MZ Journals Computing Journal

Broadband mm-Wave Power Amplifiers: A Review of Recent Advances in InP and CMOS Technologies

Andrei Popescu
Transylvania University, Romania

Abstract

This paper presents a comprehensive review of recent advances in broadband mm-wave power amplifiers (PAs), focusing on innovations in indium phosphide (InP) and complementary metal-oxide-semiconductor (CMOS) technologies. As demand for higher data rates and broader bandwidths increases, mm-wave PAs have become critical components in enabling high-frequency applications, including 5G and beyond. This review critically assesses the progress in the design and performance of mm-wave PAs, highlighting significant achievements in efficiency, linearity, and output power. The use of InP technology is emphasized for its superior electron mobility and high-frequency capability, which make it ideal for high-performance mm-wave applications. Similarly, the scalability and integration capabilities of CMOS technology are discussed, with a focus on recent developments that have improved its viability at mm-wave frequencies. This paper also explores the challenges and solutions associated with each technology, including design strategies, material considerations, and fabrication techniques. The comparative analysis provides insights into how these technologies are shaping the future of mm-wave applications, offering a glimpse into upcoming trends and potential breakthroughs in PA design.

Keywords: mm-Wave Power Amplifiers, Broadband Technology, InP (Indium Phosphide), CMOS (Complementary Metal-Oxide-Semiconductor)

1. Introduction

The expansion of 5G networks and the increasing demand for high-frequency applications in the mm-wave spectrum have catalyzed significant advancements in semiconductor technologies, notably in Indium Phosphide (InP) and Complementary Metal-Oxide-Semiconductor (CMOS)[1]. These advancements are pivotal as they enhance the performance and efficiency of mm-wave power amplifiers, critical components in wireless communication systems. This paper reviews recent progress in broadband mm-wave power amplifiers, focusing on developments in InP and CMOS technologies, which are at the forefront due to their high-frequency capabilities and efficiency in power amplification. InP technology, known for its superior electron velocity, offers significant advantages for high-frequency broadband applications, facilitating the design of power amplifiers that operate effectively at mm-wave frequencies. Concurrently, CMOS technology, traditionally favored for lower cost and integration capabilities, has seen transformative developments that allow for competitive performance at these higher frequencies. This paper explores the integration of these technologies in the design and fabrication of power amplifiers, considering the implications for future telecommunications systems[2]. The rapid evolution of wireless communication technologies has ushered in an era of unprecedented connectivity, where high-speed data transmission and low-latency communication are essential for a wide array of applications. With the advent of 5G networks and the proliferation of internet-of-things (IoT) devices, there is a growing demand for broadband communication systems capable of operating at millimeter-wave (mm-wave) frequencies (30 GHz to 300 GHz). These frequencies offer significantly larger bandwidths compared to traditional microwave bands, making them ideal for delivering high data rates and supporting ultra-dense network deployments. At the heart of these advanced communication systems lies the mm-wave power amplifier (PA), a critical component responsible for amplifying signals to sufficient levels for transmission over long distances. However, designing efficient and high-performance PAs at mm-wave frequencies presents unique challenges. These challenges include addressing nonlinearity, minimizing power consumption, and ensuring robustness across a wide bandwidth[3]. In recent years, significant progress has been made in the development of mm-wave PAs, particularly leveraging advancements in semiconductor technologies such as indium phosphide (InP) and complementary metal-oxide-semiconductor (CMOS). InP offers superior electron mobility and high-frequency performance, making it well-suited for high-power and high-efficiency mm-wave amplification. On the other hand, CMOS technology provides scalability, integration, and cost-effectiveness, making it an attractive option for mass-produced mm-wave systems. This review provides a comprehensive overview of recent advances in broadband mm-wave power amplifiers, with a specific focus on developments in InP and CMOS technologies. It examines the design methodologies, performance metrics, and emerging trends shaping the field of mm-wave amplification. Through a critical analysis of recent research findings and technological innovations, this review aims to provide insights into the current state-of-the-art in mm-wave PA design and highlight future directions for research and development[4].

Moreover, the remaining sections discuss the challenges and potential solutions in scaling these technologies for widespread commercial and industrial applications. The subsequent sections of this review delve into the specific advancements and challenges associated with InP and CMOS technologies, providing a comparative analysis of their respective strengths and limitations.

2. Challenges Associated with InP and CMOS Technologies:

The use of InP and CMOS technologies in the development of mm-wave power amplifiers (PAs) presents unique challenges that stem from their material properties, fabrication processes, and performance characteristics at high frequencies[5]. Addressing these challenges is crucial for optimizing amplifier performance and ensuring the viability of mm-wave systems for broad applications, including telecommunications, radar, and imaging systems. InP substrates are more brittle and expensive compared to other semiconductor materials like silicon. This increases the cost and complexity of manufacturing and handling, which can limit the widespread adoption of

InP-based devices. InP devices often exhibit superior high-frequency performance but can suffer from significant self-heating effects. Efficient thermal management is critical to maintain performance stability and reliability, especially under high power and high-frequency operation conditions[6]. While InP offers excellent high-frequency performance, integrating InP-based components with other semiconductor technologies (like CMOS) for more complex circuits can be challenging. This integration is often necessary for developing fully integrated mm-wave systems. The fabrication infrastructure for InP is less developed compared to silicon-based technologies. This can limit the ability to scale up production, which is essential for cost reduction in large-volume applications. Although CMOS technology benefits from maturity, scalability, and cost-effectiveness, its intrinsic material and process characteristics typically limit its performance at higher frequencies. As frequency increases, the performance of CMOS PAs tends to degrade, particularly in terms of output power and efficiency. CMOS amplifiers can struggle with linearity and power handling capabilities at mm-wave frequencies[7]. This can lead to increased signal distortion and lower efficiency, particularly in communication systems where high linearity is crucial. CMOS devices generally exhibit higher noise figures at mm-wave frequencies compared to InP. This can significantly affect the sensitivity and overall performance of receivers in communication and radar systems. While CMOS is excellent for integration and miniaturization, combining it with high-performance materials like InP or GaN within the same system to enhance overall performance presents technological challenges. Designing mm-wave PAs involves intricate trade-offs between gain, efficiency, bandwidth, and linearity. Advanced simulation tools and design techniques are required to optimize these parameters effectively. At mm-wave frequencies, even minute imperfections in packaging and interconnects can cause significant performance losses. Developing suitable packaging techniques that minimize parasitism and preserve signal integrity is crucial. Standardization of testing protocols and performance metrics for mm-wave PAs remains a work in progress[8]. Consistent testing methods are essential for accurate comparison of performance across different technologies and designs. In the rapidly evolving landscape of mm-wave power amplifiers, indium phosphide (InP) and complementary metal-oxide-semiconductor (CMOS) technologies are two predominant materials that play crucial roles. Each brings distinct advantages to the table, but they also come with specific challenges that impact their efficacy and application in mm-wave systems. Understanding these challenges is critical for advancing the state-of-the-art in mm-wave power amplifiers. While CMOS technology is well-established in lower-frequency applications, its performance at mm-wave frequencies is typically limited by lower electron mobility and parasitic effects. This can reduce the gain and efficiency of CMOS-based mm-wave PAs. CMOS transistors generally exhibit poorer linearity and lower power handling capabilities compared to InP transistors. This can affect the overall performance of PAs, particularly in applications requiring high output power with minimal distortion[9]. At higher frequencies, the intrinsic noise of CMOS devices tends to increase, which can compromise the noise figure of CMOS-based mm-wave PAs. Managing this noise is crucial for applications where signal integrity is paramount. As the scale of CMOS devices continues to decrease with advancements in technology, the voltage headroom for the transistors decreases, which can pose challenges for high-power mm-wave applications. Additionally, as dimensions shrink, variability and reliability issues become more pronounced. Addressing these challenges requires ongoing research and innovation in both materials and design techniques. For InP, efforts are focused on improving manufacturing techniques to reduce costs and enhance yield and developing better thermal management and integration strategies[10]. For CMOS, research is geared towards enhancing device performance through innovative circuit design, improved material quality, and advanced process technologies capable of mitigating the effects of scaling on performance and reliability. Both technologies are also exploring hybrid approaches, such as silicon-germanium (SiGe) and CMOS-on-InP, to combine the best attributes of both worlds and overcome individual limitations[11]. **Figure 1** presents the state-of-the-art millimeter-wave (mm-wave) power amplifiers (PAs), focusing on broadband design techniques, including Si, gallium arsenide (GaAs), GaN, and other III–V materials, and both field-effect and bipolar transistors:

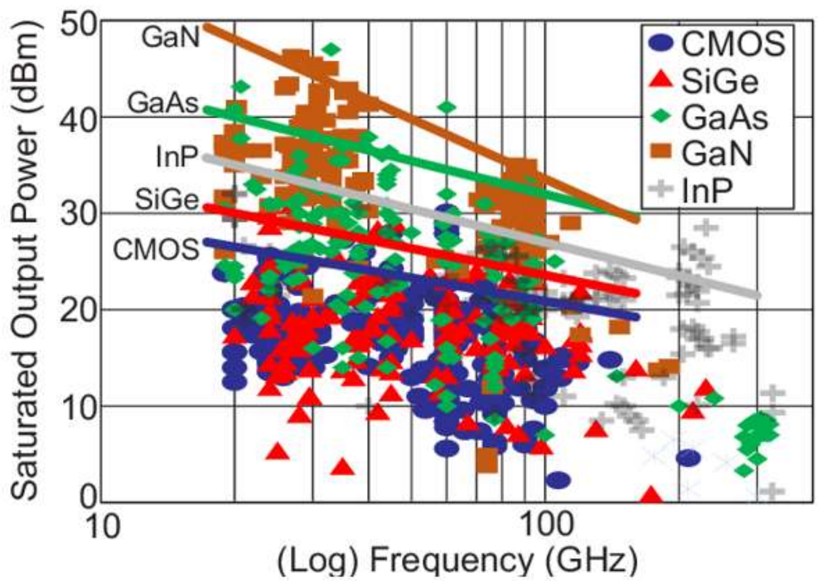

Figure 1: Review of Technologies and Design Techniques of Millimeter-Wave Power Amplifiers

3. Potential Solutions for Widespread Commercial and Industrial Applications

Scaling indium phosphide (InP) and complementary metal-oxide-semiconductor (CMOS) technologies for widespread commercial and industrial applications present a set of challenges, as previously discussed[12]. However, several potential solutions and strategies can be implemented to overcome these hurdles, facilitating broader adoption and integration in various sectors. Streamlining the fabrication processes and developing more cost-effective material growth techniques such as epitaxial growth can reduce the costs associated with InP. Advances in automation and precision in manufacturing could also yield higher throughput and lower defect rates, making InP more economically viable for broader markets. Developing and integrating advanced thermal management solutions can enhance the performance reliability of InP devices at high power densities. Techniques like improved heat sinking, microchannel cooling, and thermoelectric cooling could be critical. Figure 2 describes the design of self-healing for mm-wave PAs, where on-chip self-healing improves output power, dc power consumption, and linearity under a broad range of nonidealities, such as process variations, modeling inaccuracies, load mismatch, and even partial and total transistor failure:

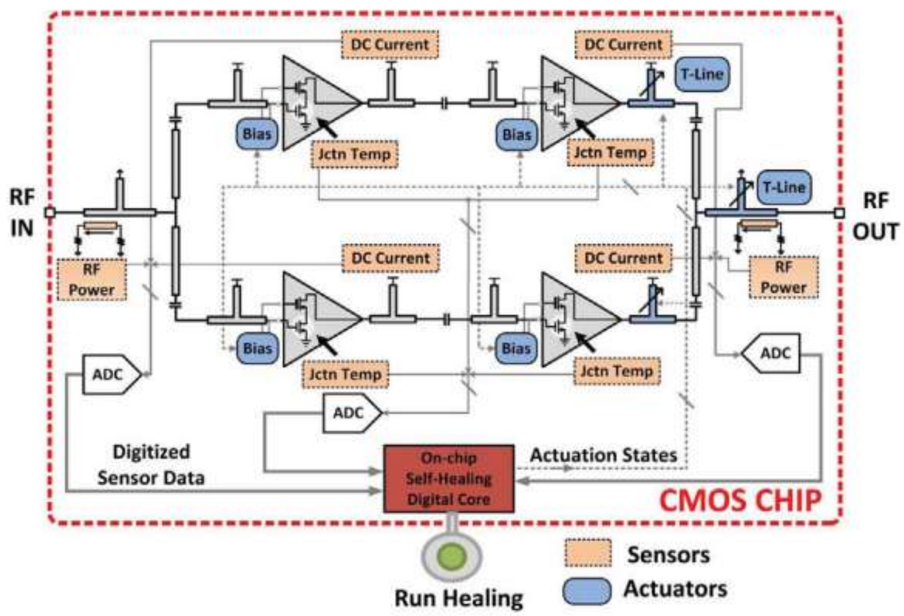

Figure 2: Self-healing PA system Amplier

Support from government and industry in the form of subsidies, research grants, and public-private partnerships can accelerate the development and scaling of InP technology, especially for strategic applications like telecommunications and defense[13]. Developing new design methodologies that enhance the performance of CMOS at mm-wave frequencies is crucial. Techniques such as using non-minimum length transistors for improved power handling, adopting cascade configurations for better isolation, and exploring novel interconnect and shielding methods to reduce parasites could be beneficial. Integrating high-k dielectrics, using strain-engineered silicon, or incorporating materials with higher mobility such as germanium or III-V compounds directly into the CMOS process can enhance electron mobility and overall transistor performance[14]. Designing scalable mm-wave architectures that can be efficiently produced in large volumes is essential. This includes the development of modular designs that can be customized for specific applications, thereby reducing both development time and costs. Developing advanced packaging techniques that can handle the increased density of mm-wave circuits while providing excellent electrical and thermal performance is critical. Techniques such as 3D integration, wafer-level packaging, and the use of high thermal conductivity materials can help manage power densities and integration complexities. Establishing industry-wide standards and protocols for the design, testing, and integration of InP and CMOS-based devices can reduce complexity and foster broader adoption. Investing in education and training to develop a skilled workforce that understands the nuances of advanced semiconductor technologies like InP and CMOS can facilitate innovation and efficient scaling. Conducting seminars, workshops, and demonstrations to showcase the capabilities and benefits of advanced InP and CMOS technologies can help in sensitizing potential industries to their applicability and advantages[15].

4. Conclusion

In conclusion, the exploration of recent advancements in broadband mm-wave power amplifiers within InP and CMOS technologies reveals a promising trajectory towards addressing the escalating demands of next-generation wireless communication systems. InP technology, celebrated for its superior high-frequency performance and efficiency, continues to evolve, overcoming previous limitations regarding cost and manufacturability. Simultaneously, CMOS technology has made significant strides, enhancing its viability at mm-wave frequencies through innovative design adjustments and process improvements, making it an increasingly competitive option for large-scale applications. Moreover, fostering a collaborative environment among academia, industry, and regulatory bodies will be essential to align technological developments with market needs and regulatory standards. Ultimately, the ongoing innovation in InP and CMOS technologies for mm-wave power amplifiers is set to play a critical role in shaping the future of telecommunications and a host of other applications, underscoring the importance of this dynamic field of study.

References

[1] Z. Liu, T. Sharma, C. R. Chappidi, S. Venkatesh, and K. Sengupta, "Transformer-based broadband mm-wave inp pa across 42-62 GHz with enhanced linearity and second harmonic engineering," in 2020 IEEE/MTT-S International Microwave Symposium (IMS), 2020: IEEE, pp. 1295-1298.

[2] V. Camarchia, R. Quaglia, A. Piacibello, D. P. Nguyen, H. Wang, and A.-V. Pham, "A review of technologies and design techniques of millimeter-wave power amplifiers," IEEE Transactions on Microwave Theory and Techniques, vol. 68, no. 7, pp. 2957-2983, 2020.

[3] D. Y. Lie, J. C. Mayeda, Y. Li, and J. Lopez, "A review of 5G power amplifier design at cm-wave and mm-wave frequencies," Wireless Communications and Mobile Computing, vol. 2018, 2018.

[4] P. M. Asbeck, N. Rostomyan, M. Özen, B. Rabet, and J. A. Jayamon, "Power amplifiers for mm-wave 5G applications: Technology comparisons and CMOS-SOI demonstration circuits," IEEE Transactions on Microwave Theory and Techniques, vol. 67, no. 7, pp. 3099-3109, 2019.

[5] Z. Liu, Y. Yu, and K. Sengupta, "A 44 to 64 GHz broadband 90° hybrid Doherty PA with quasi non-foster tuner in 0.13 μm SiGe," IEEE Microwave and Wireless Components Letters, vol. 31, no. 6, pp. 760-763, 2021.
[6] J. Du Preez and S. Sinha, Millimeter-wave power amplifiers. Springer, 2017.
[7] Z. Liu, E. A. Karahan, and K. Sengupta, "A compact SiGe stacked common-base dual-band PA with 20/18.8 dBm P sat at 36/64 GHz supporting concurrent modulation," IEEE Microwave and Wireless Components Letters, vol. 32, no. 6, pp. 720-723, 2022.
[8] H. Wang, P. M. Asbeck, and C. Fager, "Millimeter-wave power amplifier integrated circuits for high dynamic range signals," IEEE Journal of Microwaves, vol. 1, no. 1, pp. 299-316, 2021.
[9] T.-W. Li, M.-Y. Huang, and H. Wang, "Millimeter-wave continuous-mode power amplifier for 5G MIMO applications," IEEE Transactions on Microwave Theory and Techniques, vol. 67, no. 7, pp. 3088-3098, 2019.
[10] Z. Liu, T. Sharma, C. R. Chappidi, S. Venkatesh, Y. Yu, and K. Sengupta, "A 42–62 GHz transformer-based broadband mm-wave InP PA with second-harmonic waveform engineering and enhanced linearity," IEEE Transactions on Microwave Theory and Techniques, vol. 69, no. 1, pp. 756-773, 2020.
[11] Y.-H. Hsiao, Z.-M. Tsai, H.-C. Liao, J.-C. Kao, and H. Wang, "Millimeter-wave CMOS power amplifiers with high output power and wideband performances," IEEE Transactions on Microwave Theory and Techniques, vol. 61, no. 12, pp. 4520-4533, 2013.
[12] Z. Liu and K. Sengupta, "A 44–64-GHz mmWave broadband linear Doherty PA in silicon with quadrature hybrid combiner and non-foster impedance tuner," IEEE Journal of Solid-State Circuits, vol. 57, no. 8, pp. 2320-2335, 2022.
[13] S. M. Bowers, K. Sengupta, K. Dasgupta, B. D. Parker, and A. Hajimiri, "Integrated self-healing for mm-wave power amplifiers," IEEE Transactions on Microwave Theory and Techniques, vol. 61, no. 3, pp. 1301-1315, 2013.
[14] Z. Liu, T. Sharma, and K. Sengupta, "80–110-GHz broadband linear PA with 33% peak PAE and comparison of stacked common base and common emitter PA in InP," IEEE Microwave and Wireless Components Letters, vol. 31, no. 6, pp. 756-759, 2021.
[15] B. Park et al., "Highly linear mm-wave CMOS power amplifier," IEEE Transactions on Microwave Theory and Techniques, vol. 64, no. 12, pp. 4535-4544, 2016.