Analysis of proper biasing in Power Amplifiers

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***Abstract*— The aim of this study is to analyze the behavior of a 130 nm CMOS Cascode Power Amplifier (PA) as the biasing voltage changes. The analysis aims to achieve ideal biasing for high gain, a 1dB compression point, and high power added efficiency for a PA applied to mobile devices. In order to best analyze the PA's behavior, several simulations were conducted to optimize the PA for the desired application. Sweeping V_{bias} from 0.4 V to 2.9 V it was noticeable the severe drop in performance and efficiency in values out of the 0.6 V to 0.9 V range.**

Keywords—Power Amplifier, CMOS, Biasing, compression point.

I. Introduction

Radio Frequency (RF) Power amplifiers (PAs) are essential components in wireless transmitters. Their primary function is to boost the power of signals transmitted over short and long distances, especially in a connected world that heavily relies on mobile communication. However, designing efficient RF PAs involves addressing several challenges as the demand for smaller, more efficient, and more powerful PAs continue to grow. Some of the important metrics needed to engineer such PAs today are linearity, spectral efficiency, and mainly power efficiency, given that when so many devices run on limited energy sources such as lithium batteries [1]. When discussing nonlinearity, and increasing the linear behavior of our PA, it is vital to understand how the Output Compression Point at 1dB (OCP1dB) dictates how the PA will perform and how the bias voltage affects where the OCP1dB will be. If a PA is underbiased, the OCP1dB will be at a lower Output Power (P_{out}), making the PA perform closer to cutoff and reducing its linearity. On the opposite end, overbiasing makes the PA perform closer to saturation and the OCP1dB is at a higher P_{out}, but greatly reduces efficiency and can generate distortion. The aim is to achieve optimal biasing, getting the OCP1dB as high as possible while balancing gain and efficiency – one of the major challenges of Pas designs.

The Power Gain of a PA is one of its most important characteristics, and it is determined by a series of factors, such as topology, biasing and physical aspects like the transistors used and the component's attributes, such as transconductance for example. This means that, the gain is heavily dependent on proper biasing to achieve the desired levels. The circuit used in this study is adapted from [2] and [3] and utilizes the exact same structure.

As previously mentioned, power efficiency is a central aspect of today's mobile communication. The main metric that we rely on to determine how power efficient the PA is, is the Power Added Efficiency (PAE (%)), which tells us how much DC voltage is being consumed for any given signal determined by our biasing. The challenge arises in trying to improve the OCP1dB and Gain while also maintaining a desired value of PAE.

The objective of this work is to analyze different Bias Voltages (V_{bias}(V)), considering a biasing adjustment method that looks at the Output Impedance (Z_{out}) at the OCP_{1dB}. To further improve biasing, a wide range of Bias Voltages was investigated to better balance Gain, PAE, and OCP_{1dB} in the adapted amplifier as a proof of concept for utilizing the same method in the full amplifier [2] in the future.

II. Power Amplifier

The PA studied in this work is an adapted version of [2] and [3]. The resulting circuit is a cascode amplifier, having an upper transistor in Common Gate (CG) configuration and a lower transistor in Common Source (CS) configuration. The frequency of function is 2.45 GHz and the output impedance matching was also adapted, with a capacitance of 13.8 pF and inductance of 1.67 nH. Fig.2 shows the adapted PA with Port components defined as input, with Input Impedance (Zin(Ω)) as 0 Ω and V_{bias} as 0.4 V; and the output initially defined with Zin as 50 Ω.

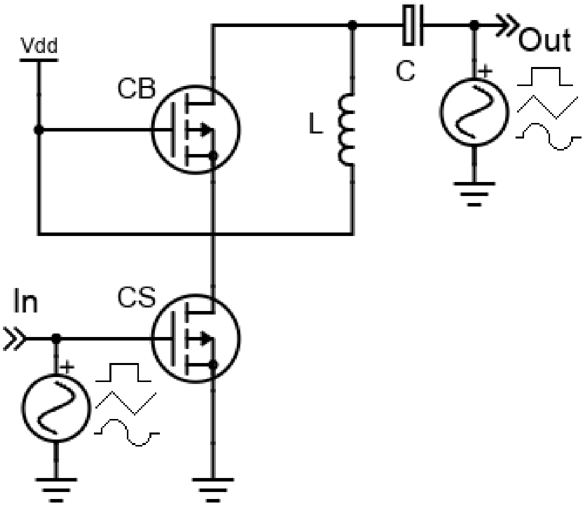

Fig. 1. Adapted PA

The purpose of the adaptation was to make this analysis straightforward for examining the gain stage behavior when applying different $V_{bias.}$ This change enables easier testing and verification of the results obtained in this paper.

In order to analyze the behavior of our PA, some values were required.

A. Compression point at 1dB (OCP_{1db})

This refers to the point where the gain decreases by 1dB from its maximum linear value. Beyond this point, the behavior is generally considered nonlinear. Achieving a high OCP1dB is of interest in this study.

B. Output impedance ($Z_{out}(\Omega)$)

This is the impedance at the output port at the OCP_{1dB}, it is crucial for obtaining other parameters at the OCP_{1dB}.

C. Power Added Efficiency (PAE(%))

This parameter measures how much DC voltage consumed is converted into power in the output signal. For applications like mobile amplifiers, maximizing PAE is a key objective. In this study, PAE is always measured at the OCP_{1dB}.

D. Gain (dB)

This is the ratio of output power (P_{out}) to input power (P_{in}) of the PA. It determines the extent to which the input signal is amplified.

E. Saturated Output Power (P_{sat}(dBm))

This is the maximum P_{out} that an amplifier can produce before saturating.

F. Maximum Power Added Efficiency (PAE_{max}(%))

This represents the highest efficiency value achievable by the amplifier. It indicates how effectively the amplifier converts DC and useful P_{in} into P_{out}.

III. Technology and Simulation

Cadence Virtuoso software was employed to build and simulate the PA of interest. Using a pre-layout schematic, three types of Harmonic Balance simulations were performed: Loadpull, Compression Point, and Sweep P_{in}. The procedure involved applying each bias voltage and determining the OCP_{1dB} and Z_{out} via Loadpull simulation through the Smith chart.

Subsequently, the obtained impedance, Z_{out} = 10.9 -j14.16 Ω was incorporated into the output port of the PA, and the Compression Point Simulation was executed. This allowed for the analysis of the PAE at OCP_{1dB} and the PA's gain. The Sweep Pin simulation was utilized to ascertain PAE_{max} and P_{sat}, which are crucial parameters for characterizing a PA's behavior. This process was repeated for each voltage of interest. The systematic approach provided a comprehensive analysis of the PA's performance under various conditions.

A. Loadpull

This involves optimizing the impedance seen by the amplifier output to find the maximum gain and highest OCP_{1dB}, starting with an initial Z_{out} of 50 Ω. Fig. 2 shows the simulation result, it displays a Smith chart with five loadpull contours. The key result is the OCP1dB at the maximum gain, indicated by the blue point on the chart.

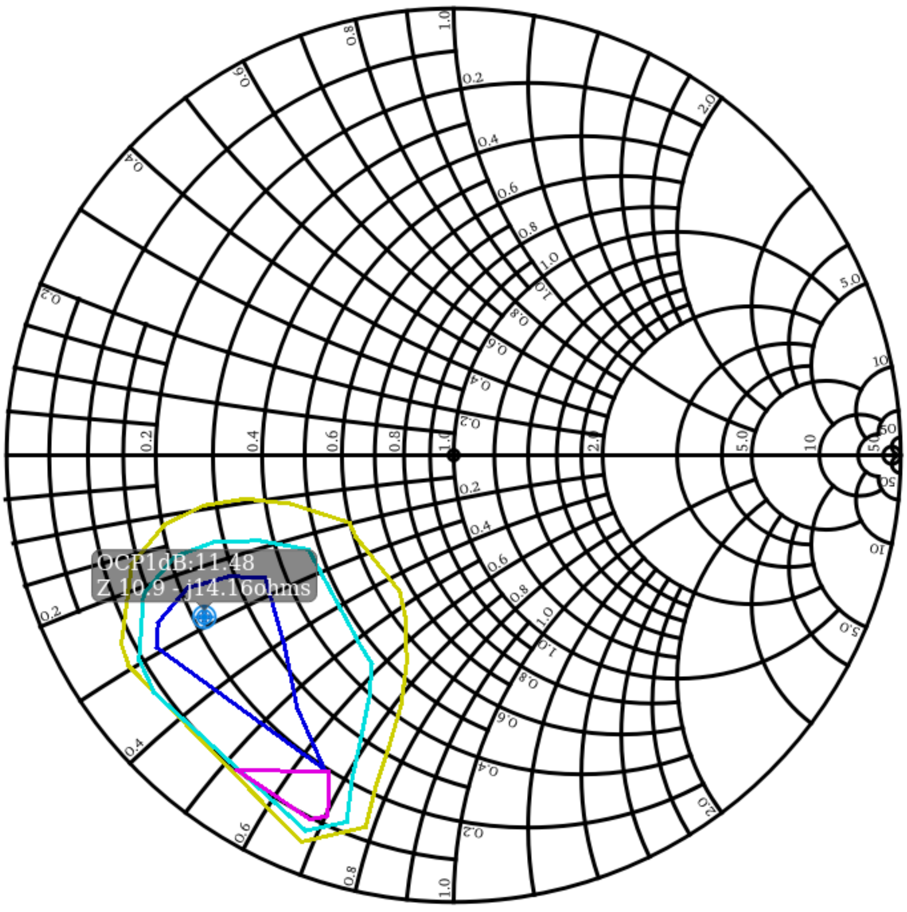

Fig. 2 Smith Chart: Vbias = 0.4 V, OCP1dB = 11.48 dB and Zout = 10.9 - j14.16 Ω.

B. *Compression Point*

This is used to characterize the PA's linearity and dynamic range. By using the Z_{out} found in the loadpull simulation, it is possible to use the desired compression point, and retrieve PAE and gain at the OCP_{1dB}. It is also a way to validate OCP_{1dB}, as the loadpull and compression point simulations should produce the same OCP_{1dB}. Table 1 shows the results from this simulation: OCP_{1dB}, gain, and PAE.

TABLE I. RESULTS FROM COMPRESSION POINT SIMULATION V_{BIAS} = 0.4 V AND Z_{OUT} = *10.9 – j14.16* Ω.

Values	Results
OCP_{1dB} (dB)	11.48
Gain (dB)	20.7
PAE (%)	18.67

C. *Sweep P_{in}*

This involves systematically varying the P_{in} across a range of values so that we can observe the PA's behavior across its entire operating range. The specified range varies from -20 dBm to 30 dBm, allowing for evaluation from small to large input signals. Fig. 3 shows the curves of PAE and P_{out} vs. P_{in}, enabling the acquisition of PAE_{max} and P_{sat}, 44.2% and 18.5 dBm, respectively.

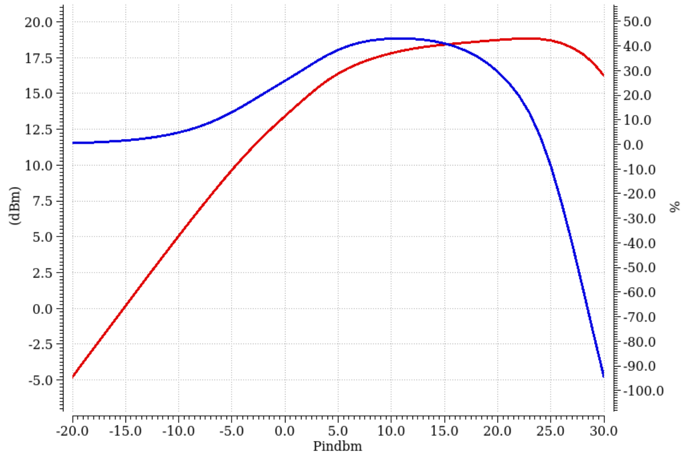

Fig.3. P_{out} (dBm) in red and PAE(%) in blue x P_{in}(dBm). V_{bias} = 0.4V and Z_{out} = 10.9 – j14.16 Ω.

IV. RESULTS AND DISCUSSION

The procedure explained above was repeated over a wide range of V_{bias} from 0.4 V to 2.9 V (V_{dd}), with increments of 0.2 V. After acquiring the results, points with higher performance were identified, and additional V_{bias} values were tested between them. Table 2 shows the results obtained for all the evaluated voltages.

Table II. All Vbias simulation results.

Biasing Table	Compression				Sweep	
V_{bias} (V)	Z_{out} (Ω)	OCP_{1dB}	PAE (%)	Gain (dB)	P_{sat} (dBm)	PAE_{max} (%)
0.4	10.9-j14.16	11.5	18.7	20.7	18.5	44.2
0.5	10.9-j14.16	14.7	23.9	21.2	18.6	42.8
0.6	14.8-j13.61	15.6	20.9	20.5	18.8	38.8
0.7	14.8-j13.61	14.3	11.9	19.9	18.9	37.2
0.8	14.8-j13.61	11.8	5.4	18.3	18.9	35.2
0.9	14.8-j13.61	17.9	25.3	15.1	18.9	33.3
1	10.9-j14.16	18.3	27.9	13.5	19.0	33.4
1.1	10.9-j14.16	18.5	27.9	12.2	19.0	31.9
1.3	10.9-j14.16	18.5	26.1	10.1	19.0	28.7
1.5	10.9-j14.16	18.5	23.5	8.5	19.0	25.2
1.7	10.9-j14.16	18.4	20.8	7.0	19.1	21.5
1.9	10.9-j14.16	18.4	17.9	5.8	19.0	17.9
2.1	10.9-j14.16	18.3	14.9	4.7	19.0	15.1
2.3	10.9-j14.16	18.2	11.7	3.7	19.0	12.4
2.5	10.9-j14.16	18.1	8.3	2.8	19.0	9.4
2.7	10.9-j14.16	18.0	4.9	2.0	19.0	6.2
2.9	10.9-j14.16	20.0	1.0	1.2	18.9	4.0

Analyzing Table II, it is noticeable that V_{bias} starts to saturate the PA at 1V since there isn't any significant improvement in OCP_{1dB}. Another proof that the PA becomes overbiased after 1V is the gain starting to drop abruptly; these two parameters end up dropping to as low as 1% and 1dB at higher voltages. On the opposite end, the results for the lowest V_{bias} (0.4V and 0.5V) also lacked performance. The PA had acceptable PAE and gain but displayed an OCP1dB at too low values. These outputs indicate that the PA was underbiased for these two values.

The V_{bias} values that rendered the best performance were from 0.6V to 0.9V, with the exception of 0.8V. In this case, every parameter apart from gain dropped a significant amount, leading to further testing at this point. The entire analysis was redone, utilizing a loadpull simulation with almost triple the amount of points, yet the same values were acquired.

One very interesting factor is Z_{out}; the results were almost fixed at exactly two values: 10.9-j14.16 Ω and 14.8-j13.61 Ω. It appears that the first result occurs when the PA is under or overbiased, as the V_{bias} values were 0.4V, 0.5V, and from 1V to 2.9V. The second result only occurred when the PA seems to be closer to ideal biasing, from 0.6V to 0.9V. This behavior of Z_{out} was confirmed by redoing the loadpull simulation with more than double the points, and the new results showed less than 1 Ω of difference. After applying the new Z_{out} to the circuit, the other simulations showed almost no variation, thus fundamentally confirming the behavior. Fig. 4 shows the behavioral curves of each parameter for V_{bias} ranging from 0.6V to 0.9V.

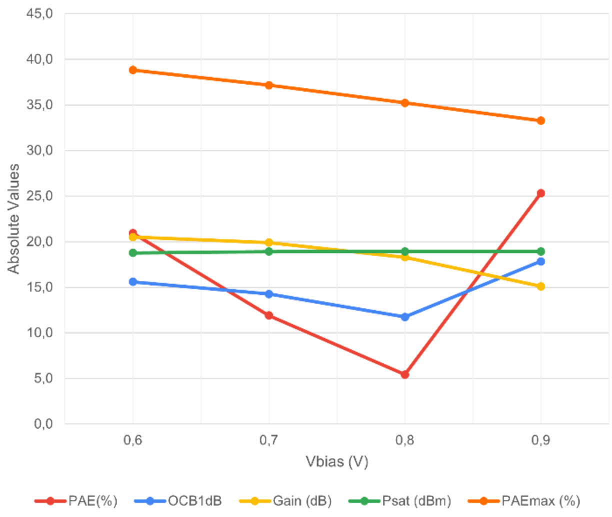

Fig. 4. PAE(%) in red, OCP_{1dB} in blue, Gain (dB) in yellow, P_{sat} (dBm) in green and PAE_{max} (%) in orange x Vbias.

Therefore, it is possible to analyze among these V_{bias} values which one is more suited to the expected behavior of the PA. In this case, the one that resembles the desired application's requirements best is V_{bias} of 0.9V, as it exhibits the highest PAE value without compromising too much Gain and OCP_{1dB}.

V. CONCLUSION

The main purpose of this paper was to analyze the behavior of the adapted PA using the loadpull, compression point, and sweep simulation methods, inspecting a wide range of V_{bias}.

When analyzing the complete spectrum of V_{bias}, it is possible to understand how applying higher voltages affects the PA's behavior. The gain decreases abruptly as V_{bias} increases, especially after 0.9V, as well as PAE and PAE_{max}. In contrast, OCP_{1dB} and P_{sat} increase and fluctuate until reaching a plateau of 18 dBm and 19 dBm, respectively, where they become almost static, rendering the increase in V_{bias} useless, and causing an abrupt decrease in PAE values. Fig. 5 shows the behavioral curves for every value analyzed.

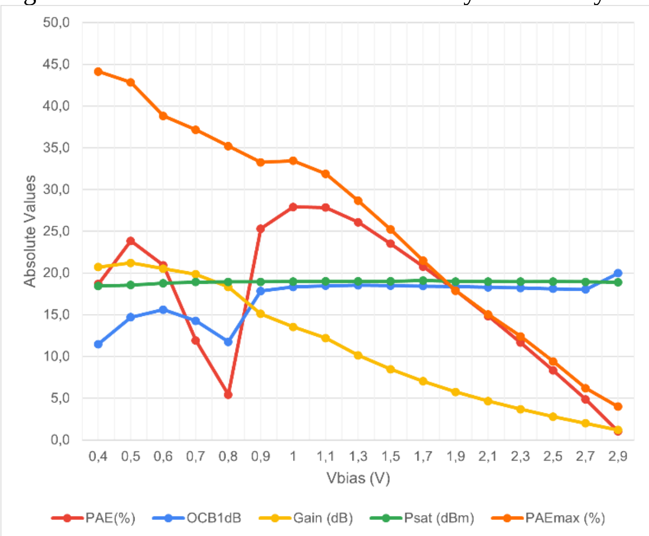

Fig. 5. PAE(%) in red, OCP_{1dB} in blue, Gain (dB) in yellow, P_{sat} (dBm) in green and PAE_{max} (%) in orange vs V_{bias}.

This work demonstrates to what extent increasing V_{bias} results in better outcomes, because not only does the efficiency drop, but the overall performance as well.

VI. REFERENCES

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