MULTI-HARMONIC TUNING BEHAVIOR OF MOSFET RF POWER AMPLIFIERS

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***Abstract* -- This paper categorizes, for the first time, multi-harmonic tuning behavior into four basic modes: both odd/even harmonics SHORT (SS), odd harmonics SHORT and even harmonics OPEN (SO), odd harmonics OPEN and even harmonics SHORT (OS), and both odd/even harmonics OPEN (OO). Conventional power amplifiers (Class AB, E, F, etc.) can be characterized using these modes of operation in so far as multi-harmonic tuning is concerned and a systematic simulation procedure can be used to find the optimal harmonic terminations. A simulation and experimental study of the multi-harmonic tuning behavior of MOSFET RF power amplifiers reveals that the odd/even harmonics OPEN (OO) mode results in the highest efficiency for such devices.**

I. INTRODUCTION

High efficiency power amplifiers operating at low supply voltages are required for portable wireless communication devices. Multi-harmonic tuning techniques have been proposed for GaAs MESFET and HEMT power amplifiers to improve efficiency [1]-[6]. However, there is no complete classification of multi-harmonic tuning behavior and the relationship between conventional power amplifiers (Class AB, E, F, etc.) and multi-harmonic tuning is vague.

Silicon based devices have recently received considerable attention for low-cost integrated implementations of power amplifiers. However, there is no report on the multi-harmonic tuning behavior of silicon MOSFET power amplifiers.

In this paper multi-harmonic tuning is classified into four basic modes. Conventional power amplifiers can be characterized using this classification and a systematic harmonic balance simulation procedure can be used to find the optimal harmonic terminations. The multi-harmonic tuning behavior of MOSFET RF power amplifiers is then studied.

II. CLASSIFICATION OF MULTI-HARMONIC TUNING

As shown in Fig. 1, the multi-harmonic tuning behavior can be classified into four basic types according to the phases of the harmonic load reflection coefficients Γ_L (the magnitudes are assumed to be close to 1.0). The four basic modes are:

- SS mode: Both odd and even harmonics are SHORT. The drain voltage waveform is sinusoidal, containing no harmonic components. This type includes conventional Class A, AB, B and C.
- OS mode: Odd harmonics are OPEN and even harmonics are SHORT. The drain voltage waveform is square-like, containing only odd harmonic components. This type corresponds to the Class F [1],[2].
- SO mode: Odd harmonics are SHORT and even harmonics are OPEN. The drain current waveform is square-like, containing only odd harmonics. The peak voltage is higher than twice the power supply. This type corresponds to the Inverse Class F [5],[6].
- OO mode: Both odd and even harmonics are OPEN. The drain current waveform is sinusoidal, containing no harmonics, resulting in little or no energy wasted at harmonic frequencies and yielding high efficiency. The peak voltage is also higher than twice the power supply. This type *includes* the low-order Class E [7]. This mode has not been reported in previous work on multi-harmonic tuning.

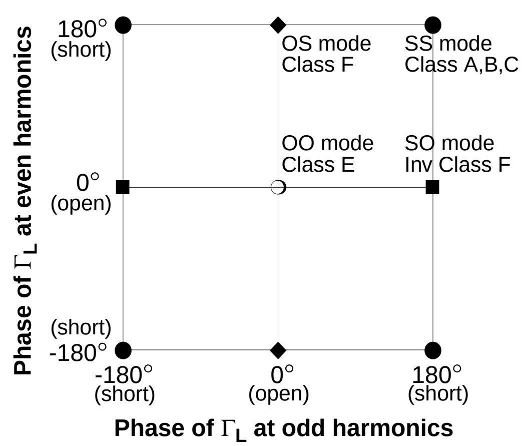

Fig. 1. Classification of multi-harmonic tuning

In Fig. 1 it is interesting to note that the OS mode (Inverse Class F) is the dual of SO mode (Class F), and the OO mode (Class E) is the dual of SS mode (Class A, B, C).

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III. Harmonic Balance Simulation Procedure

Fig. 2 shows the circuit used in harmonic balance (HB) simulations in an HB simulator such as Agilent Technologies' ADS. On the load side, only the 2nd and 3rd harmonics are considered and the magnitudes of their reflection coefficients are set to be 0.99. Because higher order harmonics have smaller amplitudes and hence do not have significant effects, they are ignored by terminating them to 50Ω. On the source side, all harmonics are also terminated to 50Ω. The HB simulations take into account the effect of harmonic terminations on the optimal fundamental load impedance. The procedure used to find the optimal harmonic terminations is as follows:

1. Estimate the load resistance R_L at the fundamental frequency (ω_0) according to the available power supply V_{DD} and the required output power *Pout*:

$$R_L \sim (V_{DD} - V_{knee})^2 / 2Pout \quad (1)$$

   where V_{knee} is the knee voltage, usually estimated to be $0.1V_{DD}\sim 0.2V_{DD}$. Then determine the fundamental source impedance $ZS(\omega_0)$ for good input match.
2. For each multi-harmonic tuning mode, set the phases of $\Gamma_L(2\omega_0)$ and $\Gamma_L(3\omega_0)$, perform load-pull simulations to find the optimal fundamental load impedance $ZLo(\omega_0)$. Retuning $ZS(\omega_0)$ may be necessary.
3. For each $ZLo(\omega_0)$ obtained in step 2, simultaneously sweep the phases of $\Gamma_L(2\omega_0)$ and $\Gamma_L(3\omega_0)$. Compare the results and chose the best mode and corresponding load impedance.

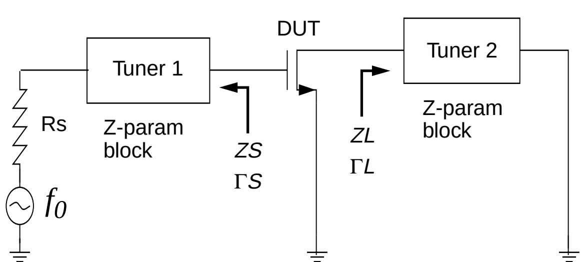


Fig. 2. Circuit used in HB simulations

IV. Multi-Harmonic Tuning Behavior of MOSFET Power Amplifiers

Class F (OS mode) and Inverse Class F (SO mode) have been found to achieve the highest efficiency for GaAs MESFET/HEMT power amplifiers[1]-[6]. An important difference between GaAs devices and silicon devices MOSFETs for power amplifier applications is that GaAs devices have smaller output capacitances (C_{OUT}) because of the semi-insulating substrate. For devices with large output capacitance such as power MOSFETs, the question is which multi-harmonic tuning mode yields the highest efficiency.

In order to investigate this issue, a power MOSFET implemented in a conventional 0.25um CMOS process was used. The device had a W/L aspect ratio of 2mm/0.25um. The BSIM3V3 device model including layout parasitics was used in harmonic balance simulations. The probe-contact resistance (0.5Ω) in the on-wafer load-pull test setup was also included in the model. Key device parameters are: Vth=0.6V, BV_{DS}=7.0V, Ron=0.57Ω, C_{OUT}=3.4pF, f_T=30GHz, f_{max}=19GHz. The device was biased at V_{DD}=2.0V and Vgs=0.7V.

Using the HB simulation procedure described in Section III, the fundamental load resistance R_L to obtain over 200mW output power at 1.88GHz was estimated to be 6Ω and $ZS(\omega_0)$ was determined to be 6+j14.8Ω. The optimal fundamental impedances obtained from load-pull simulations for each harmonic tuning mode are compared in Table I. The highest efficiency was achieved in the OO mode where $ZL(\omega_0)$=5.6+j7.8Ω. Since the corresponding output power was only 22.4dBm, further trade-off between output power and efficiency must be made to achieve high efficiency and the required power simultaneously. By inspecting the PAE and power contours shown in Fig. 3, the optimal $ZL(\omega_0)$ was finally chosen to be 6.5+j4.0Ω.

TABLE I Optimal $ZL(\omega_0)$ of the MOSFET optimized for maximum PAE (Pin=12dBm)

	max PAE (%)	$ZLo(\omega_0)$ (Ω)	Pout (dBm)
SS mode	52.4	6.3+j2.4	23.2
OS mode	59.1	6.3+j3.7	23.1
SO mode	68.1	5.8+j7.7	22.2
OO mode	68.9	5.6+j7.8	22.4

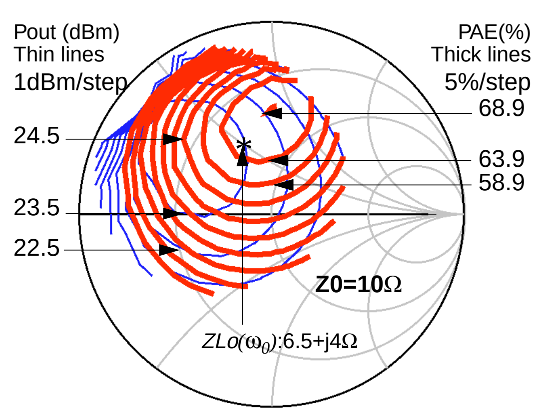


Fig. 3. PAE and Pout contours for OO mode (Pin=12dBm)

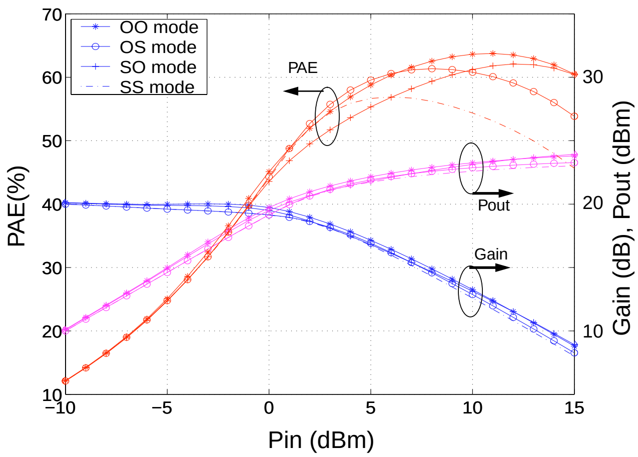
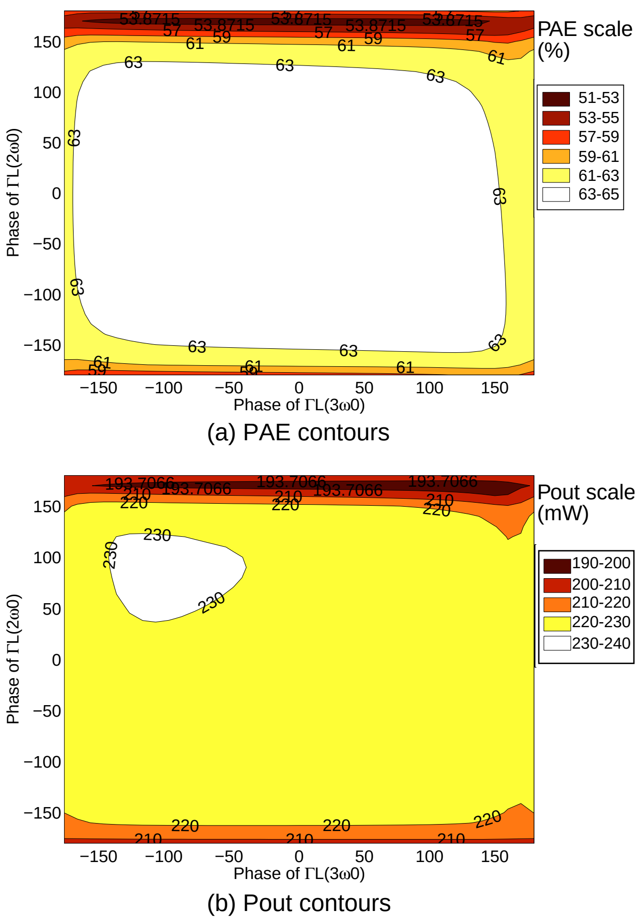


Fig. 4. PAE, Pout and Gain vs. Pin of the MOSFET



(a) PAE contours

(b) Pout contours

Fig. 5. PAE and Pout contours vs. phases of Γ_L of the MOSFET power amplifier ($ZL(\omega_0)$=6.5+j4.0Ω, Pin=12dBm)

Fig. 4 plots the power, gain and efficiency variation as a function of the input power for the various modes considered. At low gain compression, the OO mode and OS mode (Class F) exhibit higher efficiency than the SO mode (Inverse Class F) while at higher gain compression, the OO mode achieves the highest efficiency.

Fig. 5 shows the PAE and Pout contours versus the phases of Γ_L at $2\omega_0$ and $3\omega_0$ for Pin=12dBm. The variations of PAE and Pout are insensitive to the phase of $\Gamma_L(3\omega_0)$. In Fig. 5(a) the white region is the region of the highest efficiency and is somewhat independent of the phases of $\Gamma_L(2\omega_0)$ and $\Gamma_L(3\omega_0)$, enabling easy implementation of the load network.

The above simulation results show that the OO mode yields the highest efficiency at high gain compression for MOSFET RF power amplifiers.

V. Experimental Results

On-wafer harmonic load-pull measurements were conducted for the MOSFET (W/L=2mm/0.25um) used in Section IV. The micrograph of the device is shown in Fig. 6. The device consisted of four cells with an interdigitated layout structure. The test setup is shown in Fig. 7. A harmonic tuner was connected between the DUT output and the fundamental tuner for second harmonic tuning. The magnitude of $\Gamma_L(2\omega_0)$ at the DUT plane was 0.90. The third harmonic reflection coefficients $\Gamma_L(3\omega_0)$ were not controlled but were measured. The magnitude of $\Gamma_L(3\omega_0)$ was around 0.7 and the phase of $\Gamma_L(3\omega_0)$ ranged from 5° to 40°. The spectrum analyzer was used to monitor unwanted oscillations. Specific calibrations using a network analyzer were performed to obtain the input/output power and the impedances at the DUT input/output planes. The device was biased at V_{DD}=2.0V and Vgs=0.7V. The fundamental operating frequency was 1.88GHz. $ZS(\omega_0)$ and $ZL(\omega_0)$ were set at 6+j14.8Ω and 6.5+j4.0Ω, respectively.

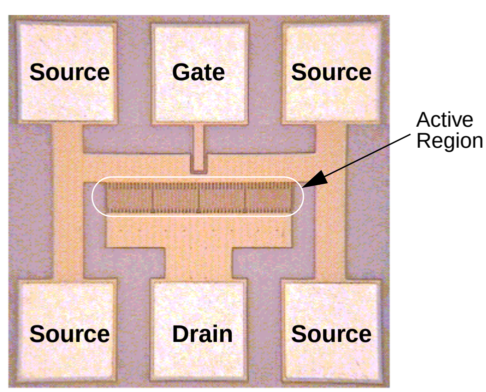


Fig. 6. Micrograph of the power MOSFET

Since PAE and power are insensitive to the phase of $\Gamma_L(3\omega_0)$, only the variations of power and PAE with the phase of $\Gamma_L(2\omega_0)$ were measured and compared with the

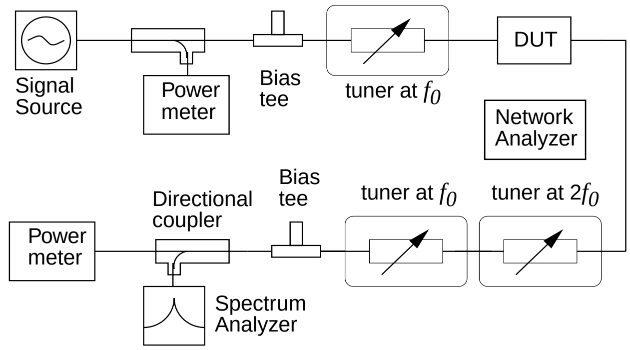
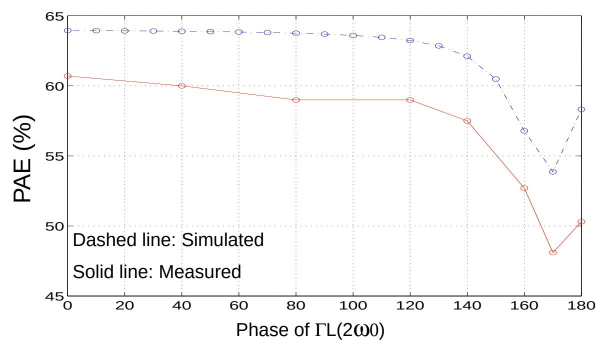
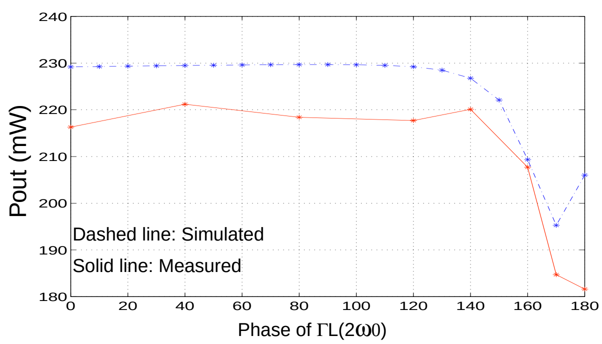


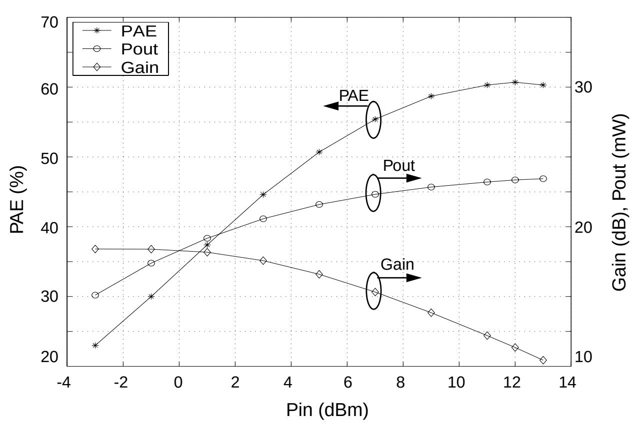
Fig. 7. Measurement system setup



(a) Measured PAE vs. Phase of $\Gamma_L(2\omega 0)$ (Pin=12dBm)



(b) Measured Pout vs. Phase of $\Gamma_L(2\omega 0)$ (Pin=12dBm)



(c) Measured PAE, Pout and Gain vs. Pin in OO mode

Fig. 8. Measured characteristics of the power MOSFET operating at V_{DD}=2.0V, Vgs=0.7V, $ZS(\omega_0)$=6+j14.8Ω, $ZL(\omega_0)$=6.5+j4.0Ω, f_0=1.88GHz.

simulated values at an input power of 12dBm as shown in Fig. 8(a) and (b). Fig. 8(c) shows the measured output power, gain and efficiency variations with the input power for the OO mode. The highest efficiency (PAE=61%) was obtained with an output power of 216mW. These measured results are in good agreement with the simulated ones.

VI. Conclusions

This paper classified multi-harmonic tuning behavior into four basic modes (SS, OS, SO and OO). Conventional power amplifiers can then be characterized using these modes of operation in so far as multi-harmonic tuning is concerned. A systematic harmonic balance simulation procedure was introduced to find the optimal harmonic terminations. The study of the multi-harmonic tuning behavior of MOSFET RF power amplifiers revealed that the OO mode yields the highest efficiency for such devices.

Acknowledgments

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