Accurate Power Control Technique for Handset PA Modules with Integrated Directional Couplers

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Abstract — **This paper describes an accurate power control technique for handset PA modules (PAMs) with internal closed loop control. Our design approach is the first to include two integrated directional couplers in a handset RF PAM. It significantly improves power control accuracy over load variations. Directivity of the integrated couplers is also proved to be critical for establishing accurate power control over phase variations at high values of load VSWR. With our unique design we achieved directivity as high as 14.3dB. When the load VSWR is equal to 6:1, we demonstrated that our design reduces output power variation to +/-1.2dB. Under the same conditions, we measured two other major commercial modules that are not utilizing integrated directional couplers. They exhibited an output power variation of 5.5dB.**

I. INTRODUCTION

It is becoming standard for handset manufacturers to utilize RF power amplifier modules (PAMs) with embedded power control functionality. In the past, it required a lot of effort for these manufactures to design power management circuitry surrounding PAMs on the handset boards. An integrated solution not only relieves them from this burden, but it also reduces time-to-market, handset production cost, and its size.

The existing PAMs with integrated power control are using either voltage or current sensing methods to manage transmit power. Neither of them is using directional couplers to detect output power. Output voltage or supply current are sensed to control bias and thus, delivered power through a negative feedback loop. Both the voltage and current variables are dependent on the phase associated with the complex load impedance applied to the PA. As a consequence, delivered power exhibits strong variations over the phase at high values of load VSWR. This variation is quite significant and can cause calls to be dropped by a base station. To overcome this problem, we will show that it is essential to use integrated directional couplers in the control loop.

In the following sections, we will present the theory of closed loop power control, which ensures minimum output power variation over phase at high values of load VSWR.

II. THE BASIC THEORY OF CLOSED LOOP CONTROL WITH INTEGRATED COUPLERS

Simplified block diagram PA module with internal closed loop power control circuitry that utilizes directional coupler is presented in Fig. 1.

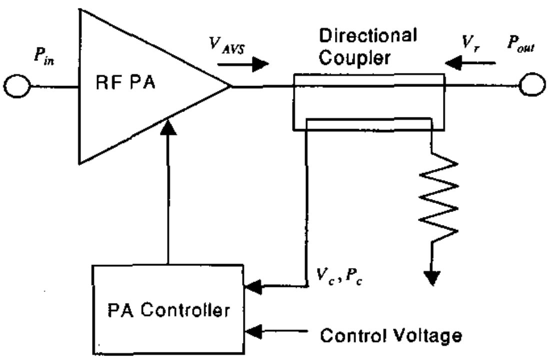

Fig. 1. PAM with integrated directional coupler and power control.

In Fig. 1, the power generated by the PA is fed into the directional coupler. The power delivered to the load, P_{out}, is equal to the difference between incident power and the power reflected from the load. Under nominal conditions, i.e., when the load impedance is equal to 50Ω, the reflected power is equal to zero and the power delivered to the load is equal to the power available from the PA, which we denote as P_{AVS}.

For any given load reflection coefficient the voltage detected at the coupled arm, V_c, is a vector sum of voltage coupled from the forward signal generated by the PA V_{AVSc} and voltage coupled from the reverse signal reflected by the load V_{rc}.

$$V_c = V_{AVSc} + V_{rc} = |V_{AVS}|\left(C + \frac{C}{D}|\Gamma_L|e^{-j\theta}\right), \quad (1)$$

where C is the numerical voltage coupling factor, D is the numerical directivity of the coupler, $|\Gamma_L|$ is the load

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reflection coefficient magnitude, and θ is the phase associated with the load reflection coefficient or the phase difference between V_{AVSc} and V_{rc} vectors [1]. We can see from Eq. 2 that the magnitude of V_c vector varies as a function of phase associated with the load. This is illustrated in Fig. 2.

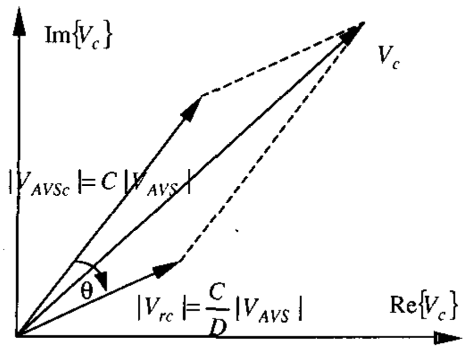

Fig. 2. Magnitude of V_c varies as a function of θ.

Assuming that the input of the controller is matched to 50Ω, the power detected at the coupled arm is derived from Eq. 1 and is given by

$$P_c = P_{AVS}\left|C + \frac{C}{D}|\Gamma_L|e^{-j\theta}\right|^2 \quad (2)$$

For any given load, the power controller compares power given in Eq.2 to some set value and adjusts P_{AVS} in such a way that coupled power is equal to that set value. This will make available power, as well as delivered power, functions of phase. The power delivered to the load in this case is expressed as

$$P_{out} = P_{AVS}\left(1 - |\Gamma_L|^2\right) \quad (3)$$

Combining Eqs. 2 and 3 we get

$$P_{out} = P_{c0} \cdot \frac{1}{\left|C + \frac{C}{D}|\Gamma_L|e^{-j\theta}\right|^2} \cdot \left(1 - |\Gamma_L|^2\right) \quad (4)$$

where P_{c0} is coupled power for the nominal case when $|\Gamma_L|$=0, or when the PA is presented with the matched load:

$$P_{c0} = C^2 P_{AVS0}. \quad (5)$$

P_{AVS0} is the available power in Watts when PA is presented with the matched load. Finally, we can express delivered power as

$$P_{out} = P_{AVS0} \cdot \frac{1}{\left|1 + \frac{1}{D}|\Gamma_L|e^{-j\theta}\right|^2} \cdot \left(1 - |\Gamma_L|^2\right). \quad (6)$$

Eq. 6 is independent of the coupling factor. However, delivered power is a function of directivity of the coupler. Looking at Eq. 6, we conclude that for higher directivity, P_{out} is less sensitive to phase variations at fixed magnitude of the load reflection coefficient.

To illustrate how much impact directivity has on delivered power, we present two theoretical examples. In both cases we choose load VSWR to be 6:1. This corresponds to having $|\Gamma_L|$ approximately be 0.714. We set the available output power for matched load to be 21dBm. In one case, however, we chose directivity to be 15dB and in the other case 0dB. The resulting delivered power as a function of $\theta - \pi/2$ is shown in Fig. 3. The offset of $\pi/2$ was added to make it easier for the reader to see the main points of the plot.

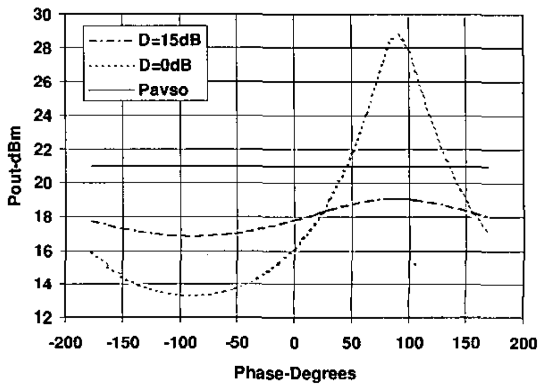

Fig. 3. Delivered power over phase when directivity is 15dB and 0dB as predicted by Eq. 6.

We observe that 15dB directivity can reduce the variation in the output power by over 13dB. This is quite significant.

Now, let us go back to Eq. 6. The maximum and minimum output power is seen when θ is equal to +/- 180°. For these two extreme cases we can rewrite Eq. 6 as

$$P_{\max} = P_{AVS0}\frac{1 - |\Gamma_L|^2}{\left(1 - \frac{|\Gamma_L|}{D}\right)^2} \quad (7)$$

$$P_{\min} = P_{AVS0} \frac{1 - |\Gamma_L|^2}{\left(1 + \frac{|\Gamma_L|}{D}\right)^2} \quad (8)$$

Eqs. 7 and 8 can be used to determine minimum directivity required to ensure that the output power falls into the acceptable power range as defined by the standard. For example if we assume that the nominal power transmitted by the PAM is set to +21dBm, the maximum power variation that is allowed according to the GSM standard is +/-4dBm. Therefore we can write

$$P_{AVS0} - \delta \le P_{out} \le P_{AVS0} + \delta \quad (9)$$

Where P_{AVS0}=+21dBm and δ=4dB. Substituting Eqs. 7 and 8 into Eq. 9 and solving for D we find

$$D \ge \frac{|\Gamma_L|}{\sqrt{\frac{1 - |\Gamma_L|^2}{10^{-\delta/10}}} - 1} \quad (10)$$

The graph for the function in Eq. 10 is plotted in Fig. 4.

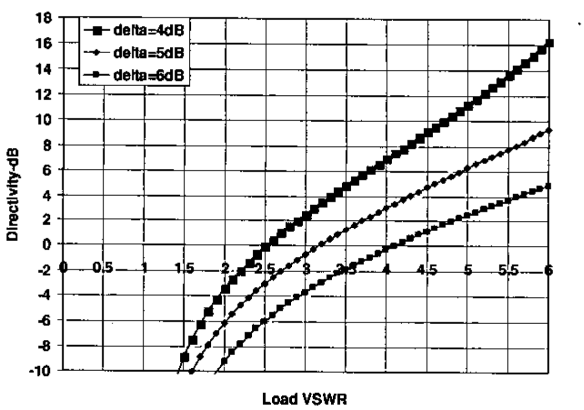

Fig. 4. Minimum directivity necessary to meet +/-4dB power variation as a function of the load VSWR.

According to the graph in Fig. 4, if we assume that the maximum VSWR seen by PAM is equal to 5:1 then the minimum directivity needed to meet the specification is equal to 11.3dB. If the directivity is less than that, the call may be dropped. As a reference, we also plotted Eq. 10 for δ=5dB and δ=6dB. These two values represent additional GSM standard tolerances for various power levels in the GSM900 and DCS1800 bands.

III. LOAD-PULL MEASUREMENTS

To verify the theoretical derivations presented in the previous section we have measured several PAMs using a load-pull system. The simplified block diagram of the system used in our measurements is shown in Fig. 5.

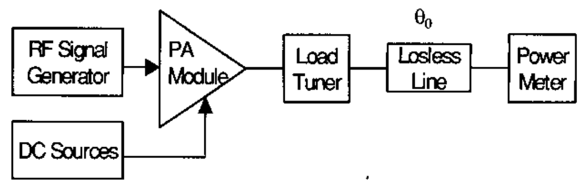

Fig. 5. Simplified block diagram of the load-pull setup.

θ_0 in Fig. 5 is the phase associated with the losless line that must be accounted for in the measurement data.

First, we characterized our module ADL5551. This module is the first to feature two integrated directional couplers and closed loop power control circuitry in a single package with two InGaP HBT power amplifier ICs. In these couplers we have achieved 30dB coupling and 14.3dB directivity. The cost savings of having integrated couplers as opposing to the use of external ones is approximately $0.17 per module.

We set the biasing to achieve 21dBm available power, and thus delivered power, in the matched load case. Higher values of power were not used to avoid saturation effects. At high values of VSWR, delivered power was a stronger function of phase. This is also predicted by Eq.6. Most of the handset manufacturers are interested in module performance for VSWR up to 6:1. Therefore, we chose this value to present our results. Fig. 6 shows measured and theoretical output power as a function $\theta + \theta_0$.

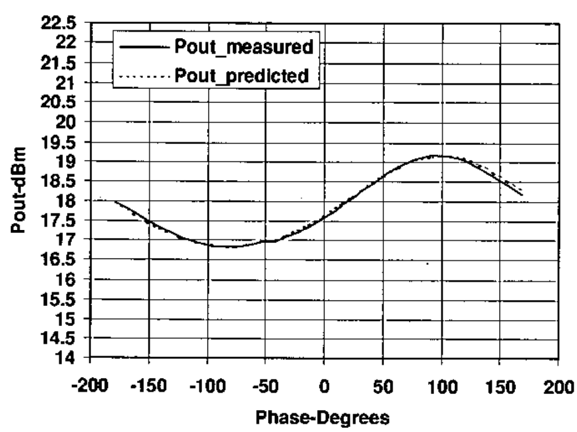

Fig. 6. Predicted versus measured results for our module with directional couplers; VSWR=6:1.

Here, θ_0 is approximately 79°. Also, we can see that high directivity of our couplers ensures a worst-case output power variation to be ±1.2dB. In addition, we observe that theoretical predictions agree very well with the measured results. The errors fall within the tolerances of the load-pull system as well as the slight imperfections in the power control circuitry.

Next, in Figs. 7 and 8, we present results from the two major competitor commercial modules. One is using open loop control, and one is using current sensing with low directivity.

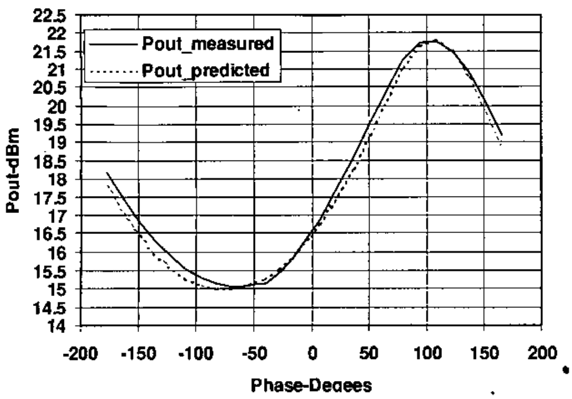

Fig. 7. Predicted versus measured results for module using open loop controller without integrated couplers; VSWR=6:1.

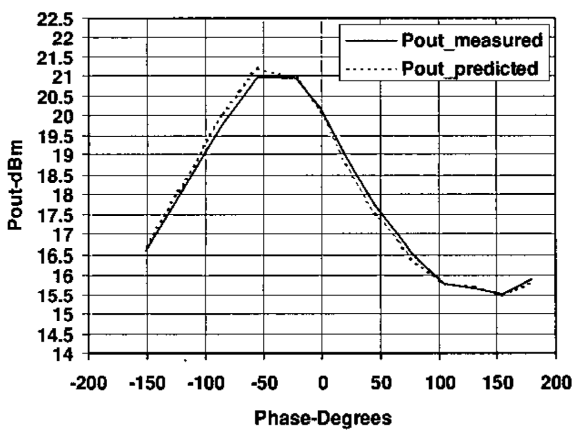

Fig. 8. Predicted versus measured results for module using current sensing; VSWR=6:1.

As we can see, competitor modules have output power variation that exceeds 6.5dB in Fig. 7, and 5.5dB in Fig. 8. both plots, phase is equal to $\theta + \theta_0$. For the measurement in Fig. 7 θ_0 was approximately 164° and for Fig. 8 θ_0 was approximately -137° . In the Fig. 7, we also plotted P_{out} calculated using Eq.6 with estimated directivity of 5.5dB. For Fig. 8 estimated directivity is 6.5dB.

V. Conclusion

In this paper we showed that it is necessary to utilize high directivity directional couplers in handset PA modules to achieve accurate power control over phase. For the load VSWR as high as 6:1 we demonstrated that 14.3dB directivity of the couplers reduces output power variation in our module by about 4dB compared to other major competitor modules.

Acknowledgement

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References

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