RF-optical signal conversion via Dual Active-Cavity modulator in a Monolithic Electronic-Photonic SOI Platform

Manuj Singh[1,*], **Xinchang Zhang**[1], **Deniz Onural**[1], **Ruocheng Wang**[2], **Bohan Zhang**[1], **Kenaish Al Qubaisi**[1], **Vladimir M. Stojanović**[2] **and Miloš A. Popović**[1,†]

[1] *Department of Electrical and Computer Engineering, Photonics Center, Boston University, Boston, MA 02215, USA*
[2] *Department of Electrical Engineering and Computer Sciences, UC Berkeley, Berkeley, California 94709, USA*

[*] *manujks@bu.edu*, [†] *mpopovic@bu.edu*

Abstract: We demonstrate a Dual Active-Cavity RF modulator combining T-shaped spoked junction with a novel "half-rib" waveguide in a monolithic electronic-photonic platform. We measure a sideband efficiency of -52 dB at 66 GHz RF carrier frequency.

Photonic integrated circuits (PICs) have the potential to significantly enhance RF and millimeter-wave signal processing, including applications in phased array antennas for 5G/6G+ wireless communication [1–3] and Earth sensing [4]. Efficient RF-to-optical (EO) transducers [5–7] are essential for these circuits. When designed to be efficient, scalable, compact, and monolithically integrable with RF-CMOS circuits like low-noise amplifiers, they can enable a new class of powerful electronic-photonic integrated circuits for RF/mmWave applications. In this paper, we show the first demonstration of a dual-cavity active photonic modulator in a next-generation 45 nm SOI CMOS platform (GlobalFoundries 45CLO [8]). The monolithic 45CLO platform is an attractive platform for such PICs thanks to their CMOS compatibility and minimal propagation loss. Since the 45CLO process allows partial etch step, we employ a special kind of "half-rib" waveguide design in which one wall of the waveguide is fully-etched while the other etched is partially etched shown in Fig. 1(e).

Fig. 1(a) shows a schematic of the dual-cavity RF-optical transducer. The device features two identical coupled microring resonators with built-in electro-optic (EO) phase shifters. This coupled-cavity system supports two resonant states (supermodes) with symmetric and antisymmetric field distributions. A continuous-wave (CW) differential electrical drive, matching the supermode frequency splitting, modulates the cavity resonances, optimizing the coupling between supermodes. Thus, the electrical data signal is coupled to one of the optical supermodes, mediated by the CW optical drive signal. Fig. 1(b) shows the micrograph of the test sites with the dual-cavity modulator on the 45CLO platform. Fig. 1(c) and Fig. 1(d) depicts the 3D renders of the modulator without and with the metal layers respectively. The silicon device layer has a ring-radius of 6 μm with a core width of 410 nm shown in Fig. 1(d). Electro-optic phase shifters are implemented with "T-shaped" spoked-junction p-n diodes built into the core of the ring waveguides. The

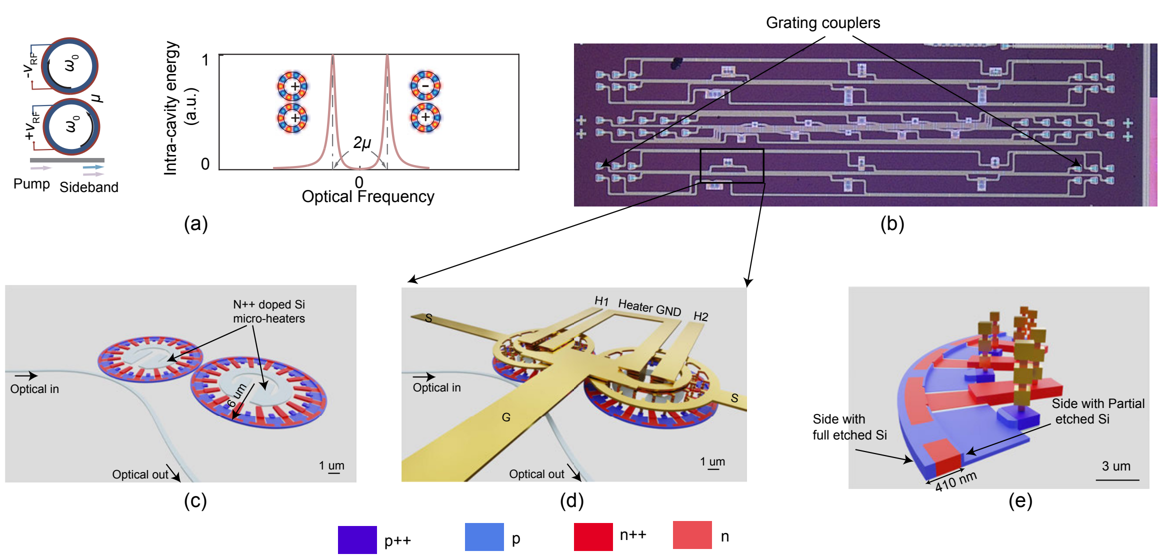

Fig. 1: (a) Dual-cavity modulator, modulated in push-pull and corresponding SM splitting dependent on the ring-to-ring coupling strength μ . (b) Zoomed-in micrograph of the test structures on the 45CLO platform. (c,d) 3D rendering of the dual-cavity modulator without and with the metal layers and its (e) cross-section showing the formation of "half-rib" waveguide.

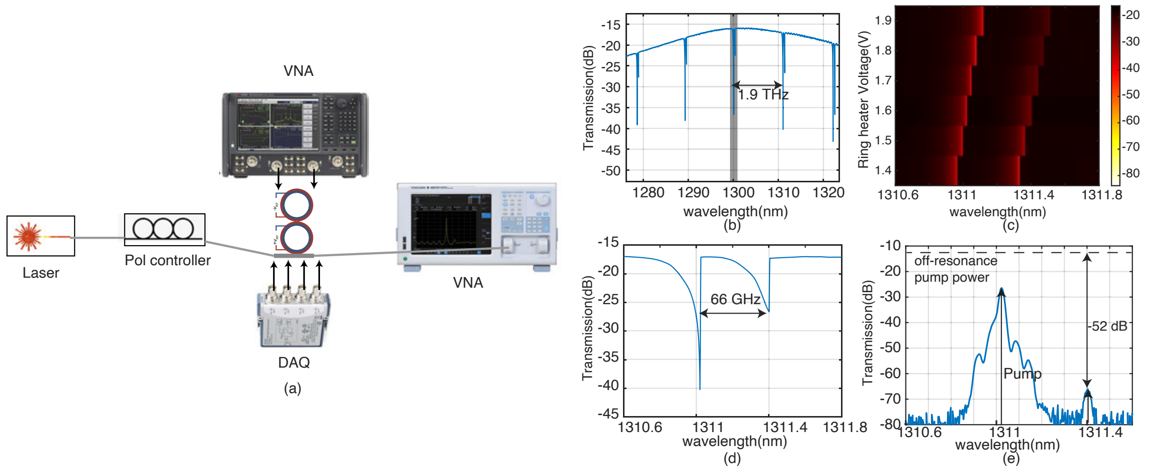

Fig. 2: (a) Experimental setup for characterizing the dual-cavity "half-rib" modulator. (b) Optical transmission response of the dual-cavity "half-rib" modulator in O-band. (c) Passive optical transmission spectrum versus ring heater voltages on one ring. (d) Supermode resonances of the dual-cavity "half-rib" variant with 66 GHz mode splitting at a 1.6V ring heater voltage. (e) Sideband generation of the dual-cavity "half-rib" modulator with 66 GHz RF carrier frequency.

cross-section and doping profile of the phase shifter are illustrated in Fig. 1(d). In the waveguide core, the low-level implants are used to form the junction and are marked as n and p regions. The highest implant n++ and p++ level are used in the 160 nm-thick spokes, which are placed at 600 nm distance from the waveguide core. Electrical vias are placed on these spokes. The strong doping and metal silicidation in these regions ensure low-resistance ohmic contact between the vias and the silicon device layer. Ring-shaped microheaters are placed inside the cavities to enable tuning of the ring resonances by using highest implant n++ level.

The experimental setup, depicted in Fig.2(a), utilizes 70 GHz GSG probes and a 70 GHz Hyperlabs BALUN to generate a push-pull drive for the dual-cavities. The setup consists of a fiber connecting a CW laser to the chip, and the RF power is incident from a network analyzer. Fig.2(b) illustrates the optical transmission response of the dual-cavity "half-rib" modulator in the O-band, showing a 1.9 THz FSR. Fig.2(c) presents the passive optical transmission spectrum as the ring heater voltage on one ring is varied from 1.4V to 1.9V, with the other ring fixed at 1.2V. At a 1.6V ring heater voltage, the Supermode resonances exhibit a 66 GHz mode splitting, as shown in Fig.2(d). We launched 5 dBm optical power at 1311.02 nm using on-chip O-band gratings and drove the dual-cavities in push-pull with around 0 dBm RF power at 66 GHz, maintaining bias voltages around 0V. The measured sideband efficiency was -52 dB, with an off-resonance power of -14 dBm at a 66 GHz RF carrier frequency, as shown in Fig. 2(e).

In conclusion, this is the first demonstration of a dual-cavity "half-rib" modulator using a monolithic 45CLO process. We introduced a new active phase shifter design with a spoked junction and a partial etch, making the entire ring active while maintaining a single-mode waveguide. This eliminates the need for a complex wrapped bus coupler for efficient mode-coupling. The device could serve as a crucial component for future on-chip millimeter-wave sensing, communication, and photonic signal processing systems, potentially realizable as silicon CMOS systems-on-chip.

Acknowledgments: This work was funded in part by NSF FuSe grant no. 2328947. We would like to thank Ayar Labs, Inc. for their support related to the 45CLO platform. Chips were fabricated by GlobalFoundries on the Dwayne test vehicle.

References

1. M. Singh, et al.,"Electronic-photonic millimeter-wave sensing element based on monolithically integrated LNA and triple-cavity ring modulator", 49th European Conference on Optical Communications (ECOC) (2023).
2. R. Wang, et al.,"A Monolithically Integrated Electronic-Photonic Front-end Utilizing Micro-ring Modulators for Large-Scale mm-wave Sensing", 49th European Solid State Circuits Conference(ESSCIRC) (2023).
3. P. Sanjari et al., "An integrated photonic-assisted phased array transmitter for direct fiber to mm-wave links", Nat. Commun. 14, 1414.
4. T. Pett et al., "Photonics-based Microwave Radiometer for Hyperspectral Earth Remote Sensing" 2018 Int. Top. Meet. on Microw. Photonics
5. M. Singh et al.,"Photonic molecule electro-optic modulators for efficient, widely tunable RF sideband generation and wavelength conversion", Frontier in optics (FiO) (2021).
6. H. Gevorgyan, *et.al.*, "Triply resonant coupled-cavity electro-optic modulators for ...",Optics Express 28(1), pp. 788-815 (2020) .
7. M. Singh, et al.,"Efficient wideband tunable RF-optical signal conversion via triply-resonant active-passive photonic molecules", Optica Open (2024).
8. M. Rakowski, *et al.*, "45nm CMOS - Silicon Photonics Monolithic Technology (45CLO) for next-generation, low power and high speed optical interconnects" Optical Fiber Communication Conference (OFC), paper T3H.3.