Proposal for CMOS-compatible Optoelectronic Integrated Circuit for Online Wideband PCA

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***Abstract*—We propose an integrated optoelectronic circuit capable of tracking on real-time the first principal component of an array of wideband analog RF signals. Preliminary results warrants the suitability of photonic components for wideband PCA.**

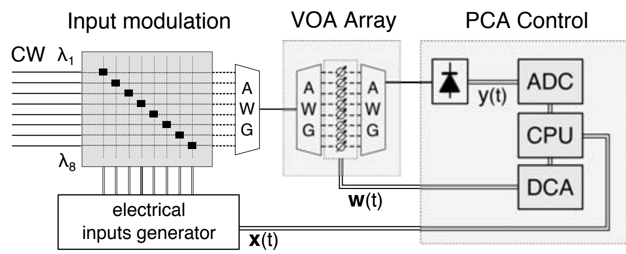
In this paper, we propose an integrated photonic circuit to perform online principal component analysis (PCA) on a scalable number of partially correlated wideband inputs. PCA is a technique for unsupervised pattern recognition and dimensionality reduction in multidimensional random variables. The first principal component (PC) represents the original data in one dimension while maximizing the amount of "information explained". Unsupervised learning could also be extended to actively control photonic distributed processing networks, with applications to wideband intelligent radio processing [1]. Arrayed-antenna systems in particular often digitizes largely redundant multidimensional signals. Fast statistical techniques for dimensionality reduction in analog RF signals could reduce strain on digital signal processing requirements in wideband, multi-antenna RF systems.

Past proof-of-concept work achieved 1GHz PCA signal bandwidth and extremely slow (10s of seconds) learning speed, since learning is CPU-mediated [2]. Many techniques for RF photonic filtering [3], beamforming [4], and other applications can handle high-bandwidth analog signals, but most lack control algorithms that can tune system parameters fast enough to perform online analysis in dynamic environments.

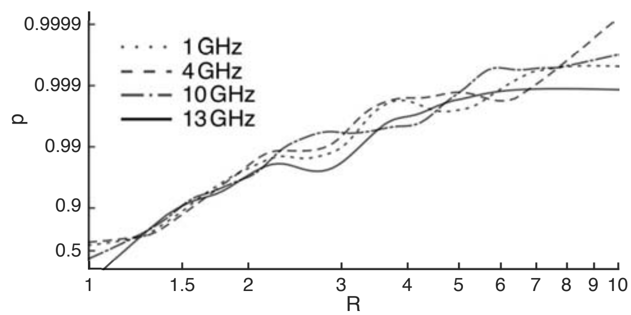
Here we propose a bio-inspired optoelectronic PCA controller for accelerating the learning speed. Compared to matrix-based SVD algorithms, the simple operations required for unsupervised rules for bio-inspired PCA learning are more feasible for an analog optoelectronic controller, which can be implemented in co-integration platforms. Unsupervised learning rules from computational neuroscience, such as Hebbian and Oja (1), could provide multivariate statistical methods to RF photonic devices while eliminating the CPU from the control loop.

$$
\begin{aligned}
\frac{d}{dt}\mathbf{w}(t) &= \eta[\mathbf{z}(t) - y^2(t)\mathbf{w}(t)] \\
y(t) &\equiv \mathbf{w}(t) \cdot \mathbf{x}(t) \\
\mathbf{z}(t) &\equiv y(t) \cdot \mathbf{x}(t)
\end{aligned} \tag{1}
$$

Demonstrations of high fan-in signal processing are fundamentally difficult for electronic elements to command simultaneously high performance and scale. We present here preliminary results for batch wideband PCA fidelity (see Fig. 1a, adapted from [2]). Despite the use of fast photonic components, its convergence speed was limited by the time-costly I/O transfer overhead, and the bandwidth by the cutoff frequency of our waveform generator—13GHz. Nonetheless, the optical elements remained insensitive to wide bandwidth, warranting excellent levels of variance explained (Fig. 1b).



(a) Demonstrated batch PCA experiment via software-driven Oja's rule.



(b) Performance results as a function of different input bandwidth and eigenvalue ratios.

Fig. 1. The setup was adapted from [2]. The batch sampling window was fixed to $T = 200\text{ns}/\text{Bandwidth}(\text{GHz})$. Because this experiment was offline, the correlation matrix $\mathbf{\Sigma} = \left\langle \mathbf{x}\mathbf{x}^T \right\rangle$ can be estimated by averaging over T, and therefore its eigenvalues λ and eigenvectors (principal components) $\mathbf{W}$. The convergence rate of an iterative method depends highly on the ratio between the first two greatest eigenvalues of $\mathbf{\Sigma}$: $R \equiv \lambda_1/\lambda_2$—intuitively how distinctively correlated the signals are. The higher the ratio, the faster the algorithm converges. The simulation was stopped after 40 steps and its performance was recorded as $p \equiv \langle \mathbf{w}, \mathbf{W}_1 \rangle$.

Online PCA requires fast computation of equation (1). It is crucial that the weighted addition term $\mathbf{w}(t) \cdot \mathbf{x}(t)$ is calculated accurately at high-bandwidth. We propose a photonic/electronic integrated circuit that controls $\mathbf{w}(t)$ according to Oja's rule (Fig. 2)—resulting in online PCA. The circuit can be divided into regions according to their operational speed requirements: the photonic components side operates at

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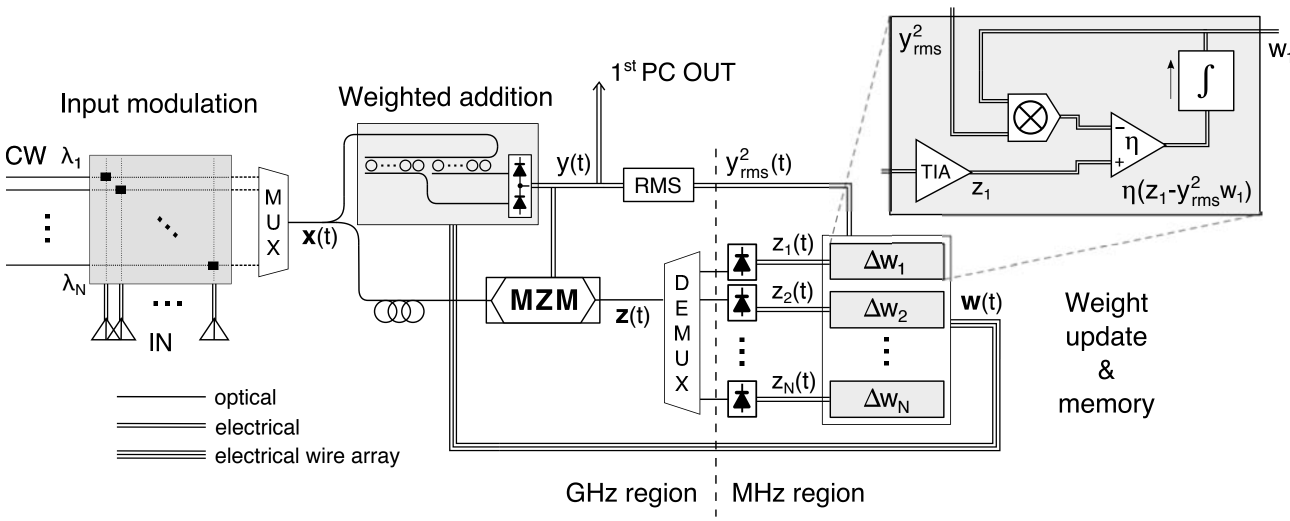

Fig. 2. Proposed photonic integrated circuit for wideband online PCA. An array of N input electric signals ($\mathbf{x}(t)$) are encoded into multi-wavelength continuous-wave (CW) light via power modulation. Through wavelength division multiplexing (WDM), all single-wavelength lightwaves are channeled into one waveguide. Weighted addition ($\mathbf{w}(t) \cdot \mathbf{x}(t)$) is carried out by a bank of tunable microring resonator filters as described in [6], plus two fast balanced photodetectors (see ref. [5]) which sum all weighted outputs into unbiased AC voltage via a transimpedance amplifier (TIA). The output $y(t)$ is used to modulate a Mach-Zehnder modulator (MZM) to yield $\mathbf{z}(t)$ in a multiplexed lightwave. Also, a wideband RMS power detector [8] yields MHz-bandwidth $y^2_{rms}(t)$. After demultiplexed, $\mathbf{z}(t)$ is fed into N identical weight update circuits (gray boxes) whose inputs are $z_i(t)$ and $y^2_{rms}(t)$ and output $w_i(t)$. The detailed weight update circuit show standard CMOS components necessary to solve (1): an analog multiplier ($w_i(t) \cdot y^2(t)$); a differential amplifier ($\eta[z_i - w_i(t) \cdot y^2(t)]$); and an integrator (~MHz low pass filter) to yield $w_i(t) = \int \eta(z_i - w_i(t) \cdot y^2_{rms}(t)$. This design assumes that the effective principal component does not evolve quickly over a time period of $1\mu s$, reasonable for considered applications.

tens of GHz, whereas the electronic circuits at a few MHz—respectively named “GHz” and “MHz” regions.

The central MZM [7] yields the effective product of two GHz signals ($\mathbf{z}(t) = y(t) \cdot \mathbf{x}(t)$), whose sub-MHz-frequency components are used in the “MHz” region. Similarly, the stabilization term in equation 1, given by $y^2(t) \cdot \mathbf{w}(t)$, has its important information contained in the MHz bands. However, $y(t)$ is an AC RF electric signal, for which squarer circuits have yet to be demonstrated in CMOS. Nevertheless, for our purposes, a RMS analog power detector suffices, because we are only interested in MHz components of $\langle y^2(t) \rangle \to y^2_{rms}(t)$. This has been demonstrated for bandwidths up to 34GHz [8].

Henceforth all remaining operations of the weight update rule have standard component designs in CMOS: infrared photodetector, analog multiplier, transimpedance amplifier (TIA), differential amplifier and integrator circuits. Our proposed design for the weight update is detailed in Fig. 2.

The batch PCA experiment generally converges after tens of iteration steps to one of the most important PCs, especially for $R > 1.5$. If, however, the initial weight $\mathbf{w}(0)$ is close to the first PC, the algorithm aligns $\mathbf{w}$ to that PC after only a few iterations with 99% accuracy. Therefore, the proposed device is expected to track the first PC of 20GHz input RF signals within a conservative time estimate of $10T = 1\mu s$, which corresponds to a learning rate of ~1MHz. Furthermore, if the input signals “decorrelate” (i.e. $\langle \mathbf{x}\mathbf{x}^T \rangle = \mathbb{1}$) for a certain period of time, it can be demonstrated that $d\mathbf{w}/dt = 0$ and the circuit holds the current value of $\mathbf{w}$, guaranteeing stability against signal acquisition disruptions, or holding “memory” for neuromorphic applications.

The necessary step to achieve reliable, fast, online wideband PCA is to integrate analog control into an optoelectronic circuit. By blending capabilities of silicon photonics together with fast electronics on CMOS, the first PC of a large number of wideband signals can be actively tracked, thus enabling a wide range of applications in RF signal processing and neuromorphic computing.

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