Broadband High-Performance Silicon-Based Power Amplifiers and Transmitters for Terahertz Applications

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***Abstract*—This report summarizes the research outcomes supported in part by the 2024 IEEE MTT-S Graduate Fellowship Program. Over the past year, we focused on the analysis and design of broadband high-performance silicon-based power amplifiers (PAs) and transmitters (TXs) for terahertz applications. A modified three-conductor (TC) broadband on-chip power combining technique, along with a IF-beamforming and sliding-IF TX architecture, is proposed. As proofs of concept, a 3-stage 4-way THz PA and a 300-GHz-band single-channel TX are implemented using a 130 nm SiGe BiCMOS process, both demonstrating broadband operation with high performance.**

***Index Terms*—Terahertz (THz), broadband, power amplifier (PA), transmitter (TX), SiGe BiCMOS.**

I. Introduction

To meet the ever-growing demand for wireless services in the B5G/6G era, it is essential to push wireless communication [1], radar [2], and sensing [3] systems toward the terahertz (THz) band. With the rapid advance of silicon-based semiconductor technology in recent years, it has become possible to implement THz circuits and systems with low cost and high integration. However, due to the low breakdown voltage, limited f_T/f_{max} of silicon-based transistors, and high loss of on-chip passive devices, it still remains challenging to implement high-performance silicon-based THz circuits and systems with wide bandwidth and high efficiency, especially in the aspects of power amplification and system integration. Therefore, it is necessary to explore key techniques to improve the comprehensive performances of THz silicon-based circuits and propose practical solutions for realizing broadband high-performance silicon-based THz systems.

To overcome such challenges, this report proposes a modified three-conductor (TC) broadband on-chip power combining technique and a IF-beamforming and sliding-IF transmitter (TX) architecture. Based on these techniques, a broadband high-performance silicon-based THz power amplifier (PA) and TX is fabricated in 130-nm SiGe BiCMOS.

II. Project Outcomes

A. A 110-to-203-GHz 18.3-dBm Broadband Power Amplifier

In recent years, the traditional three-conductor (TC) on-chip power combiner [4] has been widely adopted in THz PAs due to its compact footprint and design simplicity. However, its core component, the TC balun, inherently exhibits a narrow-band response as it functions as a single-resonator circuit. In addition, it requires several external capacitors for PA biasing and output DC blocking, which limits its ability to achieve broadband low-loss power combining. To address these limitations, we propose an modified TC balun that integrates traditional TC baluns with coupled lines (CP-lines), enabling the realization of multi-way hybrid power combiners. The incorporation of CP-lines transforms the combiner into a coupled-resonator structure with wide-band characteristics, while eliminating the need for external bypass and DC-blocking capacitors and enhancing the combining efficiency.

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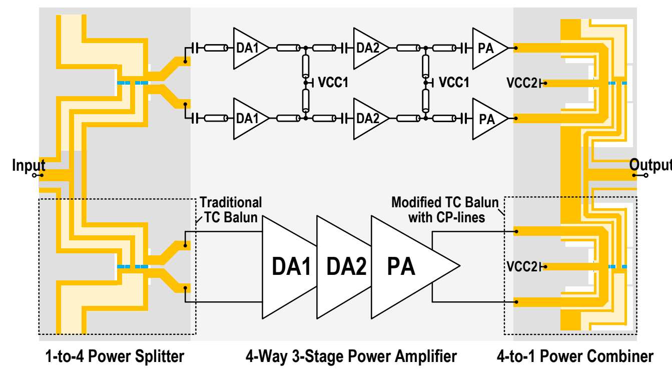

Fig. 1. Circuit schematic of the PA.

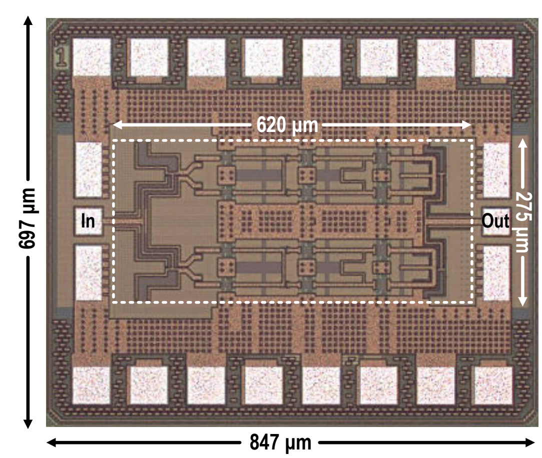

Fig. 2. Die photo of the PA.

Based on the proposed modified TC balun, a broadband high-power THz PA is implemented in 130-nm SiGe BiCMOS.As shown in Fig. 1, the PA consists of a 1-to-4 power splitter, a three-stage four-way amplifier unit, and a 4-to-1 power combiner. Fig. 2 shows its die photo. The proposed PA exhibits a small-signal gain of 19.0–22.0 dB over the 110–175 GHz frequency range, corresponding to a 3-dB bandwidth of 65 GHz, and achieves a peak gain of 25.2 dB at 187 GHz. It delivers a peak saturation output power (P_{SAT}) of 18.3 dBm

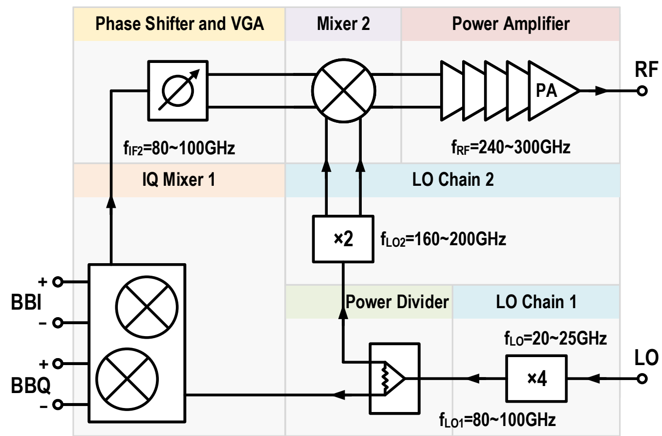

Fig. 3. Architecture of the TX.

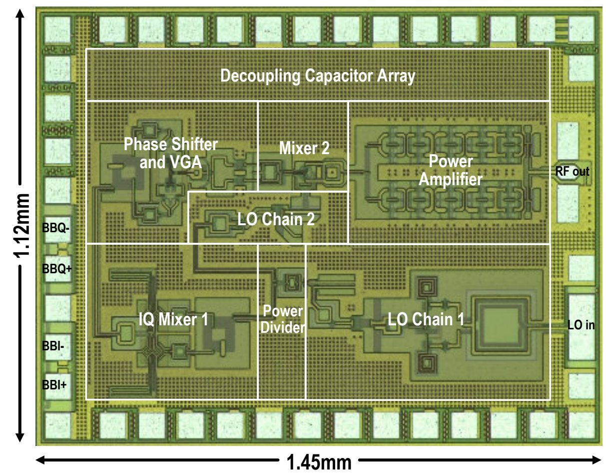

Fig. 4. Die photo of the TX.

at 119 GHz and maintains P_{SAT} above 15.3 dBm from 110 to 203 GHz, resulting in a 3-dB P_{SAT} bandwidth of 93 GHz. Across this frequency range, the output 1-dB compression point (OP_{1dB}) ranges from 12.83 to 16.73 dBm, while the maximum power-added efficiency (PAE_{max}) varies between 4.17% and 8.64%. Compared to state-of-the-art broadband sub-THz PAs, the proposed design offers superior OP_{1dB}, P_{SAT}, PAE, and bandwidth performance within a highly compact core area.

B. A 300-GHz-Band High-Power Transmitter with Phase-Shifting Architecture for Phased-Array Systems

The extremely high frequency of THz waves places heavy demand on the architecture design of the phased array system, as it consists of numerous modules (e.g., PA, mixer, phase shifter, and LO chain) operating at different frequency bands and faced with distinct challenges. Fig. 3 presents the proposed IF-beamforming and sliding-IF TX architecture for THz phased array systems, which aims to provide an optimal operating frequency for each module and finally to maximize system performance. The advantages of the proposed architecture are summarized as follows: (1) The sliding IF scheme [5] lowers the operating frequencies of mixers and multipliers, thereby alleviating circuit design challenges and improving overall performance. (2) With the IF beamforming architecture, the operating frequency of the phase shifter can be also decreased to obtain higher gain and greater resolution. (3) By appropriately selecting the IF and two LO frequencies, the final RF frequency can be placed sufficiently far from the IF frequency and the second LO frequency, resulting in a high image and LO rejection ratio. (4) The PA-last configuration further boosts the output power and extends the communication range.

Based on the proposed architecture, a 300-GHz-band high-power single-channel TX with phase-shifting architecture is implemented in 130-nm SiGe BiCMOS. Fig. 4 demonstrates its chip layout. By tuning the base bias of the second mixer, the fabricated TX can switch between a high-frequency narrow-band mode and a low-frequency broadband mode. In the high-frequency narrow-band mode, with a IF frequency of 100-MHz, the TX achieves a maximum conversion gain of 31 dB at 282 GHz, while maintaining over 20-dB gain, 6-dBm P_{SAT}, and 22-dBc LO/image rejection from 240 to 300 GHz. In the low-frequency broadband mode, the TX delivers a 22–25-dB conversion gain, 6–8.5-dBm P_{SAT}, 4.6–6.7-dBm OP_{1dB} from 242 to 282 GHz, with a maximum DC power consumption below 1 W. In both modes, from 240 to 300 GHz, the TX achieves 6-bit phase shifting with low RMS gain and phase errors of 0.17 dB and 1.3°, respectively. The modulation measurement is currently in progress, and the testing of a four-channel phased-array transmitter extended from this system has also been planned.

III. Fellowship Impact and Career Plan

I am deeply honored to receive the 2024 IEEE MTT-S Graduate Fellowship Award, which has provided invaluable support for my research and will continue to inspire my academic journey. Looking ahead, I am dedicated to applying the outcomes of my Ph.D. project to advance ultra-high-speed optical module technologies. I would also like to express my heartfelt gratitude to my supervisor, Prof. Wenhua Chen, for his unwavering guidance and support throughout my research.

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