# Silicon photonic coherent adder for communication and sensing with time-multiplexed control feedback

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**Abstract.** Time-multiplexed control of a reconfigurable silicon photonic coherent adder is demonstrated by means of monolithically integrated CMOS electronics. Time-multiplexing is used to interrogate integrated photodetectors and drive thermal actuators with few electrical signals, realizing accurate compensation and locking of mutual phase drifts of the input signals to be combined. The optical circuit functionality is then demonstrated both with a transmission experiment, where a 25 Gbps modulated signal is reconstructed at the chip output, and in a sensing scenario, where the chip is used to assess the phase difference between the input light beams.

**Keywords:** programmable photonic circuits, monolithically integrated electronics, time multiplexing control, phase sensing

## 1 Introduction

The development of large-scale programmable photonic integrated circuits (PICs), like meshes of Mach-Zehnder interferometers (MZI) for optical computing or interconnect applications [1], requires an external control unit to configure the chip functionality, monitor it in real-time and keep it stable against possible drifts and variations, due to aging or environmental effects [2]. Therefore, to ensure adaptive operations and full programmability, these PICs require multiple on-chip light sensors and actuators, that are employed to close the external electronic configuration and stabilization loop [3]. The number of such elements is strictly related to chip complexity and can easily reach the scale of few hundreds for large PICs. Solutions to integrate photonic and electronic functionalities into the same chip have thus been investigated to reduce the number of electrical connections between the PIC and the electronics [4].

Among programmable PICs, coherent adders based on self-configuring structures are gaining popularity in recent years. They are usually implemented with meshes of MZIs arranged in a diagonal or binary tree configuration. Their credentials have already been validated with demonstrations of optical mode manipulation and free-space optical transmission among others [5,6]. However, the versatility of these PICs also allows their use in those applications where, in addition to optical transmission and routing, measurements of the input beam characteristics are required (the so-called transmission and sensing approach).

In this work, we demonstrate time-multiplexed control of an MZI-based silicon photonic coherent adder, enabled by monolithically integrated CMOS electronic circuits. Two integrated electronic multiplexers, simultaneously operated for both the readout and actuation tasks, significantly reduce the number of external connections while still maintaining feedback control over the photonic chip. The functionality of the PIC is demonstrated in a transmission and sensing scenario, where a 25 Gbps transmission experiment is carried out together with real-time tracking of the phase difference between the circuit inputs.

## 2 Time-multiplexed control of an adaptive coherent adder

The architecture of the PIC, manufactured by a commercial silicon photonics foundry (AMF, Singapore) with a zero-change approach, is illustrated in Fig. 1. Each MZI within the binary tree adder is equipped with dedicated germanium photodiodes and thermal phase shifters, all controlled by external electronic circuits. To minimize the number of electrical input/output (I/O) connections required for interfacing the chip with the control electronics, we implemented an on-chip multiplexer (MUX) that sequentially routes the current signals from the integrated sensors towards a single acquisition circuit [7]. After digitization with an analog-to-digital converter, the

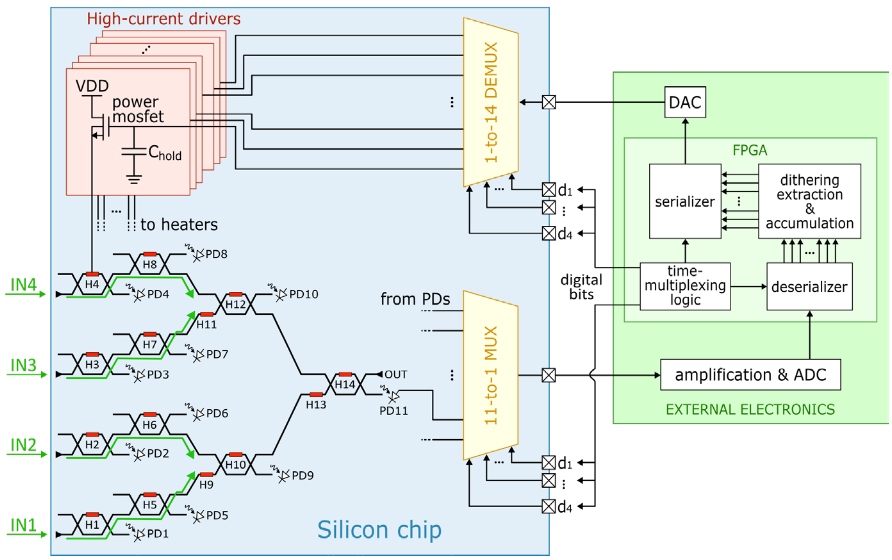


**Fig. 1.** Schematic view of the silicon chip, integrating a photonic coherent adder and two electronic multiplexers enabling sequential control of the optical functionality.

serialized signals are separated into parallel signal processing chains inside the FPGA that manages the electronic system. The conceptual operating principle of the time-multiplexed readout is shown in Fig. 2a. The elaborated information is then serialized again in the FPGA and brought back into the analog domain with a single digital-to-analog converter (DAC), driving a second integrated demultiplexer (DEMUX) that sequentially connects each MZI actuator. A critical aspect of this approach is maintaining the stability of the MZI working point when the DEMUX switches from one actuator to the next one. To achieve this, we have integrated an electronic memory on the chip, which includes a sample-and-hold (S&H) circuit connected to the current drivers of the thermal actuators [7]. The S&H circuit exploits DEMUX switches together with a memory capacitor bank to store the heater voltage information and keep it stable during the DEMUX operation. The time-multiplexed control scheme for the actuators is illustrated in Fig. 2b. During the sampling phase, commands are applied to the actuator drivers and memorized by the S&H. In the hold phase, the stored charge in the capacitors maintains the actuator commands. Notice that, thanks to the on-chip drivers, a low power external DAC is enough to operate the circuit.

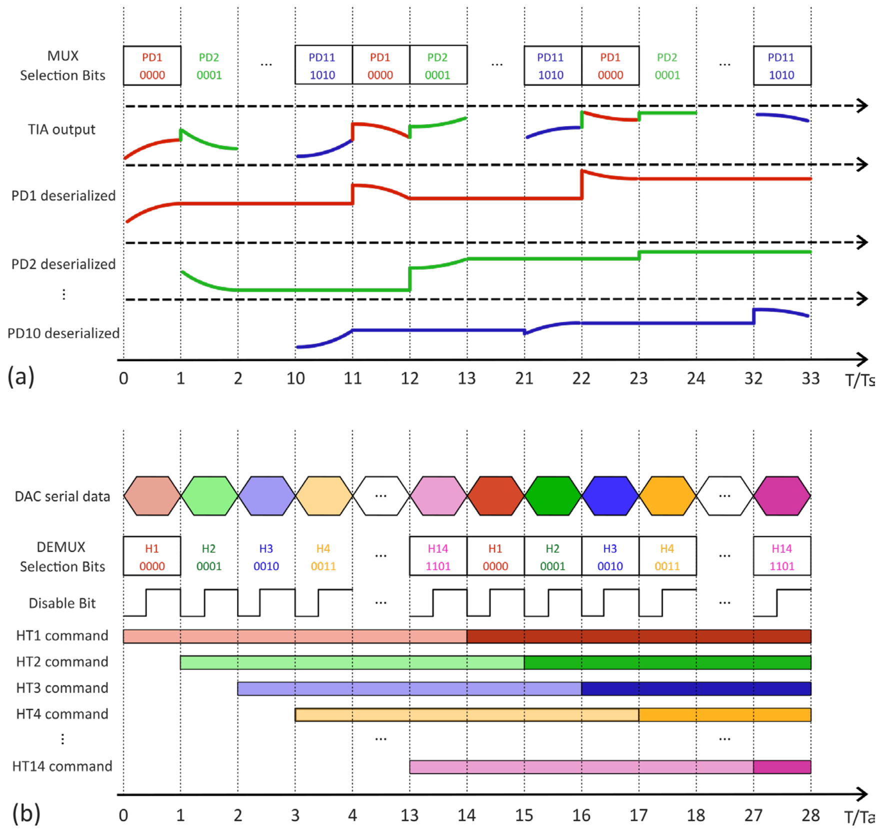


**Fig. 2.** Time-multiplexed algorithm for sequential control of (a) multiple sensors and (b) phase actuators, using a single analog input and output.

The fully time-multiplexed control, only theoretically anticipated in [7], was exploited to operate the MZI mesh as an adaptive coherent adder. The experimental setup consists of an optical fiber array for signal injection, a custom printed circuit board (PCB) serving as an interface to the external control electronics, and a single fiber for output signal retrieval (Fig. 3a). A 1550 nm laser source was equally divided by an external 1:4 fiber splitter and injected into the photonic circuit through a fiber array. Two cascaded MZI stages (1st and 2nd stages) act as high-speed optical switches to route the input signals towards the following 4×1 MZI mesh (3rd and 4th stages), functioning as a coherent adder for signal summation. Output power was coupled from the circuit via a grating coupler. To achieve autonomous MZI calibration without prior system characterization, 2 kHz dithering modulation scheme (as demonstrated in [5]) has been employed. This calibration process operates with MUX/DEMUX components cycled at 156 kHz, enabling sequential interrogation of individual channels at around 10 kHz.

Figure 3b shows the convergence curve of the photocurrent of the monitor PDs during the automatic configuration of the MZI mesh. Initially, the working points of all MZIs were set by applying random voltages to the integrated heaters. The activation of the feedback loops resulted in the minimization of the PD photocurrents by precisely adjusting phase shifter voltages and maximization of the optical power at output port (OUT). Each MZI achieves stable operation within tens of milliseconds, enabling the full configuration of the entire PIC in under 50 ms.

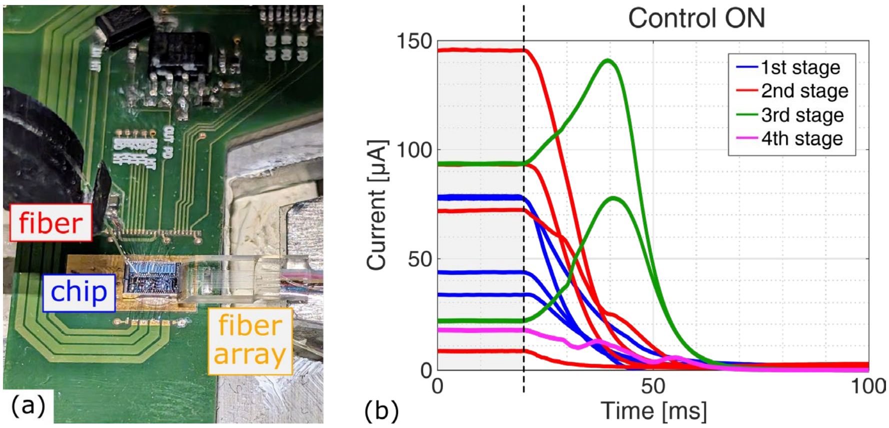


**Fig. 3.** (a) Electro-optical setup consisting of an input fiber array, integrated photonic chip, electronics interfaces and output fiber. (b) Convergence curves of the feedback control system, showing the minimization process of the photodiode signals across four stages.

## 3 25 Gbps transmission experiment

The experimental validation of the automated time-multiplexed control system has been carried out in a high-speed data transmission scenario. To perform the experiment, the laser beam has been modulated before the fiber splitter and the resulting four signals simultaneously injected into the chip. After reconstruction by the coherent adder, the output signal has been monitored with an optical oscilloscope. Figure 4 illustrates comparative eye-diagram analyses of a 25 Gbps intensity-modulated signal from the MZI mesh under different operational conditions.

Without active electronic stabilization, environmental perturbations such as thermal drifts, acoustic interference, and mechanical vibrations in the input fiber array introduce time-dependent phase drifts among the input beams of the coherent adder. Therefore, the four signals are randomly combined by the circuit and the transmitted information is completely lost, resulting in a completely closed eye diagram. On the other hand, the activation of the closed-loop control system restores optimal beam coherence, producing a well-defined open eye diagram with a measured quality factor of Q = 8.06. Successful compensation of the random phase fluctuations is achieved within the 50 ms response of the control loop, enough to mitigate the slow drifts that usually affect optical fiber components.

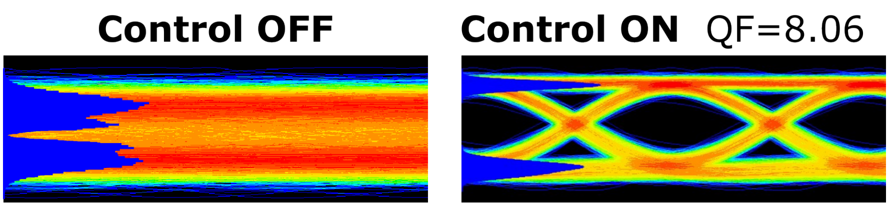


**Fig. 4.** Eye diagrams of a 25 Gbps intensity-modulated signal from the coherent adder output when the active phase stabilization is disabled (left) and enabled (right).

## 4 Input phase sensing

As previously discussed, the coherent adder can be used both for transmission and sensing purposes. In particular, the time-dependent variations in the relative phase of the input beams, caused by external factors, can be evaluated by analyzing the operating point of the MZIs. Indeed, to achieve coherent summation of the input optical powers, the phase shifts introduced by the thermo-optic actuators must satisfy the following conditions:

$$\Delta\theta = 2\tan^{-1}\left|\frac{x_1}{x_2}\right|, \quad \theta \in [0, \pi] \quad \Delta\phi = (\angle x_1 - \angle x_2) + 2N\pi \qquad (1)$$

where $x_1$ and $x_2$ are the optical fields at the input of an MZI (Fig. 5a).

Since our control strategy is based on active feedback, it is possible to continuously monitor the electrical power supplied to the input thermo-optic actuators to retrieve in real-time the phase mismatch $\Delta\phi$ between the optical input beams of the 4×1 binary tree (Fig. 5b). The computed phase mismatch is relative to a fixed reference at a given time instant $t_0$.

This idea has been experimentally verified. Fig. 5c shows the evolution of the phase difference between the inputs of the coherent adder (third stage of the PIC), obtained by analyzing the heater command generated by the feedback loop. The measurement confirms the presence of phase fluctuations due to environmental effects, that can be as high as 0.4π on a time span of few minutes. The continuous control action, performed by the feedback electronics, thus allows to both estimate the magnitude of this phenomenon and to counteract it in real-time.

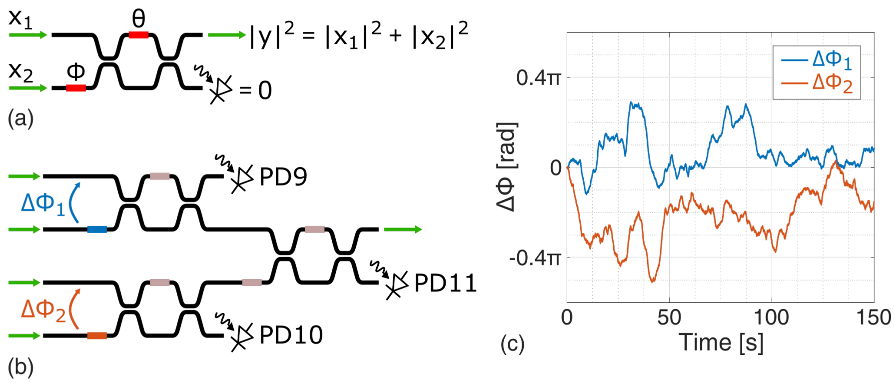


**Fig. 5** (a) MZI used in a coherent adder scheme. (b) 4×1 binary tree of MZIs used to evaluate the input phase variations, thanks to the active feedback loop that constantly routes light to the output of the circuit. (c) Long-term experimental measurement of the input phase drifts, showing time-dependent variations in the relative phase shifts ($\Delta\phi_1$, $\Delta\phi_2$).

## 5 Conclusions

We presented the electronic control of a programmable silicon PIC where, for the first time, on-chip time-multiplexing is used both for interrogating integrated monitor PDs and driving volatile thermal actuators. The proposed methodology requires no modifications to commercial silicon platforms and minimizes the number of electrical I/Os, thus enabling scalability to larger photonic chips. The effectiveness of the approach is demonstrated by accurate and stable configuration of an integrated MZI-based coherent adder, achieved by real-time compensation of phase drifts in the input signals. The feedback-controlled chip has been used for both communication and sensing purposes, with the transmission of a 25 Gbps signal together with the estimation of the phase difference between the input beams. The latter information could be useful, for instance, in free-space applications to estimate the angle of arrival of the beam impinging on the coherent adder inputs without the need of complex algorithms.

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