IQ Photonic Receiver for Coherent Imaging With a Scalable Aperture

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ABSTRACT Silicon photonics (SiP) integrated coherent image sensors offer higher sensitivity and improved range-resolution-product compared to direct detection image sensors such as CCD and CMOS devices. Previous generations of SiP coherent imagers suffer from relative optical phase fluctuations between the signal and reference paths, which results in random phase and amplitude fluctuations in the output signal. This limitation negatively impacts the SNR and signal acquisition times. Here, we present a coherent imager system that suppresses the optical carrier signal and removes non-idealities from the relative optical path using a photonic in-phase (I) and quadrature (Q) receiver via a $90^\circ$ hybrid detector. Furthermore, we incorporate row-column read-out and row-column addressing schemes to address the electro-optical interconnect density challenge. Our novel row-column read-out architecture for the sensor array requires only $2N$ interconnects for $N^2$ sensors. An $8 \times 8$ IQ sensor array is presented as a proof-of-concept demonstration with $1.2 \times 10^{-5}$ resolution over range accuracy. Free-space FMCW ranging with $250 \mu$m resolution at 1 m distance has been demonstrated using this sensor array.

INDEX TERMS Coherent imager, silicon photonics, LiDAR, IQ receiver.

I. INTRODUCTION

OPTICAL imagers have a wide range of applications in microscopy, medical imaging, remote sensing, and 3D imaging (LiDAR) such as autonomous vehicles, robotics, and surface metrology. Traditional CCD and CMOS image sensors have performance limitations due to their dark current noise and read noise (input-referred-noise) in low-light conditions. On the other hand, coherent heterodyne detection offers improved sensitivity due to the perceived gain of the reference path, which enables coherent imagers to operate close to the shot-noise limited regime. Furthermore, the advancement of integrated optical processing technologies, such as silicon photonics (SiP) platforms, permits compact and complex waveform processing. This allows coherent photonic imagers to benefit from signal enhancement techniques available in RF heterodyne receivers and radar systems. Moreover, photonics imagers with micrometer-scale wavelengths offer smaller apertures and superior spatial resolution compared to their RF counterparts. Additionally, coherent receivers have been utilized for remote sensing, LiDAR [1], [2], and medical imaging applications (such as OCT [3]) via loss, refractive index, or time-of-flight measurements.

Coherent imagers operate either with flash illumination [4], [5] or on a point-by-point basis using electrical [6], [7], or mechanical steering [8], [9], [10]. Point-by-point illumination improves the SNR and reduces the interference [11]. As a result, point-by-point illumination has been the subject of much attention with the introduction of all-integrated optical phased arrays (OPA), which allow for solid-state beam steering [12], [13], [14]. On the receiver end, a lens [15], [16] or a solid-state beamforming receiver [17] reconstructs the image of the target, and signal detection is achieved via heterodyne mixing.

Such an imaging system is shown in Fig. 1(a). The desired image information, whether it is the refractive index, the optical absorption of the material, or time-of-flight ($\eta(x, y, z)$), can be extracted after digitization in post-processing [15], [16], [18]. There are two challenges with these architectures. First, the undesired relative optical
distribution network further improves the dynamic range of the pixel interface via this row-column read-out architecture. For a sufficiently large receiver array (for example $100 \times 100$ pixels), this receiver architecture would simplify the analog amplification back-end’s footprint and power consumption by $100 \times$ and reduce the required optical power by the same factor compared to the architectures with a uniform power distribution and dedicated TIAs per pixel [15]. On the other hand, the interconnect density challenge for the control signals is addressed using a row-column drive architecture [12] which also reduces the number of interconnects for control from $N^2$ to $2N$ for $N^2$ pixels. The details of these designs are addressed in Section III.

In this work, we demonstrate a large-scale coherent imager architecture by implementing an $8 \times 8$-pixel IQ imager with a scalable aperture in a standard silicon photonics process. Our measurements demonstrate that this imager can measure frequency differences between the reference and illumination path with $1.2 \times 10^{-5}$ resolution over range accuracy within $1$ ms signal acquisition time. Our row-column read-out architecture exhibited better than $-80$ dB cross-talk below $5$ MHz frequency offset. We characterize the performance of this imager in a practical scenario by performing a free-space FMCW ranging measurement with this sensor, obtaining $250 \mu$m range resolution at $1$ m distance.

II. PHOTONICS IQ RECEIVER

As mentioned earlier, heterodyne detection in photonic coherent detection offers improved SNR by eliminating the contribution of read-noise and the detector’s dark-current noise. The current signal at the output of the detector is the down-converted mixed component of the received and reference signals,

$$ E_r(t) = \eta A_1(t) \cos(\omega_{opt} t + B_1(t) + \phi) $$

$$ E_{LO}(t') = A_2(t') \cos(\omega_{opt}' t' + B_2(t') + \phi') $$

where $A_1(t)$ and $B_1(t)$ are amplitude and phase modulation signals, respectively, $\omega_{opt}$ is the frequency of the optical carrier, $\phi$ and $\phi'$ are the phase of the optical carrier, and $\eta$ is the complex reflection coefficient of the target. Assuming a photodetector responsivity of $R$, the output current is given by:

\[ \text{FIGURE 1. IQ coherent imager. (a) Typical coherent imaging scenario. (b) Proposed IQ imager with a scalable aperture.} \]

\[ \text{FIGURE 2. 90° hybrid detector. A directional-coupler based 90° hybrid ensures low-loss in-phase and quadrature signal generation. Balanced detectors suppress the common-mode signal.} \]
where \( \Delta \phi = \phi - \phi' \) is the contribution of the laser phase noise and receiver/illumination signal path phase mismatches. The desired target information is contained in the third term of Eq. (3). The first two terms of this equation can be subtracted using balanced detectors. If phase modulators are used for time-of-flight measurements (such as FMCW) the mixed signal will simplify to

\[
I(t) = 2 \eta R \cos(B_1(t) - B_2(t')) + \Delta \phi,
\]

where the path mismatch term \( \Delta \phi \) will degrade the signal term \( B_1(t) - B_2(t') \) as phase-noise. In this case, time-domain variations in \( \Delta \phi \) will be indistinguishable from the signal term. In the case that amplitude modulators are used for time-of-flight measurements, the mixed-signal Eq. (3) will simplify to

\[
I(t) = 2 \eta R A_1(t) A_2(t') \cos(\Delta \phi),
\]

where the path mismatch term \( \Delta \phi \) will degrade the mixed signal term \( A_1(t) A_2(t') \) as an amplitude noise. In both these cases, it is desired to completely remove the optical path phase difference term, \( \Delta \phi \), from the signal.

Instead of standard heterodyne mixing, which is prone to fluctuations in the optical carrier phase signal, the output signal can be broken down to in-phase and quadrature components using the 90° hybrid detector as shown in Fig. 2. The reference signal and the received signal are split using a 3 dB coupler and combined using directional couplers in two separate paths with a 90° optical delay difference in the signal paths. The resulting signals are detected using balanced detectors to remove the common-mode terms. The two electrical outputs of the hybrid 90° detectors are:

\[
I(t) = \eta R A_1(t) A_2(t') \cos(B_1(t) - B_2(t') + \Delta \phi),
\]

\[
Q(t) = \eta R A_1(t) A_2(t') \sin(B_1(t) - B_2(t') + \Delta \phi)
\]

Computing the sum of the square of these two signals, (6) and (7), removes the optical path phase mismatch term \( \Delta \phi \) term resulting in

\[
I^2(t) + Q^2(t) = \eta^2 R^2 A_1^2(t) A_2^2(t')^2,
\]

which completely removes the amplitude fluctuations for the case of amplitude modulated time-of-flight measurements in Eq. (5). The proposed hybrid 90° coupler in this design incorporates directional couplers, which have negligible loss compared to MMI couplers used in [28], which exhibit an additional 0.5 dB loss. Furthermore, small thermal modulators (Fig. 2) can be incorporated in the path of the reference signals to correct for deviations from the ideal 90° path difference due to fabrication mismatch, operational wavelength, or temperature change. A simulation of the output I, Q, and \( I^2 + Q^2 \) signal is shown in Fig. 3.
The two row signals set the DC bias voltage at the output of the balanced detectors as well. The relative DC voltages at the row bias nodes and the column read nodes determine which silicon diode is forward biased to allow the balanced detector’s mixed signal to be connected to the amplifier. For a given measurement cycle, all but one of the rows are in reverse bias. This blocks the signal path from the output of the balanced detectors in the other rows to the amplifiers.

The germanium photodetectors, that are disconnected because of the reversed-bias diode at a given read cycle, can get damaged due to charge build-up when there is no DC path for the generated charge in the diode to dissipate through [29]. This problem is addressed by placing a parallel resistor with each photodiode that creates a current path for the disconnected rows.

It can be observed that while the row-column read-out diode in reverse bias can provide electrical isolation between the rows, for very large arrays, the accumulated current leakage from the disabled rows can degrade the active pixel’s dynamic range. To address this, we designed a tunable power distribution block (Fig. 5) that attenuates the reference power delivered to the disabled rows. This attenuates the down-converted mixed signal output from the disconnected rows.

Another critical aspect for the scalability is row-column addressing of the thermal phase tuners (shown in Fig. 2) in the 2D grid of IQ cells. To address this scalability challenge, we incorporated a row-column drive methodology utilizing the thermal memory of the phase shifters (typically in kHz range) as shown in Fig. 6. Each row of resistors in the thermo-optic phase shifters (TOPS) is activated by forward biasing the series diodes in that row for 1/8th of the cycle with pulsed-amplitude-modulation (PAM) drivers. All thermo-optic phase shifters receive \( 8P_{TOPS} \) the required power for 1/8 of the cycle. This enables independent programming of 64 phase shifters with only 16 electrical drivers. In addition, programming the rows at MHz frequencies ensures that the thermo-optic phase shifters receive a constant average power of \( P_{TOPS} \).

IV. SILICON PHOTONICS IMPLEMENTATION

The image sensor architecture was implemented in Advanced Micro Foundry’s (AMF) standard silicon photonics process. This proof-of-concept device contains an \( 8 \times 8 \) coherent IQ pixel array, as well as a 1:8 re-configurable amplitude distribution block with calibration feedback (Fig. 1(b)).

The receiver unit cell for IQ detection, as shown in Fig. 7(a), splits the reference and received signals using 3 dB Y-junctions and mixes the two signals using directional couplers. The signal path length is adjusted by incorporating two symmetric 45° waveguide length mismatches between the reference signal and the pixel for a total of 90° path length difference for I and Q generation. The outputs of each directional coupler are fed into a balanced detector to remove the common-mode signal at each output. For the row-column operation of this pixel, (Fig. 4), 5 kΩ resistors were put in parallel with each photodiode to prevent damage via charge accumulation. A silicon diode was implemented using n-type and p-type dopants available for the silicon layer. Two small tuning resistors are included in the 90° hybrid mixer to enable fine-tuning of the structure by a few phase degrees for small changes in the operation wavelength and the fabrication mismatches. The two tuning resistors change the path length mismatch between the I and Q paths in opposite directions. This enables IQ fine-tuning with very little power consumption of around 0.5 mW for 10° phase correction for a typical thermo-optic phase shifter, based on the data reported in [12]. Each tuning resistor is broken down...
FIGURE 7. (a) Far-field pattern of the receiving element. (b) Hybrid 90° detector implementation.

FIGURE 8. Samples of the measured IQ waveforms.

into two pieces for more uniform heating and is placed in series with a silicon diode for row-column addressing. As a result, the entire tuning resistor array of 128 thermo-optic phase shifters required only 24 electrical connections. The pixel pitch for this design can be as small as 50 µm but was set to 100 µm for compatibility with commercially available micro-lens arrays.

The received signal was collected using a custom-designed and compact, 5.6 µm × 5 µm, grating coupler, as shown in Fig. 7(b). The simulated coupling efficiency of this grating coupler was −3 dB with an optimum angle of 9° and a 10° field-of-view.

The tunable amplitude couplers were implemented using length-matched spiral thermo-optic modulators, similar to [12] (Fig. 5(a)). Path-length matching reduces the thermal cross-talk via the substrate between tunable amplitude couplers. For this particular design, three stages of 1:2 tunable couplers enabled full amplitude tunability from the input to the eight outputs. This cascaded structure delivers a constant reference power to the receiver array and is more power efficient than dedicated amplitude modulators per row. The power received by each row is divided between the columns using a series of 3 dB Y-junction couplers. To calibrate the power requirements of the thermal modulators and correct for fabrication-related mismatches, a series of 1% sniffer photodiodes are placed at one of the outputs of each tunable coupler. This results in eight sniffer detectors for this array. However, since calibration is required only once per chip, the sniffer diodes at each stage were connected in parallel as shown in Fig. 5(b), resulting in a total of three sniffer photodiode current outputs. Since the input power, $P_{in}$, is known, the output current of the first stage can be calibrated with the sniffer output of the first stage. Afterward, the entire power can be diverted to the top tunable coupler by adjusting the first tunable coupler, and the output of the second sniffer current can be used to calibrate the top tunable coupler. This process can be iterated for the remaining tunable couplers. This parallel connection of the sniffer detectors reduces the number of current outputs for calibration of a $1:2^N$ splitter from $2^N - 1$ to $N$, which helps with the scalability of this architecture.

V. MEASUREMENT

For IQ imager characterization, a single pixel of the IQ imager was illuminated with fiber. A second fiber coupled the reference light into the chip. The two signals were modulated externally at 5 MHz and 5.1 MHz with lithium-niobate amplitude modulators, and amplified before coupling to the chip using erbium-doped fiber amplifiers (EDFAs) to compensate for the insertion loss of the modulator. The phase noise contribution of the EDFAs can be suppressed by the IQ detection scheme. The row-column read-out voltages were adjusted such that only the particular pixel’s row was active. The output mixed-signal current at 100 kHz modulation was amplified with an external transimpedance amplifier (TIA) with 5 kΩ gain. The low input impedance of the TIA ensures that the output current of the balanced detector flows through the op-amp and not through the parallel on-chip 5 kΩ protection resistors. The resulting I and Q signals were digitized and filtered digitally with 100 kHz band-pass filters. Two examples of these waveforms are shown in Figs. 8(a), (c). Due to the random phase fluctuations, there is a high chance that either of the I and Q signals will be attenuated (Fig. 8(a)). Computing the sum-squared term in Eq. (8) showed that while individual waveforms can exhibit amplitude fluctuations as a result of the relative optical phase fluctuations, the resulting sum-square term (Figs. 8(b), (d)) exhibits little amplitude fluctuations and can suppress the effects of the optical carrier’s phase. The experiment was
FIGURE 9. Peak-to-peak value of $I^2$, $Q^2$, and $I^2 + Q^2$ signals over several measurements.

FIGURE 10. Frequency measurement accuracy. (a) Measured frequency vs pre-set frequency. (b) Ratio of the measured frequency error and the pre-set frequency.

repeated several times with different modulation frequencies to demonstrate this effect more clearly. The voltage swing of the $I$, $Q$, and $I^2 + Q^2$ signals across these measurements are shown in Fig. 9. Individual $I$ or $Q$ signals might degrade by more than an order of magnitude; however, the sum squared term fluctuates around 4 dB within our measurements. The results in Fig. 9 further suggest that the peak-to-peak voltage swing on the sum-squared term is always larger than or equal to the peak-to-peak voltage swing of both channels.

Subsequently, we characterized the IQ imager’s frequency resolving accuracy. Starting at a fixed frequency offset of $\Delta f = 100$ kHz (modulating the two paths at 5 MHz and 5.1 MHz), we increased the frequency difference up to $\Delta f = 1$ MHz and measured the frequency difference from the optical data and compared it to the preset values from the arbitrary waveform generators. The result of this measurement is shown in Fig. 10(a). The I and Q signals were captured with 1 ms signal acquisition time and digitized. After filtering the signals with a 100 kHz digital filter, the $I^2 + Q^2$ term was calculated, and the mixed frequency was extracted from the data by measuring the zero-crossings of the mixed signal. For a frequency difference of 1 MHz, which corresponds to 1000 cycles, the error in frequency measurement was 12 Hz. This error corresponds to a frequency measurement accuracy of $1.2 \times 10^{-5}$. The plot of the frequency measurement error normalized to the pre-set frequency is shown in Fig. 10(b).

Afterward, to characterize the row-column read-out isolation, a pixel’s mixed-tone power was measured when that row was enabled versus when it was disabled. At the system’s default operation point with a mixed frequency tone in the 100 kHz to 1 MHz range, no signal was observable when the row was disabled. At an increased offset frequency of 5 MHz (from modulation frequency of 6 MHz and 11 MHz), we were able to measure $-80$ dB cross-talk from the disabled rows of the read-out circuit. This validates the high dynamic range of the proposed row-column read-out architecture.

Finally, the IQ imager was characterized for LiDAR imaging applications as shown in Fig. 11(a). The image sensor was packaged and mounted on a stationary post. The pixels were illuminated using a collimator mounted on another post with linear movement controlled using a linear micro-positioner stage. The laser signal was modulated with an FMCW signal with 2 GHz bandwidth and 1 ms chirp repetition-rate for 2 THz s$^{-1}$ chirp rate. The modulated signal was amplified with an EDFA and split with a 3 dB fiber splitter as illumination and reference signals. The illumination collimator was placed at a distance of 1 m from the coherent imager, and its location was varied by several millimeters via the micro-positioner. The mixed down-converted signal was amplified and digitized. By measuring the zero-crossing point of the captured signal, we estimated the frequency of the mixed component and converted it to distance as shown in Fig. 11(b). We measured a 250 µm change in the distance at the setup’s distance of 1 m. This resolution and range ratio corresponds to a $2.5 \times 10^{-4}$ resolution over range accuracy for the FMCW measurement.

The power consumption of this chip is dominated by the thermo-optic phase shifters in the 1:8 tunable power...
distribution block (10 mW for full switching between two outputs [12]). Only three tunable couplers are active when diverting the power to any row, which results in an average power consumption of 3 × 10 mW = 30 mW for this chip. In all of the chips that we tested, the 90° hybrid was fabricated with 90° optical path difference as designed. As a result, the thermal tuning resistors were inactive. For a worse case mismatch in fabrication, with all 64 90°-hybrid couplers detuned, the power consumption of the chip will increase by an additional 32 mW. SEM images of the coherent imager’s IQ unit cell and tunable amplitude coupler are shown in Fig. 12(a). The die photo of the 8x8 coherent imager system is shown in Fig. 12(b).

VI. CONCLUSION
In this work, we demonstrated an integrated IQ coherent receiver with an expandable aperture. This receiver can suppress the optical carrier signal phase fluctuations and improves the system SNR. Furthermore, we demonstrated a novel row-column read-out architecture in a standard silicon photonics process which can reduce the required electrical amplification and control system size as well as reduce the electronic/photon interconnect density requirements. Finally, we demonstrated LiDAR imaging in a free-space measurement stage with 250 µm resolution at 1 m distance.

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REFERENCES


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Prof. Hajimiri won the Feynman Prize for Excellence in Teaching, Caltech’s most prestigious teaching honor, as well as Caltech’s Graduate Students Council Teaching and Mentoring Award and the Associated Students of Caltech Undergraduate Excellence in Teaching Award. He was a co-recipient of the IEEE JOURNAL OF SOLID-STATE CIRCUITS Best Paper Award of 2004, the ISSCC Jack Kilby Outstanding Paper Award, the RFIC Best Paper Award, a two-time co-recipient of CICC Best Paper Award, and a three-time winner of the IBM Faculty Partnership Award as well as the National Science Foundation CAREER Award and Okawa Foundation Award. He was the Gold Medal Winner of the National Physics Competition and the Bronze Medal Winner of the 21st International Physics Olympiad, Groningen, Netherlands. He was recognized as one of the top-ten contributors to International Solid-State Circuits Conference (ISSCC). In 2002, he co-founded Axiom Microdevices Inc., whose fully-integrated CMOS PA has shipped around 400,000,000 units, and was acquired by Skyworks Inc., in 2009. He has served on the Technical Program Committee of the ISSCC, as an Associate Editor of the IEEE JOURNAL OF SOLID-STATE CIRCUITS, IEEE TRANSACTIONS ON CIRCUITS AND SYSTEMS—PART II: EXPRESS BRIEFS, a member of the Technical Program Committees of the International Conference on Computer Aided Design, the Guest Editor of the IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, and the Guest Editorial Board of Transactions of Institute of Electronics, Information and Communication Engineers of Japan. He was selected to the TR35 top innovator’s list. He has served as a Distinguished Lecturer of the IEEE Solid-State and Microwave Societies. He is a Fellow of National Academy of Inventors.