A large-scale coherent imager with digital beamforming

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Abstract: We showcase a 128-element nanophotonic coherent imager with a parallelized readout. This architecture enables single-shot coherent optical imaging without the need for on-chip phase shifting and beam scanning. Using 6 elements, we demonstrate digital beamforming and coherent image reconstruction with a 1.67° beamwidth over an 8.30° field-of-view. © 2024 The Author(s)

1. Introduction

Digital signal processing (DSP) is a valuable resource for coherent communications and sensing, driving the increase in data capacity in coherent optical communications over the last decade [1]. While DSP serves a critical role in coherent systems and has been intertwined with the hardware developments of many radio-frequency to mm-wave technologies, there has been limited work in leveraging DSP for coherent optical sensors and imagers.

Optical phased arrays (OPAs) are an emerging technology with applications in optical imaging, ranging, holography, and free-space optical communications [2,3]. While radio-frequency and mm-wave phased arrays leverage DSP techniques such as digital beamforming to enable more flexible and adaptive wavefront manipulation, digital beamforming in OPAs has yet to be explored. In this work, we demonstrate digital beamforming operating at a wavelength of 1550 nm with 6 elements of a 128-element coherent imager photonic integrated circuit (PIC). This new class of free-space photonic-electronic processors will use the advantages of DSP to improve the performance of OPA transmitters and receivers for free-space optical applications.

2. Coherent Imager Architecture

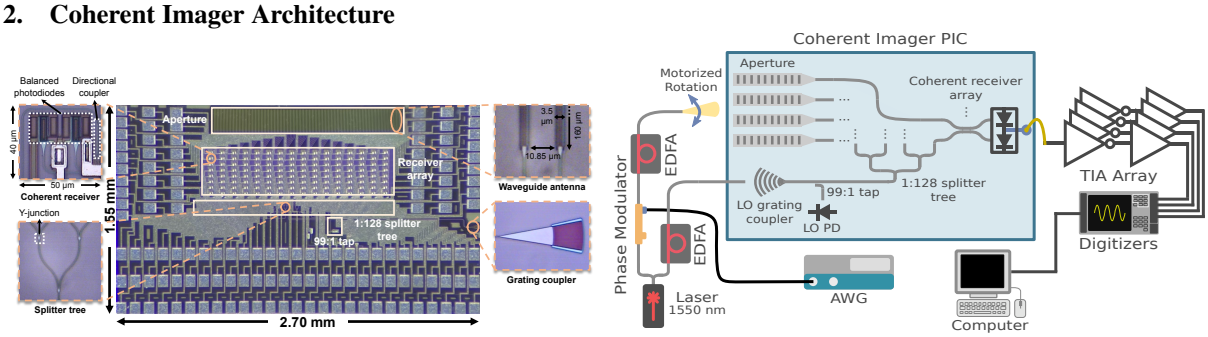


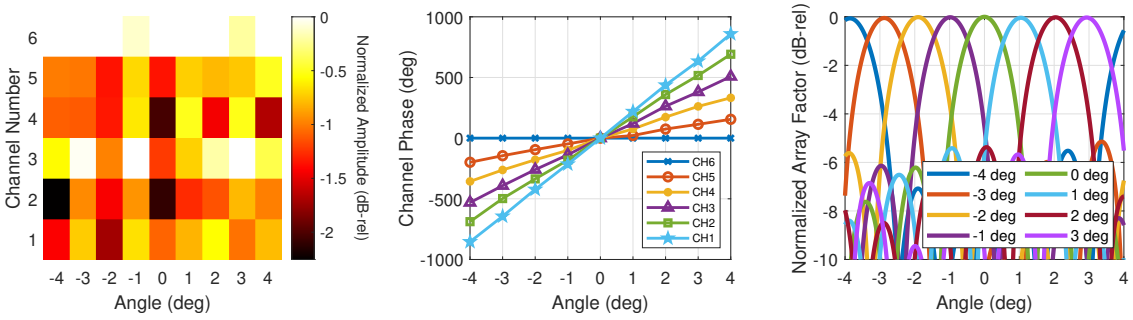
Fig. 1: a) Micrograph of the coherent imager photonic integrated circuit with the chip dimensions. b) Diagram of the chip and the measurement setup for digital beamforming and coherent image reconstruction.

The coherent imager is comprised of 128 channels of photonic receivers with parallelized readout for subsequent electronic amplification, digitization and signal processing, as shown in Fig. 1a. Each receiver has a $160 \times 3.5\ \mu m^2$ grating coupler for free-space coupling. The antennas are placed with a uniform pitch of 10.85 μm, resulting in a total physical aperture size of $1380 \times 160\ \mu m^2$. Each antenna is routed to a coherent receiver comprising a 50:50 directional coupler and a balanced pair of Ge photodiodes. Each directional coupler also accepts a local oscillator (LO) which is coupled to the chip with a grating coupler. The LO waveguide has a 99:1 tap to a photodiode for LO power monitoring and is routed to each receiver after a 1:128 splitter tree. The output of each coherent receiver is routed electrically to a pad, which is then wirebonded to a PCB that hosts an array of transimpedance amplifiers (TIAs). After amplification, all outputs are digitized for subsequent signal processing.

The parallelized readout allows amplitude and phase information to be extracted from each channel without losing any information through channel combining. This enables single-shot coherent image reconstruction of the

environment without the need for on-chip phase shifters that can increase the power consumption and calibration time of the PIC, especially with thermal crosstalk [4].

3. Digital Beamforming



(a) (b) (c)

Fig. 2: a) Extracted channel amplitudes for different illumination angles. b) Extracted channel phases for different illumination angles. c) Digitally reconstructed images of the environment for different illumination angles.

We demonstrate digital beamforming and image reconstruction with the measurement setup shown in Fig. 1b. A coherent signal and LO are generated with a 50:50 splitter using a 1550 nm laser source. The LO is phase-modulated with a voltage ramp at 1 MHz using a LiNb phase modulator. The LO is then amplified with an EDFA to ensure a quantum-limited noise floor [5]. The chip is placed on an alignment stage, and the LO is coupled to the chip with a fiber on an XYZ positioner. The aperture is illuminated by a signal fiber that is located at least 2 cm away from the chip surface for far-field operation. The signal fiber is attached to a motorized rotation stage to scan the illumination angle of the wavefront.

For each illumination angle, the channel outputs are digitized and filtered with a 10 kHz digital bandpass filter. The channel amplitudes and phases are then extracted using Hilbert transform by taking the median of amplitude and phase counts. To digitally reconstruct the environment images, one channel is used as a reference to extract the static phase offsets between the channels, and one illumination angle is set to be the 0° reference image. The resulting amplitudes and phases of the channels are shown in Fig. 2a and Fig. 2b, respectively. Assuming far-field operation, the radiation pattern image is reconstructed by calculating the array factor defined as

$$AF(\hat{r}) = \Sigma_{n=1}^{N} a_n e^{jk\hat{r}\cdot\vec{r_n}} \tag{1}$$

where a_n is the extracted complex coefficient of channel n, k is the wavenumber, $\hat{r}$ is the direction unit vector corresponding to radiation pattern angles, and r_n is the coordinate of the antenna corresponding to channel n.

The reconstructed images of the environment for different illumination angles are shown in Fig. 2c. The average half-power beamwidth of the digitally-reconstructed beams is 1.67°, and the average field-of-view is 8.30 °. The beam angles in the reconstructed images match closely with the illumination angle set by the rotation stage, showcasing accurate coherent image reconstruction with DSP.

4. Conclusion

To our knowledge, this is the first demonstration of digital beamforming with a coherent imager, leveraging DSP to use the coherent imager as a photonic-electronic free-space information processor. By employing a parallelized readout scheme, this architecture enables both photonic and electronic processing to be leveraged for coherent imaging and sensing without any information loss through channel combining. It enables single-shot coherent image reconstruction of the environment without the need for on-chip phase shifting and beam scanning.

References

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