

Analysis of Output Power Variation under Mismatched Load in Power Amplifier FEM with Directional Coupler

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Abstract --- Directional couplers are used for output power detection and control in both WCDMA and GSM/EDGE Power Amplifier (PA) Front End Modules (FEM). At high values of load VSWR, delivered power shows significant variations with the phase. Back-of-envelope calculations are used to estimate output power variations. The objective of this analysis is to define a unified platform for understanding the power control mechanism in PA FEM with directional coupler, explain known-best practices and provide insight into minimizing output power variation. It illustrates how a complex load at isolation port of directional coupler is used to compensate certain non-ideal factors in PA FEM. A practical approach to minimize delivered power variations systematically was implemented and verified in a PA FEM design.

Index Terms --- Power detection, power control, power amplifier, directional couplers

I. INTRODUCTION

Power control requirements of WCDMA and GSM/EDGE systems bring increasing challenges in power amplifier (PA) front end module (FEM) design. Output power control accuracy is often a clearly defined design specification, but the interaction of control bandwidth, switching spectrum and mismatched load are not fully investigated until late in the product development cycle. It is often one of the last few design specifications worked out near the end of a design cycle. State-of-the-art multi-mode and multi-band handset PA FEMs require dynamic range over 40 dB, and +/-0.5 dB power control accuracy at mismatched load [1].

Power detection and control architectures for handsets have two main groups: direct and indirect detection. Indirect power detection measures DC characteristics without directly evaluating the RF output power. Simple circuitry offers a lower cost and smaller size solution. However indirect detection suffers in control accuracy due to unpredictable antenna loading conditions. In contrast, direct power detection monitors the RF waveform, and often requires a directional coupler and associated design complexity. Couplers can be implemented with discrete components or embedded on a printed circuit board. Due to better power control accuracy, this method has been attractive in recent years [2]. In practice, there are some “rules of thumb” used to estimate output power variations. Madic investigated a case with 50 ohm termination at coupler isolation [3]. This analysis provides a unified

platform that can be applied to general cases, and provides insight into minimizing output power variations.

The paper first defines a unified model. Two special cases are first analyzed to explain known engineering practices, and associated limitations are also discussed. A general case is then investigated and used to illustrate the benefits of a complex load at the isolation port of a directional coupler. A practical approach to minimize delivered power variations systematically is implemented and verified in a PA FEM design. Measurement results will be discussed.

II. A UNIFIED MODEL AND THEORETICAL ANALYSIS

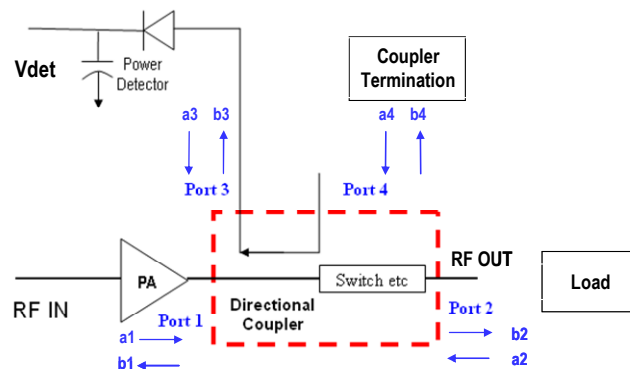


Fig. 1. A generic power amplifier FEM with directional coupler

The system represents a generic power amplifier FEM with directional coupler for output power detection and control. It is applicable to GSM/EDGE (with switch after directional coupler) or WCDMA (with duplexer after directional coupler). Antenna load is denoted as L and coupler termination is denoted as C_T . Four port system can be represented in (1):

$$\begin{pmatrix} b1 \\ b2 \\ b3 \\ b4 \end{pmatrix} = \begin{pmatrix} S11 & S12 & S13 & S14 \\ S21 & S22 & S23 & S24 \\ S31 & S32 & S33 & S34 \\ S41 & S42 & S43 & S44 \end{pmatrix} * \begin{pmatrix} a1 \\ a2 \\ a3 \\ a4 \end{pmatrix} \quad (1)$$

Coupling port (Port 3) is usually matched to 50 ohms in PA FEM system and is controlled by design. Therefore the matrix can simplified as follows:

$$\begin{pmatrix} b1 \\ b2 \\ b3 \\ b4 \end{pmatrix} = \begin{pmatrix} S11 & S12 & S13 & S14 \\ S21 & S22 & S23 & S24 \\ S31 & S32 & S33 & S34 \\ S41 & S42 & S43 & S44 \end{pmatrix} * \begin{pmatrix} a1 \\ a2 \\ 0 \\ a4 \end{pmatrix} \quad (2)$$

Where,

b2 represents the forward voltage wave at RF OUT (Port 2);
b3 represents the forward voltage wave at coupling port for PA FEM power control;

When load changes, the system adjusts a1 to maintain b3, which is usually referenced to b3 value measured with 50 ohm load;

Coupler directivity is defined in (3):

$$D = \frac{S31}{S32} \quad (3)$$

Two widely used special cases are examined in this framework under certain assumptions. Special case I focuses on ideal directional coupler, and demonstrated the impact of RF OUT port (switch or duplexer), which helps designer to estimate output power variation based on the return loss of switch or duplexer.

A.. Special case I: Perfect Directional Coupler

$$\begin{pmatrix} b1 \\ b2 \\ b3 \\ b4 \end{pmatrix} = \begin{pmatrix} S11 & S12 & S13 & S14 \\ S21 & S22 & S23 & S24 \\ S31 & 0 & S33 & S34 \\ S41 & S42 & S43 & S44 \end{pmatrix} * \begin{pmatrix} a1 \\ a2 \\ 0 \\ 0 \end{pmatrix} \quad (4)$$

With perfect coupler, coupler termination load is 50 ohm (a4=0) and coupler directivity is infinity (S32=0). After math simplification, (5) expresses b2 in terms of other parameters.

$$b2 = \frac{S21}{1 - S22\Gamma_L} * \frac{b3}{S31} = \left(\frac{S21}{S31} * b3 \right) \frac{1}{1 - S22\Gamma_L} \quad (5)$$

When load (Γ_L) moves over all phase angles, $S22^* \Gamma_L$ variation causes output power varies, which are shown in (6)-(9).

$$b2_{\max} = \left(\frac{S21}{S31} * b3 \right) \frac{1}{1 - |S22| * |\Gamma_L|} \quad (6)$$

$$b2_{\min} = \left(\frac{S21}{S31} * b3 \right) \frac{1}{1 + |S22| * |\Gamma_L|} \quad (7)$$

Therefore,

$$\Delta P_{\max} = 20 \log(1 - |S22| * |\Gamma_L|) \quad (8)$$

$$\Delta P_{\min} = 20 \log(1 + |S22| * |\Gamma_L|) \quad (9)$$

Assuming coupler is perfect (matched termination, and infinite directivity), the output power varies with mismatched load (Γ_L). To minimize power variations caused by $S22^* \Gamma_L$ variation, $|S22|$ needs to be close to zero since Γ_L is set by end user (not FEM designer). Yet $S22$ is determined by vendor (duplexer for WCDMA FEM, or switch for GSM/EDGE FEM), which is also beyond control of FEM designers. In practices, adjusting the phase between antenna and load helps to reduce $S22^* \Gamma_L$ variation, but this effect is limited. Table I shows that output power varies with RF OUT return loss (VSWR_ANT) and load conditions (VSWR_Load). At VSWR_ANT=1.5 (RF OUT return loss is ~14dB, which is usually the case), and VSWR_Load=4.0 (customer spec), the output power variation is expected to be +0.98 to -1.11 based on Table I. It seems +/-0.5 dB power control accuracy is not achievable if RF OUT return loss is not improved.

Table I

Output power variation with VSWR of RF OUT and load

VSWR_ANT	VSWR_Load	ρ_1	ρ_2	Mis Match Variation	
				+ Max	- Max
1.0	2.5	0.00	0.43	0.00	0.00
1.5	2.5	0.20	0.43	0.71	-0.78
2.0	2.5	0.33	0.43	1.16	-1.34
1.0	4.0	0.00	0.60	0.00	0.00
1.5	4.0	0.20	0.60	0.98	-1.11
2.0	4.0	0.33	0.60	1.58	-1.94

B. Special case II: Perfect RF OUT port and Matched coupler termination port

Special case II assumes ideal RF OUT port, and demonstrated the impact of non-ideal directional coupler, which helps designer to estimate output power variation based on the performance of directional coupler if ideal switch or duplexers are available.

$$\begin{pmatrix} b1 \\ b2 \\ b3 \\ b4 \end{pmatrix} = \begin{pmatrix} S11 & S12 & S13 & S14 \\ S21 & 0 & S23 & S24 \\ S31 & S32 & S33 & S34 \\ S41 & S42 & S43 & S44 \end{pmatrix} * \begin{pmatrix} a1 \\ a2 \\ 0 \\ 0 \end{pmatrix} \quad (10)$$

With perfect RF OUT port and matched coupler termination port, $a4=0$ and $S22=0$. After math simplification, (11) expresses $b2$ in terms of other parameters.

$$b2 = \frac{S21 * b3}{S31 + S32 * S21 \Gamma_L} = \left(\frac{S21}{S31} * b3 \right) \frac{1}{1 + S21 \Gamma_L / D} \quad (11)$$

When mismatch load move over all phase angles, Γ_L / D variation causes output power varies.

$$b2_{\max} = \left(\frac{S21}{S31} * b3 \right) \frac{1}{1 - S21 |\Gamma_L| / |D|} \quad (12)$$

$$b2_{\min} = \left(\frac{S21}{S31} * b3 \right) \frac{1}{1 + S21 |\Gamma_L| / |D|} \quad (13)$$

Case II was investigated by Madic etc [3], and Pozar provided math details for this case [4]. With 14.3 dB directivity, Madic achieved +/-1.2dB power variation for load VSWR=6:1. With finite coupler directivity, the output power variation is the determined by Γ_L/D variation. Given power variation requirement, coupler directivity requirement can be estimated.

In reality, even with maximized directivity, the power variation is determined by the antenna load variation Γ_L , which is not controlled by designer. Given non-ideal antenna, and non-ideal coupler, FEM designers need to look other ways to improve output power variation.

C. General case: Non-ideal RF OUT port and non-ideal directional coupler

$$\begin{pmatrix} b1 \\ b2 \\ b3 \\ b4 \end{pmatrix} = \begin{pmatrix} S11 & S12 & S13 & S14 \\ S21 & S22 & S23 & S24 \\ S31 & S32 & S33 & S34 \\ S41 & S42 & S43 & S44 \end{pmatrix} * \begin{pmatrix} a1 \\ a2 \\ 0 \\ a4 \end{pmatrix} \quad (14)$$

After math simplification of (14),

$$\frac{b2}{b3} \cong \frac{S21}{S31 - (S31 S22 - S32 S21 - \frac{S34 S42 S21 \Gamma_{CT}}{1 - S44 \Gamma_{CT}}) \Gamma_L} \quad (15)$$

If Γ_L coefficient could be zero, then $b2$ will not be affected by load variations (or Γ_L). Γ_L coefficient equates zero in (16),

$$S31 S22 - S32 S21 - \frac{S34 S42 S21 \Gamma_{CT}}{1 - S44 \Gamma_{CT}} = 0 \quad (16)$$

$$\Gamma_{CT} = \frac{S22 - S21/D}{S44(S22 - S21/D) + S34 S42 S21/S31} \cong \frac{S22 - S21/D}{S34 * S42 * S21/S31} \quad (17)$$

The significance of (17) is Γ_{CT} (termination of coupler isolation port) can be employed to offset non-ideal factors (mainly non-ideal S_{22} and finite directivity D). $\Gamma_{CT}=0$ (50 ohm termination at coupler isolation port) is not the best option if $S22 \neq 0$. In other words, 50 ohm coupler termination is not the best choice if RF OUT port is not perfect.

III. EXPERIMENTAL SETUP AND RESULTS

To verify the results described above, 2 tuners are used in a GSM/EDGE PA FEM system. One tuner is used as load, and the other one is used as coupler termination load.

Figure 1 shows the output power variation contour with load VSWR=4:1 over all phases at 1710MHz and 1910 MHz. The numbers (0.3, 0.4, 0.5, 0.6) indicate the power deviation from targeted value. Light blue arcs are for 1910MHz and magenta arcs are for 1710MHz. Blue line section is coupler termination load trajectory on s-plane from 1710MHz to 1910MHz. RC is used as complex termination of directional coupler. With RF OUT port of -14dB return loss (VSWR=1.5:1) and load VSWR=4:1, the result shows that the output power variation can be tuned below ± 0.5 dB using coupler complex termination, while special case A shows the achievable accuracy is +0.98dB to -1.1 dB if 50 ohm load is used at coupler termination (even with infinite coupler directivity).

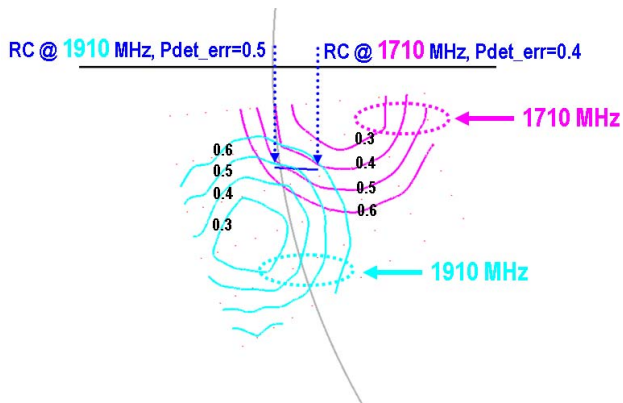


Fig. 2. Output power variation contour on s-plane using 2 tuners. From 1710MHz to 1910 MHz, the power variation is less than ± 0.5 dB.

IV. Conclusion

In special case I, the output power variation is determined by $S_{22} * \Gamma_L$ variation assuming perfect coupler (infinite directivity and 50ohm termination at coupler isolation port). Low output power variation may not be achievable if RF OUT of FEM (switch or duplexer) is not ideal, and customer system requires high Γ_L variation. In special case II, the output power variation is determined by Γ_L / D variation with perfect RF OUT port, finite coupler directivity and 50ohm termination at coupler isolation port. Low output power variation is not achievable if coupler directivity is finite and Γ_L is high.

In real design, $|D|$ is not infinite and RF OUT port is not ideal either. This analysis demonstrate that the complex termination of coupler isolation port Γ_{CT} can be employed to offset non-

ideal RF OUT port S_{22} and coupler directivity D to improve output power variation under mismatch load in PA FEM design. Terminating coupler isolation port with 50ohm ($\Gamma_{CT} = 0$) is not the best choice if RF OUT port is not ideal ($S_{22} \neq 0$) and coupler directivity is finite.

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