fig. 2(f) where a spinning umbrella is present in the scene.

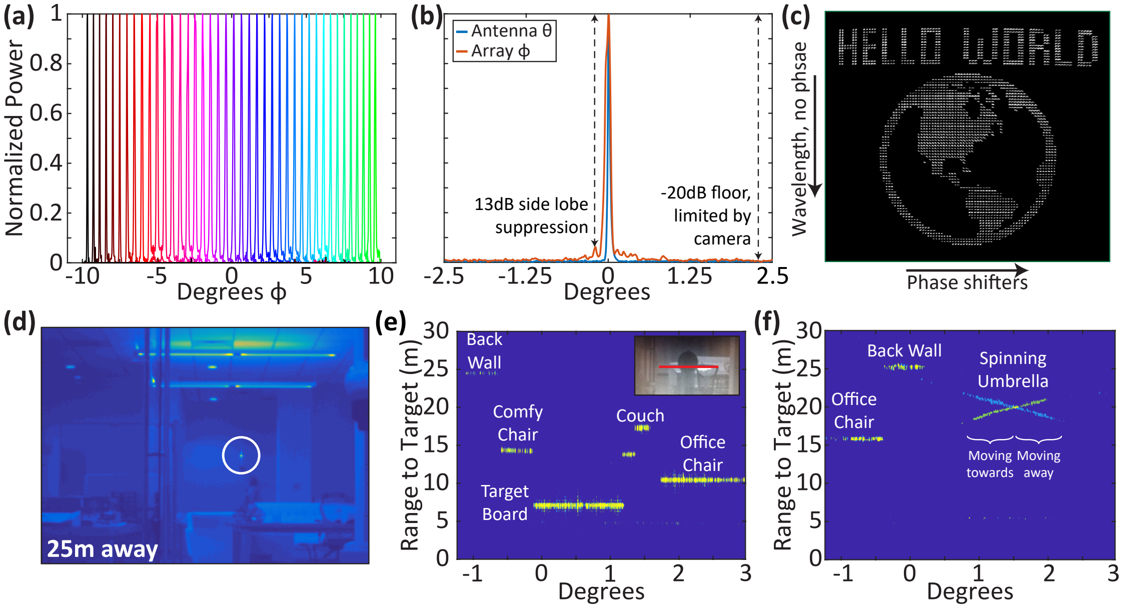

Fig. 2. (a) Beam steering with phase shifters. (b) Zoom-in of spot showing 13 dB side lobe suppression and –20 dB noise floor. (c) Sum of far field spots showing 2D beam steering. (d) Beam of large-scale passive OPA on a wall 25 m away. (e) LiDAR ranging results on diffusive targets, inset shows ranged scene. (f) LiDAR results on a spinning target showing velocity detection.

In conclusion, we have demonstrated high-performance OPA components with –0.04 dB splitter transmission, inline phase shifters with <2 µW power consumption and 2.4 dB average optical loss, and >90% antenna directionality over a ∼200 nm wavelength band. 2D beam steering was shown with independent wavelength and phase steering due to the path-length-matched elements and an output beam with 13 dB side lobe suppression and a noise floor <–20 dB. Utilizing table-top detectors, LiDAR with OPAs was shown at a 25 m range on diffusive targets with velocity extraction for the first time. This work shows the promise for silicon photonic optical phased arrays in integrated LiDAR systems.

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