

# Efficient wideband RF/mm-wave-to-optical signal transduction by a monolithic CMOS LNA and photonic molecule modulator

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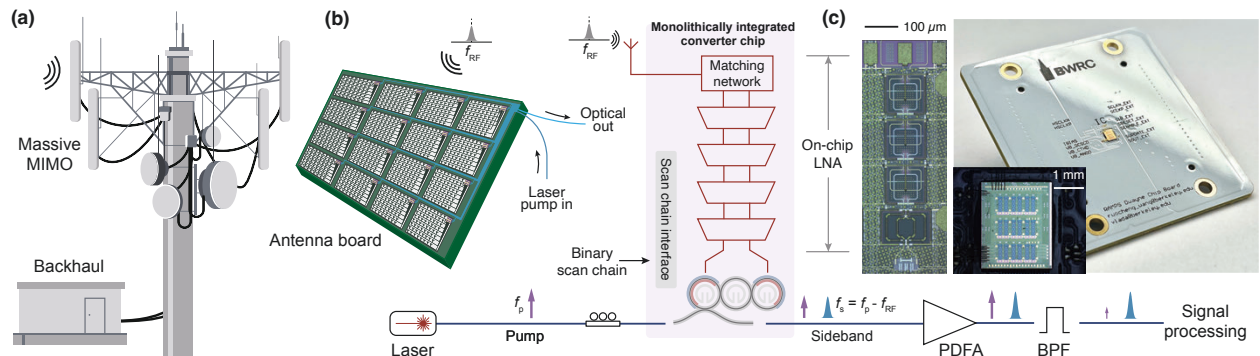
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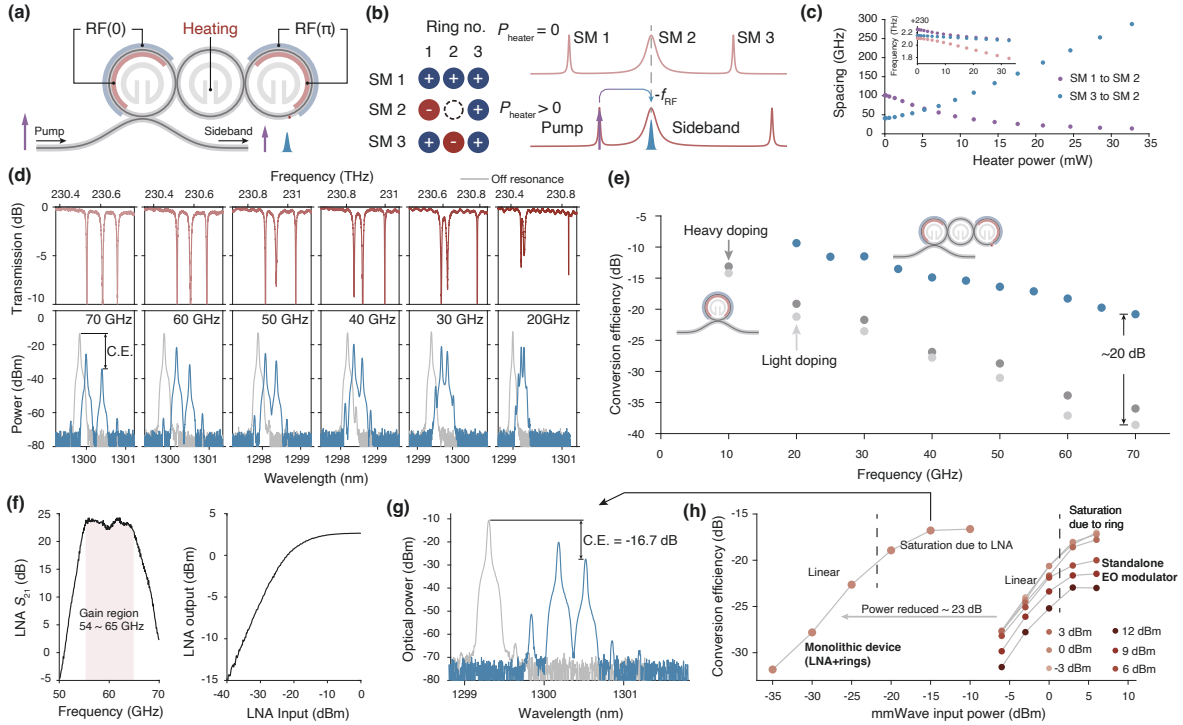
**Abstract:** We show efficient wide-tunable mm-wave-to-optical transduction (20 to 70 GHz at -9 to -18 dBc) using a triple-microring modulator. Integrated monolithically with a 18% bandwidth LNA, it generates sidebands with  $< -35$  dBm RF input. © 2025 The Author(s)

Emerging 5G/6G wireless technology could provide an important application of silicon photonics. High RF carrier frequencies (20–100 GHz) enable large-element-count array antennas and massive MIMO signal processing but at the cost of high on-array power. Optical disaggregation via wavelength-division multiplexed (WDM) analog RF/mm-wave over fiber could greatly reduce power over current state of the art (100×), but even over digital optical I/O, by removing A/D conversion [1]. For example (Fig. 1a-b), a 1,024-element (32×32) array could be removed by a bundle of 80 fibers (16 in, 64 out) carrying 16 wavelengths, and a CMOS low-noise amplifier (LNA) driving a microring-modulator at each antenna element [1]. Microrings are compact and can be spaced at mm-wave array element pitch (the complete circuit in this paper is  $250 \times 700 \mu\text{m}^2$ ), but their resonant response has a fundamental efficiency-RF carrier frequency tradeoff. This is because a higher ring Q improves gain but the narrower resonance in turn suppresses the sideband at higher RF frequencies. Dual-microring modulators fundamentally resolve this problem by providing a supermode resonance for each of the input laser and sideband. Then, increasing Q increases efficiency. Triple-ring modulators further provide tunability of input RF carrier frequency without sacrificing efficiency [2], where the middle ring is a “tunable coupling” between two active rings. This allows compensation for fabrication tolerance and/or wideband selection of RF carrier. In a CMOS silicon photonics platform (GlobalFoundries 45CLO) monolithic integration with a matched LNA with minimal parasitics further allows preamplification of weak RF signals coming from the antenna. Previously, we demonstrated RF sideband generation with such “photonic molecule” modulators at a fixed driving frequency [3], and LNA integration [1] in GF’s 45RFSOI process, but efficiencies were low.

In this paper, we integrate for the first time an LNA-driven triply resonant modulator in GF’s flagship 45CLO electronic-photonics platform, enabling high-Q modulator rings with weakly doped pn junctions that are ideal for this modulator architecture (Fig. 1c). We show the first demonstration of wideband RF signal conversion from 20 to 70 GHz in the stand-alone modulator, validating the triple-cavity tunable-RF concept, and its ability to break the fundamental tradeoff of single rings. We also show record efficiency for the LNA-driven devices (17 dB higher than [1])



**Fig. 1: Analog optical link for wireless communication featuring a single-chip mm-wave-to-optical signal transducer comprising an RF LNA and triple-cavity electro-optical (EO) modulator:** (a) Schematic of antenna tower with massive MIMO; (b) zoom-in of array antenna board with an analog optical link to transmit received mm-wave signal optically via fiber. A mm-wave-to-optical converter based photonic transmitter can be integrated with each antenna element. (c) Micrographs of the electronic-photonics mm-wave-to-optical converter, full chip, and the test chip board used for experimental characterization.



**Fig. 2: Efficient mm-wave signal transduction to optical domain by CMOS Si photonic transducer:** (a) Schematic of triply-resonant EO modulator with tunable RF frequency. (b) Energy and phase distribution among the three cavities for each super-mode. (c) Frequency spacing between super-modes 1 and 2 (or 2 and 3) is tuned by thermally tuning the middle cavity. (d) Through-port transmission spectrum and sideband generation for each RF frequency (i.e. tuned super-mode spacing) using the modulator alone (6 dBm RF power driving one active ring only). (e) Optical conversion efficiency vs. RF input of triple vs. single-cavity modulator. (f) Measured on-chip LNA gain (single-ended output instead of differential) and linearity. (g) High efficiency sideband generation with monolithic LNA+modulator integrated device under weak RF drive power (-15 dBm). (h) Comparison of efficiency for standalone triple-cavity modulator vs. the modulator monolithically integrated with LNA.

at -30 dBm RF in), showing sensitivity levels that could enable future link or array demonstrations. Fig. 1(c) illustrates a CMOS monolithic electronic-photonic transducer site for a single element, including a photonic triple-cavity silicon modulator, analog LNA circuit, mixed-signal thermal tuning driver, and digital scan chain interface. Fig. 2a shows the modulator comprising two outer, active pn-junction cavities driven in push-pull by the RF signal, and a passive middle cavity acting as a “tunable coupling”. The device has three optical super-modes, and tuning of the middle, passive cavity adjusts the mode spacing to match the RF frequency of interest (Fig. 2c). Fig. 2d shows the corresponding tuned spectra (red), and optimum sideband generation at 20 to 70 GHz (blue). Fig. 2e shows measured conversion efficiency vs. RF frequency for the triple-cavity modulator vs. a comparable single ring, showing up to 20 dB improvement at high RF frequencies. The remaining rolloff with frequency is RC dominated. Fig. 2f shows the LNA’s measured wideband (11 GHz on 60 GHz carrier, i.e. 18%) 22-24 dB gain and its linearity. Fig. 2g, the key result, shows a measured -16.7 dB conversion efficiency for the monolithic LNA-driven triple-ring modulator, at -15 dBm RF input. Fig. 2h shows conversion vs. RF input power showing sideband generation for as low as -35 dBm RF input power.

This demonstrates, to our knowledge, the highest conversion efficiency for weak mm-wave input scenarios [4, 5], showing that monolithic integrated LNA gain in silicon can be an alternative to seeking exotic EO materials. This work sets the foundation for initial link and beamforming and system demonstrations to explore analog photonic link disaggregation as a potentially transformative technology for future extreme MIMO wireless systems.

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