

A 200-GHz Power Amplifier With 18.7-dBm P_{sat} in 45-nm CMOS SOI: A Model-Based Large-Signal Approach on Cascaded Series-Connected Power Amplification

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Abstract—This article proposes a novel approach on cascaded series-connected power amplifier (PA) design. High-frequency transistor modeling is employed to analyze the stacked cell, and a methodology is developed to maximize the output power (P_{out}) and power-added efficiency (PAE) of each cell. The P_{out} and power gain of the cell are studied, and the optimum operation point is determined. A proof-of-concept integrated PA is implemented in a 45-nm CMOS silicon-on-insulator (SOI) process, where stacking and parallel power combining techniques are adopted to achieve 18.7-dBm P_{out} and 4.8% PAE at 200 GHz. Each PA unit uses three cascaded gain stages where two-stacked, three-stacked, and five-stacked architectures are employed for the first, second, and third stages, respectively. Four PA units are power-combined by a low-loss 4:1 zero-degree combiner. The amplifier consumes 1.4-W dc power and has a small-signal gain of 14.6 dB at 203.2 GHz. The designed PA occupies $1.28 \times 1.05 \text{ mm}^2$ die area, including all pads. To the author's knowledge, the designed PA achieves the highest P_{out} and PAE among all the Si counterparts at 200 GHz.

Index Terms—CMOS, G-band, high efficiency, mm-wave, power combining, saturated power, stacked power amplifiers (PAs).

I. INTRODUCTION

THE need for high-speed communication links and high-resolution radars has made mm-wave bands a promising candidate for the next generation of wireless communication systems since they offer a wide frequency span and a smaller footprint for devices [1], [2]. Power amplifiers (PAs) play a key role in mm-wave transceivers since their output power determines the communication range and overall

efficiency of the system [3]. Designing high-power, highly efficient PAs has been a major challenge in mm-wave frequencies due to the limited performance of the transistors and loss of the passive devices. Traditionally, SiGe and III–V compound semiconductors such as InP have been preferred over CMOS to implement mm-wave PAs [4], [5]. However, with recent improvements in their f_{max} , scaled CMOS technologies have become popular for implementing mm-wave PAs due to lower fabrication cost and higher integration capability. Nonetheless, CMOS transistors suffer from low drain-gate and drain-source breakdown voltages and therefore limited power generation capability [6]. To overcome this issue, transistor stacking has been presented and widely discussed in literature as a series power combining technique to increase the voltage swing and hence output power [4], [5], [6], [7]. In a stacked topology, output voltage swing of transistors add up in series to provide high output voltage swing at the load. Nonetheless, design methods of stacked PAs presented in the literature are not accurate enough for mm-wave frequencies, resulting in suboptimal performance [4], [5], [6].

In this work, we propose a stacked PA design theory compatible with mm-wave operation, where the target, as discussed in [4], [5], and [6], is to maximize the output power and PAE. Modifying the existing approaches, it is shown that the optimum design point can be determined precisely at high frequencies, and maximum output power and PAE are achievable.

The basic theory of class-A PA is applied to the stacked cell using transistor's high-frequency equivalent circuit, and the optimal values of load impedances and gate termination capacitors are calculated. It investigates how transistor parasitics limit the power generation in the stacked cell. The derived theory combines the transistor's small-signal and large-signal models to study the linearity performance of the cell. When cascading stacked cells, all transistors add the same amount of power and have the same PAE, but power gain decreases as we proceed from the first to the last stage in the chain. The study concludes that impedance transformation by intercell matching networks (IMNs) is required between the neighbouring cells to satisfy the optimum impedance.

This approach is used to design and implement a 200 GHz stacked PA in a 45-nm CMOS silicon-on-insulator (SOI)

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technology. The PA operates at close-to- f_{\max} frequencies and consists of three cascaded stages, where two and three transistors are stacked in the first and second stages, respectively. The last stage employs a five-stacked topology to increase the power and gain. To boost the output power, a four-way zero-degree power combiner is also used by combining the powers of four PA units. The proposed PA achieves 18.7-dBm output power, 14.6-dB gain, and 4.84% PAE at 200 GHz. To the authors knowledge, this is the highest PAE and output power reported for any silicon-based PA around 200 GHz.

The rest of this article is organized as follows. A brief literature review of stacked PA design and limitations of the existing approaches are presented in Section II. Section III introduces an accurate physics-based high-frequency mm-wave transistor model. The proposed analysis method of cascaded series-connected PA is described in Section IV. The designed G-band PA in SOI CMOS technology is explained in Section V, followed by the discussion of the measurement results in Section VI. Finally, Section VII concludes this article.

II. REVIEW OF STACKED PA DESIGN METHODOLOGIES

A. Circuit-Based Design Theory

The operation mechanism of the stacked PA has been described in [5], where all transistors have the same size and operate at the same biasing condition. Then, assuming a linear operation, a small-signal equivalent circuit is used to analyze the behavior of the stacked cell. The design goal in [5] is to realize the optimum voltage and current waveforms across each cell, and the analysis presented gives a good understanding of the circuit operation, from which several takeaways are noticeable.

- 1) The small-signal model includes parasitic capacitors and drain-source intrinsic current source.
- 2) Transconductance (g_m) is modeled with a real number.
- 3) The drain-source voltages (V_{ds}) of all transistors are assumed to be in phase and equal, which translates to maximum output voltage swing.
- 4) Drain-source currents (I_{ds}) of the transistors are assumed to be equal but out-of-phase with V_{ds} .
- 5) Neglecting the small-signal drain-source resistance and capacitance of the device, optimum load impedances (Z_L) for each stacked cell are derived to be primarily real and proportional to class-A load line impedance (R_{opt}).
- 6) Gate termination capacitor of each common-gate (CG) transistor is sized to present Z_L to the preceding cell.
- 7) A single-element matching network is also presented to resonate out part of the parasitics (drain-source and drain-substrate capacitors) in the intercell nodes.

Considering above limitations, the models in [5] should be revisited, and a revised design methodology is required to design stacked PAs at mm-wave frequencies. In this article, we study the performance of the stacked cell using the basic class-A PA theory. Several key points are included in the analysis, as follows.

- 1) An accurate small-signal model compatible with mm-wave frequencies is used. All parasitic losses are included in the model.

- 2) Transconductance (g_m) includes a time delay. Recent studies on FET modeling suggest a time delay in the drain-source conductance of the device [8], [9], [10], [11]. The intrinsic time delay is related to the inertia of the intrinsic output current in response to rapid changes of V_{gs} [8].
- 3) The analysis finds voltage phase alignment between the stacked transistors unnecessary, which has been traditionally considered indispensable in [4], [5], and [6].
- 4) To realize class-A operation, the effect of all parasitic components are de-embedded.
- 5) The required load and gate termination impedances in a stacked cell are determined based on the transistor equivalent circuit model.
- 6) The IMNs provide full impedance transformation and avoids mismatch in the intercell nodes which leads to a higher gain and output power compared to those of [5].

B. Two-Port Network-Based Design Theory

A two-port network-based theory has been presented in [12] for stacked PA design. The method relied on optimum voltage and current distribution across the transistors and provided full impedance matching between the cells. Additionally, the analysis in [12] has successfully predicted the optimum load and gate (base) termination impedances of the transistors, the compression level, and a constant PAE with respect to the gate (base) impedance termination of the transistors.

Despite the excellent results, the approach in [12] depends on two-port models of the devices and gives little insight for modifying or improving the performance of the stacked cell. In other words, the designer gains little knowledge about the transistor parameters that may degrade or improve the performance. The proposed method in this article is built on the network-based approach and produces the same results in output power, PAE, gain, and Z_L . It presents a more insightful theory that discusses the limitations and highlights the importance of each transistor parameter on the overall performance.

III. HIGH-FREQUENCY TRANSISTOR MODELING

The proposed analysis of stacked PA utilizes the high-frequency equivalent circuit of the transistor, which requires a precise model incorporating all the associated parasitics. In the following, we first present a high-frequency small-signal model of the transistor and then modify it for the large-signal regime. The model is narrowband and fits the device behavior only at the targeted frequency band.

A. Small-Signal Modeling

Fig. 1 shows the high-frequency small-signal equivalent circuit of an NMOS FET, where all parameters in the model have explicit physical interpretations. The intrinsic gate-source and gate-drain capacitors are shown by C_{gs} and C_{gd} , and R_{gs} and R_{gd} model the distributed channel resistances. The transconductance includes a time delay of τ and is modeled as $g_m = g_{mo}e^{-j\omega\tau}$. R_{ds} and C_{ds} describe the drain-source channel resistance and capacitance. There is also a time

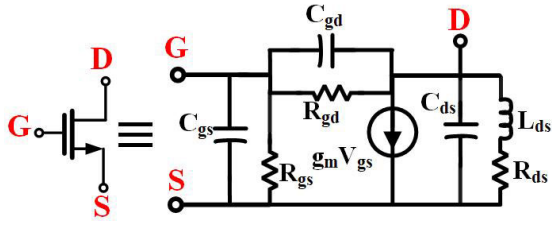


Fig. 1. Equivalent small-signal model of NMOS transistor.

TABLE I
PARAMETER VALUES FOR NMOS TRANSISTORS
AT 190 GHz IN 45-nm SOI

Parameter	Transistor Size	20.4 μm	32.4 μm	42.7 μm
C_{gs} (fF)		13	16.7	25.6
R_{gs} (Ω)		251.2	168.7	111.4
C_{gd} (fF)		7.2	11.8	15.1
R_{gd} (Ω)		629.3	448.9	295.5
C_{ds} (fF)		9.9	17.1	21.9
R_{ds} (Ω)		154.1	69.2	62.7
L_{ds} (pH)		50.1	46.7	31.3
g_{mo} (mS)		27.3	40.8	56.9
τ (psec)		21.8	21.5	20.6

Bias point: $J = 440 \mu\text{A}/\mu\text{m}$, $V_{GS} = 0.6 \text{ V}$, and $V_{DS} = 1.2 \text{ V}$. Channel length: 40-nm.

delay associated with the output conductance, necessitating an inductor (L_{ds}) connected in series with R_{ds} in the equivalent circuit [8], [9], [10], [11].

To calculate the values of the model parameters, a 20.4 μm NMOS transistor in a 45-nm SOI process is biased in class-A (i.e., $J = 440 \mu\text{A}/\mu\text{m}$, $V_{GS} = 0.6 \text{ V}$, and $V_{DS} = 1.2 \text{ V}$), and its S-parameters are fitted to those of the equivalent circuit of Fig. 1 at center frequency of 190 GHz. This procedure is repeated for 32.4- and 42.7- μm NMOS transistors, and the resulting values are presented in Table I. The model includes the routing parasitics of the transistors extracted by RC-extraction up to the fourth metal layer (C_1).

B. Large-Signal Modeling

In general, PAs are nonlinear circuits, and the small-signal model of Fig. 1 does not predict the nonlinearity, thereby necessitating modifications to consider the device's large-signal behavior. For this purpose, we will show that modifying g_{mo} based on the compression level of the device is enough to predict the large-signal behaviour, and there is no need to change the other circuit parameters in Fig. 1. In some technologies (e.g., GaN), device capacitors are voltage-dependent and introduce strong nonlinearity and generate higher-order harmonics in the drain-source current [13], [14]. This variation, nevertheless, is negligible for CMOS devices biased in class-A region, where the device is always on and no higher-order harmonics are present in I_{ds} .

To extract the g_{mo} in different compression levels of the device, we run harmonic-balance load-pull (LP) simulations at 190 GHz for the CG stacked cell at different compression levels, where the gate node of the transistor is ac-grounded. From the voltage and current distribution across the transistor,

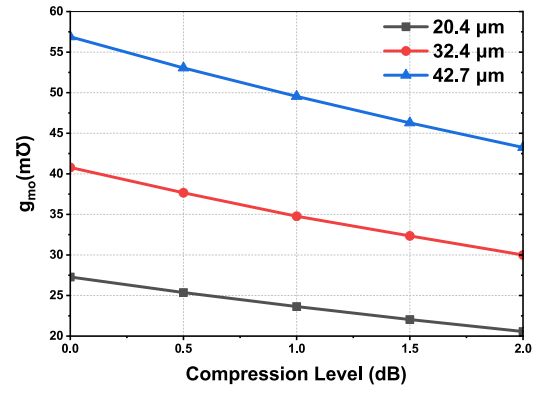


Fig. 2. g_{mo} versus the compression level at 190 GHz for 20.4-, 32.4-, and 42.7- μm NMOS transistors in 45-nm CMOS SOI ($L_g = 40 \text{ nm}$).

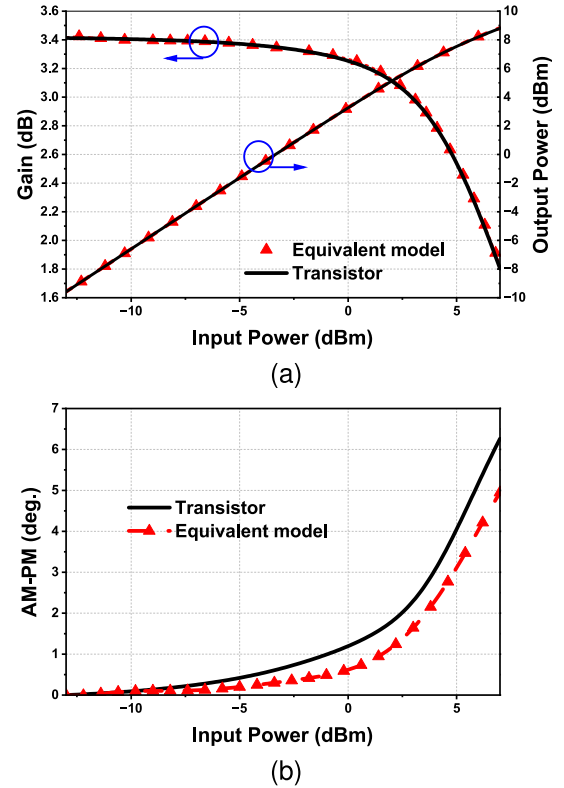


Fig. 3. (a) Output power and gain comparison between simulated transistor (solid black) and its extracted model (symbols red) versus input power at 190 GHz for 32.4- μm NMOS transistor in 45-nm CMOS SOI ($L_g = 40 \text{ nm}$). The two curves are on top of one another; (b) AM-PM curves.

g_{mo} is calculated for each compression level, and results for different device sizes are shown in Fig. 2. As expected, g_{mo} reduces with further device compression, and the designer should choose the corresponding g_{mo} at a specific compression level from Fig. 2 as the reference design parameter.

To validate the extracted large-signal model, one can compare the large-signal behavior of the device simulated in LP setup with that of the extracted model. As an example, the input power for the 32.4 μm transistor is swept and output power and gain are plotted in Fig. 3(a), which demonstrates a strong correlation between the transistor and its model. Additionally, it verifies that the nonlinearity caused by higher-order harmonics is not significant, affirming that the primary influential factor in the large signal performance of

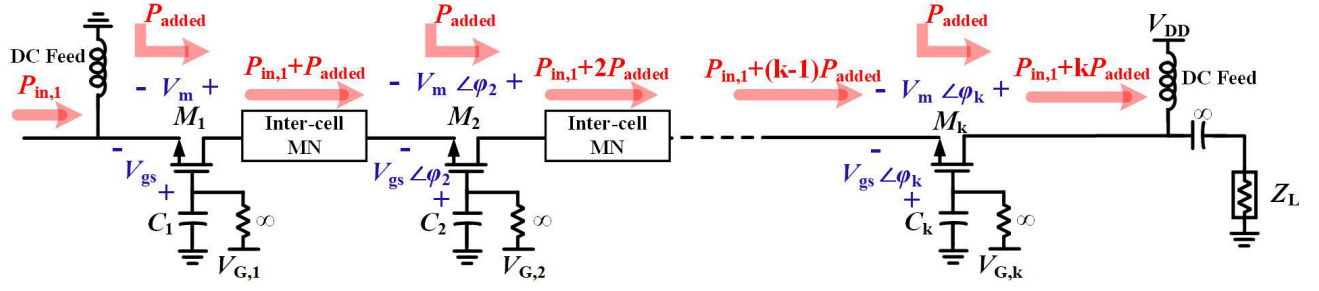


Fig. 4. Stacked PA topology.

the PA is the g_{mo} nonlinearity and reduction with high power levels. Similarly, AM-to-PM versus input power is graphed in Fig. 3(b), and the AM-PM difference between the extracted model and transistor remains below one degree, affirming linear parasitic elements.

IV. THEORY OF STACKED POWER AMPLIFIER

Herein, we use the high-frequency model discussed in Section III to study the cascaded series-connected (stacked) PA in linear and nonlinear regions. Output power, gain, efficiency, and linearity are the key metrics to consider. A single transistor has a limited gain and output power. One can make the transistor larger to elevate the output power; however, this stipulates a higher impedance transformation ratio for the output matching network (OMN) and increases the loss. In addition, larger transistors have lower f_{max} and provide a limited gain at close-to- f_{max} frequencies. Therefore, there is an optimum transistor size for mm-wave PA to achieve maximum output power and efficiency.

Parallel and series power combining is another approach to improve the gain and output power. The former only raises the output power, whereas the latter improves both output power and gain. Fig. 4 shows the circuit diagram of a stacked PA where k common-gate cells are cascaded and represents a series power combining. The gate node of each CG transistor is terminated to a finite capacitor. IMNs provide the optimum load impedance of each cell to the input impedance of the next cell. For simplicity, we assume that IMNs are lossless, and all transistors have the same size and operate in the same class-A bias point. Several design principles are considered in the stacked PA of Fig. 4.

- 1) Drain-source and gate-source voltages— V_{ds} and V_{gs} —must be realized optimally across the transistors (shown by blue color).
- 2) Drain-source voltage and current amplitudes remain constant, which guarantees the same operation point with the same efficiency for all transistors [12].
- 3) Taking the optimum drain-source voltage of the first transistor (V_m) as a reference with a phase of zero, V_{ds} and V_{gs} of the k th transistor experience a phase shift of φ_k with respect to the first transistor. The efficiency still remains unchanged due to the equal phase shift in both voltages.
- 4) Since V_{ds} and V_{gs} swings are constant, the corresponding modeling parameters of transistors also remain unchanged and are equal to the reference design point chosen initially from Fig. 2.

- 5) The phase-shift φ_k is generated by the IMNs, providing an extra degree of freedom in design. This eliminates the previously held belief of phase alignment requirement in the design of stacked PAs [5].
- 6) The maximum power that a device can potentially generate is constrained by its size/biasing and is equal for all cells having the same size.

Thus, ideally, the k th stacked cell operates at its peak efficiency and adds a constant amount of power (P_{added}) to the applied input power ($P_{in,k}$). The output power of the k th stacked cell ($P_{out,k}$) determines the drive power of the next cell ($P_{in,k+1}$). As shown in [12], for the k th cell, one can write

$$P_{out,k} = P_{in,1} + kP_{added} = P_{in,k+1} \quad (1)$$

where $P_{in,1}$ is the input power of the first transistor in the chain. The large-signal gain of the k th cell is calculated as follows:

$$G_k = 1 + \frac{P_{added}}{P_{in,1} + (k-1)P_{added}}. \quad (2)$$

Thus, the large-signal gain of the k -stacked PA is the multiplication of the gain of cells

$$G_{tot} = \prod_{i=1}^k G_i = 1 + \frac{kP_{added}}{P_{in,1}} = kG_1 + (1-k). \quad (3)$$

The PAE of an m -stacked PA is calculated by employing (1)–(3) as follows:

$$PAE = \frac{P_{in,1} + mP_{added} - P_{in,1}}{mP_{DC}} = \frac{P_{added}}{P_{DC}} \quad (4)$$

where P_{DC} is the dc power of one transistor.

A. Design Equations of the Stacked Cell

The forgoing analysis suggests that, in absence of matching losses, the overall PAE of an m -stacked cell is equal to the PAE of each CG cell, and maximum PAE is achieved by optimal design of each CG cell. Fig. 5(a) shows the circuit diagram of a CG stacked cell terminated to its optimal load impedance, Z_L , and Fig. 5(b) shows the equivalent high-frequency small-signal model of this cell, where I_m is the phasor of the intrinsic current source. From the definition of class-A mode [15], V_m and I_m are out-of-phase and their ratio determines the load line impedance of transistor as follows:

$$R_{opt} = -\frac{V_m}{I_m}. \quad (5)$$

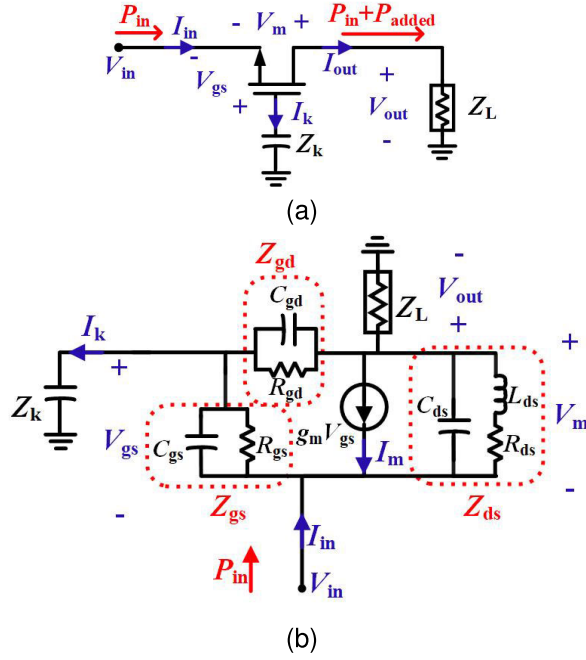


Fig. 5. (a) AC circuit diagram of a common-gate stacked cell and (b) its equivalent small-signal model.

Considering $I_m = g_m V_{gs}$, the gate-source voltage can be expressed as follows:

$$V_{gs} = -\frac{V_m}{g_m R_{opt}}. \quad (6)$$

Assuming that Z_k is reactive, (13)–(15) derived in Appendix A and $P_{in} = V_{in} I_{in}^*/2$ are used to calculate Z_k as follows:

$$Z_k = \frac{2P_{in} - \frac{V_m}{R_{opt}} \Re\left(\frac{I_{in}^*}{g_m}\right)}{j\Im(I_k I_{in}^*)}. \quad (7)$$

The details of V_{in} , I_{in} , and I_k are presented in Appendix A. (7) shows the relation between Z_k and P_{in} , indicating that a higher input power results in a larger Z_k , and thus, a smaller gate capacitor. The lowest input power is achieved when gate node is ac-grounded as follows:

$$P_{in-min} = \frac{V_m}{2R_{opt}} \Re\left(\frac{I_{in}^*}{g_m}\right). \quad (8)$$

The optimum load impedance (Z_L) is calculated by applying KCL to the output node and employing (13)–(15) as follows:

$$Z_L = \frac{(1 + g_m R_{opt})\left(1 + \frac{Z_k}{Z_{gd}}\right) + \frac{Z_k}{Z_{gs}}}{g_m - \frac{g_m R_{opt}}{Z_{ds}} - \frac{1 + g_m R_{opt}}{Z_{gd}}}. \quad (9)$$

The input impedance (Z_{in}) is calculated by combining (13) and (14) as follows:

$$Z_{in} = \frac{V_{in}}{I_{in}} = \frac{Z_{gs} + Z_k + Z_k(1 + g_m R_{opt})\frac{Z_{gs}}{Z_{gd}}}{1 + g_m Z_{gs} - g_m R_{opt}\frac{Z_{gs}}{Z_{ds}}}. \quad (10)$$

Finally, we can derive the output power delivered to the load by utilizing (5)–(9) as follows:

$$P_{out} = P_{in} + \frac{V_m}{2} \Re\left[I_{in}^* - I_k^* \left(1 + (g_m R_{opt})^{-1}\right)\right] \quad (11)$$

TABLE II
THEORETICAL AND SIMULATED ADDED POWER OF NMOS TRANSISTORS
IN 45-nm CMOS SOI AT 1-dB COMPRESSION POINT

Transistor size	20.4 μm	32.4 μm	42.7 μm
Parameter			
$P_{added,sim.}$ (mW)	1.71	2.56	2.79
$P_{added,theory}$ (mW)	1.73	2.57	2.84

Bias point: $J = 440 \mu\text{A}/\mu\text{m}$, $V_{GS} = 0.6 \text{ V}$, and $V_{DS} = 1.2 \text{ V}$. Operation frequency: 190 GHz.

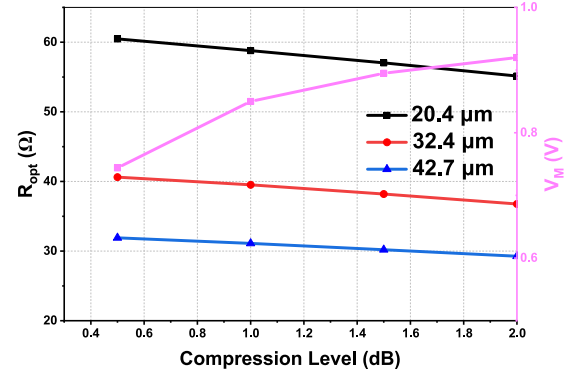


Fig. 6. R_{opt} and V_m versus the compression level at 190 GHz. NMOS transistors have a channel length of 40 nm and widths of 20.4, 32.4, and 42.7 μm .

where the second term in the right side of the equation is P_{added} , and it is only dependent on transistor model parameters. One can replace I_{in} and I_k in (11) from (13) and (15) and calculate P_{added} in terms of circuit parameters, as shown in (12), bottom of the next page. $V_m^2/(2R_{opt})$ in (12) is the power generated by the transistor, whereas the second, third, and fourth terms inside the bracket are due to the losses generated by the device parasitics. These losses will be discussed further in Section IV-B.

Referring back to (5), (7), and (9), we notice that V_m , R_{opt} , and P_{added} are the key parameters of the design and should be extracted at the design frequency of interest (190 GHz in this work). The values of V_m , I_m , and g_{mo} (shown in Fig. 2) are directly obtained from the simulation results of the LP setup, and R_{opt} is calculated using (5). P_{added} is calculated from (12) and compared with its simulated counterpart in Table II. Theoretical values are in close agreement with simulation results for all transistor sizes. R_{opt} and V_m are functions of transistor's input power. Fig. 6 presents R_{opt} and V_m versus the compression level of the device for 20.4-, 32.4-, and 42.7- μm NMOS transistors with a minimum channel length. V_m is identical for all transistor sizes and increases as the transistor compresses further. For the compression level of interest, the designer can read V_m and R_{opt} from Fig. 6 and use them along with g_{mo} (Fig. 2) and P_{added} (Table II) to calculate all other unknown parameters and metrics.

B. Loss Mechanisms Inside the Transistor

As previously discussed, losses incurred by the device parasitics reduce P_{added} and degrade the performance of the stacked cell. There are three main loss contributors in the device: the drain-source (α_{ds}), the gate-source (α_{gs}), and the gate-drain (α_{gd}) parasitic losses. The second, third, and fourth terms

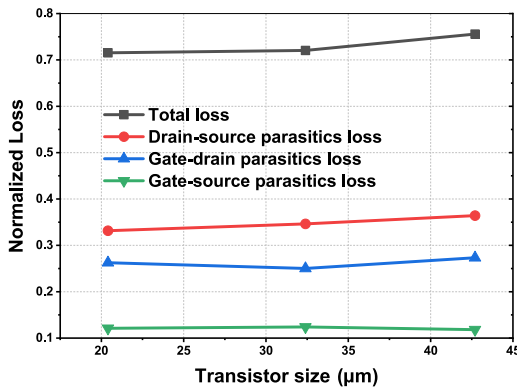


Fig. 7. Normalized loss of the device parasitics to the transistor current-source power, $V_m^2/(2R_{opt})$, for different transistor sizes in a 45-nm CMOS SOI. ($L_g = 40$ nm).

inside the bracket in (12) show α_{ds} , α_{gs} , and α_{gd} , respectively. These losses should be mitigated by a proper design of the transistor (i.e., device size selection and layout). Fig. 7 shows the loss components versus the device width when the transistor operates at 1-dB compression point at 190 GHz. The loss values are normalized to the transistor current-source power, $V_m^2/(2R_{opt})$. α_{ds} reduces P_{added} by 35% and has the highest effect, and the circuit designer should minimize the layout parasitic between the drain and source nodes. Furthermore, α_{gd} and α_{gs} decrease P_{added} by 26% and 12%, respectively. The total loss wastes 72%–76% of P_{added} , and is the main reason PAE of the transistors is limited at high end of mm-wave frequencies. It is worth mentioning that this loss increases with higher frequencies due to the changes in R_{gd} , R_{gs} , R_{ds} , and L_{ds} of the transistor.

C. Design of the Stacked PA

A 32.4-μm NMOS transistor is selected in this work to be studied in the stacked cell at 190 GHz. PAE, P_{out} , gain, and Z_k of this cell are calculated using (2), (4), (7), and (11), and the results are shown in Fig. 8. As input power and thus voltage swing becomes larger, Z_k should be increased to compensate for the high input voltage swing, avoid device failure and preserve efficiency. Also, a higher P_{in} leads to a larger output voltage swing and output power, whereas PAE remains constant, as expected from (4) and (12). Nevertheless, this is achieved at the cost of a lower gain, because a higher Z_k (lower C_k) creates a stronger feedback from the output to the gate. The optimum load and input impedances and the required C_k for the same transistor size are featured in Fig. 9(a). The real parts of Z_L and Z_{in} increase as P_{in} become larger. This can potentially reduce matching losses because of the lower impedance transformation ratio.

As a measure of linearity, we study the compression level of the CG cell at 190 GHz. The operating power gain (G_p) of the cell demonstrates the linear gain, and it is defined as the ratio of the power delivered to the load to the input

power. G_p is calculated using the Z-parameters of the cell (see Appendix B), and both large-signal and small-signal (G_p) gains for the chosen 32.4-μm NMOS transistor are plotted in Fig. 9(b). The difference between the compressed gain and G_p is the compression level, which is also illustrated in Fig. 9(b). Note that for each P_{in} , we adjust C_k , Z_L , and other parameters based on the derived design equations in Section IV-A to achieve the maximum PAE performance. The compression level decreases for higher P_{in} levels, because a larger P_{in} requires a smaller C_k [Fig. 9(a)], which results in a stronger feedback and better linearity.

As an example, we apply our developed design methodology to build a three-stacked PA at 190 GHz, as shown in Fig. 8. To maximize the PAE of the PA, all cells should operate at their peak PAE [Fig. 9(a)]. The optimal design point of each cell in the chain is marked in Fig. 8. The chosen points are mapped into the PA circuit diagram. The power flow across the chain, compression level, optimum load and input impedances, and C_k values are also shown in the figure. The following steps are required to design a class-A stacked PA that uses the same transistor size and achieves its maximum PAE.

- 1) The optimum device size should be chosen to meet the target output power and gain requirement, while trying to minimize the parasitic losses (i.e., α_{ds} , α_{gs} , and α_{gd}) for highly efficient performance. Therefore for a given technology, Fig. 7 should be replotted and used as a reference. Layout parasitics should be also minimized to mitigate the losses, especially α_{ds} .
- 2) Due to the limited gain of the device at mm-wave frequencies and loss of IMNs, the gate node of the first transistor in the chain (M_1) should be ac-grounded ($Z_k \approx 0$) to achieve the maximum gain. From Fig. 8, the input power of M_1 for $Z_k = 0$ is 5.5 dBm. The output power of M_1 determines the input power of the second cell ($P_{in,2}$), and similarly $P_{out,2} = P_{in,3}$. The blue arrows in Fig. 8 show the power flow across the cells and the optimal design point for each cell.
- 3) For the marked P_{in} points in Fig. 8, Z_k of each transistor is determined. This guarantees that all cells operate at their maximum PAE.
- 4) Compression level of each cell is determined from Fig. 9(b).
- 5) Z_L and Z_{in} of all cells are extracted from Fig. 9(a) for the specified input powers.
- 6) In the last step, we design the IMNs, which transform Z_L to Z_{in} of the next cell.

The first cell in the stacked PA provides the highest gain, while the last cell produces the lowest gain. Total gain (dB) of the stacked PA from (3) is also illustrated in Fig. 8, featuring a linear relationship with P_{in} . More cells can be added to the chain if a higher gain or output power is required.

$$P_{added} = \frac{V_m^2}{2R_{opt}} \left[1 - R_{opt} \left(\frac{R_{ds}}{R_{ds}^2 + \omega^2 L_{ds}^2} \right) - \frac{1}{|g_m|^2 R_{opt}} \left(\frac{1}{R_{gs}} \right) - \frac{1 + R_{opt}(g_m + g_m^*) + |g_m|^2 R_{opt}^2}{|g_m|^2 R_{opt}} \left(\frac{1}{R_{gd}} \right) \right] \quad (12)$$

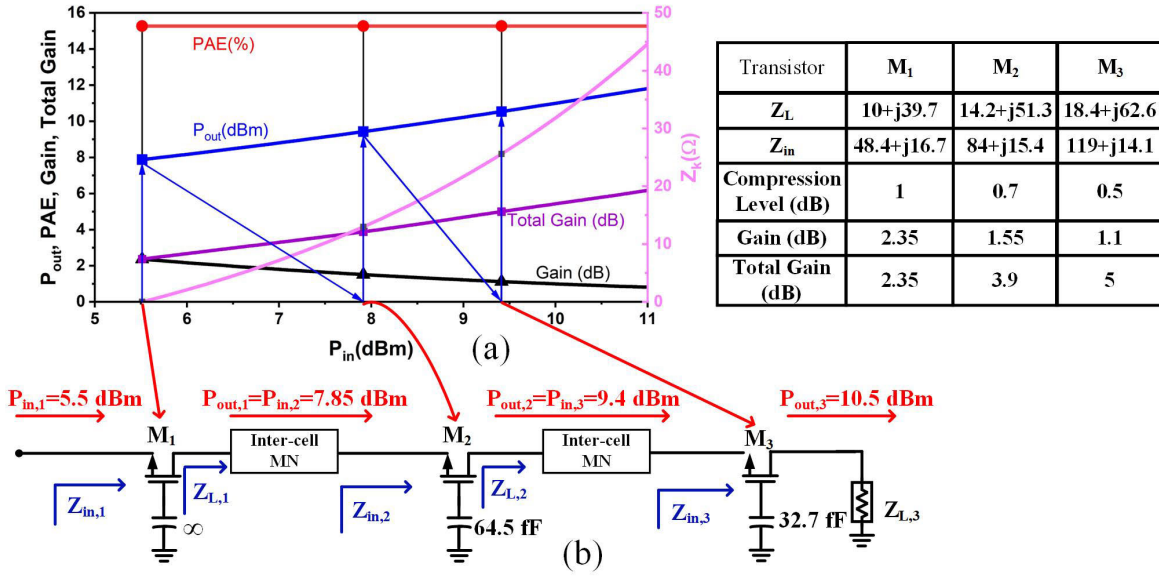


Fig. 8. (a) Output power, PAE, gain, total gain, and Z_k versus the input power for a 32.4-μm NMOS transistor with 40-nm channel length. Optimum design points for the case of three cascaded stacked cells are specified with vertical lines. (b) Schematic of the designed three-stacked PA with power levels and impedances at different points in the chain.

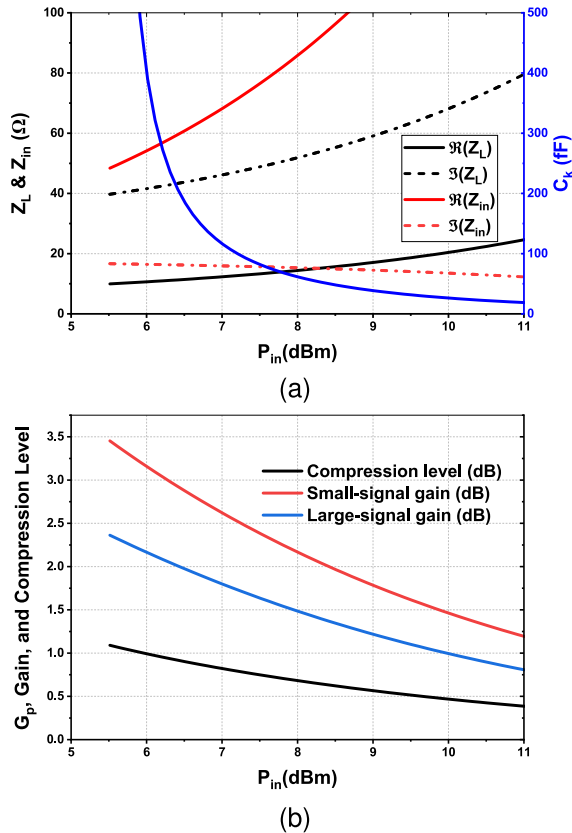


Fig. 9. (a) Load impedance, input impedance, and gate termination capacitor versus P_{in} for a 32.4-μm NMOS transistor with 40-nm channel length, and (b) Compression Level (dB) of the stacked cell versus P_{in} for the same device size. Design parameters are extracted at 1-dB compression point at 190 GHz.

D. Lossy IMNs

In practice, IMNs are lossy and degrade the gain of the stacked cell. The IMN loss should not exceed the cell gain in Fig. 8, and therefore, there is a lower bound for C_k . One may need to tune the selected P_{in} levels and increase C_k values to

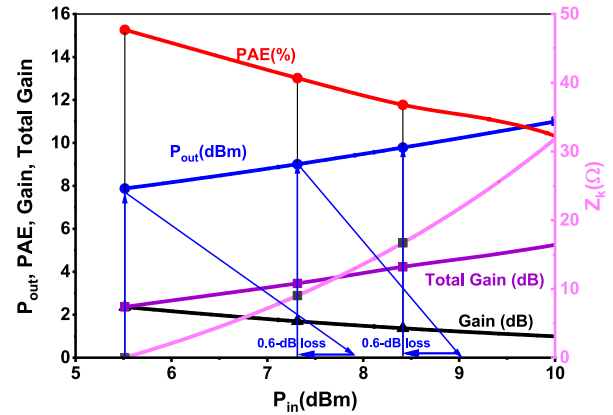


Fig. 10. Output power, PAE, gain, total gain, and Z_k versus the input power for a 32.4-μm NMOS transistor with 40-nm channel length. Optimum design points for the case of three cascaded stacked cells are specified with vertical lines assuming 0.6-dB IMN loss.

compensate for the loss of IMNs. Assuming 0.6-dB loss for the IMNs, the design procedure for Fig. 8 is repeated and the results are demonstrated in Fig. 10. Due to IMN losses, the design points for second and third cells are shifted to the left, and total PAE is degraded. The loss becomes more dominant for higher input powers, degrading the PAE, significantly.

V. CIRCUIT DESIGN

In this work, a four-way stacked PA is designed and implemented in a 45-nm CMOS SOI process with eight metal layers and trap-rich substrate. Thin-oxide floating-body NMOS FETs with 40-nm channel length are used. Significant effort has been made during the layout process to mitigate the impact of interconnect parasitics [16], [17], [18]. Table III concludes the final layout information of the devices. Channel width (W) is optimized to achieve the highest gain at the center frequency and maximum f_{max} . The widths per finger are in range of 0.82–0.85 μm, and the gates are double-side contacts

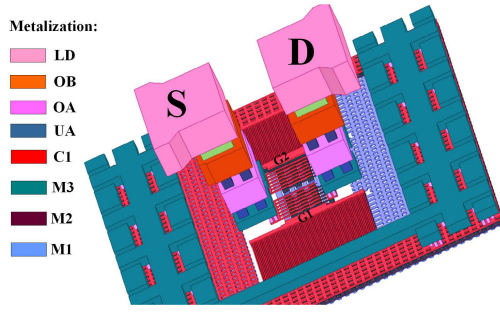


Fig. 11. 3-D layout of a 32.4- μm NMOS transistor with a 40-nm channel length.

TABLE III

LAYOUT INFORMATION OF NMOS TRANSISTORS USED IN THE DESIGN

Transistor size (μm)	20.4	32.4	42.7
Multiplicity	3	3	4
Number of fingers	8	13	13
Channel Width (nm)	850	831	821

and relaxed-pitch to minimize the resistance. The 3-D layout of two 32.4- μm NMOS transistors in parallel is presented in Fig. 11. The source and drain of the two transistors are connected in sixth metal layer (OA), and the gates (G1 and G2) are terminated to gate termination capacitors realized in the bottom four layers (M_1 – C_1) with interdigitated structure to obtain high Q and capacitor density [16], [17], [18]. Two other transistors with 20.4- and 42.7- μm sizes are laid out in a similar fashion. The 42.7- μm transistor has an f_{max} of 275 GHz when referenced to the fourth metal layer (C_1). All transmission lines (TLs) are implemented in the top 4.1- μm -thick aluminum layer to minimize the loss. All passive networks realized in UA–LD were simulated using 2.5-D electromagnetic simulator.

The transistors in the stacked cells operate in class-A and are biased at $J = 440 \mu\text{A}/\mu\text{m}$, $V_{\text{GS}} = 0.6 \text{ V}$, and $V_{\text{DS}} = 1.2 \text{ V}$. Fig. 12 presents the schematic of the PA unit. Four PA units are power combined to increase the output power. The PA unit includes a five-stacked output stage, preceded by three-stacked and two-stacked driver stages to improve the gain. The design details will be discussed in the following.

A. Power Stage of the PA Unit

The last (power) five-stacked stage of the PA unit biased at $V_{\text{DD3}} = 6 \text{ V}$ employs four-cascaded CG cells and a common-source (CS) driver to achieve a targeted output power of 11 dBm from each PA unit. The CS cell improves the overall gain of the power stage and uses a $2 \times 42.7 \mu\text{m}$ transistor. The chosen transistor size for the CS cell is larger than that of the CG cells (i.e., $2 \times 32.4 \mu\text{m}$) to ensure that it stays linear while four-cascaded CG cells are getting compressed. The gates of the two parallel transistors in each CG cell are terminated to 360-fF bypass capacitors which is the highest capacitor of the process with sufficiently higher self-resonance than 190 GHz. As a result, the gain of the cell decreases by 0.3 dB [i.e., 3.1-dB small-signal gain from Fig. 9(b)] compared to that of the cell with the ideal ac-grounded gate. Moreover, the 360-fF capacitors has an impedance of $(1 - j2.3) \Omega$

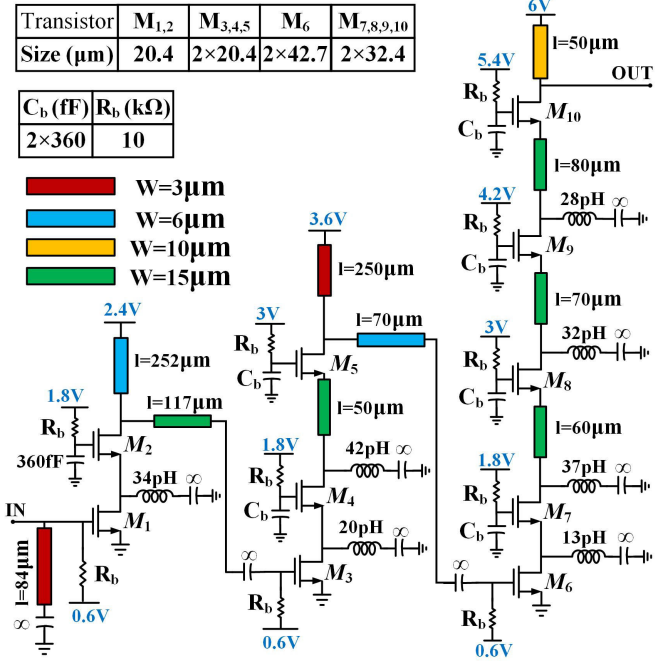


Fig. 12. Schematic of the PA unit.

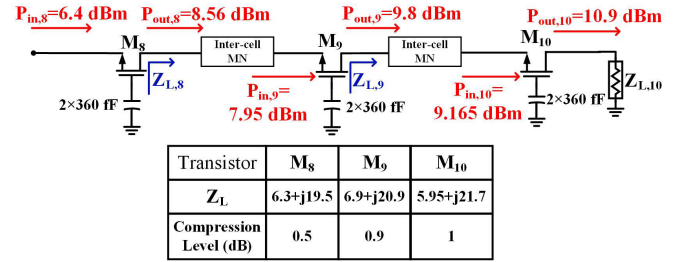


Fig. 13. Power flow and realized impedances across the compressed CG cells in the power stage of the PA unit at 190 GHz.

at 190 GHz, and its ohmic loss causes additional 0.3-dB gain drop. Therefore, each CG cell achieves a small-signal gain of 2.8 dB at 190 GHz. The CS cell along with the following CG cell are designed for conjugate-matching and deliver a P_{in} of 6.4 dBm to the third cell. Fig. 13 illustrates the power flow as well as the realized impedances across the last three cells which are operating in the compressed region.

From Fig. 9(a), $Z_L = (10.8 + j41.6)/2 = (5.4 + j20.8) \Omega$, and thus the values of post-layout load impedances are in agreement with the theoretical counterparts. The third, fourth, and fifth cells of the stage are operating in 0.5-, 0.9-, and 1-dB compression points, respectively (Figs. 9(b) and 13). IMNs are designed using a short stub and a series TL and introduce about 0.6 dB dissipative loss at 190 GHz. Further stacking requires C_k sizing (Fig. 8) and is avoided at 190 GHz because the gain of the added cell drops below 1-dB considering IMN loss.

B. Driver Stages in the PA Unit

Two driver stages with similar architecture are added to achieve a targetted 15-dB small-signal gain from the PA unit. The second stage employs a CS cell as a driver and two-cascaded CG cells, while the first stage has a CS cell

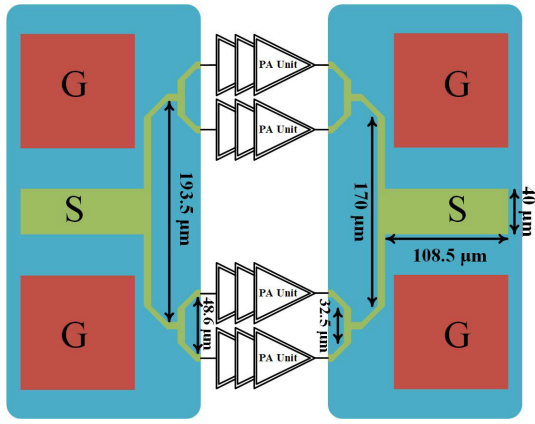


Fig. 14. Block diagram of the four-way PA.

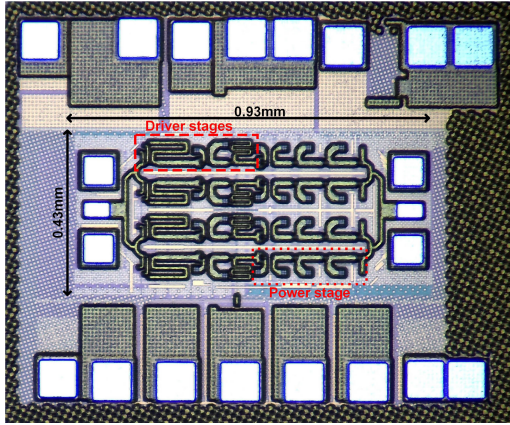


Fig. 15. Die photograph of the 200-GHz CMOS PA.

followed by a CG cell. The number of transistors cascaded in each stage, transistor sizes, and the required PA stages (three in this design) are chosen to provide enough gain and power. The gates are similarly terminated by 360-fF capacitors to obtain the highest gain from each CG cell, and all cells are designed for conjugate matching, having 2.6–3.3-dB small-signal gain. Transistor sizes and supply voltages are scaled down in the driver stages to improve the PAE and gain. The first and second stages are biased at $V_{DD1} = 2.4$ V and $V_{DD2} = 3.6$ V, respectively. Interstage matching networks (ISMNs) are used between the unit PA stages to provide conjugate matching.

C. Four-Way Combiner

Zero-degree power combining shows lower loss compared to the transformer-based and Wilkinson power combining at G -band [20] and is utilized to combine the output power of four PA units. Fig. 14 shows the block diagram of four-way PA. The PA uses the same network as the power splitter at the input. The power combiner is designed using 60- Ω TLs with a width of 6.5 μ m. EM simulation of the combiner and pad shows 0.2-dB loss at 190 GHz. A shunt stub is employed to bias the last stages of the unit PAs, and it is absorbed in the OMN. The stub adds 1.6-dB extra loss to that of the power combiner. The total loss of the OMN is 1.8 dB, which degrades the PAE by 34%.

VI. MEASUREMENT RESULTS

The G -band stacked PA is implemented in a 45-nm CMOS SOI process. Fig. 15 shows the die photo of the fabricated PA.

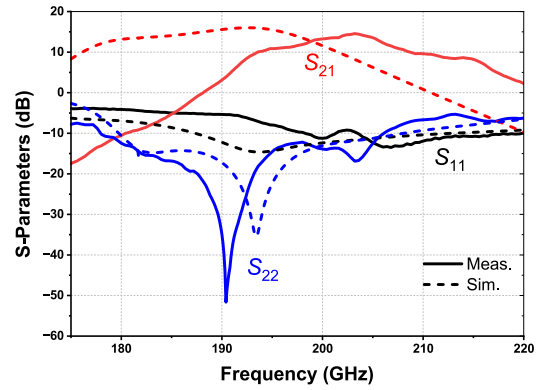
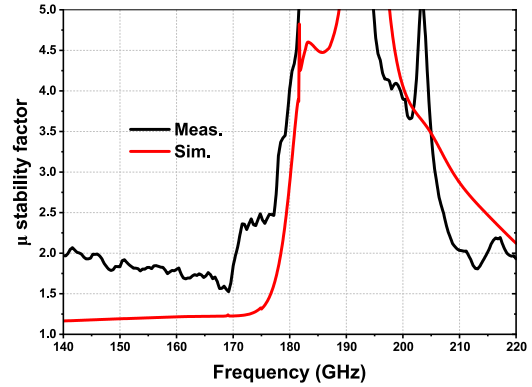


Fig. 16. Measured (solid) and simulated (dashed) S-parameters.

Fig. 17. μ -factor based on the measured and simulated S-parameters.

The dimensions of the chip are $430 \times 930 \mu\text{m}$ excluding the dc pads. The S -parameters of the PA were characterized by a Keysight N5247A PNA-X connected to two VDI WR-5.1 frequency extenders. Fig. 16 illustrates the measured and simulated S-parameters. The PA achieves 14.6-dB peak gain at 203.2 GHz with a 3-dB bandwidth of 9.4 GHz from 197.4 to 206.8 GHz. The maximum gain is 1.4 dB lower than the simulated gain. The measured center frequency is shifted toward higher frequencies about 5.3 % compared to the simulation. This shift is likely due to imprecise high-frequency transistor modeling and inaccuracies related to EM simulation of the passive components. To minimize the simulation time period, we divided the simulation into three distinct parts: the PA unit, input and OMNs. However, it is important to recognize that this approach does not account for the coupling between the PA units with one another and matching networks, which can potentially introduce inaccuracies in the frequency response. The measured input and output reflection coefficients remain lower than -9 dB across the bandwidth. The stability of the PA is probed using the μ -factor. Fig. 17 shows the μ -factor of the PA calculated from the measured and simulated S-parameters. The PA is unconditionally stable.

Fig. 18 shows the large-signal measurement setup. Measurement was done in four steps to calibrate the loss of the probes and S-bends. The initial measurement setup consisted of an Anritsu signal generator, followed by a VDI WR-5.1 frequency extender and a VDI WR4.3 amplifier. The amplifier was directly connected to and its output power was measured by the Erikson PM5 power meter in the 190–205-GHz range.

TABLE IV
COMPARISON BETWEEN STATE-OF-THE-ART PAs OPERATING AROUND 200 GHz

Reference	[19]	[20]	[21]	[22]	[23]	[24]	This Work
Technology	130nm BiCMOS	130nm BiCMOS	130nm BiCMOS	65nm CMOS	65nm CMOS	250nm InP HBT	45nm SOI CMOS
Process f_{\max} (GHz)	370	500	450	395	400	650	355
3-dB Bandwidth (GHz)	200-220	200-255	211-263	227.5-257.5	195-209	190-210	197.4-206.8
f_o/f_{\max}	0.57	0.45	0.52	0.61	0.5	0.31	0.56
Gain (dB)	25	12.5 (15.5 [†])	16.4	13.9	19.5 (22.5 [†])	22	14.6
OP1dB (dBm)	4	9 (10.5 [†])	11.5	-5.1	6.3 (7.8*)	17.4	12.1
P_{sat} (dBm)	9.6	12 (13.5 [†])	14.7	-3.3	9.4 (10.9*)	18.5	18.7
PAE _{max} (%)	0.5	2.14 (3 [†])	3.13	1.6	1.03 (1.4*)	8.5	4.84
DC Power (mW)	1824*	740	924	23.8	732	814	1398
Active Size (mm ²)	0.84	0.83	0.221	0.053	0.92 (0.52 [‡])	0.61*	0.4
$P_{\text{sat}}/\text{Area}$ (mW/mm ²)	10.9	19.1 (27 [†])	133.5	8.8	9.5 (23.7 [†])	116.1	185.3
FOM [△]	39.7	38.3 (44.3 [†])	47.6	23.2	34.6 (40.4 [†])	52.6	45

*Loss of the output balun/power combiner is excluded.

[†]Loss of the input and output balun/power combiner is excluded.

[‡]Active area, excluding the area occupied by input and output baluns and DC pads.

*Calculated from the reported numbers and/or graphs.

◇Maximum drain efficiency is reported.

△FOM = $P_{\text{sat}}[\text{dBm}] + \text{Gain}[\text{dB}] + 10\log(\text{PAE}_{\text{MAX}}[\%]) + 20\log(\text{Freq}/f_{\max}) + 10\log(\text{BW})$

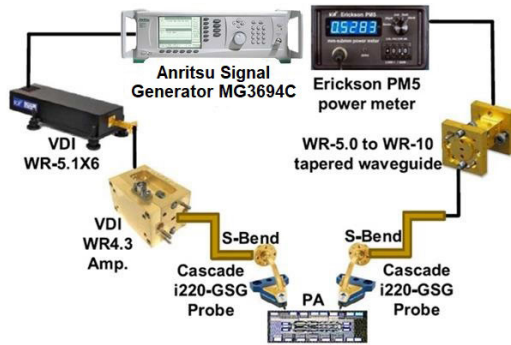


Fig. 18. Large-signal measurement setup.

Cascade i-220 GSG probes and S-bends were added to the setup. The probes landed on the through line of a WR5 calibration kit and the output power was measured again across the same frequency range. Comparing the two data sets, the combined probes and S-bends losses were extracted. Next, the output power of the PA was measured in 193–205-GHz band for different input power levels. Finally, the PA's input and output probes and S-bends were swapped, and the previous step was repeated to calibrate the loss difference between the input and output probes and S-bends.

The output power and power gain of the PA were calculated by de-embedding all losses, and the results are shown in Fig. 19. The PA achieves a peak saturated output power of 18.7 dBm with associated PAE of 4.8% and power gain of 10.9 dB at 200 GHz. The results show a good consistency with their simulation counterparts at 188 GHz. P_{sat} remains within 2 dB of its maximum from 198 to 202.9 GHz, as shown in Fig. 20, and shows a similar behavior with frequency shift to its simulation counterpart. The OP1dB is 12.1 dBm at 200 GHz and remains higher than 10 dBm over 193–205 GHz.

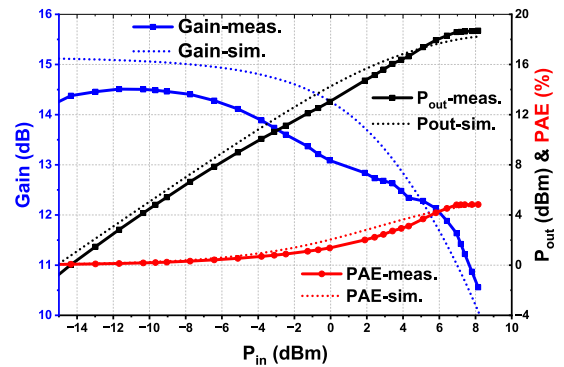


Fig. 19. Measured (marked) and simulated (dotted) power gain and output power of the PA at 200 GHz.

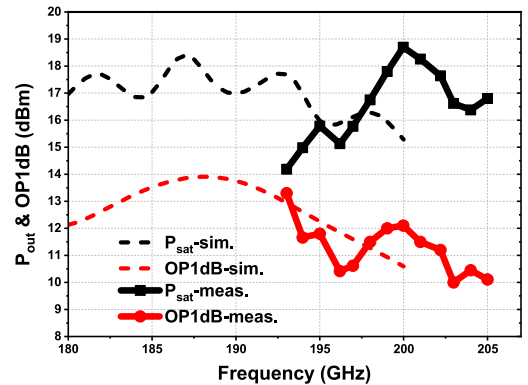


Fig. 20. Simulated (dashed) and measured (solid) saturated output power and OP1dB versus frequency.

The discrepancy in OP1dB between measurement and simulation at frequencies lower than 195 GHz is because of lower gain experimentally compared to its simulation counterpart,

thereby making OP1dB and P_{sat} very close to each other at 193 GHz.

Table IV summarizes the performances of the state-of-the-art PAs at G-band. To the authors' knowledge, this work demonstrates record P_{sat} , PAE, and power density ($P_{\text{sat}}/\text{Area}$) amongst the silicon-based PAs at 200 GHz. The PA operate at $0.56f_{\text{max}}$, showing an excellent performance at close-to- f_{max} region where device gain is limited.

VII. CONCLUSION

A novel methodology is developed in this article to predict the power gain, output power, PAE, and compression level of mm-Wave stacked PAs. The proposed approach determines the optimum design point of the PA to obtain maximum efficiency and output power. A 200-GHz CMOS stacked PA was designed and implemented in 45-nm CMOS SOI based on the proposed technique. The presented PA achieves record P_{sat} and PAE performance at close-to- f_{max} frequencies (200 GHz) in silicon. The PA consumes 0.4 mm² active die area and features the highest power density ($P_{\text{sat}}/\text{Area}$) among the state-of-the-art CMOS, SiGe BiCMOS, and InP HBT PAs.

APPENDIX A

DESIGN EQUATIONS OF THE STACKED CELL

From (5) and (6), the input current (I_{in}), the input voltage (V_{in}), and the current flowing to the gate termination (I_k) can be derived as follows:

$$I_{\text{in}} = V_m \left(\frac{1}{R_{\text{opt}}} - \frac{1}{Z_{\text{ds}}} + \frac{1}{g_m R_{\text{opt}} Z_{\text{gs}}} \right) \quad (13)$$

$$V_{\text{in}} = \frac{V_m}{g_m R_{\text{opt}}} \left(1 + \frac{Z_k}{Z_{\text{gs}}} + \frac{Z_k}{Z_{\text{gd}}} + \frac{Z_k g_m R_{\text{opt}}}{Z_{\text{gd}}} \right) \quad (14)$$

and

$$I_k = \frac{V_m}{g_m R_{\text{opt}}} \left(\frac{1}{Z_{\text{gs}}} + \frac{1 + g_m R_{\text{opt}}}{Z_{\text{gd}}} \right) \quad (15)$$

wherein

$$Z_{\text{gs}} = \frac{R_{\text{gs}}}{1 + sC_{\text{gs}}R_{\text{gs}}} \quad (16a)$$

$$Z_{\text{gd}} = \frac{R_{\text{gd}}}{1 + sC_{\text{gd}}R_{\text{gd}}} \quad (16b)$$

$$Z_{\text{ds}} = \frac{R_{\text{ds}} + sL_{\text{ds}}}{1 + sC_{\text{ds}}R_{\text{ds}} + s^2L_{\text{ds}}C_{\text{ds}}}. \quad (16c)$$

APPENDIX B

Z-PARAMETERS OF THE STACKED CELL

The Z-parameters of the CG stacked cell is derived using the model presented in Fig. 5(b) as follows:

$$Z_{11} = Z_k + Z_{\text{gs}} \parallel \left(\frac{Z_{\text{ds}} + Z_{\text{gd}}}{1 + g_m Z_{\text{ds}}} \right) \quad (17a)$$

$$Z_{12} = Z_k + \frac{Z_{\text{gs}} Z_{\text{gd}}}{g_m Z_{\text{ds}} Z_{\text{gs}} + Z_{\text{ds}} + Z_{\text{gs}} + Z_{\text{gd}}} \quad (17b)$$

$$Z_{21} = Z_k + \frac{Z_{\text{gs}} Z_{\text{gd}} (g_m Z_{\text{ds}} + 1)}{g_m Z_{\text{ds}} Z_{\text{gs}} + Z_{\text{ds}} + Z_{\text{gs}} + Z_{\text{gd}}} \quad (17c)$$

$$Z_{22} = Z_k + Z_{\text{gd}} \parallel (Z_{\text{ds}} + Z_{\text{gs}} + g_m Z_{\text{ds}} Z_{\text{gs}}). \quad (17d)$$

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