Guest Editorial: Integrated Devices, Circuits, and Systems for the 6G Era

THIS Special Issue of the IEEE JOURNAL ON EMERGING AND SELECTED TOPICS IN CIRCUITS AND SYSTEMS (JETCAS) is dedicated to demonstrating the latest research progress on integrated devices, circuits and systems for the 6G Era. As 5G rolls out worldwide, teams of visionary experts are developing roadmaps and revolutionary applications for the next-generation wireless network: 6G. Indeed, the 6G mobile networks will establish new standards to fulfill the unreachable performance required by the current 5G networks. It is anticipated that 6G technology will be capable of supporting extremely high-performance connectivity with massive numbers of connected devices.

At present, the rapid progress in miniaturized devices, integrated circuits, and 'smart' systems have already paved the way for cutting-edge electronic products, including Wi-Fi families, phased-array transceivers operating at 24/28/39-GHz bands for cellular networks, E-band for back-haul systems and 77-GHz automotive anti-collision radars, just to name a few. These solutions are the enabling hardware foundation of the current 5G technology, as they support multi-gigabit communication as well as low-latency real-time sensing services. They will continually play a critical role in the 6G era with further enhanced performances. Meanwhile, although the spectrum allocated for 6G has not been finalized yet, the spectrum between 90 and 300 GHz, known as the sub-terahertz (sub-THz) region, will likely be exploited in the 6G era. The increasing use of a higher carrier frequency with a wider bandwidth has posed new challenges to the overall design of associated RF systems. To exploit the spectrum range above 90 GHz, 6G must address the challenge of scattering and absorption in the ambient environment that leads to substantial path loss compared with the spectrum range below 90 GHz. It is therefore worthwhile to explore.

This Special Issue aims to provide a comprehensive perspective on cutting-edge research in the field of integrated devices, circuits, and systems for the 6G era through a selection of recent contributions. Only 12 papers were accepted for publication after a rigorous review process, and they can be cataloged into four themes: 1) design of ON-chip passive components and antenna-in-package technology; 2) sub-THz integrated circuit design; 3) millimeter-wave integrated circuit design; and 4) microwave circuit design.

I. DESIGN OF ON-CHIP PASSIVE COMPONENTS AND ANTENNA-IN-PACKAGE TECHNOLOGY

This group of papers focuses on passive component design, including ON-chip filtering devices, and interconnections between chipsets and packages. Passive components, especially filters, play a very critical role in many modern wireless systems. They are used to improve the signal-to-noise ratio (SNR) at the "front-end' of the transceiver by suppressing the undesired interferences, which otherwise are difficult to deal with using active components, as well as out-of-band noise. In addition, high-density wafer-level packaging technology has become more and more mature, which will be widely used to support heterogeneous integration that has also been recognized as a technology enabler in the 6G era.

In [A1], Khiabani et al. present the design, implementation, and measurements of ultra-wideband millimeter-wave antennas. These antennas are made using a combination of metamaterial and advanced high-density interconnect (HDI) antenna-in-package (AiP) technologies, ideal for beyond 5G (B5G) and 6G networks.

In [A2], Chakraborty et al. designed three designs of transverse resonance-based high-order ON-chip low-pass filters are designed in 0.15-μm gallium arsenide (GaAs) pseudomorphic high-electron-mobility-transistor (pHEMT) technology with very compact sizes, sharp-rejection capabilities, and extended stopband as merits.

In [A3], Nericua et al. provide an overview of complementary metal-oxide–semiconductor (CMOS) integrated millimeter-wave passive devices for band-pass and band-stop filtering applications while also reporting originally conceived filter developments and future trends.

II. SUB-THZ INTEGRATED CIRCUIT DESIGN

The sub-THz spectrum has been identified as an enabling factor for the B5G and 6G. Thus, three papers are included on this topic. Two of them are focused on signal generation using bulk CMOS technology, and the other one is related to signal amplification in SiGe HBT technology.

In [A4], Yang et al. present a 65-nm CMOS-based THz radiator array integrating two elements, each of which consists of two fundamental oscillators operating at half of the output frequency, a push-push frequency doubler, and an ON-chip square-shaped loop antenna. It achieves a peak effective isotropically radiated power (EIRP) of 3.9 dBm, which results in a figure-of-merit (FoM) of 170.1 dBc/Hz.

In [A5], Wang et al. present a 340-GHz compact THz amplifier-frequency-multiplier chain (AMC) offering a full 360° phase shifting range for phased-array applications. The proposed THz AMC is implemented in a 40-nm CMOS technology and achieves a peak output power of −3.5 dBm at 360 GHz with a conversion gain of 1.8-dB and a 3-dB bandwidth from 340 to 376 GHz.

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In [A6], Zhang et al. theoretically analyze the optimum designs by varying the base impedances for power gain and output power level enhancement. In addition, numerical results are given to prove that non-zero base impedances are key parameters toward gain and output power enhancements. To validate the design theory, a 220-GHz power amplifier is fabricated in a 130-nm SiGe technology. The measurement reveals that the amplifier achieves an operation bandwidth from 185 to 240 GHz, a power gain of 25 dB, and a saturated output power of 9.5 dBm.

III. Millimeter-Wave Integrated Circuit Design

Since millimeter-wave technology has already been adopted in many applications in the current 5G network, it will be the driving force in the transition from 5G to 6G. Therefore, the design of millimeter-wave integrated circuits is discussed in this section. There are four papers included on this topic.

In [A7], a low-phase noise oscillator is a crucial component in wireless systems, and the design challenge of the oscillator significantly increases as the operating frequency rises. This paper focuses on the design and analysis of a 60-GHz CMOS sextuple sub-harmonically injection-locked voltage-controlled oscillator with a frequency tracking loop. The measured phase noise at a 1-MHz offset and the rms jitter integrated from 1 kHz to 10 MHz are both lower than −109.4 dBc/Hz and 43 fs, respectively.

In [A8], Chen et al. present to improve the efficiency at a power back-off region, a novel symmetrical load-modulated balanced amplifier architecture. The designed power amplifier is fabricated in a 45-nm CMOS SOI technology. At 39 GHz, a 22.1-dBm saturated output power with a maximum power-added efficiency (PAE) of 25.7% is achieved. In addition, 1.68 times drain efficiency enhancement is obtained over an ideal Class-B operation at 6-dB power back-off.

In [A9], instead of using a silicon-based technology node, a 90-nm GaAs pHMET is employed in this work for the wide-band attenuator design. Two design examples are presented, and they cover the operational frequency range from 26 to 110 GHz.

In [A10], Fu et al. designed two power amplifiers in 0.15-μm GaAs pHEMT technology and operate at 24–32 GHz and 24–38 GHz, respectively. Both provide at least 24-dBm saturated output power and the PAE is better than 24% across the bandwidth.

IV. Microwave Circuit Design

Although the millimeter-wave and sub-THz technologies will be the main players in the B5G and 6G eras, the spectrum allocated for microwave frequency bands still plays an important role due to its unique characteristics, such as low channel loss and great penetration of many materials. Therefore, the final group of papers is focused on classical circuit design techniques used for microwave circuits. Two papers are included on this topic. One is related to a Doherty-like amplifier, while another is related to a wideband voltage-controlled oscillator (VCO) design.

In [A11], Bai et al. present a new power amplifier architecture. It can bring new circuit design freedom, which expands the operating bandwidth of the load modulation network. As a proof-of-concept, a broadband asymmetrical Doherty power amplifier is designed using fabricated gallium nitride (GaN) HEMT transistors. The power amplifier generates 44–46 dBm output power across a bandwidth of 1.9–2.9 GHz. The drain efficiency is 42.1%–68.9% at saturation and 45.5%–58.5% at 8-dB power back-off, respectively.

In [A12], Lyu et al. present a constructive switched magnetic coupling technique, realizing dual-band operation with the Q improvement into one band due to the in-phase coupling and the explicit switch. For validation purposes, a dual-band VCO is designed in a 65-nm CMOS technology. The VCO is measured with an oscillation frequency range of 37.8% from 11.3 to 16.6 GHz. Within the entire frequency coverage, the measured phase noise ranges from −129.6 to −123.7 at a 10-MHz offset, resulting in a FoM of 186–192.1 dBc/Hz.

Acknowledgment

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APPENDIX: RELATED ARTICLES

[A1] N. Khiabani, C.-W. Chiang, N.-C. Liu, P.-Y. Chen, Y.-C. Kuan, and C.-T.-M. Wu, "Metamaterial-enabled ultrawideband mmWave antenna-in-package using heterogeneously-integrated silicon IPD and HDI-PCB for B5G/6G applications," *IEEE J. Emerg. Sel. Topics Circuits Syst.*, vol. 14, no. 1, pp. 7–18, Mar. 2024.

[A2] S. Chakraborty, S. Gayatri, M. Heimlich, and A. Verma, "Compact transverse-resonance low-pass filter with wide stop-band rejection implemented in gallium arsenide technology," *IEEE J. Emerg. Sel. Topics Circuits Syst.*, vol. 14, no. 1, pp. 19–29, Mar. 2024.

[A3] R. Nericua, K. Wang, H. Zhu, R. Gómez-García, and X. Zhu, "Low-loss and compact millimeter-wave silicon-based filters: Overview, new developments in silicon-on-insulator technology, and future trends," *IEEE J. Emerg. Sel. Topics Circuits Syst.*, vol. 14, no. 1, pp. 30–40, Mar. 2024.

[A4] M. Yang, C. Zhang, L. Wu, and Q. Xue, "A 299–315-GHz dual-band radiator array with cascaded transmission line-based feedback network for phase noise improvement," *IEEE J. Emerg. Sel. Topics Circuits Syst.*, vol. 14, no. 1, pp. 41–51, Mar. 2024.

[A5] C. Wang, P.-C. Chiu, C.-L. Ko, S.-H. Tseng, and C.-H. Li, "A 340-GHz THz amplifier-frequency-multiplier chain with 360° phase-shifting range and its phase characterization," *IEEE J. Emerg. Sel. Topics Circuits Syst.*, vol. 14, no. 1, pp. 52–66, Mar. 2024.

[A6] X. Zhang, N. Zhu, and F. Meng, "A 185-to-240 GHz SiGe power amplifier using non-zero base-impedances for power gain and output power optimizations," *IEEE J. Emerg. Sel. Topics Circuits Syst.*, vol. 14, no. 1, pp. 67–74, Mar. 2024.

[A7] W.-C. Chen and H.-Y. Chang, "Design and analysis of a V-band CMOS sextuple SILVCO using transformer and cascade-series coupling with a frequency-tracking loop," *IEEE J. Emerg. Sel. Topics Circuits Syst.*, vol. 14, no. 1, pp. 75–87, Mar. 2024.

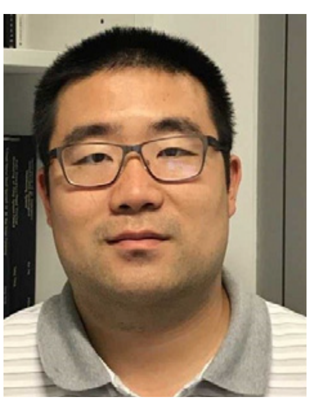
[A8] L. Chen, L. Chen, D. Sun, Y. Sun, Y. Pan, and X. Z. Member, "A 39 GHz Doherty-like power amplifier with 22dBm output power and 21% power-added efficiency at 6dB power back-off," *IEEE J. Emerg. Sel. Topics Circuits Syst.*, vol. 14, no. 1, pp. 88–99, Mar. 2024.

[A9] Y. Wang et al., "Broadband millimeter-wave GaAs dual-function switching attenuators with low insertion loss and large attenuation range," *IEEE J. Emerg. Sel. Topics Circuits Syst.*, vol. 14, no. 1, pp. 100–110, Mar. 2024.

[A10] Z.-H. Fu, M.-X. Li, T.-G. Ma, C.-S. Wu, and K.-Y. Lin, "Millimeter-wave GaAs ultra-wideband medium power amplifier and broadband high-power power amplifier for 5G/6G applications," *IEEE J. Emerg. Sel. Topics Circuits Syst.*, vol. 14, no. 1, pp. 111–121, Mar. 2024.

[A11] G. Bai et al., "Design of broadband Doherty power amplifier based on single loop load modulation network," *IEEE J. Emerg. Sel. Topics Circuits Syst.*, vol. 14, no. 1, pp. 122–132, Mar. 2024.

[A12] Y. Lyu, C. Song, P. Qin, and L. Wu, "A 11.3–16.6-GHz VCO with constructive switched magnetic coupling in 65-nm CMOS," *IEEE J. Emerg. Sel. Topics Circuits Syst.*, vol. 14, no. 1, pp. 133–141, Mar. 2024.



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