Compact Modeling of MicroRing-based RF/mmWave-to-Optical Modulators

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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 cmWave and mmWave front-ends with massive MIMO beamforming, that can seamlessly operate over a large range of spectrum become indispensable. Further, the high data rates transmitted over these links necessitate investigation of architectures that transcend the data capacity limitations of traditional electronic integrated circuits (ICs) and copper-based links.

Technology development leveraging RF photonics has thus far largely focused on isolated implementation of optical modulators and detectors [2]. Exploitation of silicon-based integrated optoelectronics can alleviate challenges with signal processing and distribution of mmWave waveforms, e.g. using Radio-over-Fiber links. These potential opportunities motivate system designers to investigate linearized electrooptic modulators that can convert RF/mmWave signals into optical domain with high dynamic range and SFDR. Breakthrough in this area will lead to transformative system-level functionality and reconfigurability over multi-GHz range in the last 50 feet of wireless, and potentially eliminate copper-based links in the front- and back-haul networks.

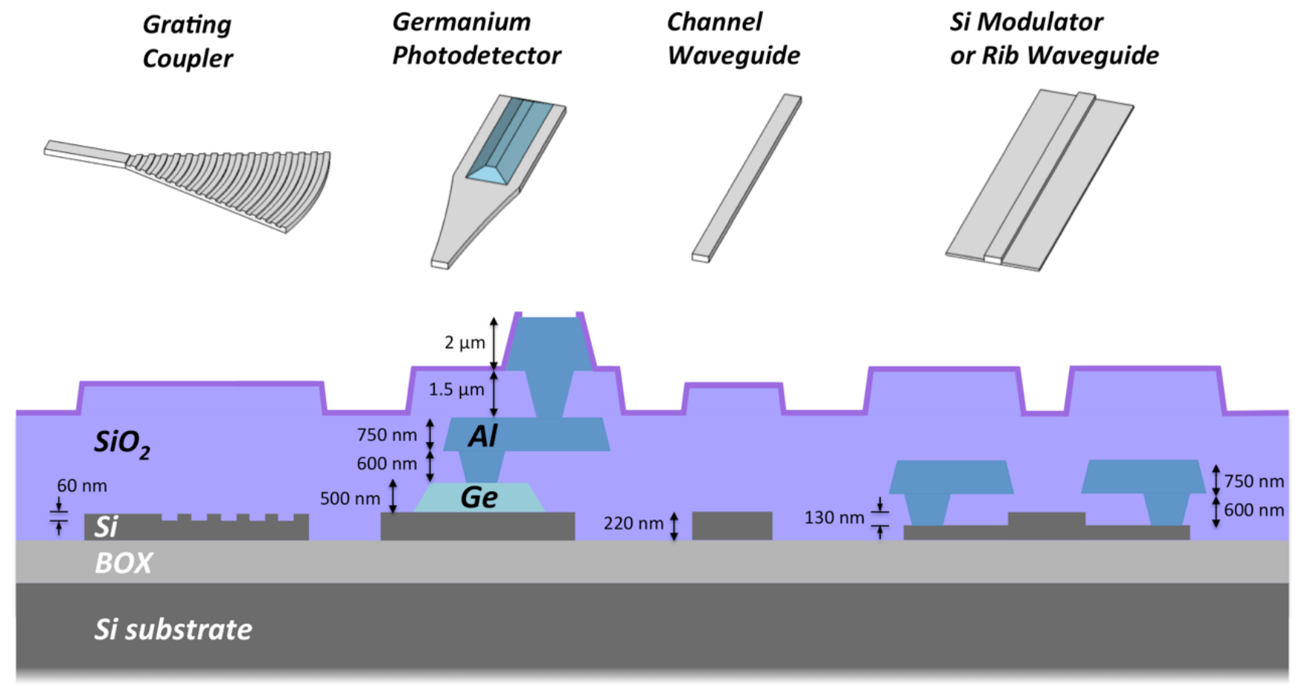

Figure 1: Cross-section illustration of SOI photonic fabrication technology available through IME [3].

2. Linearized CMOS Photonics Modulators

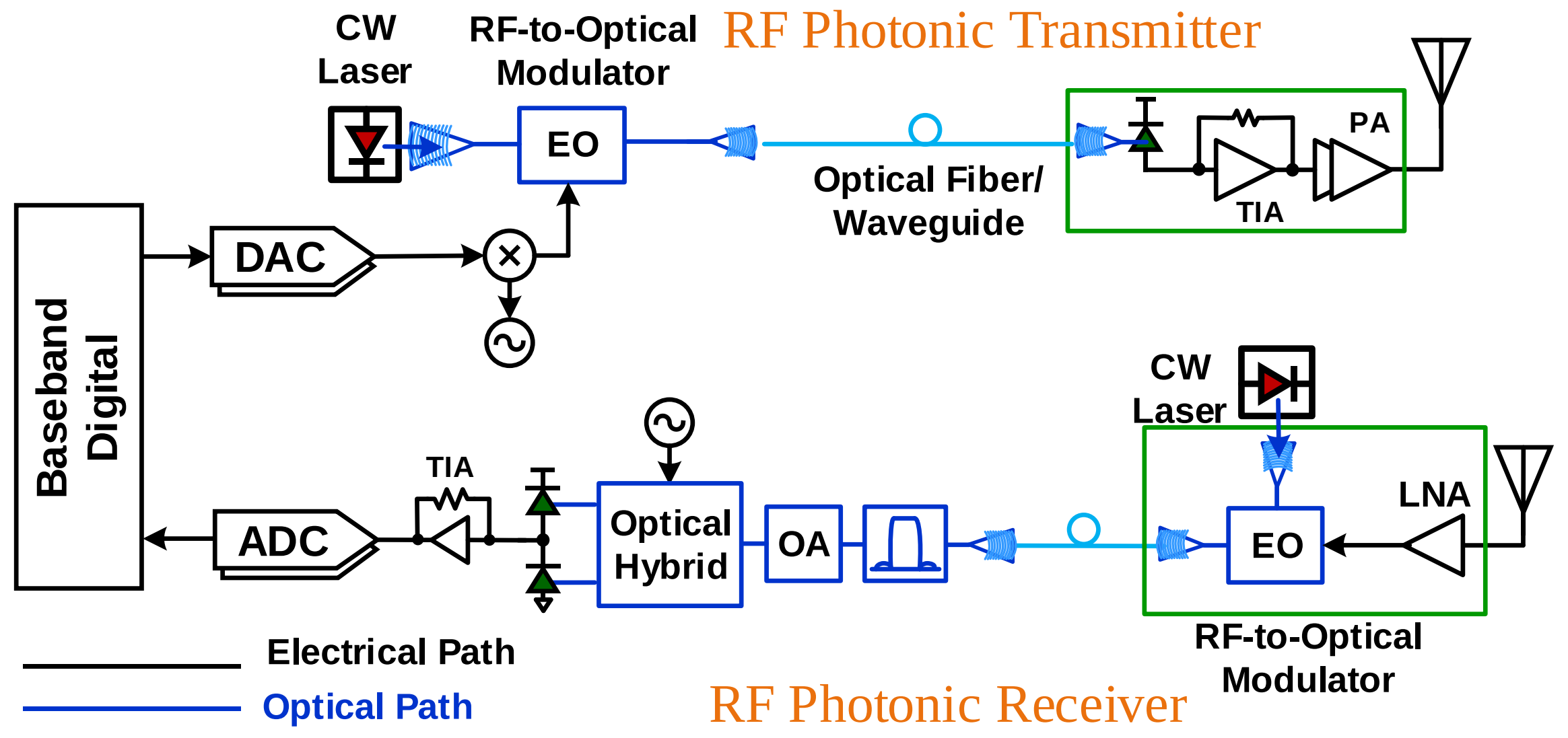

Figure 2. Envisioned RF/mmWave-photonic transceiver architecture.

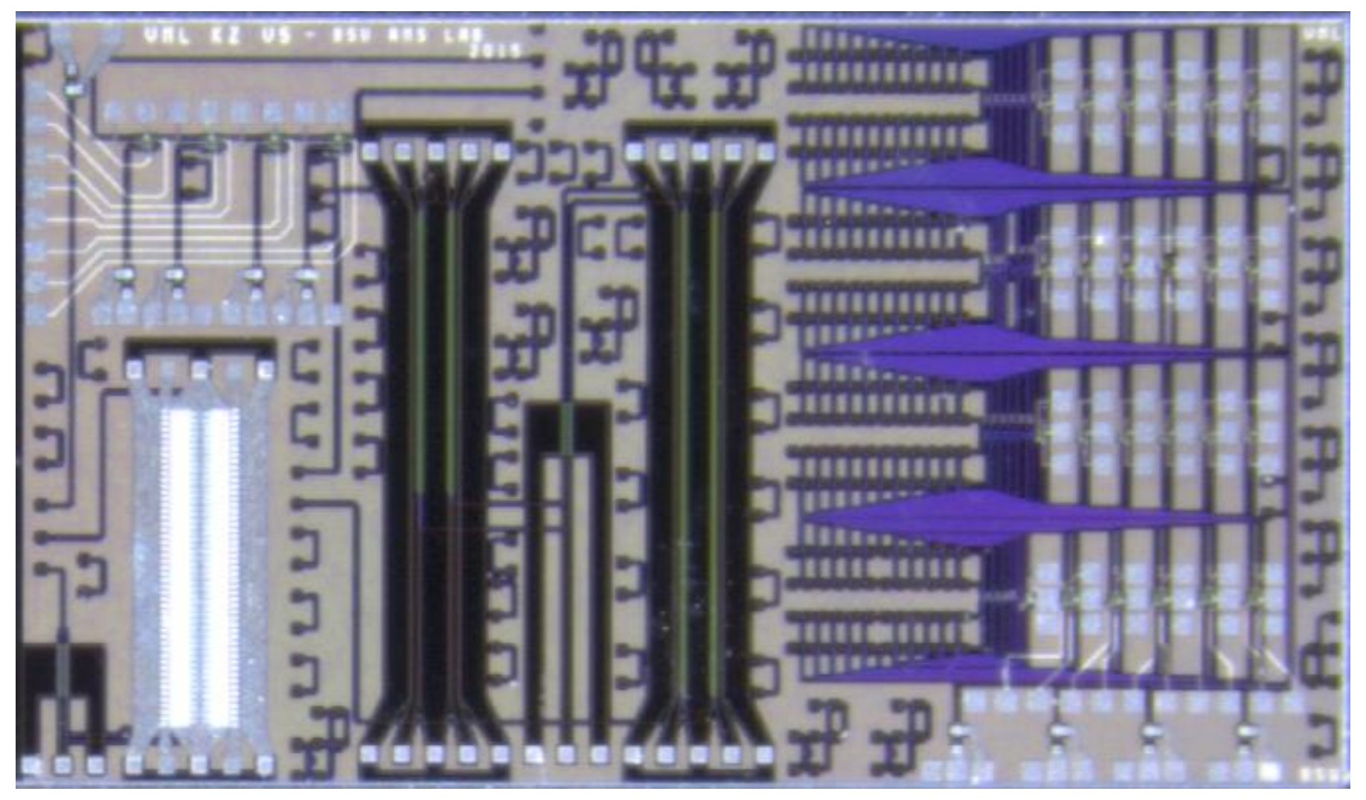

Figure 3. Micrograph of a fabricated 130-nm SOI photonic chip with Mach Zehnder and Ring modulators, filter banks, and detectors.

3. Research Approach

Ring Modulators: Compact ring modulators (~30µm radius) eliminate the need for a traveling-wave type CMOS driver for the Mach Zehnder modulators resulting in a simple lumped capacitance interface. Depletion-mode (or reversed-biased) *pn*-junction based phase shifters available in SOI Photonic processes are used in the ring modulator to realize >30 GHz electro-optic bandwidth. Typically, we design the optical components using FDTD, Modes and optical design software packages. However, compact modeling of ring-based structures is important as it allows co-simulation of photonic components with the interfacing electronic circuits in Cadence circuit design environment. Modeling challenges include accurate capture of transient response with electrical and optical time-constants. A dynamic model that treats the ring modulator as a voltage controlled oscillator, and given by equations [4]:

$$\frac{\partial a(t)}{\partial t} = (j(\omega_0 - \omega_r) - \frac{1}{\tau_l(t)} - \frac{1}{\tau_c(t)})a(t) + j\mu E_0 e^{j(\omega_0-\omega_r)t} \quad (1)$$

$$E_{out}(t) = E_0 e^{j(\omega_0-\omega_r)t} + j\mu a(t) \quad (2)$$

Here, $a(t)$ is the energy amplitude circulating in the ring, $\omega_0 = \frac{2\pi}{\lambda_0}$ is the laser carrier frequency with $\lambda_0 = 1550nm$, ω_r is the resonant angular frequency of the ring. E_o and E_{out} are the input laser intensity. The time-constants $\tau_l(t)$ and $\tau_c(t)$represent the energy amplitude decay in the ring and the coupling losses respectively.

The coupling factor µ relates to the coupling coefficient as $\mu = \sqrt{\frac{\kappa^2 v_g}{2\pi R}} = \sqrt{2/\tau_c}$, where v_g is the group velocity and R is the ring radius [4]. Here, $E_0 e^{j(\omega_0-\omega_r)t}$ is the frequency-translated analytic model which significantly speeds up the differential equation solution in Spectre.

Furthermore, $\tau_l(t) = f(V_{DC} + v_{in}(t))$ has been curve-fitted using simulation (and experimental) results for depletion-mode ring modulator for input DC bias, V_{DC}, and electrical signal v_{in}(t).

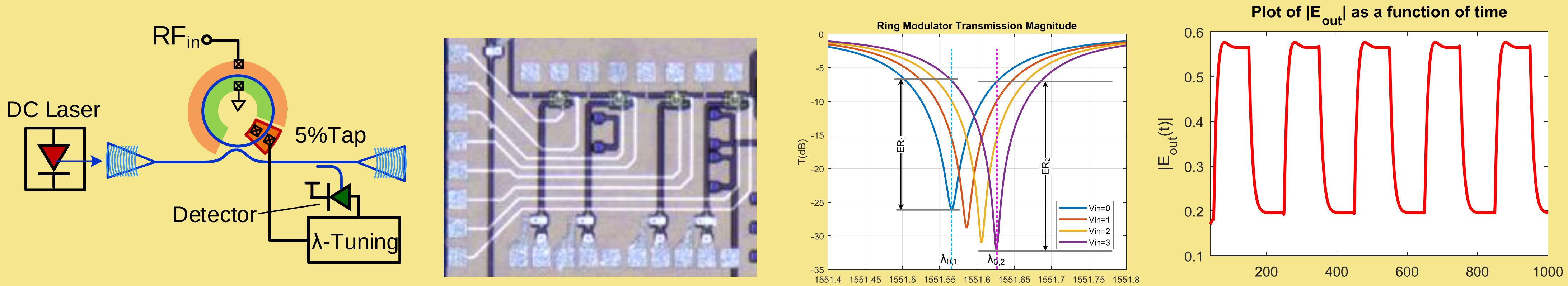

Figure 5. (a) SOI-based Ring Modulator, (b) micrograph of WDM ring modulators, (c) Ring Static tuning curves, (d) Transient response.

4. Research Progress

Compact Linearized EO Modulator: We are investigating compact SOI-photonic modulators, including the self-calibrating ring-assisted Mach-Zehnder modulator (RAMZI) as shown in Figure 6. Here, compact ring modulators (~30µm radius) in a differential drive structure eliminate the need for a traveling-wave type CMOS driver for the modulator [5], resulting in a simple lumped capacitance interface. Depletion-mode pn-junction based phase shifters are used in the ring modulator to realize >50 GHz electro-optic bandwidth. Compact modeling based simulations exhibit 10dB higher IIP3 and 105 dB SFDR.

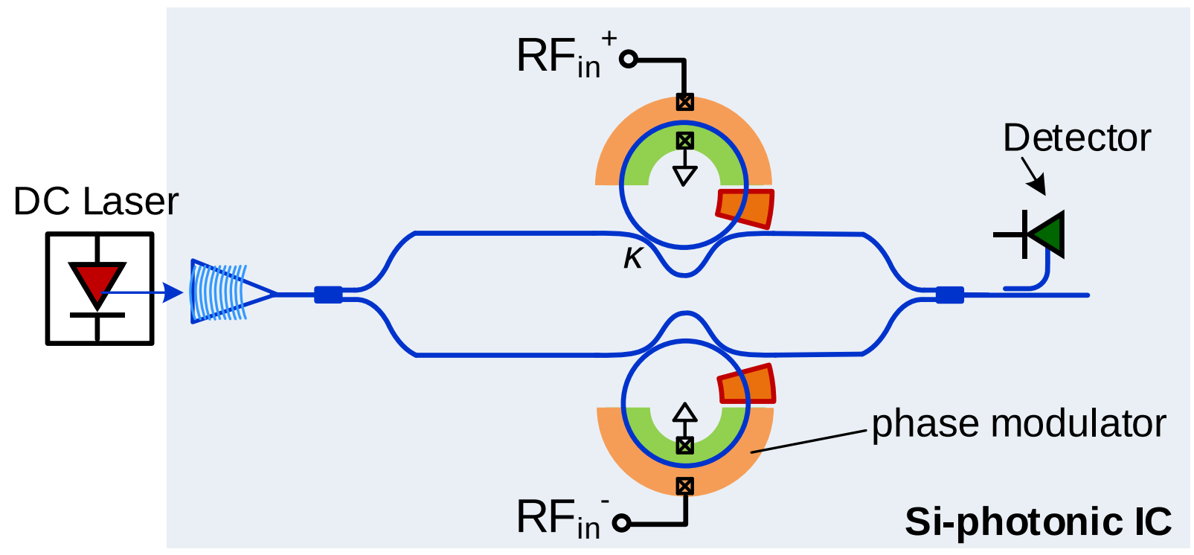

Figure 6. Ring-assisted Mach-Zehnder (RAMZI) EO modulator with adaptive calibration.

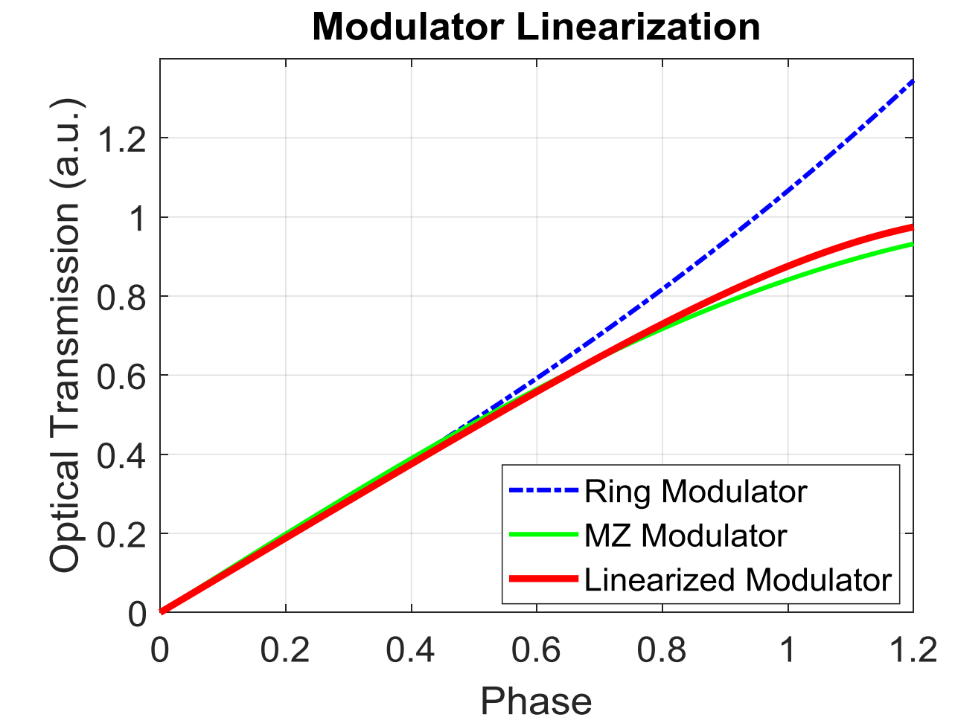

Figure 7. Optical transmission response showing a linearized RAMZI modulator.

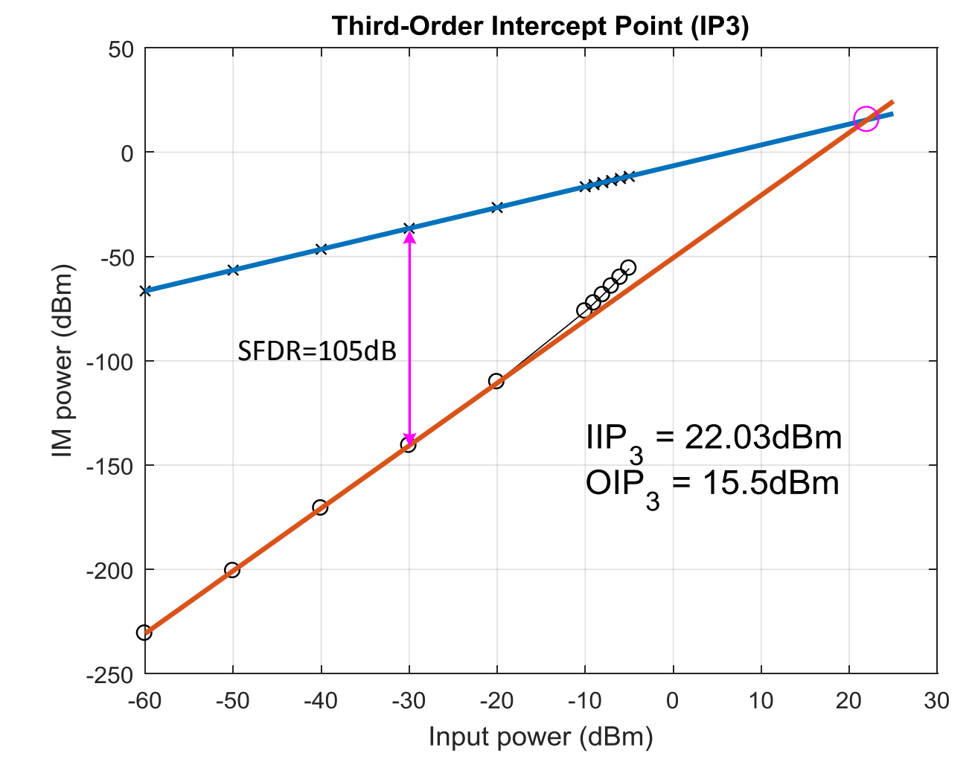

Figure 8. Linearized RAMZI modulator 3rd order intercept (IP_3). 10 dB higher IIP_3 than MZM.

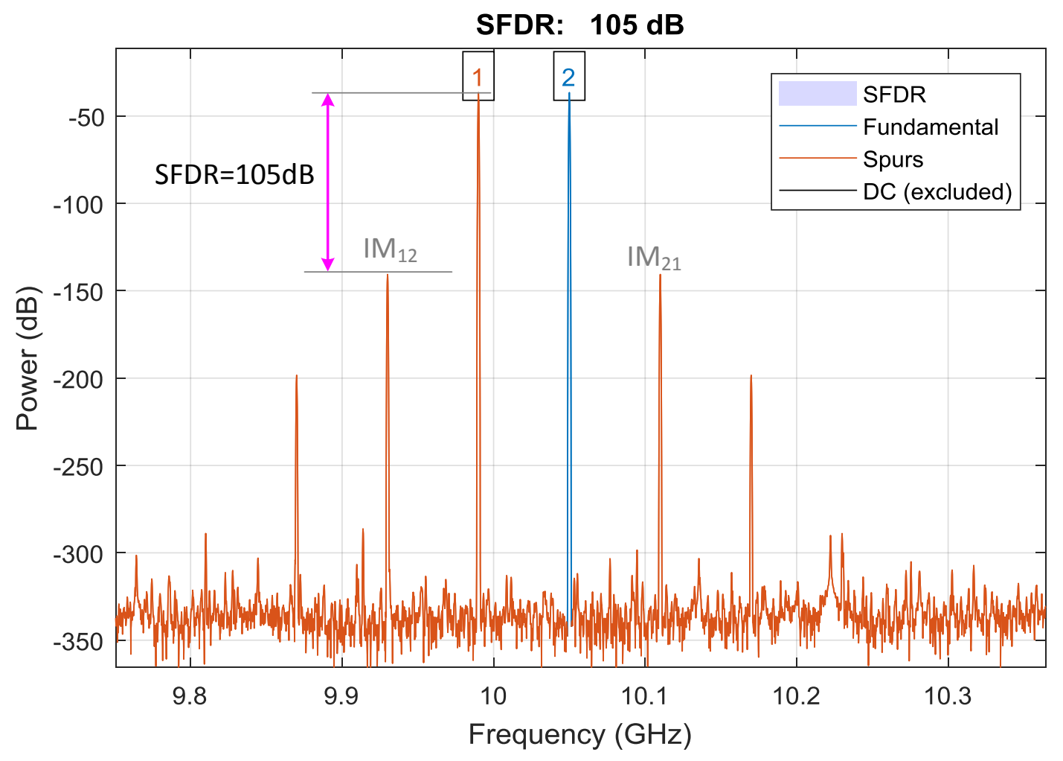

Figure 9. RAMZI SFDR is >105dB for -30dBm@10 GHz input; MZM had 75dB SFDR.

7. Conclusion and Broader Impact

Linearized mmWave photonic modulators with >100 dB SFDR will novel hybrid CMOS photonic system concepts; critical breakthrough required for making the next leap in broadband wireless communication to satisfy the ever growing demand for data capacity. Low cost and small form-factor mmWave photonic transceivers developed using the proposed approach can potentially transform the U.S. wireless and semiconductor industry by enabling multi-beam and multi-Gbps data rates.

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