An Analytical Model for Improvement of Linearity and Efficiency of RF Linear Power Amplifiers for Radar Systems

Amir Al-Mslmany, *Member IACSIT*, Caiyun Wang, and Qunsheng Cao

***Abstract*—Power amplifier is the key component in radar systems, so linearity and efficiency is the most important parameters in order to maintain the performance of power amplifier, based on matlab curve fitting toolbox an analytical model for improvement of linearity and efficiency of radio frequency (RF) linear power amplifiers (PAs) is introduced. This model simplifies the traditionally complicated methods of analysis of RF PA. According to a change of the direct current (DC) bias as a function of the alternative current (AC) input signal of RF linear PA the linearity and efficiency can be improved.**

***Index Terms*—AC and DC analyses, ADS, biasing, efficiency linearity.**

I. Introduction

Power amplifiers are the master component in wireless transceivers, especially in radar systems their function is to amplify the signal and generate the required RF power that allows transmission of the signal over the appropriate range.Linear power amplifiers are needed in many modern wireless communication systems, such as radar systems, enhanced data rate Bluetooth, wireless local area network. One of the issues that faced in design of linear amplifiers for specific digital modulation standards is how to simulate and predict the behaviour of the design when amplifying modulated signals, the stringent requirement of linearity complicates the design of transceivers [1], especially design of the power amplifier module in transmitters.

A recently works on PAs showed that the linearity can be optimized by tuning the source/load impedance of the baseband and the 2nd harmonic frequency [2]. The traditionally nonlinear analysis method is more difficult because it uses more complicated mathematical solutions, such as voltera series [3] based on small signal model transistors, while it hardly describes the large signal nonlinearity [4] for the omission of the DC offset with AC input. Wu Tuo Chen, Hongyi and Qian Dahong [5] introduced a model to improve the linearity of RF PAs; this model indicates that the DC bias resistance can affect the nonlinearity, but this model is very difficult to study, and more complicated to make any modification required for improvement of linearity and efficiency, this paper introduces a computer simulation analytic model to improve the linearity and efficiency of RF linear PAs.

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II. Theoretical Analysis

The circuit shown in Fig. 1 introduces the commonly used DC bias circuit for linear bipolar PAs (regular bias), (I_{Bias} = const, $R_{Bias} = \infty$).

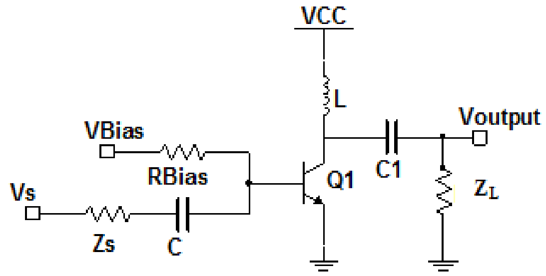

Fig. 1. Regular bias model.

Fig. 2 shows the simplified large signal equivalent circuit of a bipolar linear PA based on Gummel Boon (GB) model.

It consists of C_{couple} (the DC blocking capacitor) and L_{choke} (the RF chock) , Z_S is the source impedance and Z_L is the load impedance, C_d is the base diffusion capacitance, which is related to the forward transmit time τ and the collector current i_c .C_{je} and C_{jc} are the junction capacitances of BE and BC respectively, which are approximately constant compared to the nonlinear C_d .

The collector and base voltage-controlled current sources are respectively [5]:

$$i_c = I_S\left(exp\frac{V_{BE}+v_{be}}{V_T} - 1\right) \approx I_o exp\frac{v_{be}}{V_T} \qquad (1)$$

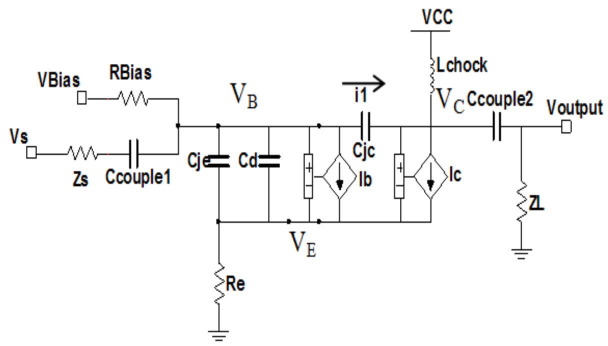

Fig. 2. Large signal equivalent circuit of a bipolar linear power amplifier.

$$i_b \approx \frac{i_c}{\beta} = \frac{I_o}{\beta} exp\frac{v_{be}}{V_T} \qquad (2)$$

where $$I_o = I_S exp\frac{V_{BE}}{V_T} \qquad (3)$$

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Using the AC and DC analysis for the show circuits it can be easily to derive the following equations:

$$I_o = \frac{I_{oq}}{1+\frac{K{V_{sm}}^2}{1+\frac{\beta V_T}{I_{oq}R_{Bias}}}} \quad (4)$$

where

$$K = \frac{|C_1(S)|^2}{4}$$

is constant, $C_1(s)$ is solved by voltera series which is more difficult to solve it numerically, if the bias is an ideal current source, so $R_{Bias} = \infty$, and

$$I_o \approx \frac{I_{oq}}{1+K{V_{sm}}^2} \approx I_{oq}(1 - K{V_{sm}}^2) \quad (5)$$

From equation (5) it is seen that I_o would reduce with an increase of V_{sm} and R_{Bias}.

Draw equation (4) using matlab, and then using Matlab curve fitting toolbox to get:

$$I_o = \frac{a_i * e^{b_i 10 \log R_{Bias}}}{C_1 + d_i * e^{e_i * \log R_{Bias}}} \times {V_{sm}}^2 + 1 \quad (6)$$

where a_i = - 0.01296 , b_i =2.103, c_i =1.145, d_i= 0.0621, e_i =2.106 are the constants of curve fitting.

Fig. 3 shows the relation between (normalized) I_o and $(V_{sm})^2$ at different R_{Bias} for two cases:

- Previous model using matlab.
- Present model using matlab curve fittingtoolbox.

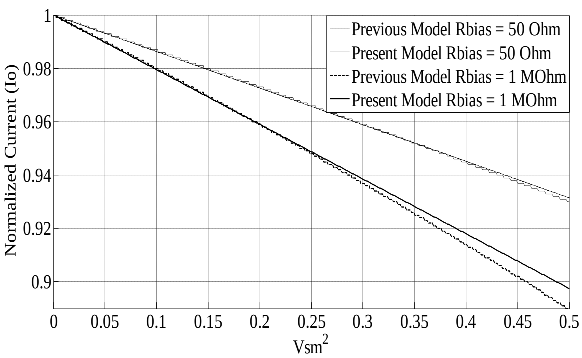

Fig. 3. Curves of the DC current I_o versus V_{sm} and R_{Bias}.

Comparing these curves it is found that the error between the two curves is less than 2%, thus equation (6) is approximately the same as equation (4).

Assume an input composed of two adjacent tones,

$$V_s = \frac{{V_{sm}}^2}{\sqrt{2}}(\cos\omega_1 t + \cos\omega_2 t) = \frac{V_{sm}}{2\sqrt{2}}(e^{s_1 t} + e^{-s_1 t} + \text{es2t+e−s2t} \quad (7)$$

The 3rd intermodulation ratio is[6]:

$$|IMR3| = \left|\frac{3}{4}\frac{F_3(S_1,S_1,-S_2)}{F_1(s_1)}\right| \left|\frac{V_{sm}}{\sqrt{2}}\right|^2 = \frac{3|V_{sm}|^2}{8} f_1(I_o) \quad (8)$$

where

$$f_1(I_o) = |C_1(S)|^2 \left|\frac{E_3(S)}{E_1(S)} - C_1(S)B_3(S) + 2B_2C_1[C_1(S)B_2(S) - \text{E2SE1S]} \quad (9)$$

and

$$B_2C_1 = \frac{2B_2(0)C_1(0)+B_2(2S)C_1(2S)}{3} \quad (10)$$

The function of $f_1(I_o)$ is complex but also it can be plotted using MATLAB and then to use Matlab Curve Fitting Toolbox to get the approximated form:

$$f_1(I_o) = a_f \times e^{b_f \times I_o} + c_f \times e^{d_f \times I_o}) \quad (11)$$

With constants (a, b, c and d) and its values are:

a_f =138.7, b_f = -13.25,

c_f =14.34, d_f = -2.823

Fig. 4 shows the relation between the (normalized $f_1(I_o)$) and (I_o) for two different cases the same as Fig. 3.

Comparing these curves it is found that the error between the two curves is less than 2%, thus equation (11) is approximately the same as equation (9).

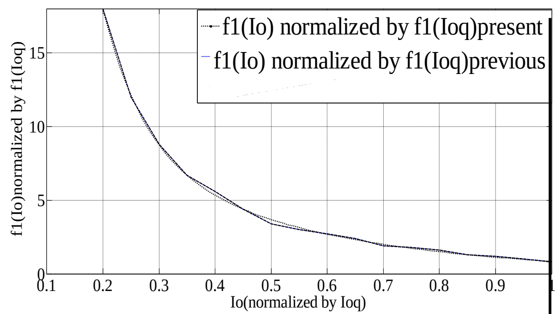

Fig. 4. The relation between $f_1(I_o)$ and normalized current I_o.

From Fig. 3 and Fig. 4 it is seen that $f_1(I_o)$ will increase as V_{sm} increases, so that the 3rd order intermodulation product (IMR3) would reduce compared to the standard results, which means the IMR3 is proportional to $|V_{sm}|^2$. Equation (6) indicates that a larger bias resistance would generate more nonlinearity. Thus, to gain a better linearity in the design of an RF linear PA, R_{Bias} should be chosen to be small, so a diode bias model is introduced. Fig. 5 shows the DC bias circuit for linear bipolar PA (diode bias)

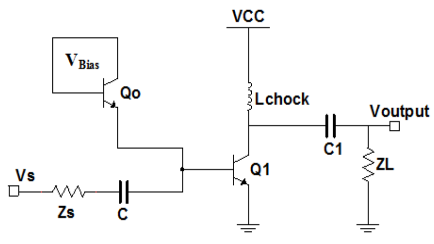

Fig. 5. Diode bias.

Generally, the size of the diode is very small, which means that the AC resistance of the bias branch can be neglected in the analysis of the linear PA.Using the same analysis as in the case of regular bias to get:

$$I_o \approx I_{oq}\,(1 - \frac{KV_{sm}{}^2}{2}) \qquad (12)$$

Comparing equation (12) and equation (5) we can see that the offset of I_o as a function of an increase in V_{sm} for the diode biased PA equation (12) is approximately half that for a regular current biased PA equation (5), so the current I_o for the diode bias is greater than I_o for regular bias and hence the linearity of the diode biased PA is better than the regular bias [7].

From the comparative results of the two bias types, it was shown that the diode bias can improve the linearity by decreasing the drop of the DC current I_o, so if the bias can completely compensate the drop, the linearity can be further improved.

Fig. 6 shows the circuit of the proposed model for improving linearity of linear PA.

This model reduces the leakage from the bias branches, the bias resistance can be large (R_{ad}; R_{Bias}>> R_e), Using the same analysis as in the case of regular bias and diode bias we find that:

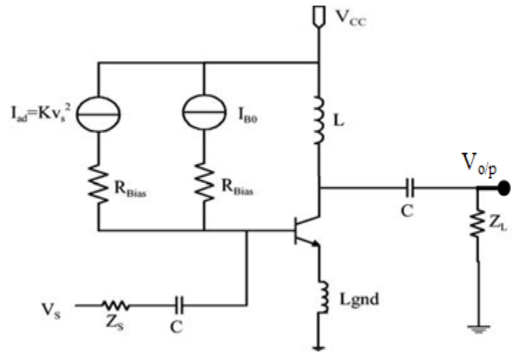

Fig. 6. The proposed bias model of RF linear PA.

This model reduces the leakage from the bias branches, the bias resistance can be large (R_{ad}; R_{Bias}>> R_e), Using the same analysis as in the case of regular bias and diode bias we find that:

$$V_T\,ln\frac{I_o}{I_s} + R_{Bias}\left(\frac{I_o + i_{c|DC}}{\beta} - i_{ad}\right) - V_{Bias} = 0 \qquad (13)$$

where

$$i_{ad} = \frac{i_{c|DC}}{\beta} = \frac{I_o|C_1(S)|^2}{4\beta}V_{sm}{}^2$$

The DC voltage v_{be} and the DC current I_o will not be affected by V_{sm}. So, the linearity could be improved.

III. Simulation

The circuit shown in Fig. 6 used for ADS simulation for the bias model of RF linear PA, the adaptive DC current bias I_{ad} is proportional to the input AC power:

$$I_{ad} = K_1 v_s{}^2 \qquad (14)$$

Using the harmonic balance (HB) simulation, with sweeping

$$K_1\text{: From (0) to } (K_{opt} = \frac{I_{B0|C_1(S)|^2}}{4})$$

The output power is shown in Fig. 7. From this figure it is seen that the bias could improve the maximum linear output power.

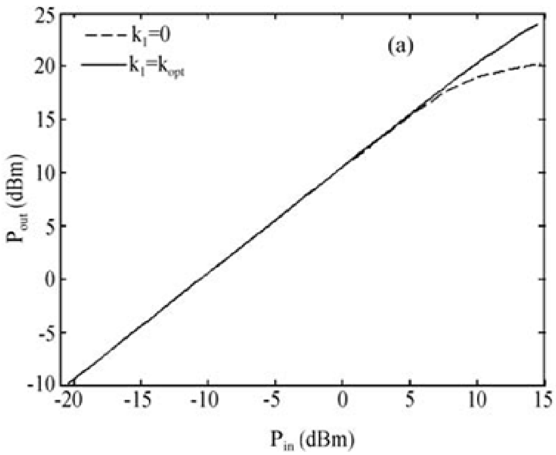

Fig. 7. Simulated output power.

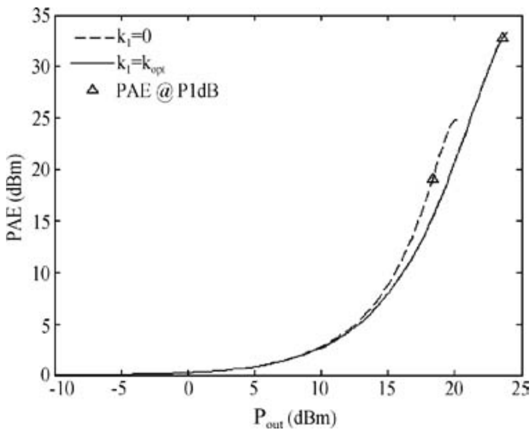

Fig. 8. Simulated power added efficiency of different bias PAs.

Fig. 8 shows that although the power added efficiency (PAE) of the improved bias PA is lower, the PAE at P_{1dB} can be increased from 20% to 32% when increasing P_{1dB}.

IV. Results

From the present simulation it is found that larger bias resistance would generate more nonlinearity.

Thus, to gain a better linearity in the design of an RF linear PA, R_{Bias} should be chosen to be small.

V. Conclusion

In this paper an analytical model is proposed for simplicity of numerical analysis of the regular bias model to improve the linearity of linear PA. This analytical model goes away from the difficult mathematical problems, such as voltera series.

Also this paper discusses the effect of biasing on linearity and efficiency of the linear power amplifier.

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REFERENCES

[1] A. Burr, *Modulation and Coding for Wireless Communications*, Beijing: Publishing House of Electronics Industry, 2003.

[2] J. Vuolevi and T. Rahkonen, "The effects of source impedance on the linearity of BJT common-emitter amplifiers," in *Proc. the International Symposium on Circuits and Systems*, vol. 4, 2000.

[3] S. C. Cripps, *RF Power Amplifiers for Wireless Communications*, Norwood, Artech House Inc, 1999.

[4] N. B. Carvalho and J. C. Pedro, "Large and small signal IMD behavior of microwave power amplifiers," *IEEE Trans Microw Theory Tech*, 1999, vol. 47, pp. 2364.

[5] T. C. Wu Y. Hong, and D. H. Qian, "Theoretical analysis and an improvement method of the bias effect on the linearity of RF linear power amplifiers," *Institute of Microelectronics*, vol. 30, no. 5, 2009.

[6] P Wambacq, *Distortion Analysis of Analog Integrated Circuits*, Kluwer Academic Publishers, 1998.

[7] S. N. Youn and S. P. Chul, "PCS/W-CDMA dual-band MMIC power amplifier with a newly proposed linearizing bias circuit," *IEEE J Solid State Circuits*, 2002, vol. 37, no. 1096.

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