Hybrid CMOS Photonic Integrated Circuits for Millimeter Wave Communication

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1. Introduction

The need for growing wireless capacity will utilize more spectrum in the centimeter wave (cmWave, 6 to 30 GHz) and millimeter wave (mmWave, 30-100 GHz) range, and deploy small cells and heterogeneous networks to provide a Terabit/s/km² capacity by 2030 [1]. As a result, flexible wideband RF front ends that can seamlessly operate over a large range of spectrum become indispensable. In 2016, FCC freed nearly 11 GHz of spectrum (Licensed:28, 37 & 39 GHz bands, Unlicensed: 64-71 GHz bands) for supporting 5G services [2].

Silicon-on-insulator (SOI) photonics is a potentially disruptive technology that can alleviate the challenges associated with conventional radio frequency (RF) and mmWave integrated circuits (ICs). Technology development leveraging silicon-based photonics for RF signal processing has thus far largely focused on isolated implementation of reconfigurable filters, and optical modulators [3]. These systems follow a traditional approach where only optical-domain functionality is demonstrated at the component level; they cannot be directly used in an integrated system.

To enable future RF photonics circuits for wideband and flexible transceivers, we are investigating ***hybrid RF/mmWave Photonic*** paradigm by leveraging extremely wideband signal processing capability and tunability of integrated photonic circuit structures.

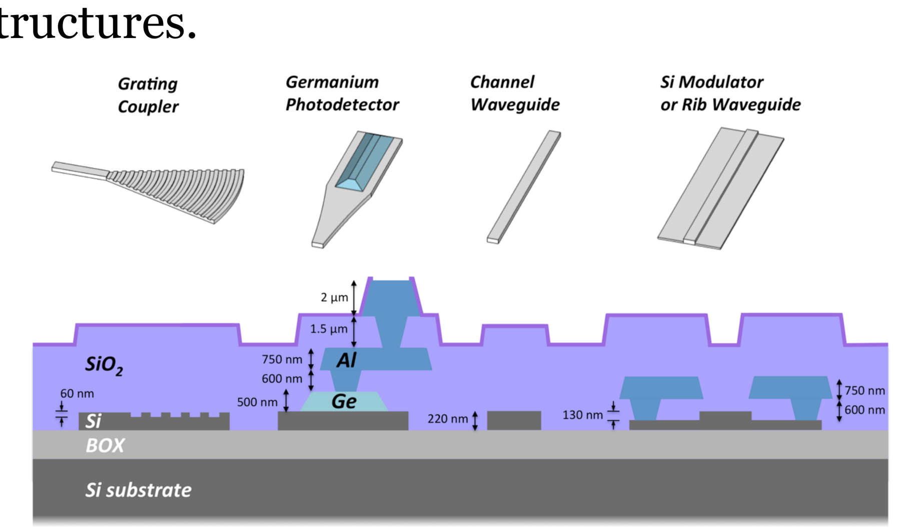

Figure 1: Cross-section illustration of SOI photonic fabrication technology available through IME [3].

2. Envisioned Hybrid RF Photonic Front-End

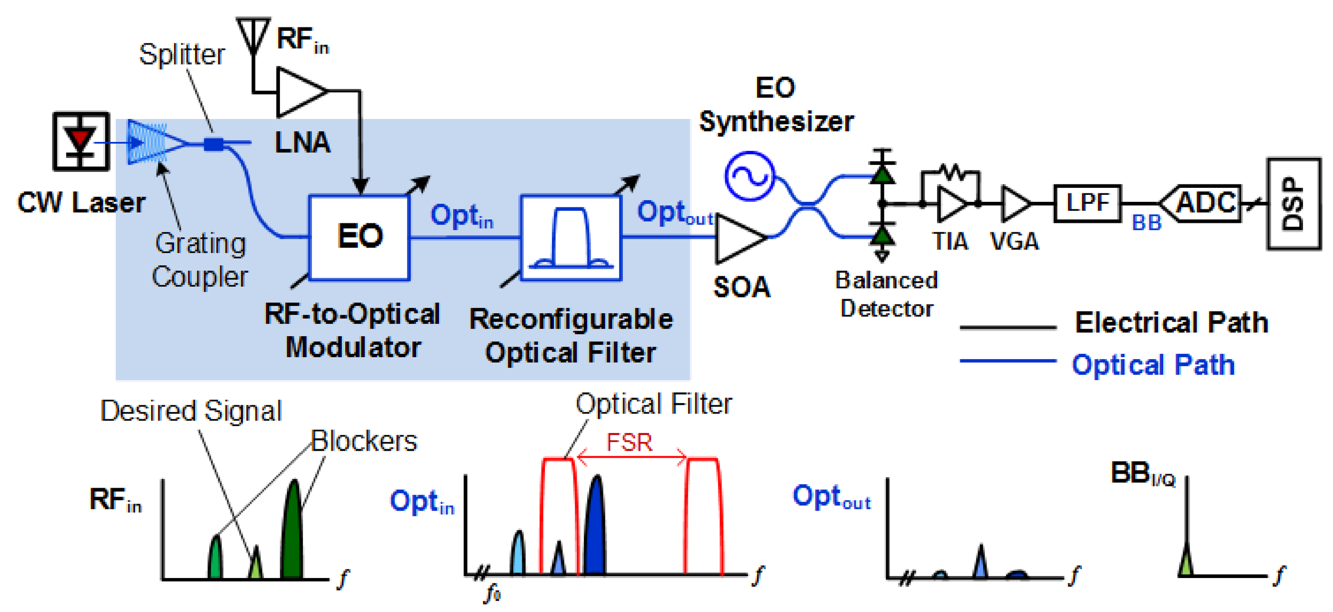

Figure 2. RF-photonic receiver architecture envisioned by the PI.

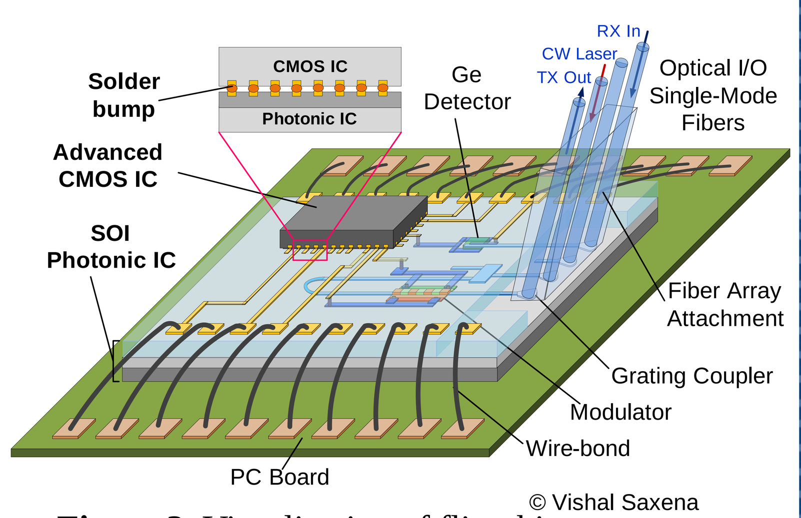

Figure 3. Visualization of flip-chip integration of CMOS and photonic chips.

3. Research Challenges

Integration of nanophotonics into RF ICs allows several advantages: ultra-wide bandwidth signal processing, reconfigurability over several 10's of GHz, scalable optical interconnects with several Tb/s capacity eliminating copper, and potentially low phase noise oscillators. To realize a prototype hybrid mmWave photonic receiver front-end the following challenges need to be addressed:

Linear EO Modulator: A highly linear electrical to optical (EO) modulator to convert incoming RF/mmWave signals into optical domain while providing: (i) low NF with a wide-bandwidth, and (ii) low-distortion over a large dynamic range. Typical SOI modulators exhibit a bandwidth of 50 GHz but have non-linear transfer characteristics [3]. Novel EO modulator topologies are being investigated that provide a passive RF interface while allowing high linearity (>95 SFDR). Hybrid CMOS photonic integration allows CMOS circuits to calibrate against PVT mismatches.

Tunable Optical Filters: SOI photonics has enabled the potential for chip-scale photonic filters with high selectivity and unparalleled tuning range over several 10's of GHz. This can lead to compact, wideband and flexible band selection filter [4]. Challenges include obtaining sharp cutoff filter characteristics using tunable photonics with selectivity close to 0.1 GHz, in presence of PVT variations and thermal crosstalk. PI has implemented tunable Vernier ring filters in SOI photonics process with CMOS feedback to obtain the desired filter shape. Future work involves extending these to higher-order filters with CMOS calibration.

EO Synthesizer and Down-conversion Mixer: Optical domain down-conversion using balanced photo-detection offers promising tradeoffs with CMOS-only architectures. Challenges include design of widely tunable LOs with optical-domain output, and investigation effects of laser intensity/phase noise, and PVT mismatch on the overall performance.

CMOS Photonics Co-Design: PI has successfully developed a hybrid design methodology where the hybrid circuit architecture is partitioned into electronic and photonic sub-circuits. Here, photonic components are represented by parameterized cells with compact Verilog-A models that allow accurate system-level verification in Cadence environment [5].

4. Research Progress

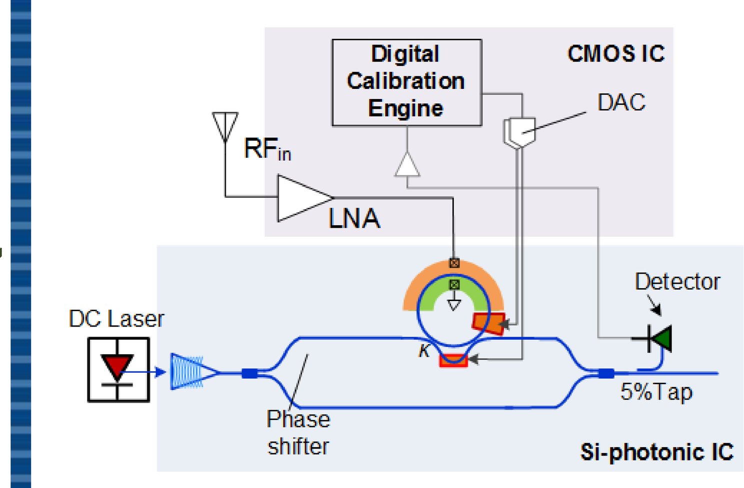

Figure 4. Ring-assisted Mach-Zehnder (RAMZI) EO modulator with adaptive CMOS calibration.

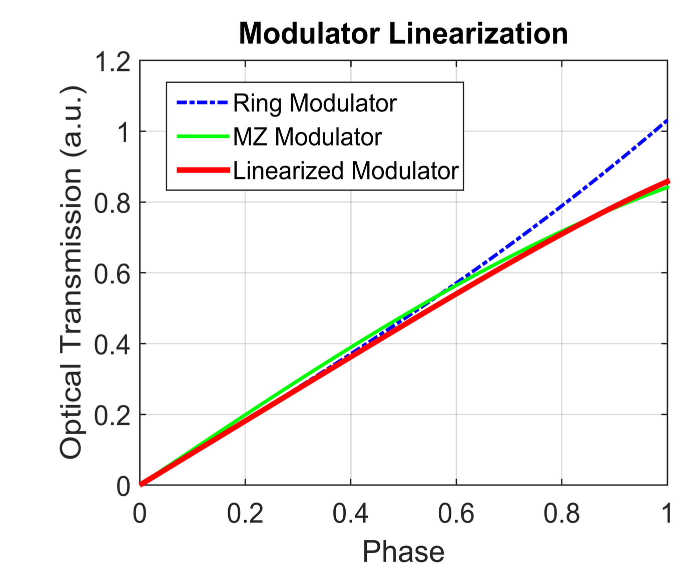

Figure 5. Optical transmission response showing a linearized RAMZI modulator.

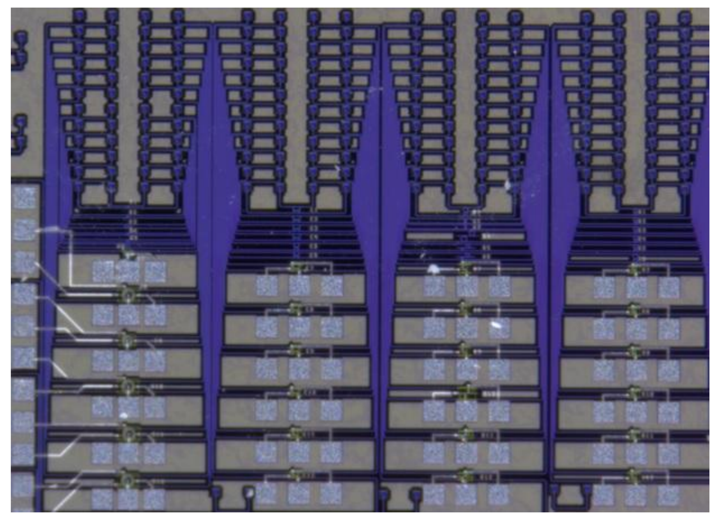

Figure 6. SOI photonic chip micrograph showing microring filter and modulator test array structures with grating couplers and RF/DC probes.

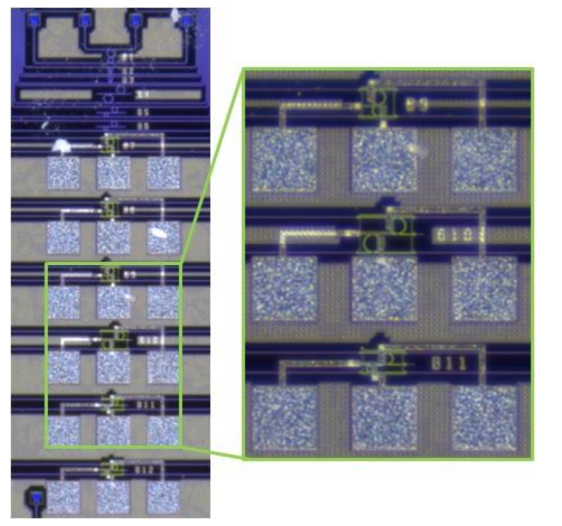

Figure 7. Chip micrographs showing Vernier ring filters, with *n*-doped resistive heaters probed using DC pads.

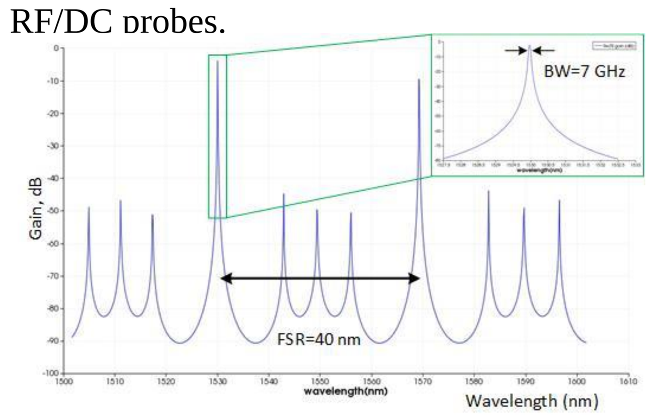

Figure 8. System-level simulations confirm the functionality of Vernier ring structures and high-Q microring filters.

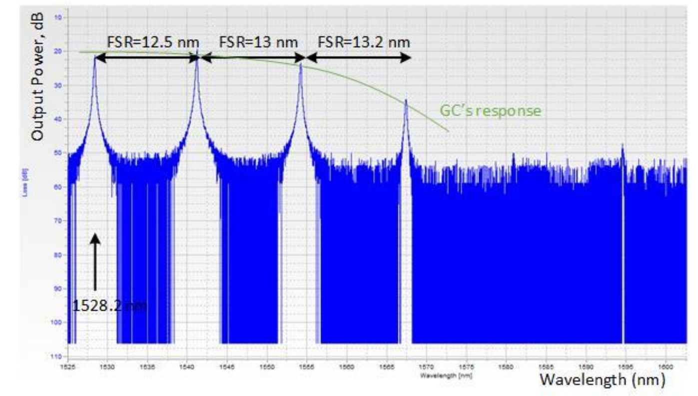

Figure 9. Measured response of microring filters using grating coupler based test setup.

7. Conclusion and Broader Impact

The proposed research seeks to investigate hybrid systems that use the optical domain signal processing to alleviate performance bottlenecks in wireless transceiver architectures. Research outcomes will empower mmWave IC researchers by equipping them with a new photonics expertise to take on design challenges in future multi-standard RF/mmWave radios.

Acknowledgements: Author gratefully acknowledges support from NSF CAREER Award EECS-1454411, AFOSR YIP FA9550-17-1-0076, and Keysight URC Award; and Kehan Zhu and V. Molina for chip tape-out.

AFOSR NSF KEYSIGHT TECHNOLOGIES Micron Foundation

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