

# Scalable Photonic Neurons for High-Speed Automatic Modulation Classification

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**Abstract**—Automatic modulation classification (AMC) is becoming increasingly critical in the context of growing demands for ultra-wideband, low-latency signal intelligence in 5G/6G networks. Photonics-based AMC addresses the bandwidth and real-time adaptability limitations faced by traditional radio-frequency (RF) electronics. This paper presents the first experimental photonic implementation of AMC, achieved through a fully functional photonic neural network built from scalable microring resonators that co-integrate electro-optic modulation and weighting. This work also represents the first system-level deployment of such compact photonic neurons in a real photonic neural network, demonstrating the significant potential of photonic computing for large-scale, complex RF intelligence in next-generation wireless communication systems.

**Keywords**—integrated photonics, neuromorphic photonics, automatic modulation classification

## I. INTRODUCTION

The 5G/6G landscape features increasingly congested and adversarial spectrum environments, where rapid and intelligent interpretation of signals is essential and prior knowledge of signals is often unavailable, such as in electronic warfare scenarios. Automatic modulation classification (AMC) thus becomes pivotal, as correct demodulation requires real-time

inference of unknown modulation formats. Neural networks (NNs) have emerged as a leading solution for AMC due to their high classification accuracy, ability to handle complex channel conditions, and robustness to noise, outperforming traditional model-based methods in low signal-to-noise ratio (SNR) environments [1]. However, the limited speed and throughput of electronics-based NN implementations, particularly when processing high-frequency RF signals, restrict their applicability in real-time wideband scenarios. To address these limitations, photonic neural networks (PNNs) leverage the ultra-wide bandwidth and optical-domain propagation with picosecond-scale latency, enabling classification orders of magnitude faster than their electronic counterparts. Despite these advantages, PNNs face persistent scalability challenges, including resonance mismatches induced by fabrication variations and footprint limits dictated by the wavelength of light, which significantly hinder their deployment in large-scale system-level applications.

In this paper, we present the first experimental realization of photonic AMC, enabled by a scalable implementation of novel on-chip microring resonators (MRRs) that integrate both electro-optic modulation and weighting into a single device. The proposed compact MRR structure is experimentally validated in a functional PNN, marking its first system-level demonstration.

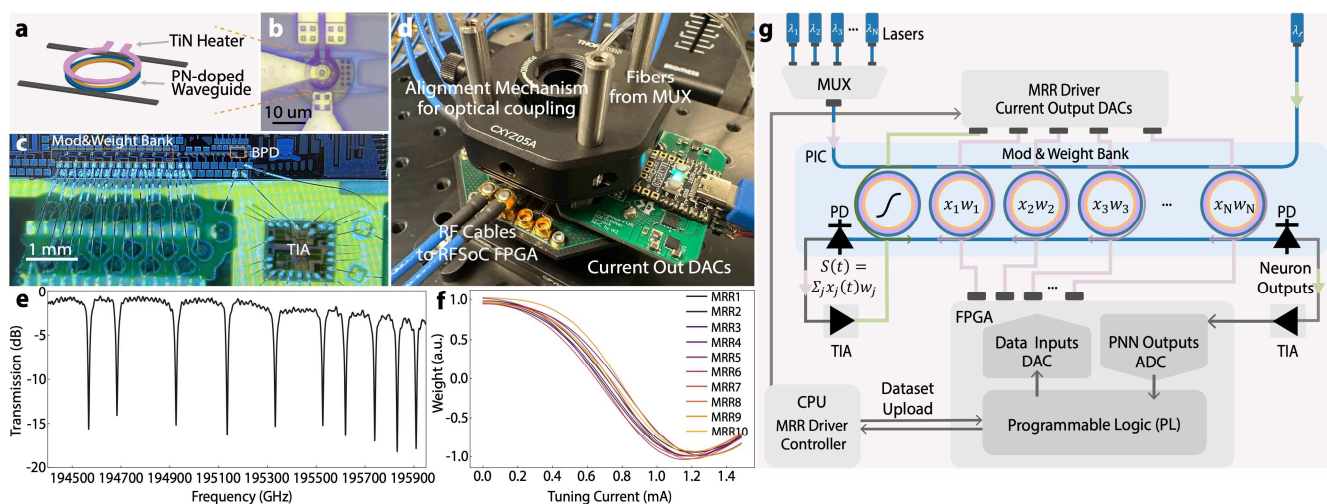


Fig. 1: (a) Structural design of the modulation-and-weight microring resonator (MRR). (b) Modulation-and-weight MRR layout. (c) Micrograph of the photonic integrated circuit (PIC). (d) Fully packaged PIC. (e) Measured transmission spectra of the MRR bank. (f) Electro-optic response of the MRR bank under current tuning. (g) Schematic diagram of photonic system.

This architecture also fundamentally addresses the scalability challenges of PNNs by eliminating inter-component resonance-misalignment and substantially reducing both footprint and power consumption. Leveraging this design, our photonic system achieves high-speed, high-accuracy, and SNR-robust modulation classification, showcasing the strong potential of energy-efficient photonic computing in machine learning and real-time RF signal processing at the scale and speed required by next-generation wireless applications.

## II. METHODS

To realize this scalable photonic architecture, we designed and fabricated a compact MRR-based photonic processor with unified modulation-and-weighting MRRs (Fig. 1(a) and 1(b)). Unlike traditional photonic processors with discrete components, our MRR design enables plasma-dispersion-based modulation by doping the ring as a PN junction and supports thermo-optic weight tuning via a metal microheater. This unified design eliminates the need for separate modulators and weighting elements, reducing power consumption by up to 20 $\times$  compared to prior structures [2]. It also avoids routing delays in modular architectures, achieving picosecond-scale on-chip latency. Critically, co-locating modulation and weighting within the same MRR addresses the scalability bottlenecks caused by wavelength mismatches from fabrication variance, a pervasive issue in photonic integration. In conventional systems, such mismatch between separately fabricated modulating and weighting MRR pairs prevents wavelength-aligned operation, as a tunable laser can only match one resonance at a time. Our integrated approach ensures natural alignment as both functions reside within the same device, enabling robust and scalable operation. To demonstrate AMC capabilities, we implemented a photonic neuron comprising ten MRRs with radii ranging from 8 to 8.10917  $\mu\text{m}$  (Fig. 1(c)), achieving 12.12 nm spectral spacing (Fig. 1(e)) and a per-input footprint of 0.165  $\text{mm}^2$  including bonding pads and traces, demonstrating the compactness and scalability of the design.

Building on the integrated photonic neuron, we developed a full system with electro-optical-electrical integration. The photonic chip was fully packaged for AMC experiments, and characterized for current-driven wavelength tuning, with Fig. 1(f) showing the current-weight response. Neurons were mapped onto a simplified temporal convolutional network architecture tailored for AMC with one convolutional layer: weighted summation is performed by the MRR-based modulation-and-weight bank, while nonlinearity is introduced by re-routing the output through an additional MRR, leveraging its Lorentzian profile as the activation function. In the complete system, RF signals generated by a field-programmable gate array (FPGA) are routed through a custom printed circuit board (PCB) to the PIC, which is wire bonded to the same PCB. Within the PIC, the signals undergo simultaneous modulation and weighting, and the resulting optical outputs, which are shaped by the MRR transmission nonlinearity, are converted back into the electrical domain via an on-chip photodetector, establishing a closed-loop signal processing pipeline. The classification accuracy and SNR robustness are evaluated based on the detected outputs, demonstrating the classification capability of the system.

## III. RESULTS

To quantify AMC performance, we input raw IQ samples from the RadioML 2016a dataset into the system, covering six modulation types (AM-DSB, AM-SSB, CPFSK, GFSK, PAM4, and QAM16), with 400 randomly sampled snippets per class, each truncated to the first 25 samples. Fig. 2(a) presents testing accuracy across SNR levels from 0 to 18 dB, demonstrating the strong robustness of the system even under significant noise conditions. In particular, the system achieves 80.21% at 18 dB and 76.67% at 10 dB, confirming consistently reliable classification results. The confusion matrices at 0, 10, and 18 dB (Fig. 2(b)–(d)) further illustrate high-accuracy classification results under varying noise conditions. The photonic processor's picosecond-scale latency ensures instantaneous classification, making it suitable for real-time modulation classification.

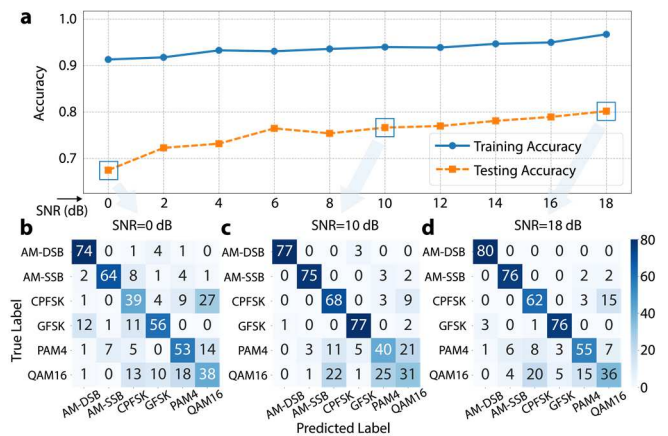


Fig. 2: (a) Training and testing accuracy across SNR levels from 0 to 18 dB. (b)–(d) Validation confusion matrices at 0, 10, and 18 dB, respectively.

The experimental platform features a fully integrated EOE pipeline, incorporating an HTG-ZRF16 FPGA interfaced with SPI-connected DACs (LTC2662, LTC2686, Analog Devices) and routing RF signals through a custom PCB on Rogers 4003C substrate. Optical coupling is achieved by a Thorlabs optical cage system, with a  $\sim 7$  dB per-pass fiber-to-chip loss, and a thermoelectric cooler (TEC) ensures thermal stability.

In summary, by leveraging the compact modulation-and-weight MRR-based architecture with less than half the footprint, only 5% of the thermal tuning energy consumption, and WDM-compatible scalability, our photonic system experimentally achieves high-speed, high-accuracy, and noise-robust AMC, supporting high-bandwidth RF signal processing across widely used wireless bands [3]. These results confirm the practical feasibility of photonics for scalable, energy-efficient, and low-latency neuromorphic computing in next-generation intelligent wireless communication systems.

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