Dynamic Output Phase to Adaptively Improve the Linearity of Power Amplifier under Antenna Mismatch

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Abstract **— We present the development of a new adaptive circuit that preserves a power amplifier's (PA) performance under impedance mismatch caused at the antennas. The circuit includes a phase detector and a phase shifter that dynamically provide the optimal phase of the reflection coefficient at the output of the PA, to achieve the optimal performance under mismatch. Using this technique, the power amplifier maintains its performance close to that at 50Ω, even under severe mismatch of VSWR 10:1. A 900MHz CDMA GaAs power amplifier achieves an improvement of 6.4dB in IP3 and 6.9dB in the P_{1dB} in a high power mode (28.5dBm) at a VSWR of 10:1. The same PA in low power mode (18.6dBm) has improvement of 4.35dB in IP3 and 2.3dB in P_{1dB} at a VSWR of 10:1. A SiGe PA at 2.4GHz using the adaptive technique shows an improvement in IP3 by 5.8dB and in P_{1dB} by 4.5dB at a VSWR of 20:1.**

Index Terms **— Antenna mismatch, power amplifiers, linearity, adaptive phase.**

I. INTRODUCTION

Impedance mismatch at an antenna caused from the surrounding objects, especially metallic structures, significantly deteriorates the performance of a power amplifier and a wireless hand-held device. The antenna mismatch causes the RF power reflected back into the PA and reduces the power amplifier's linearity, RF output power and efficiency. The most severe effect is the degradation in the linearity due to clipping of large RF voltage swings [1].

One of the oldest techniques to deal with antenna mismatch is to use an isolator at the output of a PA. An isolator absorbs the reflected power and improves the linearity, but limits the transmitted power under mismatch. Furthermore, an isolator is bulky for hand-held devices. A popular technique being used today is to adaptively lower the drive level at the input of the PA so that the output voltage swing can be reduced under mismatch [1, 2]. This circuit includes a power detector and a feedback network to reduce the drive level under mismatch and avoid clipping of the RF output voltage. However, this technique significantly reduces the transmitted RF output power.

In this paper, we propose a new circuit technique to preserve the linearity while maintaining the RF output power of a PA under severe antenna mismatch. We have experimentally demonstrated that the RF performance of a PA is strongly dependent on phase of load. For each magnitude of a load mismatch (up to VSWR of 10:1), there is an optimal phase of the load reflection coefficient (at the output of the output matching network), at which the power amplifier maintains its performance close to that at VSWR of 1:1. Our adaptive circuit enables the output matching network to dynamically adjust to the optimal load reflection coefficient phase. Using our new adaptive circuit, a 900MHz CDMA GaAs power amplifier (P_{1dB} ~28.5dBm and IP3 ~34.5dBm at VSWR of 1:1) maintains P_{1dB} at ~24dBm and IP3 at ~32dBm, at mismatch of VSWR=10:1 and a 2.4GHz SiGe PA (P_{1dB} ~21dBm and IP3 ~31.5dBm at VSWR of 1:1) maintains P_{1dB} at 16.8dBm and IP3 at 28.5dBm, at mismatch of VSWR=10:1.

II. ANTENNA MISMATCH

The input impedance of the antenna in a wireless hand-held device such as a cellular phone is affected by surrounding objects in its close vicinity. Fig. 1 shows the output stage of the PA connected to load Z_L that will represent the changes of impedance due to antenna mismatch. The RF output power (P_{out}), transducer gain (G_T) and minimum peak collector voltage (V_{cmin}) of the PA is related to the load by the following equations [3]:

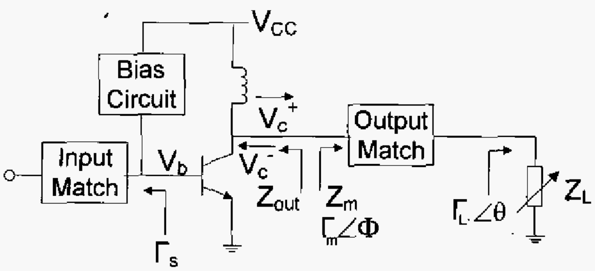

Fig. 1. Block diagram of a power amplifier output stage

$$P_{out} = \frac{1}{2}\frac{|V_c^+|^2}{Z_L}\left(1-|\Gamma_L|^2\right) \quad (1)$$

$$G_T = \frac{1-|\Gamma_S|^2}{|1-S_{11}\Gamma_S|^2} S_{21} \frac{1-|\Gamma_L|^2}{|1-S_{22}\Gamma_L|^2} \quad (2)$$

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$$V_{c\min} = V_{cc} - V_c^-\left(1+|\Gamma_m|e^{j\phi}\right) \qquad (3)$$

where $|\Gamma_m|$ and Φ are the magnitude and phase of the reflection coefficient at the input of output matching network.

When an antenna is near high reflection objects, the complex impedance Z_L will change and this alters the amplitude of the RF voltage at the collector as well as the collector load impedance Z_m. Hence, the RF output power delivered by the transistor and the transducer gain are significantly reduced as seen from equations (1) to (2). As the magnitude of Γ_m increases, the peak collector voltage (V_{cmin}) approaches V_{cesat} and causes distortion due to the clipping of collector voltage (3). This is the main cause for the degradation of linearity under severe antenna mismatch.

The effect of antenna mismatch on PA performance is experimentally analyzed on a commercially available CDMA GaAs PA at 900MHz in high power and low power modes; as well as on a SiGe PA at 2.4GHz. Table 1 summarizes the performance of these power amplifiers at 50Ω condition.

Table. 1. RF performance of PAs at 50Ω condition

Parameters	Units	CDMA GaAs PA		SiGe PA
		High	Low	
Frequency	MHz	900	900	2400
Supply Volt	V	3.4	1.6	3.3
P_{1dB}	dBm	28.5	18.6	21
IP3	dBm	34.5	24.7	31.5
Gain	dB	29	27.5	28.5
PAE	%	33.5	18.2	18.5

The RF performance of the GaAs PA measured at 900MHz, 3.4V supply voltage and a load (Z_L) mismatch magnitude of VSWR =10:1 at all phase angles is shown in Fig. 2. The load reflection coefficient Γ_L is varied using a Maury Microwave automatic impedance tuner. As seen in the figure, the P_{1dB}, G_T, PAE and IP3 vary with the phase (θ) of load reflection coefficient; the best P_{1dB} and IP3 occurring at θ=150° and the worst at θ=-90°. The P_{1dB} swings from 25dBm to 18.3dBm, IP3 varies by 6.5dBm, PAE varies from 12.8% to 4.7%, while G_T is around 24.5dBm. In low power mode, the GaAs PA follows a similar trend at VSWR=10:1 with P_{1dB} varying from 18.2dBm to 10.6dBm, IP3 swinging from 24dBm to 17.1Bm while PAE varies from 19% to 4.7%. The SiGe PA at 2.4GHz and 3.3V supply voltage has similar characteristics at VSWR=10:1, with the P_{1dB} varying from 18dBm to 13Bm; and IP3 swinging from 29dBm to 22.3dBm. However, in case of SiGe PA the gain also varies by 4dB with phase θ, while PAE is lower than 6.8% for all phases of the load reflection coefficient.

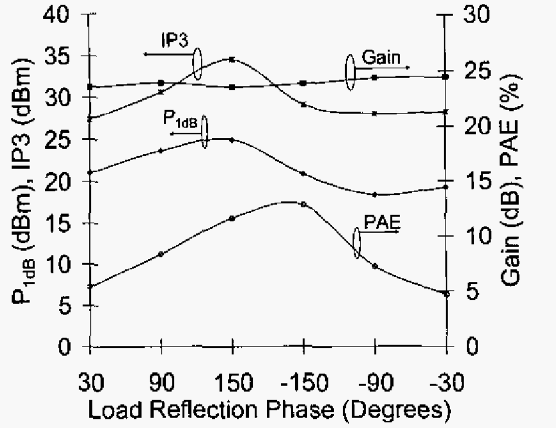

Fig. 2. Measured RF performance of the GaAs PA in high power mode at VSWR=10:1, 900MHz, 3.4V

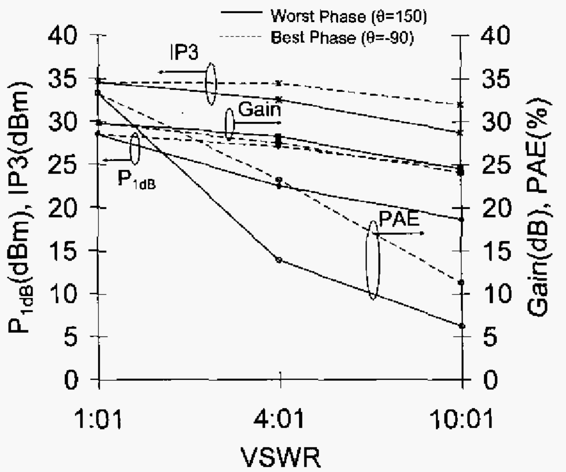

Fig. 3. Measured RF performance of the GaAs PA in high power mode with magnitude of mismatch, at best (θ=-90°) and worst (θ=150°) phases, 900MHz, 3.4V

Fig. 3 and Fig. 4 show the measured RF output power, transducer gain, PAE and IP3 of the GaAs PA (in high power mode) and the SiGe PA with varying VSWR (magnitude of Γ_L) at the worst phase condition and the best phase condition respectively. As the magnitude of mismatch increases, the RF output power, and IP3 at the worst phase condition drops rapidly for both the PAs, thereby severely degrading the linearity of the PA. However, at the best phase condition, the RF output power and IP3 remains close to that of the 50Ω condition. The transducer gain for GaAs PA is constant for both the best and worst phase conditions and the drop with mismatch is gradual. However, in case of SiGe PA, the G_T drops rapidly at worst phase condition and is close to that of the 50Ω condition at the best phase condition. The PAE for both the PAs reduces drastically with mismatch. The performance of GaAs PA in low power mode is similar to that of the high power mode.

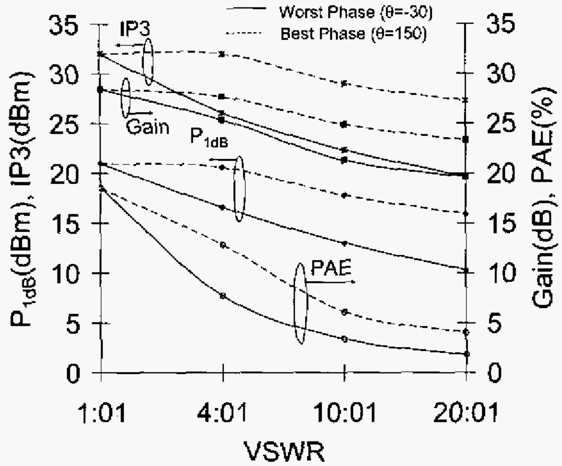

Fig. 4. Measured RF performance of the SiGe PA with magnitude of mismatch, at best (θ=150°) and worst (θ=-30°) phases, 2400MHz, 3.3V

III. LINEARITY IMPROVEMENT TECHNIQUE

Based on our analysis in section II, we propose a new adaptive circuit that dynamically adjusts the phase of the reflection coefficient at output of the PA (output of the output matching network) to an optimal, best phase condition, under antenna mismatch. The phase of the reflection coefficient can be adaptively tuned either by using an adaptive output matching network or a circuit with a phase shifter at the output of the PA. Fig. 5 shows the adaptive circuit which has a phase shifter incorporated into the PA module. The current phase (θ_{act}) of load reflection coefficient, Γ_L, is detected using a phase detector, which compares the phase of the load at the output of transistor to a reference phase and generates a control voltage proportional to the phase difference. This control voltage tunes the phase shifter, incorporated at the output of the PA to achieve the desired optimum performance. The phase shifter is tuned in such a way that the reflection coefficient phase (θ) at the output of the PA is optimum best value ($\theta=\theta_{opt}$) under all conditions. A variable analog phase shifter with transmission phase range from 0° to 180° provides the desired 0° to 360° reflection tuning range.

The experimental demonstration in this work uses a power amplifier, a double balanced mixer as the phase detector and a phase shifter; all controlled through a computer controlled system. The current phase (θ_{act}) of Γ_L is detected at the output of the phase shifter using the phase detector and it generates a DC voltage which is given through the computer controlled setup to the power supply controlling the analog phase shifter. The impedance tuner is used to generate the desired mismatch condition. In low power mode, the implementation uses a reflection type phase shifter consisting of varactor diodes and transmission line inductors. The phase shifter is designed to handle the required power as well as maintain high linearity, so that the distortion of the diodes does not affect the PA performance. The insertion loss of the phase shifters is less than 2dB over the entire control range. Fig. 6 shows the picture of the CDMA PA and reflection type phase shifter used in the low power mode.

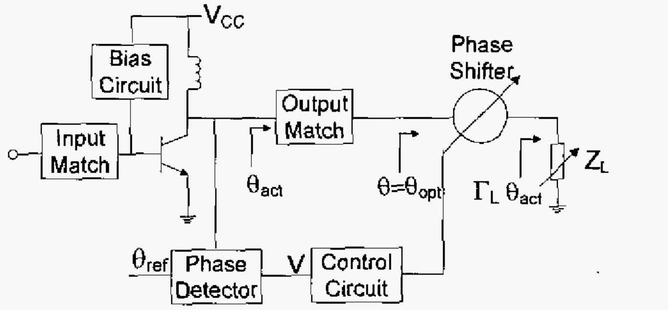

Fig. 5. Adaptive linearity improvement circuit

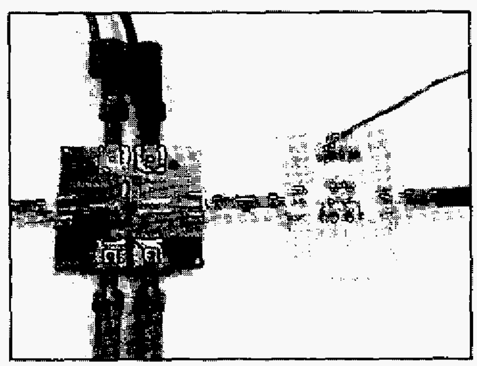

Fig. 6. Picture of CDMA GaAs PA and phase shifter used in the implementation of adaptive linearity improvement technique

IV. MEASURED RESULTS

The measured performance of the CDMA GaAs PA at 900MHz under mismatch of VSWR=10:1, by incorporating the adaptive linearity improvement circuit, is shown in Fig. 7 and Fig. 8 for high power and low power modes respectively. In the high power mode, the maximum increase in the RF output power (P_{1dB}) is 6.9dB, while the maximum increase in IP3 is 6.4dB. The P_{1dB} improves by a maximum of 2.3dB and the IP3 by a maximum of 4.3dB in the low power mode. The maximum increase in PAE is from 4.7% to 12.2% for both the modes. Fig. 9 shows the measured RF performance of the SiGe PA with the adaptive circuit. The maximum improvement in the RF output power (P_{1dB}) and IP3 is 4.5dB and 5.8dB respectively at a mismatch of VSWR=20:1.

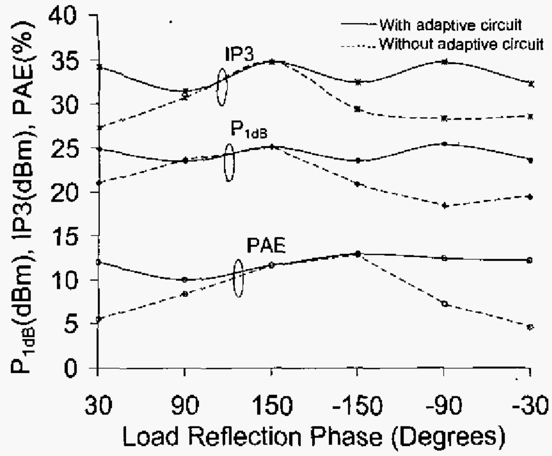

Fig. 7. Measured RF performance of the GaAs PA in high power mode with and without the adaptive circuit at VSWR=10:1

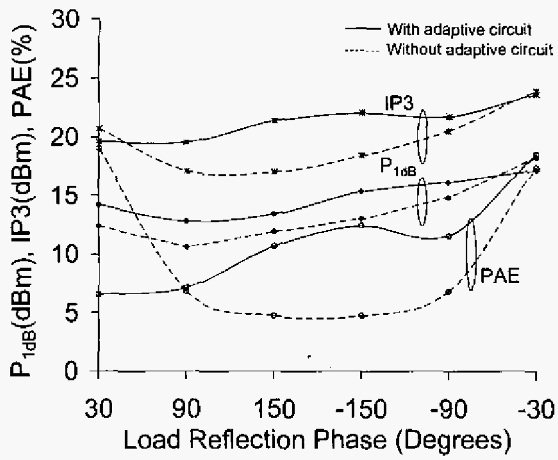

Fig. 8. Measured RF performance of the GaAs PA in low power mode with and without the adaptive circuit at VSWR=10:1

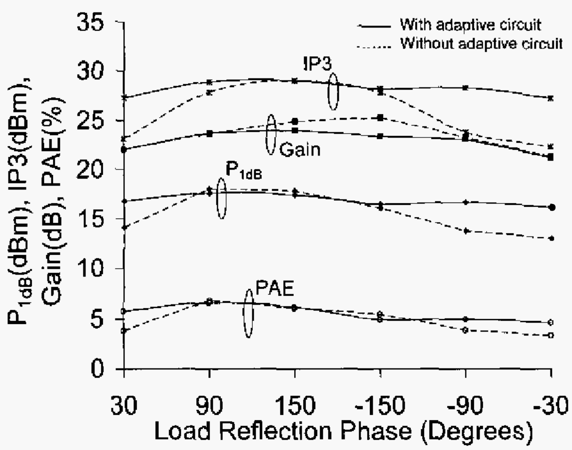

Fig. 9. Measured RF performance of the SiGe PA with and without the adaptive circuit at VSWR=10:1

The overall maximum improvement in the RF output power, linearity and efficiency for the GaAs and the SiGe PAs, under different mismatch conditions is summarized in table 2. As seen, there is a significant improvement in the linearity and RF output power of the PAs under antenna mismatch upto VSWR of 10:1.

Table. 2. Improvement in RF performance of PAs under different mismatch conditions

PA	VSWR	ΔP_{1dB} (dB)	ΔIP3 (dB)	ΔPAE (%)
GaAs PA: High Power	4:1	3.45	2.22	8.0
	10:1	6.9	6.4	7.5
GaAs PA: Low Power	*4:1*	*1.9*	*1.92*	*1.43*
	10:1	*2.3*	*4.35*	*7.5*
SiGe PA	4:1	3.6	3.87	1.9
	10:1	3.2	5.0	1.25
	20:1	4.5	5.8	1.4

At 50Ω condition, the degradation in the performance of the PAs due to addition of phase shifter is minimal and can be further improved by optimizing the matching network of the PA to account for the phase shifter.

V. Conclusion

A novel adaptive circuit technique to improve the linearity of the power amplifiers under antenna mismatch is proposed in this paper. The performance of the power amplifier under severe mismatches (upto VSWR of 10:1) stays close to that at 50Ω, at an optimum phase of the load reflection coefficient. The phase of the reflection coefficient at the output of the PA can be adaptively tuned to this optimal phase, either by using a circuit with a tunable phase shifter at the output of the PA or an adaptive output matching network. Significant improvements in the linearity of the GaAs and SiGe PAs are achieved by using the dynamic phase tuning technique.

Acknowledgement

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