A SYSTEMATIC SCHEME FOR POWER AMPLIFIER DESIGN USING A MULTI-HARMONIC LOADPULL SIMULATION TECHNIQUE

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ABSTRACT

This paper presents, for the first time, a systematic procedure for narrowband power amplifier design using a multi-harmonic loadpull simulation technique. This scheme explores the effects of each harmonic termination on amplifier performance and finds the optimal load at each harmonic. Following this systematic design procedure we can improve the amplifier performance significantly. The advantages of our method are demonstrated for two power amplifiers. Very promising results are obtained.

INTRODUCTION

With the rapid development of wireless communication in recent years, the quality of the power amplifier is becoming an increasingly critical component of the entire communication system. A good power amplifier design can significantly improve the performance of the system and reduce the cost. Loadpull techniques and harmonic load tuning have been successfully used for power amplifier design (e.g., [1]-[4]). However, the design procedure has never been systematically described. This prevents or restricts the practical usage of the loadpull techniques.

In this paper we present a systematic scheme to use the loadpull technique efficiently in narrowband power amplifier design. Multi-harmonic loadpull simulation using the harmonic balance (HB) method is used as a vehicle for our presentation. Harmonic loading contours are simulated by sampling the corresponding impedance of an ideal tuner connected to the output port. A step by step design procedure is described.

Our process can be simply classified into two major steps: finding the optimal loading at each harmonic and checking the power levels of higher harmonics. By checking the power levels of higher harmonics we can readily see the effects of higher harmonic loading on amplifier performance. Further steps are carried out based on the investigation of the higher harmonic loading effects. Though simple and easy it is a very effective way for microwave engineers to achieve good, if not the best, results in power amplifier design.

Two power amplifier design examples are demonstrated for our systematic procedure. Very good results are obtained.

MULTI-HAMONIC LOADPULL SIMULATION USING HARMONIC BALANCE

Our multi-harmonic loadpull simulation is implemented within our nonlinear simulator: Microwave Harmonica [5] which uses an efficient HB technique [6]. The formulation can be generally expressed as

$$\boldsymbol{E}(\boldsymbol{X}, \boldsymbol{Z}) = 0$$

where $\boldsymbol{E}$ is the vector of HB errors, $\boldsymbol{X}$ the set of all harmonic state-variables and $\boldsymbol{Z}$ the harmonic loads on all external ports. The kth subvector of $\boldsymbol{E}$ can be written as

$$\boldsymbol{E}_k(\boldsymbol{X},\boldsymbol{Z}) = \boldsymbol{A}(k\omega_0,\boldsymbol{Z})\boldsymbol{\Phi}(\boldsymbol{X},\boldsymbol{Z}) + \boldsymbol{B}(k\omega_0,\boldsymbol{Z})\boldsymbol{\Psi}(\boldsymbol{X},\boldsymbol{Z}) + \boldsymbol{D}(k\omega_0,\boldsymbol{Z})$$

where $0 \le k \le N_H$ (N_H is the number of harmonics used in the simulation), $\boldsymbol{A}$ and $\boldsymbol{B}$ are circuit matrices, $\boldsymbol{D}$ is a set of driving functions, $\boldsymbol{\Phi}$ and $\boldsymbol{\Psi}$ are respectively the harmonic vectors of instantaneous voltages $\boldsymbol{v}$ and currents $\boldsymbol{i}$ at the nonlinear subnetwork ports.

The harmonic loads $\boldsymbol{Z}$ can be written in the following matrix form

$$\boldsymbol{Z} = \begin{bmatrix} Z_1(0\omega_0) & Z_1(1\omega_0) & \cdots & Z_1(N_H\omega_0) \\ Z_2(0\omega_0) & Z_2(1\omega_0) & \cdots & Z_2(N_H\omega_0) \\ \vdots & \vdots & \vdots & \vdots \\ Z_M(0\omega_0) & Z_M(1\omega_0) & \cdots & Z_M(N_H\omega_0) \end{bmatrix}$$

where M is the number of external ports considered and $Z_i(k\omega_0)$ is the load at the kth harmonic and the ith port with

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$(0\omega_0)$ representing the DC component. The purpose of multi-harmonic loadpull simulation is to find the optimal harmonic loading w.r.t. the design specifications. An impedance sampling method is used in our implementation of multi-harmonic loadpull simulation. Only one component of $\boldsymbol{Z}$ is sampled at the defined impedance plane while the others are kept constant at each step. The HB simulation is performed at each sampling point to solve for the circuit responses specified. After the simulations are finished at all sampling points loadpull contours are plotted on the Smith chart and then the optimal point is located.

SYSTEMATIC PROCEDURE FOR POWER AMPLIFIER DESIGN

The circuit for our amplifier design can be briefly sketched as Fig. 1 where tuners are placed at the source and load ports.

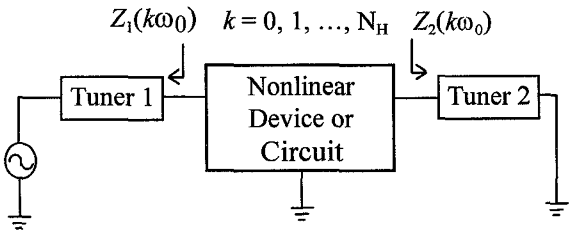

Fig. 1 Circuit topology for amplifier design.

The impedance sampling is achieved by adjusting the tuner parameters which can be described as follows.

$R_i(k\omega_0)$ - the resistance at the ith tuner and the kth harmonic, $i = 1, 2$, and $k = 1, 2, \ldots, N_H$

$X_i(k\omega_0)$ - the reactance at the ith tuner and the kth harmonic, $i = 1, 2$, and $k = 1, 2, \ldots, N_H$

Only the impedance at one selected tuner i and one harmonic k, i.e., $Z_i(k\omega_0)=R_i(k\omega_0)+jX_i(k\omega_0)$, is allowed to be tuned at a time and the other harmonic impedances are fixed at any meaningful values. Our design procedure can be described as:

Step 1: Start loadpull simulation by sampling the impedance at the fundamental frequency $Z_i(\omega_0)$ and find the optimal load $Z_{io}(\omega_0)$.

Step 2: Fix $Z_i(\omega_0)$ at $Z_{io}(\omega_0)$ and check the output spectrum to see the effects of higher harmonic loads on the amplifier responses. If the effects of higher harmonic loads are significant, let $k = 2$, go on to Step 3. Otherwise stop.

Step 3: Perform loadpull simulation by sampling the kth harmonic impedance $Z_i(k\omega_0)$ and find the optimal load $Z_{io}(k\omega_0)$.

Step 4: Fix $Z_i(k\omega_0)$ at $Z_{io}(k\omega_0)$ and check the output spectrum to see the effects of higher harmonic loads on the amplifier responses. If the effects of higher harmonic loads are significant, let $k = k + 1$, go to Step 3. Otherwise stop.

This procedure can be repeated for all the tuners to achieve the optimal solution. It can be summed up as a loadpull simulation and spectrum checking (LSSC) process. The flowchart in Fig. 2 illustrates this procedure.

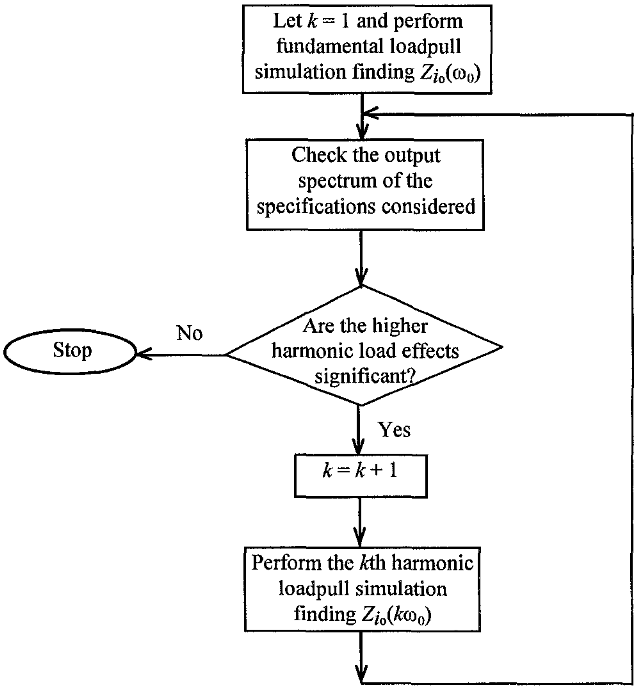

Fig. 2 Flowchart of the design procedure.

DESIGN EXAMPLES

Two power amplifiers are used as examples to demonstrate the LSSC design procedure. The amplifiers are designed to operate at 0.5GHz. The circuit schematic of the amplifier is shown in Fig. 3. A Siemens power MESFET CLY10 [7] is used in our design. The MESFET is modeled by the modified Materka model implemented in Microwave Harmonica [5]. Without losing generality and for easy illustration we fix all harmonic impedances of Tuner 1 at the source port at 50Ω and tune Tuner 2 at the load port for both examples. Six harmonics are used in the HB simulation.

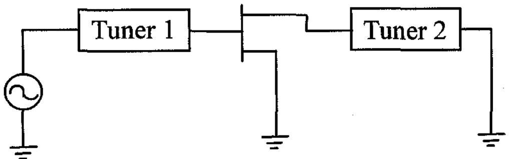

Fig. 3 The MESFET power amplifier schematic.

In Example 1 the MESFET is biased at V_{gs} = -1.3V and V_{ds} = 5V and the amplifier is designed as a normal Class A type with a 10dBm input power. Following the procedure described above we perform loadpull simulation by sampling $Z_2(\omega_0)$ of Tuner 2 while other harmonic impedances of Tuner 2 are fixed at 50Ω. The loadpull contours of power gain are plotted in Fig. 4. The optimal load $Z_{2o}(\omega_0)$ is found to be 9.07+j12.99 at which the power gain is 18.54dB and power added efficiency (PAE) is about 20%. The output power spectrum at this point is plotted in Fig. 5. By checking the output power spectrum of Fig. 5 we can see that the power at all higher harmonics are very small. Therefore, the higher harmonic loads will not have significant effects on the amplifier performance.

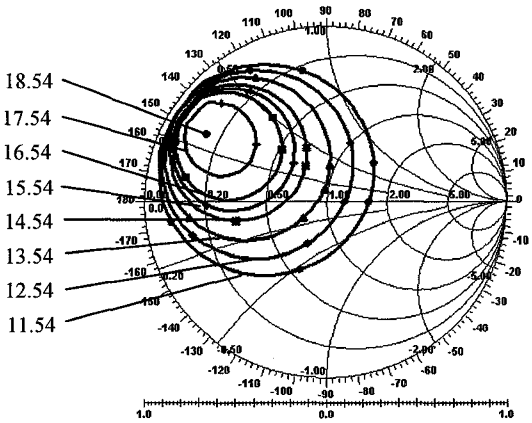

Fig. 4 Contours of power gain (dB) of Example 1 obtained from fundamental loadpull simulation.

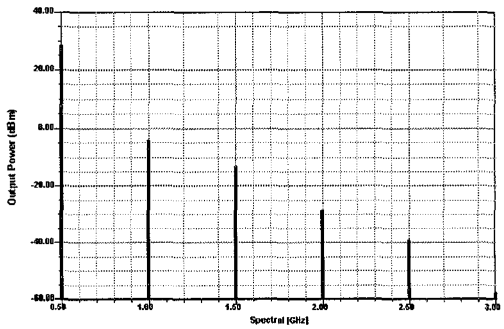

Fig. 5 Output power spectrum of Example 1 when $Z_2(\omega_0) = Z_{2o}(\omega_0)$.

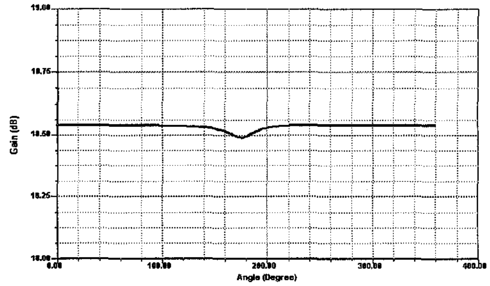

Fig. 6 Power gain v.s. the phase of $\Gamma_2(2\omega_0)$ for Example 1.

To verify this conclusion we perform loadpull simulation by sampling $Z_2(2\omega_0)$ of Tuner 2 while $Z_2(\omega_0)$ is fixed at $Z_{2o}(\omega_0)$. It is found that the best performance w.r.t. power gain and PAE is obtained for purely reactive second harmonic loads which is consistent with the results obtained in [2]. The output power versus the phase of $\Gamma_2(2\omega_0)$ is shown in Fig. 6 from which we can see the influence of $Z_2(2\omega_0)$ is very small and our conclusion is justified.

In order to illustrate the effects of higher harmonic loading on the amplifier performance the MESFET is biased at $I_d = 0.14 I_{DSS}$ and V_{ds} = 5V and the input power is increased to 20dBm in Example 2. Fig. 7 shows the contours of PAE at the fundamental loadpull simulation. The optimal load $Z_{2o}(\omega_0)$ is 4.31+j13.30 for power gain (12.66dB) and 7.61+j13.11 for PAE (44.28%). Though a compromise between the power gain and PAE can be obtained we select 7.61+j13.11 as our $Z_{2o}(\omega_0)$ and consider the PAE as the primary specification throughout the following process. The output spectrum at this point is shown in Fig. 8 which indicates that the output power at higher harmonics are significant and thus the higher harmonic loads are critical to the amplifier performance.

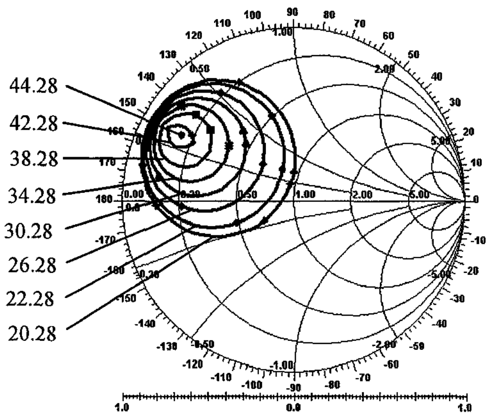

Fig. 7 Contours of PAE (%) of Example 2 obtained from fundamental loadpull simulation.

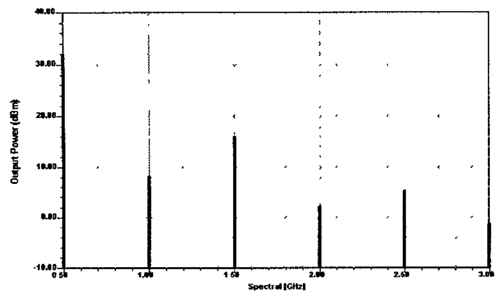

Fig. 8 Output power spectrum of Example 2 when $Z_2(\omega_0) = Z_{2o}(\omega_0)$.

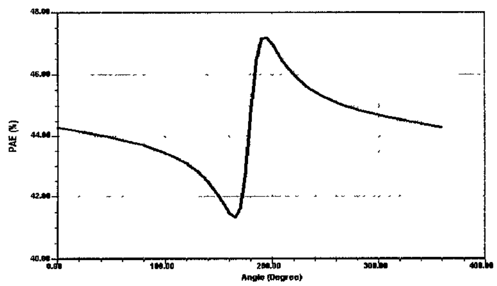

Fig. 9 PAE versus the phase of $\Gamma_2(2\omega_0)$ for Example 2.

By fixing $Z_2(\omega_0)$ at 7.61+j13.11 and sampling $Z_2(2\omega_0)$ we perform the second harmonic loadpull simulation. The result also indicates that the best point for the second harmonic load will be pure reactance. The effect of the phase of $\Gamma_2(2\omega_0)$ on PAE is shown in Fig. 9. The optimal value of $Z_{2o}(2\omega_0)$ is -j6.58 where the phase of $\Gamma_2(2\omega_0)$ is 195 degrees. The PAE is improved from 44.28% to 47.18%. Following the same procedure we perform loadpull simulations up to the 6th harmonic. The results are

Harmonic load	Optimal value
$Z_2(\omega_0)$	7.61+j13.11
$Z_2(2\omega_0)$	-j6.58
$Z_2(3\omega_0)$	-j65.16
$Z_2(4\omega_0)$	-j2.18
$Z_2(5\omega_0)$	-j28.81
$Z_2(6\omega_0)$	-j23.32

The PAE is 48.13% and power gain is 12.38dB at the final design. The output power spectrum of the final design is shown in Fig. 10 which indicates that the output power levels at the second and higher harmonics have been significantly suppressed compared to those shown in Fig. 8.

CONCLUSIONS

We have presented a systematic procedure for power amplifier design using a multi-harmonic loadpull simulation technique. With this simple LSSC scheme we

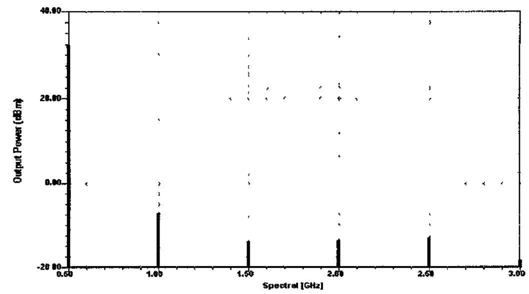

Fig. 10 Output power spectrum of Example 2 at the final design.

have demonstrated that the amplifier performance can be significantly improved by a proper design of harmonic loads. Though only the loadpull design is illustrated in this paper the source pull design can also be carried out in a similar way. This method can be applied to any power amplifier design to achieve the optimal solution and utilize the maximum potential of the devices used in amplifier circuits.

ACKNOWLEDGMENT

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REFERENCES

[1] R. Hajji, F. Beauregard and F. Ghannouchi, "Multitone power and intermodulation load-pull characterization of microwave transistors suitable for linear SSPA's design," *IEEE Trans. Microwave Theory Tech.,* vol. 45, pp. 1093-1099, 1997.

[2] P. Berini, M. Desgagné F. Ghannouchi and R.G. Bosisio, "An experimental study of the effects of harmonic loading on microwave MESFET oscillators and amplifiers," *IEEE Trans. Microwave Theory Tech.*, vol. 42, pp. 943-950, 1994.

[3] M.A. Khatibzadeh and H.Q. Tserng, "Harmonic tuning of power FETs at X-band," *IEEE MTT-S Int. Microwave Symp. Digest*, pp. 989-992, 1990.

[4] B. Kopp and D.D. Heston, "High-efficiency 5-watt power amplifier with harmonic tuning," *IEEE MTT-S Int. Microwave Symp. Digest*, pp. 839-842, 1988.

[5] *Microwave Harmonica Reference Manual*, Ansoft Corporation/Compact Software Division, Elmwood Park, NJ.

[6] V. Rizzoli, C. Cecchetti, A. Lipparini and F. Mastri, "General-purpose harmonic balance analysis of nonlinear microwave circuits under multitone excitation," *IEEE Trans. Microwave Theory Tech.,* vol. 36, pp. 1650-1660, 1988.

[7] *Einzelhalbleiter Discrete and RF Semiconductors*, Siemens Data Book 02.97, 1997.