



High Performance 200GHz Differential Power Amplifier for Short Range Imaging Applications

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ABSTRACT

The sub-terahertz (Sub-THz) frequency range offers interesting possibilities for short range high data-rate wireless communication systems as well as high-resolution imaging and sensing of objects than lower frequency radio waves. This is due to its shorter wavelength having a range of 10mm to 0.33mm. Another notable aspect is that, sub-THz cameras are used in Body Area Networks (BANs) for vital organs monitoring, medical imaging for surgery, early detection of viruses, tumors, as well as for security screening and so on. However, one major challenge of sub-THz systems is low output power which results in poor image resolution. Readings from poor images can constraint efficient surgery and early diagnoses of ailments, which can lead to a plethora of challenges, one of which is the loss of patients' lives. To mitigate these problems, high powered sub-THz power amplifiers (PAs) are required. On this premise, this paper presents a differential power amplifier (PA) design with 130-nm SiGe BiCMOS technology. Simulated results showed that the stability measure at 200GHz showed a stability factor of $k = 2$, which makes it unconditionally stable. Additionally, the S-parameter showed a maximum signal gain of 27 dB. The gain in the forward direction at $s_{21} > 10\text{dB}$ falls within the frequency range of 115-211GHz with a gain of about 18dB at 200GHz. Furthermore, the PA achieves 12.5dBm of saturated output power with 27dB peak gain and a peak PAE of 7.1%. Finally, the PA delivers more than 10 dBm of P_{out} from 150-205 GHz with PAE more than 4%. The high output power of the PA makes it a candidate to be used in power combiner circuits to obtain large power in the G-band.

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INTRODUCTION

The spectrum of frequencies of electromagnetic radiation extends from very low values over the range of radio waves, television waves, and microwaves to visible light and beyond to the substantially higher values of ultraviolet light, X-rays, and gamma rays (Phillips & Fritzsche, 2021.). Gamma rays, x-rays, and some ultraviolet waves are "ionizing," meaning these waves

have such a high energy that they can knock electrons out of atoms. Exposure to these high-energy waves can alter atoms and molecules and cause damage to cells in organic matters hence considered biologically harmful. On the other hand, radio waves, micro waves, infrared and the lower parts of ultraviolet are "Non-ionizing" meaning these waves has low photon energy which does not result into any

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impairment linked with ionizing radiation and hence considered biologically harmless, making it appealing for many health applications and gradually replacing some of the current imaging modalities (Heidari, 2015). Figure 1 depicts electromagnetic spectrum and some of its applications.

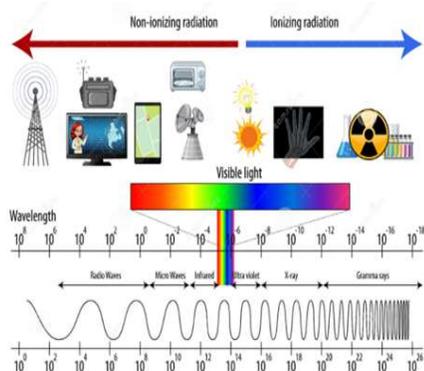


Figure 1: Electromagnetic Spectrum and its Applications (Heidari, 2015)

The THz has a value of 10^{12} hertz (Hz). In certain contexts, the Sub-THz or the low THz band is defined as situated between 100 GHz and 1 THz band and has a frequency that lies between the spectrum's upper part of millimeter waves and lower part of the THz waves; approximately from 0.1THz up to 1THz and is the frequency band for our research (Božani, 2019). This is shown in Figure 2.

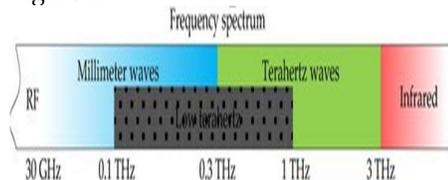


Figure 2: Sub-THz Band (Božani, 2019)

High-frequency transistors based on both silicon (Si) technologies, such as silicon-germanium bipolar complementary metallic oxide semiconductor heterogeneous bipolar

transistor (SiGe BiCMOS HBT, CMOS), and group III-V technologies, such as indium phosphate heterogeneous bipolar transistor (InP HBT), are continually improving in terms of operating speed, such as transient frequency (ft) & maximum oscillation frequency. In general, group III-V devices outperform Si devices in terms of ft, fmax, breakdown voltages (BV_{CEO} and BV_{CBO}), and output power. Due to their advantage in large scale and high-level integration, Si devices are preferred over group III-V devices. In addition, the development of various signal sources at sub-THz frequencies for many applications, such as high-speed short-range wireless communication, high-resolution imaging, sensing, phased arrays, and radar systems, has been made possible by the advanced SiGe BiCMOS technologies' f_{max} up to 500 GHz (Rücker & Heinemann, 2018). Oscillators, Power Amplifiers (PAs), and frequency multipliers are the main components that make up high frequency signal sources. Among them, the design of the PA is extremely important to get beyond the prevailing losses brought on by the chain's subsequent multiplication in order to provide a higher output power for better system performance (Ali et al., 2020).

In this paper, the design of single-ended PA using IHP's 130-nm SiGe BiCMOS technology for the frequency band 150–200 GHz. Cascode (CC) topology is exploited in the design of the PA. The subsequent sections of this paper are as follows: section II presents a review of similar works. Section III, discusses the design procedure for a single-ended PA. Section VI outlines the materials used in this research. The experimental results and discussion on the findings are presented in section V. finally, section VI concludes this report.

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REVIEW OF SIMILAR WORKS

The following reviews are a compilation of academic papers that are relevant to this study. The aim of the review is to inform readers about the current state of the art in the field of study, as well as the numerous difficulties that other scholars have faced, which will serve as the foundation for this work.

Ali et al., (2018), research objective of the work was to design and compared a single stage PA based on Common Emitter (CE) and Cascode (CC) topologies. The PA was designed at 183 GHz using 130nm silicon/germanium (SiGe) Heterojunction Bipolar Transistor (HBTs) technology. The importance of characterizing different topologies for the design of PAs in terms of Maximum Available Gain (MAG), Stability, optimum impedances, output power, and efficiency at Sub-THz frequencies was stressed. Such characterization will assist the PA designer in choosing the best topology for power amplifier design. The effect of the interconnects on performance of the two PAs was also reported. Simulation results for MAG, stability factor, output power, efficiency, gain, and optimum source/load impedances were contrasted for the two topologies. Based on Electromagnetic (EM) simulation, it was shown that the optimum input/output impedances for high power, and efficiency were affected less in case of CE PA than Cascode PA. The CE PA showed better output power and efficiency than Cascode PA but they are not suitable for Sub-THz PA design due to limited gain. This was because at mm-wave and Sub-THz frequencies, the power amplifier gain and output power were limited due to high conductor losses and small breakdown voltage of transistors. Another reason for the limited power at Sub-THz frequency was the continuous scaling down of the

transistor periphery to improve cutoff and maximum oscillation frequency (f_t & f_{max}). The amplifier stage used in the work had limited output power which affected the overall efficiency of the design.

Ali et al., (2019), designed a single-ended Power Amplifier at 185GHz with Output Power More than 12dBm-Designed a single-ended power amplifier (PA) using innovations for high Performance microelectronics (IHP)'s 130-nm silicon germanium (SiGe) BiCMOS technology for the frequency band of 150-200GHz. The technology provides heterojunction bipolar transistors (HBTs) with f_{max} of 500GHz, which is sufficient for the design of PA at 185GHz. The method by (Ali, et al., 2018) was used in choosing the optimal sizes for the transistors in the design of single-ended PA. It resulted in an area of $8 \times 70 \times 900 \text{nm}^2$ for the HBT transistor as the standard cell. The collector to emitter break down voltages (BVCEO) and collector to base break down voltages (BVCBO) were 1.7V and 4.8V, respectively. The constraints on the breakdown voltages must be respected for high reliability, while designing a PA. Their design consists of three stages; a power stage and two driver stages. These stages were designed to have Cascode Topology under class A biasing. Cascode (CC) topology was exploited in their design because it provides better isolation and high gain by minimizing the Miller's effect. The driver stage was designed using load pull simulations to get optimum load impedance for maximum power at 185GHz. Conjugate and power matching are performed at the input, and output of each stage, respectively. The matching networks are designed by using MIM capacitors, and 50Ohm transmission lines with deferent electrical lengths realized via back-end of the line (BEOL) process.

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Electromagnetic (EM) simulation of the designed PA was then performed with ADS. The result surpasses the highest power added efficiency (PAE) of 5.7% reported in other previous works that used the same technology at or near 160GHz. It shows a saturated output power (P_{sat}), maximum gain, and Power Added Efficiency (PAE) of 12.4dBm, 27dB, and 7% respectively at 185GHz. The PA shows more than 10dBm of P_{sat} from 150–205GHz with PAE more than 4% with a stability factor (μ -factor) of > 1 . The 3dB small signal gain bandwidth is 28GHz. Such performances are state of the art for single-ended PAs based on SiGe HBTs. Power and conjugate matching were also performed at the load and source side, respectively. The high output power of the PA makes it a candidate to be used in power combiner circuits to obtain large power in the G-band. It can also be used to drive a frequency multiplier chains. Nice design though, it was not fabricated and the determination of the circuit behaviors was not fully carried out. Also, due to high demand for PA at higher frequencies with the same power, there is need to consider other silicon based technology with higher f_t/f_{max} and power combiners to realize the same PA at higher frequency. These provide areas for future work.

Ali *et al.*, (2020), 168-195GHz Power Amplifier with Output Power larger than 18dBm in BiCMOS Technology-They realized a 4-way combined 3 stages G-band power amplifier (PA) fabricated with a 130nm SiGe BiCMOS process. The process offers high performance heterojunction bipolar transistors (HBTs) with $f_t / (f_{max})$ of 300/450 GHz and breakdown voltages of $BV_{CEO} = 1.7$ V, and $BV_{CBO} = 4.8$ V, respectively. First, a single-ended PA based on the Cascode topology (CT) is designed at 185GHz. The PA consists of

three stages to get an overall gain and an output power higher than 27dB and 13dBm, respectively. Then, a 4-way combiner/splitter was designed using low-loss transmission lines at 130-210GHz. Finally, the combiner was loaded with four single-ended PAs to complete the design of a 4-way combined PA. The amplifier occupies an area of 1.35mm², and can be utilized in the design of different solid-state systems for various future applications. The realized PA shows a saturated output power of 18.1dBm with a peak gain of 25.9dB and power-added efficiency (PAE) of 3.5% at 185GHz. A maximum output power of 18.7dBm with PAE of 4.4% is achieved at 170GHz. The 3dB and 6dB bandwidth of the PA are 27 and 42 GHz, respectively. In addition, the PA delivers a saturated output power higher than 18dBm in the frequency range 140-186GHz. To the best of their knowledge, the power reported in this paper is the highest for G-band SiGe BiCMOS PAs. However, the PA has a small-signal bandwidth, high DC power consumption and large area of chip consumption which future work can be focused on without significantly degrading the large-signal performance.

Summary of Literature Review

The study of the literature revealed an upward trend in Sub-THz PA research. In order to better utilize the immense benefits of Sub-THz transmissions, research into PA for power amplification is essential. Additionally, research indicates that the present HBT on the market today has a f_{max} of just 0.45THz due to the limitations of semiconductor devices due to their physical scaling and technological constraints. Existing transistors cannot efficiently operate at sub-THz frequencies without significantly degrading their

performance as a result of parasitic effects. As a result, power amplifiers above 450GHz, which is substantially higher than the current maximum oscillation frequency of HBT transistors, face a hurdle. In order to increase output power for better performance and a wider range of applications for PAs, it is important to adopt technology with a higher f_{max} and to carefully choose a combiner. The following is a list of the restrictions based on all the articles evaluated thus far: 1. Many of the works studied have achieved frequencies as high as 0.45 THz using SiGe technology. 2. The highest output power obtained is 22dBm at frequencies below the specified range and is about 29% of the maximum PAE amplifier. 3.

Using complicated to implement semiconductor devices for integrated circuits is not easily practicable. 4. It is possible to achieve output powers of (25dBm), low phase noise (100@10MHz), P_{sat} powers of (>40dBm), PAE powers of (>30%), and conversion gains of (>32%). The proposed Sub-THz PA that will be implemented by this research

will enable acquisition of microscopic and macroscopic images with greater details than currently attainable. So far, a resolution of 4096 pixels have been achieved using technologies that has lower efficiency, consumed high DC power and high noise.

DESIGN OF THE POWER AMPLIFIER

Two unit cells of the proposed PA was built using the modified differential power amplifier from the work of (Kucharski et al., 2019), which is depicted in figure 3. Each unit cell featured two driver stages (driver1 and driver2), a modified differential power amplifier, and a power stage with a Marchand balun at the input. Due to its higher gain over Common Emitter (CE), although the Miller effect results in a significant loss in Maximum Available Gain, every stage operates in cascode (CE-CB) mode (MAG). The modified schematic diagram of the unit cell in Figure 4 addresses this problem.

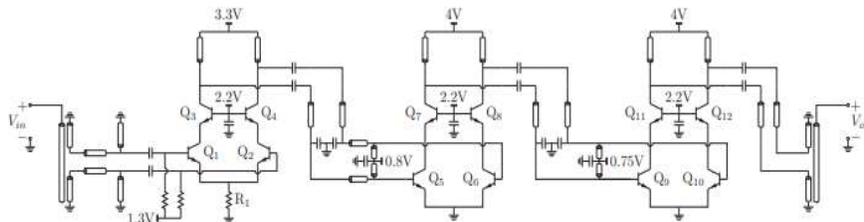


Figure 3: Schematic of the 3-Stage Power Amplifier (Kucharski et al., 2019)

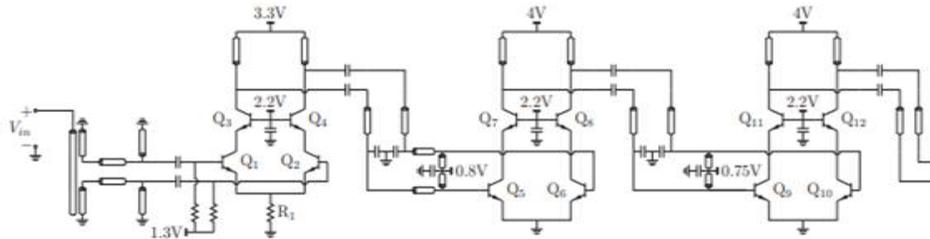


Figure 4: Proposed Unit Cell of a Modified 3Stage PA(Kucharski *et al.*, 2019)

Figure 5 is the circuit diagram of a unit cell of a single ended PA as presented by (Ali *et al.*, 2020) and consist of 2 driver stages and a power stage all configured in a cascade topology. The

single ended PA is substituted with a differential PA as shown in Figure 6 in order to give higher output power with reduced area of chip occupation.

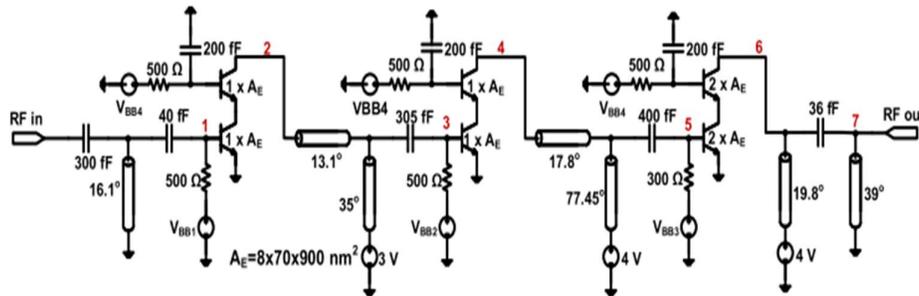


Figure 5: Circuit Diagram of a Unit Cell of a Single Ended PA by (Ali *et al.*, 2020)

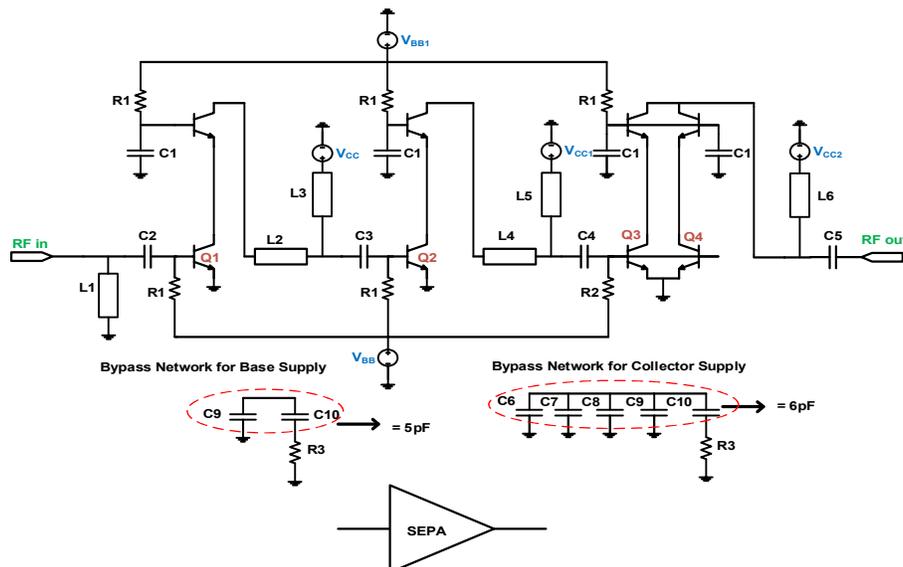


Figure 6: Circuit Diagram of the proposed 200GHz Differential PA

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MATERIALS

The design and simulation software (ADS from Key Sight), the electromagnetic simulation program (ADS Momentum), the design software kit (IHP SG13G2 PDK), the laptop HP Latitude with the HP Core i5 running Windows 10, the power meter network, and the work of Ali et al. are the materials used (2020).

RESULTS AND DISCUSSION

Both small and big signal conditions were used to characterize the realized power amplifier on the wafer. The supply voltages used for the characterisation were $V_{CC} = 3V$, $V_{CC1} = V_{CC2} = 4V$.

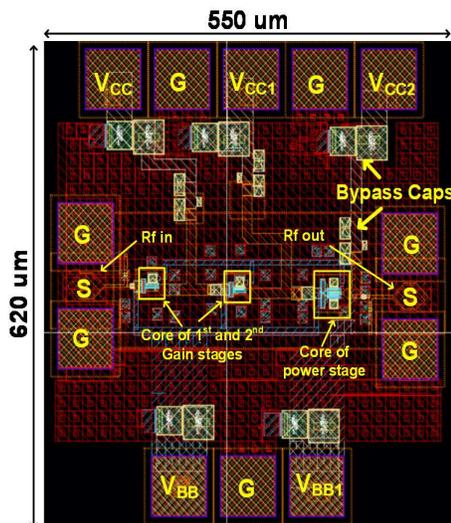


Figure 7: Chip micro-photograph of the Differential PA (0.62mm × 0.55 mm)

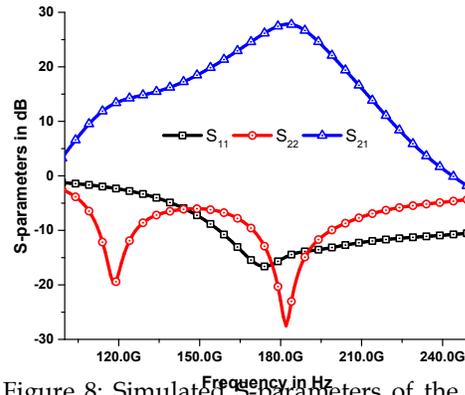


Figure 8: Simulated S-parameters of the Differential PA

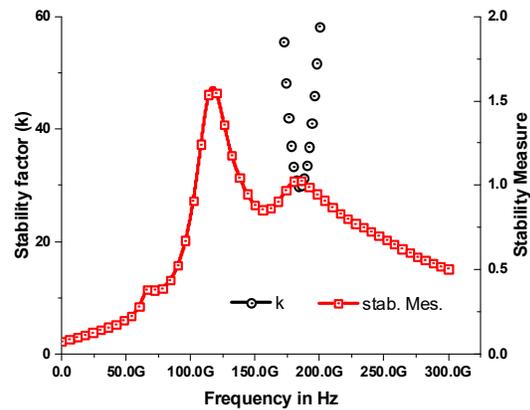


Figure 9: Stability factor (μ_1) of the Differential PA

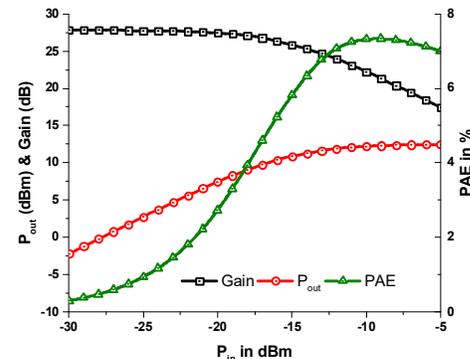


Figure 10: Simulation results depicting gain, output power, and PAE of the CT power-stage at 200 GHz without and with interconnections.

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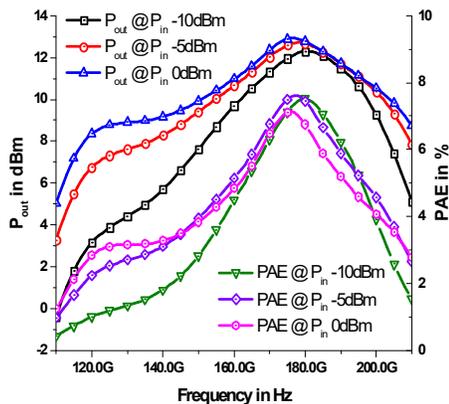


Figure 11: Simulation results depicting gain, output power, and PAE of the CT power-stage at 200 GHz

Figure 8 depicts that at 200 GHz, there is a maximum signal gain of 27 dB, with s_{11} and s_{22} better than -10 dB. The gain in the forward direction at $s_{21} > 10\text{dB}$ falls within the frequency range of 115-211GHz with a gain of about 18dB at 200GHz. With such capabilities, the differential PA is ideally suited for usage in upcoming wireless applications. Figure 9 shows that the stability factor (k) has a differential PA that is unconditionally stable at 200GHz, which fulfills the condition for stability, that is, $k > 1$ (Ali et al., 2020). On the other hand, $k < 1$ depicts the operating frequency ranges where the differential PA becomes potentially unstable. This potential instability within the operating frequency ranges occurs as a result parasitic oscillations. The influence of this stems from oscillation due to internal feedback, low frequency oscillations produced by thermal feedback effects, negative resistance or conductance-induced instabilities due to transit-time effects and avalanche multiplications, and oscillation due to external feedback as a result of insufficient decoupling of the DC supply. Nonetheless, due to the satisfaction of the $k > 1$ at the operating frequency

range of 200GHz, the PA is absolutely reliable for short range imaging applications. Within the operating frequency range, the stability factor (K) dropped below 25 within 0 - 100GHz and within 225 - 300GHz, which made up about 41.7% of the operational frequency. On the other hand, about 58.3% of the operational frequency range was within the operational frequency, with about 28.7 at 200GHz. In the same vein, the stability measure at 200GHz was ($k = 2$), which makes it unconditionally stable.

Figure 10 shows that at 200GHz, the PA achieves 12.5dBm of saturated output power with 27dB peak gain and a peak PAE of 7.1%. Power Added Efficiency (PAE) is a convenient parameter that is used to determine how much DC power contributes to the amplification of an input signal. In figure 4.3, it is observed that the reduction experienced in the PAE as the gain reduces is as a result of the conversion process as energy is dissipated in the form of heat. At which point the DC output power gradually stops rising linearly and maintains a steady state, with a peak PAE earlier stated as 7.1%.

Figure 11 displays the differential PA's output power and PAE for different input power and frequencies. The PA delivers more than 10 dBm of P_{out} from 150-205 GHz with PAE more than 4%. The high output power of the PA makes it a candidate to be used in power combiner circuits to obtain large power in the G-band.

CONCLUSION

The low output power of sub-THz systems, which leads to limited image resolution, is one of their main drawbacks. Poor image readings can prevent effective surgery and early disease diagnosis, which can pose a number of problems, including the



potential loss of patient lives. High powered sub-THz power amplifiers (PAs) are necessary to alleviate these issues. This work describes a differential power amplifier (PA) design using 130-nm SiGe BiCMOS technology based on this premise. Simulated results showed that the stability measure at 200GHz showed a stability factor of $k = 2$, which makes it unconditionally stable. Additionally, the S-parameter showed a maximum signal gain of 27 dB. The gain in the forward direction at $s_{21} > 10dB$ falls within the frequency range of 115-211GHz with a gain of about 18dB at 200GHz. Furthermore, the PA achieves 12.5dBm of saturated output power with 27dB peak gain and a peak PAE of 7.1%. Finally, the PA delivers more than 10 dBm of P_{out} from 150–205 GHz with PAE more than 4%. The high output power of the PA makes it a candidate to be used in power combiner circuits to obtain large power in the G-band.

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