

Optimum Design of a Predistortion RF Power Amplifier for Multicarrier WCDMA Applications

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Abstract—This paper provides a design guide for optimum design of an RF power amplifier with a predistortion linearizer. For a two-tone signal, three performance degradation factors, higher order terms, amplitude, and phase mismatches are analyzed quantitatively. The results are implemented to the design of optimized predistortion power amplifier for a WCDMA signal application. For the experiments, a 2.4-GHz class-AB power amplifier is fabricated using an LDMOSFET with a 30-W peak envelope power. A simple third-order predistorter is used to measure the relative phases of the harmonics, as well as to linearize the amplifier. The performance of the optimized predistortion power amplifier is excellent for a IS-95 code-division-multiple-access signal. Finally, a method for reducing the memory effects of the amplifier is devised to get a good cancellation performance for a wide-band signal, and the performance degradation caused by the memory effects is analyzed. For a forward-link four-carrier WCDMA signal, the predistortion power amplifier delivers an adjacent channel leakage ratio of -46 dBc at a 4-W average output power with a cancellation of 13.4 dB.

Index Terms—Adjacent channel leakage ratio (ACLR), intermodulation (IM), linearity, memory effects, predistorter, power amplifier, wide-band code division multiple access (WCDMA).

I. INTRODUCTION

IN CURRENT wireless communication systems such as IS-95 series, code division multiple access (CDMA)-2000, wide-band code division multiple access (WCDMA), etc., highly linear power amplifiers are in great demand. To meet the stringent requirement for linearity, various linearization techniques are adopted. Among the techniques, the feed-forward method provides extremely linear and broad-band characteristics. However, it is an expensive solution, consisting of auxiliary error amplifiers and complicated control circuits [1]–[7]. On the other hand, a feedback technique has decisive disadvantages of instability and bandwidth limitation [6]–[8]. Hence, a predistortion technique is preferred for linear power amplifiers due to simple structure and low cost [9]–[13]. Most analog predistorters have focused on reducing the third-order intermodulation (IM3) distortion components. Most provide

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a qualitative explanation of their operation principles with a two-tone signal. Therefore, we can neither predict its cancellation performance for WCDMA applications, nor judge whether it is an optimum design for WCDMA signals.

In this paper, we will discuss the effects of linearity degradation factors of a predistorter such as a higher order term, amplitude, and phase mismatches. Based on the data, we find the level to which a predistortion power amplifier can be maximally linearized with CDMA signals. For this purpose, a simple and general third-order predistorter is used. Instead of just adjusting the predistorter for the amplifier, we optimize the amplifier and predistorter as a pair. In order to verify our analyses, a predistortion power amplifier is implemented and tested using a IS-95 CDMA signal and a four-carrier WCDMA signal. The test results show superior performances.

II. TWO-TONE SIGNAL ANALYSIS FOR PERFORMANCE OF THIRD-ORDER PREDISTORTER

In this section, we find the permissible cancellation level of a third-order predistorter for a two-tone signal. For the analyses, the level of higher order intermodulation (IM) terms are evaluated and the permissible amplitude and phase errors for a given linearity target limited by the higher order term are derived.

A. Negligible Level of Higher Order IM Components

We assume that the fifth-order intermodulation (IM5) term is dominant among all higher order components and the amplifier is memoryless. The Taylor series expansion of input–output relations up to the fifth-order nonlinear terms can then be written as

$$y = a_0 + a_1 \cdot x + a_2 \cdot x^2 + a_3 \cdot x^3 + a_4 \cdot x^4 + a_5 \cdot x^5 \quad (1)$$

where a_0, \dots, a_5 are constants. If an equal-power two-tone input signal given by

$$x = A \cos(\omega_1 t) + A \cos(\omega_2 t) \quad (2)$$

is applied to the amplifier, the harmonics of the in-band output signal are expressed as

$$\text{FUND}_{\text{amp}} = A \cdot a_1 + \frac{9}{4} A^3 \cdot a_3 + \frac{25}{4} A^5 \cdot a_5 \quad (3)$$

$$\text{IM3}_{\text{amp}} = \frac{3}{4} A^3 \cdot a_3 + \frac{25}{8} A^5 \cdot a_5 \quad (4)$$

$$\text{IM5}_{\text{amp}} = \frac{5}{8} A^5 \cdot a_5 \quad (5)$$

We define IMD3_{amp} and IMD5_{amp} as amplitude ratios of IM3 and IM5 to the fundamental output signal, respectively, i.e.,

$$\begin{aligned} \text{IMD3}_{\text{amp}} &= \left| \frac{\text{IM3}_{\text{amp}}}{\text{FUND}_{\text{amp}}} \right| \\ &= \left| \frac{\frac{3}{4}A^3 \cdot a_3 + \frac{25}{8}A^5 \cdot a_5}{A \cdot a_1 + \frac{9}{4}A^3 \cdot a_3 + \frac{25}{4}A^5 \cdot a_5} \right| \end{aligned} \quad (6)$$

$$\begin{aligned} \text{IMD5}_{\text{amp}} &= \left| \frac{\text{IM5}_{\text{amp}}}{\text{FUND}_{\text{amp}}} \right| \\ &= \left| \frac{\frac{5}{8}A^5 \cdot a_5}{A \cdot a_1 + \frac{9}{4}A^3 \cdot a_3 + \frac{25}{4}A^5 \cdot a_5} \right|. \end{aligned} \quad (7)$$

At this point, we consider a third-order predistorter for the amplifier. In this case, the input signal of the amplifier may be changed as

$$\begin{aligned} x' &= A \cos(\omega_1 t) + A \cos(\omega_2 t) + B e^{j\phi_1} \cos(2\omega_1 - \omega_2) \\ &\quad + B e^{j\phi_2} \cos(2\omega_2 - \omega_1) \end{aligned} \quad (8)$$

where ϕ_1 and ϕ_2 indicate phases of lower and upper IM3 (IM3L and IM3H, respectively) created by the predistorter for cancelling the IM3 terms generated by the amplifier, respectively, and B is the amplitude of the predistorter IM3 components represented as

$$B = \left| \frac{\frac{3}{4}A^3 \cdot a_3 + \frac{25}{8}A^5 \cdot a_5}{a_1 + \frac{9}{4}A^2 \cdot a_3 + \frac{25}{4}A^4 \cdot a_5} \right| \quad (9)$$

where the denominator is the gain of the amplifier.

If the proper ϕ_1 , ϕ_2 , and B are selected, the IM3 components of the amplifier will be perfectly cancelled out. However, additional IM5 components are generated at the output due to nonlinearities of the amplifier. Fig. 1 shows the generation process. Since the additional lower and upper IM5s (IM5L and IM5H, respectively) are created by the same mechanism, we consider IM5L only. The terms can be easily extracted using (1) and (8) and the resulting total IM5L, i.e., $\text{IM5L}_{\text{PD+amp}}$, is given by

$$\begin{aligned} \text{IM5L}_{\text{PD+amp}} &= \frac{3}{4} \left[A(B e^{j\phi_1})^2 + A^2(B e^{j\phi_2}) \right] \cdot a_3 \\ &\quad + \left[\frac{5}{4} \left\{ A(B e^{j\phi_1})^4 + A^4(B e^{j\phi_2}) \right\} + \frac{15}{8} \right. \\ &\quad \left. \cdot \left\{ A^3(B e^{j\phi_1})^2 + A^2(B e^{j\phi_2})^3 \right\} + \frac{5}{8}A^5 \right] \\ &\quad \cdot a_5. \end{aligned} \quad (10)$$

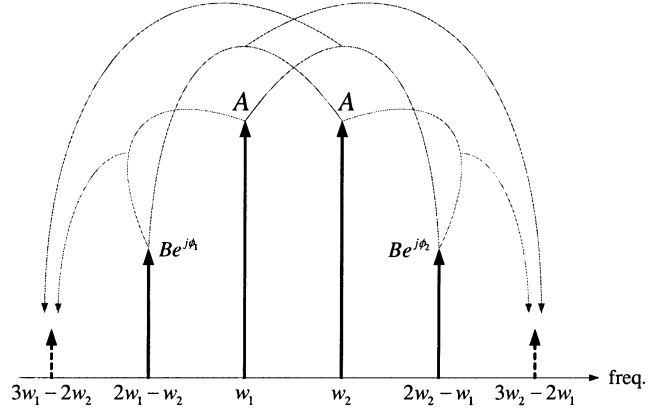


Fig. 1. Generation mechanism of additional IM5 terms when IM3 components are applied to the amplifier.

Again, we define $\text{IMD5}_{\text{PD+amp}}$ as the amplitude ratio of $\text{IM5L}_{\text{PD+amp}}$ in (10) to FUND_{amp} in (3), and normalize A to unity. See (11), shown at the bottom of this page, where β is the normalized value of B .

Next, a_1 , a_3 , and β can be represented as functions of a_5 , IMD3_{amp} , and IMD5_{amp} . The resultant equations are

$$\beta = \Delta_3 \quad (12)$$

$$a_1 = \left(\frac{5}{8} \frac{1}{\Delta_5} + \frac{25}{8} + \frac{15}{8} \frac{\Delta_3}{\Delta_5} \right) \cdot a_5 \quad (13)$$

$$a_3 = - \left(\frac{25}{6} + \frac{5}{6} \frac{\Delta_3}{\Delta_5} \right) \cdot a_5 \quad (14)$$

where Δ_3 and Δ_5 indicate IMD3_{amp} and IMD5_{amp} , respectively. For (12)–(14), we assume that a_1 and a_5 are positive constants, while a_3 is a negative constant. Substituting (12)–(14) into (11), it becomes

$$\begin{aligned} \text{IMD5}_{\text{PD+amp}} &= \left| \Delta_5 (1 - 3e^{j\phi_2} \Delta_3 - 2e^{j2\phi_1} \Delta_3^2 + 3e^{j3\phi_2} \Delta_3^3 \right. \\ &\quad \left. + 2e^{j4\phi_1} \Delta_3^4) - \Delta_3^2 (e^{j\phi_2} + e^{j2\phi_1} \Delta_3) \right|. \end{aligned} \quad (15)$$

If ϕ_1 and ϕ_2 are adjusted to 90° and 180° , respectively, which is the conditions for maximum $\text{IMD5}_{\text{PD+amp}}$, (15) becomes

$$\text{IMD5}_{\text{max}} \cong \Delta_5 (1 + 3\Delta_3 + 2\Delta_3^2) + \Delta_3^2 (1 + \Delta_3) \quad (16)$$

or

$$\begin{aligned} \text{IMD5}_{\text{max}}(\text{dBc}) &\cong 20 \log \left[10^{(\delta_5/20)} \left(1 + 3 \cdot 10^{(\delta_3/20)} + 2 \cdot 10^{(\delta_3/10)} \right) \right. \\ &\quad \left. + 10^{(\delta_3/10)} \left(1 + 10^{(\delta_3/20)} \right) \right] \end{aligned} \quad (17)$$

$$\begin{aligned} \text{IMD5}_{\text{PD+amp}} &= \left| \frac{\text{IM3L}_{\text{PD+amp}}}{\text{FUND}_{\text{amp}}} \right| \\ &= \left| \frac{\frac{3}{4} \left[(\beta e^{j\phi_1})^2 + (\beta e^{j\phi_2}) \right] \cdot a_3 + \left[\frac{5}{4} \left\{ (\beta e^{j\phi_1})^4 + (\beta e^{j\phi_2}) \right\} + \frac{15}{8} \left\{ (\beta e^{j\phi_1})^2 + (\beta e^{j\phi_2})^3 \right\} + \frac{5}{8} \right] \cdot a_5}{a_1 + \frac{9}{4}a_3 + \frac{25}{4}a_5} \right| \end{aligned} \quad (11)$$

where

$$\begin{aligned}\delta_3 &= 20 \log(\Delta_3) = 20 \log(\text{IMD}_{3\text{amp}}) \\ \delta_5 &= 20 \log(\Delta_5) = 20 \log(\text{IMD}_{5\text{amp}})\end{aligned}$$

which have negative signs.

Note that (17) defines the achievable maximum linearity target limited by the IM5 level, when only a third-order predistorter is used.

B. Amplitude Error Criterion for IM3 Components

For a predistorter with amplitude error ΔB , but with perfect phase match, the residual third-order intermodulation distortion (IMD3) at the output of amplifier due to the amplitude mismatch can be represented as

$$\text{IMD}_{3\Delta B} = \left| \frac{G \cdot \Delta B}{\text{FUND}_{\text{amp}}} \right| = \left| \frac{\Delta B}{A} \right| \quad (18)$$

where G is the gain of the amplifier.

For a linearity target of τ dBc, but less than the limitation given by (17), the permissible range of amplitude mismatch is given by

$$\left| \frac{\Delta B}{A} \right| \leq 10^{(\tau/20)}. \quad (19)$$

Substituting (6) and (9) into (19), we have

$$|\Delta B| \leq 10^{(\tau/20)} A = \frac{10^{(\tau/20)}}{\text{IMD}_{3\text{amp}}} B = 10^{((\tau-\delta_3)/20)} B. \quad (20)$$

Next, we define the amplitude error ratio E_A as a ratio of a predistorter $\text{IM3}(B + \Delta B)$ amplitude to the desirable IM3 level (B) for the amplifier, i.e.,

$$E_A = \frac{B + \Delta B}{B} = 1 + \frac{\Delta B}{B}. \quad (21)$$

From (20),

$$1 - 10^{((\tau-\delta_3)/20)} \leq E_A \leq 1 + 10^{((\tau-\delta_3)/20)} \quad (22)$$

or, in decibels,

$$\begin{aligned}20 \log \left[1 - 10^{((\tau-\delta_3)/20)} \right] &\leq E_A(\text{dB}) \\ &\leq 20 \log \left[1 + 10^{((\tau-\delta_3)/20)} \right]\end{aligned} \quad (23)$$

where $\delta_3 > \tau$.

Note that E_A (or $E_A(\text{dB})$) is very useful to determine the allowable amplitude error range of the predistorter because it is related only to the IMD3 levels. If $\tau = -50$ dBc and $\delta_3 = -40$ dBc, for example, an amplitude error in the range of $-3.3 \text{ dB} \leq E_A \leq 2.4 \text{ dB}$ is acceptable with the proper phase. Inequality (23) is plotted in Fig. 2, where the horizontal axis indicates IMD3s of the amplifier and vertical axis displays' allowable amplitude error limits for several linearity targets. From this figure, we can confirm that a stringent linearity target requires tighter amplitude tolerance.

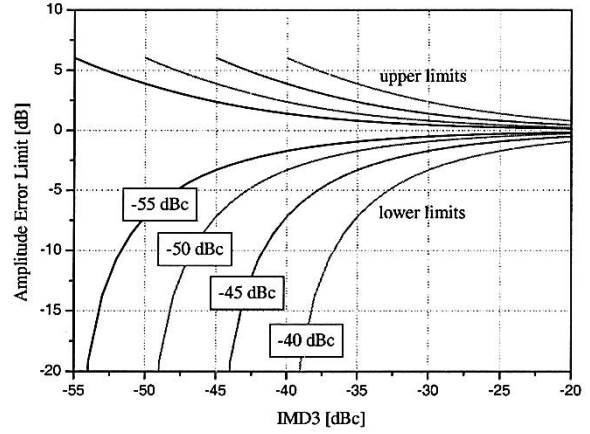


Fig. 2. Allowable amplitude error limits of a predistorter when a linearity target is given.

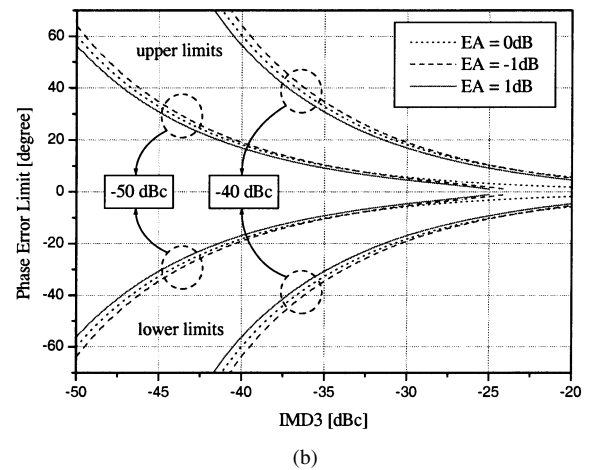
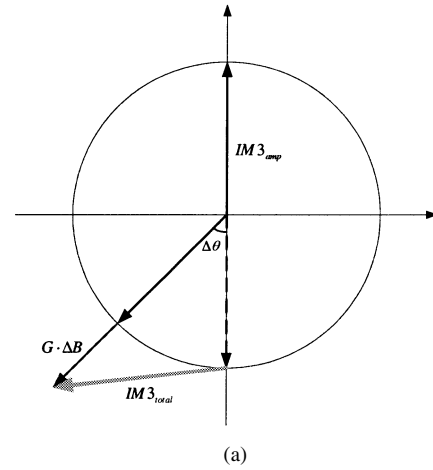


Fig. 3. (a) Vector diagram for evaluating IM3 deviation due to amplitude and phase errors. (b) Allowable phase-error limits for given amplitude errors and linearity targets.

C. Phase-Error Criterion for IM3 Components

Fig. 3(a) shows the vector diagram for evaluating the residual IMD3 due to a phase error for a given amplitude mismatch. The total IM3 created by the amplitude and phase mismatches can be calculated using a law of cosine, as shown in (24), at the bottom of the following page, where $\Delta\theta$ represents the phase error. For an arbitrary linearity target, τ in dBc, we can obtain

an inequality represented as (25), shown at the bottom of this page, which can be simplified as follows:

$$4E_A(\text{IMD3}_{\text{amp}})^2 \sin^2\left(\frac{\Delta\theta}{2}\right) + (\text{IMD3}_{\text{amp}})^2 (E_A - 1)^2 \leq 10^{(\tau/10)}. \quad (26)$$

From inequality (26), we can find the range for the allowable phase error as follows:

$$|\Delta\theta| \leq 2 \sin^{-1} \left[\frac{1}{2} \sqrt{\frac{10^{(\tau/10)} - (\text{IMD3}_{\text{amp}})^2 (E_A - 1)^2}{E_A (\text{IMD3}_{\text{amp}})^2}} \right] \quad (27)$$

or, in a more practical form,

$$|\Delta\theta| \leq 2 \sin^{-1} \left[\frac{1}{2} \sqrt{10^{\frac{(2\tau - 2\delta_3 - E_A(\text{dB}))}{20}} - 2 \left(\cosh \frac{E_A(\text{dB})}{20} - 1 \right)} \right]. \quad (28)$$

If $\tau = -50$ dBc, $\delta_3 = -40$ dBc, and $E_A(\text{dB}) = 1$ dB, for example, a phase error less than 16.9° is acceptable.

Fig. 3(b) shows the plotted version of inequality (26), where the vertical axis displays allowable phase-error limits for given amplitude errors and linearity targets. From this figure, we can obtain some information. First, an amplitude error restricts the cancellation performance of the predistorter. For an amplitude error of 1 dB, IMD3 of the amplifier should be better than -25 dBc in order to satisfy -50 -dBc linearity target. Second, a negative amplitude error is more tolerant than the positive amplitude error, increasing the allowable phase-error range. This fact will be confirmed in Sections II-D and IV-B.

D. Optimum Predistorter Amplitude With a Given Phase Error

No phase error between the predistorter and amplifier is the best, regardless of any amplitude errors. However, we may be confronted with inevitable phase errors. For a given phase error due to the mismatch between the predistorter and amplifier,

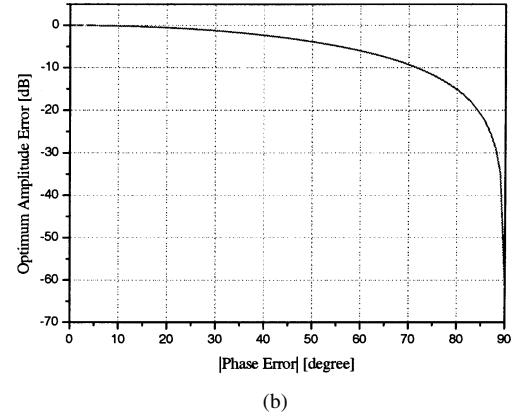
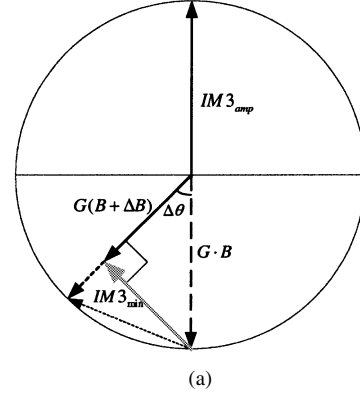


Fig. 4. Minimizing IM3 by amplitude error when a phase error exists. (a) Vector diagram for evaluation. (b) Optimum amplitude error.

IMD3 of the amplifier is minimized with some amplitude error and the condition is analyzed quantitatively using Fig. 4(a). The condition for the minimum IM3 (IM3_{min}) is given by

$$G(B + \Delta B) = G \cdot B \cos(\Delta\theta), \quad |\Delta\theta| \leq 90^\circ. \quad (29)$$

Substituting (21) into (29) and rearranging it, we have

$$E_{A,\text{opt}} = \cos(\Delta\theta)$$

or, in decibels,

$$E_{A,\text{opt}}(\text{dB}) = 20 \log [\cos(\Delta\theta)]. \quad (30)$$

$$\begin{aligned} |\text{IM3}_{\text{total}}| &= \sqrt{|\text{IM3}_{\text{amp}}|^2 + (|\text{IM3}_{\text{amp}}| + G \cdot \Delta B)^2 - 2|\text{IM3}_{\text{amp}}| (|\text{IM3}_{\text{amp}}| + G \cdot \Delta B) \cos(\Delta\theta)} \\ &= \sqrt{4|\text{IM3}_{\text{amp}}|^2 \sin^2\left(\frac{\Delta\theta}{2}\right) + 4G \cdot \Delta B |\text{IM3}_{\text{amp}}| \sin^2\left(\frac{\Delta\theta}{2}\right) + G^2(\Delta B)^2} \end{aligned} \quad (24)$$

$$\text{IMD3}_{\text{total}} = \left| \frac{\text{IM3}_{\text{total}}}{\text{FUND}_{\text{amp}}} \right| = \frac{\sqrt{4|\text{IM3}_{\text{amp}}|^2 \sin^2\left(\frac{\Delta\theta}{2}\right) + 4G \cdot \Delta B |\text{IM3}_{\text{amp}}| \sin^2\left(\frac{\Delta\theta}{2}\right) + G^2(\Delta B)^2}}{\text{FUND}_{\text{amp}}} \leq 10^{(\tau/20)} \quad (25)$$

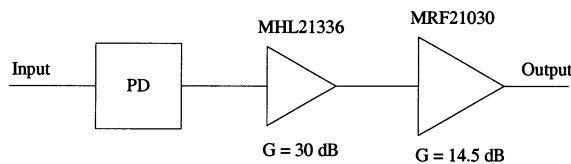


Fig. 5. Lineup of the predistortion power amplifier.

This equation is plotted in Fig. 4(b). If there is 30° of phase error, for example, IMD3 of the amplifier can be minimized by matching the IM3 magnitude of the predistorter by -1.5 dB.

Inversely, (30) means that a negative amplitude error can increase a permissible phase-error range. This fact was mentioned in the previous section and will be visualized in more detail in Section IV-B. For a given linearity target, of course, $E_{A,opt}$ (dB) and $\Delta\theta$ have to meet the relationship given in inequality (28).

III. OPTIMUM DESIGN OF A PREDISTORTION POWER AMPLIFIER

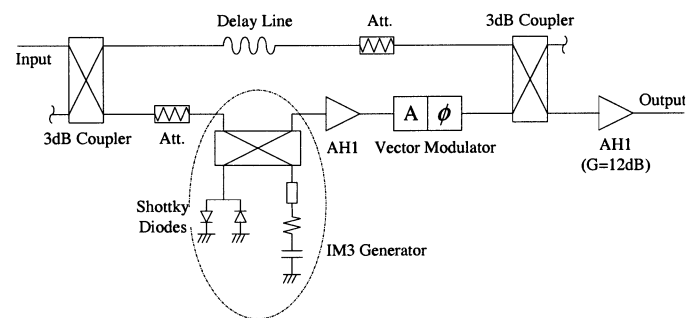
In Section II, we have analyzed the allowable error level for IM components of the predistorter. To design a predistortion power amplifier with a high performance, the predistorter and amplifier should be designed as a pair to meet the allowable error level criterion for a given linearity target throughout the swept power range. Here, we design a narrow-band predistortion amplifier with tone spacing of 1 MHz to exclude memory effects [14]–[16]. The memory effects are treated in Section IV due to their importance. Fig. 5 shows the amplifier lineup for this study, configured to generate a 4-W average output power for a CDMA signal with a high peak-to-average ratio (in this experiment, an IS-95 signal).

A. Implementation of a Third-Order Predistorter

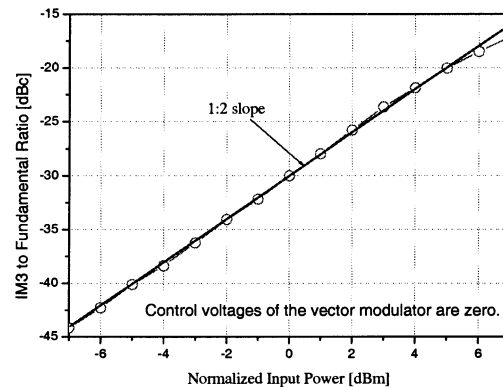
Fig. 6(a) shows the circuit diagram of the third-order predistorter used in this experiment. A two-tone input signal is divided into the signal and the IM3 generation paths by a 3-dB coupler. At the IM3 generation path (lower path), the two-tone signal is attenuated and applied to the IM3 generator, which creates the IM3 component using Shottky diodes (Hewlett-Packard's HSMS2850). Although the IM3 generator has a simple structure, it can effectively cancel the fundamental signal by selecting a proper length of the transmission line, resistor, and capacitor [13]. In this experiment, electrical length of 0.12λ , $1\text{-}\Omega$ resistor, and 2.7-pF capacitor have been used. After the generated IM3 components are amplified, their amplitudes and phases are controlled by the vector modulator consisting of a variable attenuator and phase shifter. These controlled IM3 components are combined with a fundamental two-tone signal by a 3-dB coupler. Finally, the combined signals are amplified and supplied at the power amplifier stage. Fig. 6(b) shows the measured IMD3 at the output of the predistorter with zero applied voltage at the vector modulator. It shows that IMD3 has a 2-dBc/dBm slope for the power normalized to the input power of the amplifier. The phase of the IM3 will be discussed in Section III-B.

B. Optimum Design of Predistortion Amplifier and Test Results

Fig. 7 shows a schematic diagram of the amplifier used for this experiment. The power amplifier was designed using Mo-



(a)



(b)

Fig. 6. (a) Circuit diagram and (b) measured IM3 characteristic of the third-order predistorter.

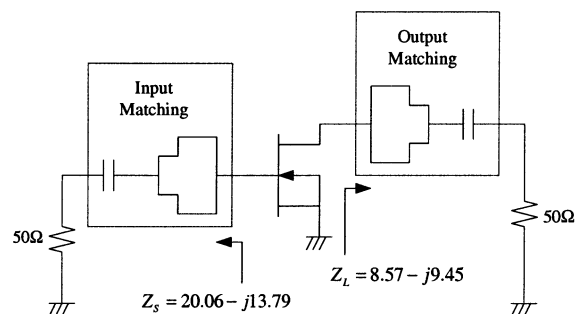


Fig. 7. Schematic diagram of the class-AB amplifier.

torola's MRF21030 LDMOSFET with a 30-W peak envelope power (PEP) operated at $I_{DQ} = 280$ mA and $V_{DD} = 28$ V and an MHL21336 driver. All circuits were implemented with RF35 ($\epsilon_r = 3.5$, $h = 0.5$ mm) circuit boards at 2.14-GHz center frequency. The implemented amplifier has output power of 44.1 dBm for 1-dB gain compression. To optimize the predistortion power amplifier for the CDMA signal using two-tone IMD3 data, we assume that instantaneous powers of the CDMA signal are mostly within the 15-dB range (from -8 to $+7$ dB from the average power). It is roughly equivalent to the 9-dB range (from -5 to $+4$ dB) sweep since a two-tone signal has basically 3-dB peak-to-average power ratio (PAR). As a result, the amplitude and phase of the predistorter should follow the IM3 of the amplifier according to the power levels and the variations within inequalities of (23) and (28).

If there is phase error $\Delta\theta$ between IM3s of the predistorter and amplifier, E_A of the predistorter should be given by (30) for an optimum design of the predistortion power amplifier. Since

IMD3 is generally worse at a high power level than at a lower power level, the permissible amplitude and phase errors given by inequalities of (23) and (28) must be smaller at a high power level. Thus, the predistorter must be adjusted at a high power level by control voltages of the vector modulator. These considerations provide information for the optimum design of the predistortion power amplifier.

For a two-tone signal, the measured IM characteristics are represented in Fig. 8. Fig. 8(a) shows the fifth-order intermodulation distortion (IMD5) characteristics of the amplifier and those of the worst case calculated with (17). Our linearity target for the CDMA signal is limited to an adjacent channel leakage ratio (ACLR) of -48.3 dBc due to the effect of IM5. Fig. 8(b) and (c) shows IMD3 and the phase error according to power levels, respectively, where IMD3L and IMD3H are almost equal, indicating that there are no significant memory effects. The phase error according to the power levels has been measured relatively using the predistorter [15]. Due to the procedure, we do not need to know the absolute phase information for the predistorter and amplifier. In Fig. 8(b), the straight line with the slope of 2 dBc/dBm is the approximated IMD3 characteristic of the implemented predistorter, and the line with the star symbols indicates the optimal IMD3 curve of the amplifier for the predistorter with the phase error represented in Fig. 8(c). In this experiment, the two lines are quite similar because the phase error is small. The IMD3 generated by the amplifier has a similar slope to optimum IMD3 at a high power level, but IMD3 is deviated slightly upward from it at a low power level. Since a wider range of amplitude error is tolerable at a low power, these characteristics are acceptable. Therefore, we have designed a near-perfect amplitude compensation predistorter. The permissible amplitude and phase-error limits of the predistorter for linearity target of -48.3 dBc have also been plotted in Fig. 8(b) and (c) using the inequalities of (23) and (28).

Since both the amplitude and phase errors caused by the predistorter are within permissible ranges, we can expect the linearity of at least -48.3 dBc for this narrow-band predistortion amplifier. Fig. 9 shows the linearized spectrum for the IS-95 CDMA signal at a 4 -W average output power. As expected, the predistortion power amplifier displays a -48.4 -dBc ACLR at a 885 -kHz offset with a 14 -dB cancellation performance. If the amplitude and/or phase errors exceed the limits, it is advised that the vector modulator in the predistorter should be adaptively controlled to satisfy the limits. Otherwise, the linearity will be degraded.

IV. PERFORMANCE DEGRADATION BY MEMORY EFFECTS

In Section III, we have treated a narrow-band amplifier without memory effects. For a signal with a wide bandwidth, such as a multicarrier WCDMA signal, however, we should consider additional nonlinear effects caused by electrical memory effects, which degrade the performance of the predistorter. For the experiment, we tried to reduce the memory effects of amplifier and then quantitatively analyze it for performance degradation caused by the effects.

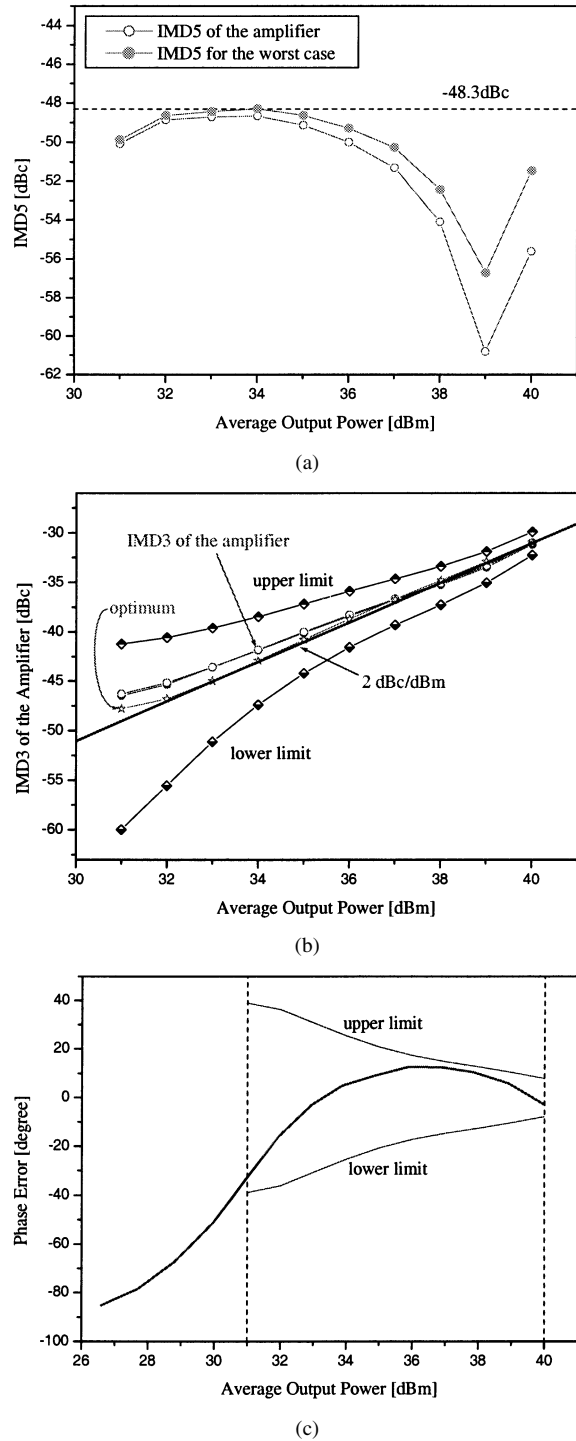


Fig. 8. Two-tone IM characteristics of the amplifier according to the power levels. (a) IMD5. (b) IMD3. (c) Phase error of IMD3.

A. Reduction of Memory Effects

Memory effects are introduced by changes in the instantaneous bandwidth of an input signal. For the case of a four-carrier WCDMA signal, the bandwidth extends up to 20 MHz. In other words, the envelope frequency of the signal covers up to 20 MHz. If input and output impedances at the envelope frequencies are not zero or a constant value, the envelope signal will see the different impedances and memory effects are created [15]. Thus, we have tried to create a short circuit across the

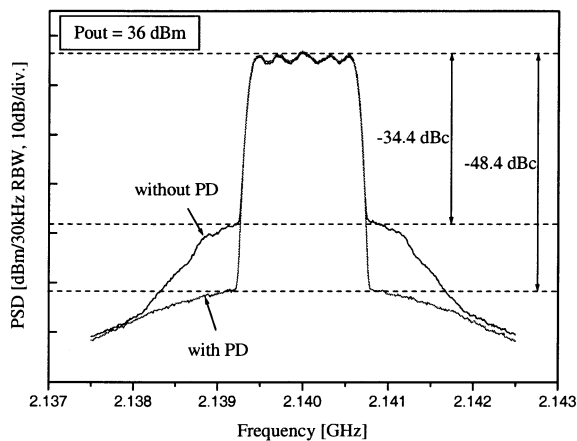


Fig. 9. Linearized spectrum for an IS-95 CDMA signal at 36 dBm.

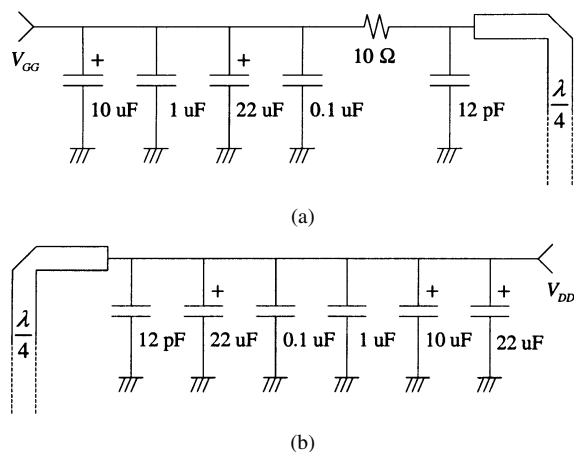


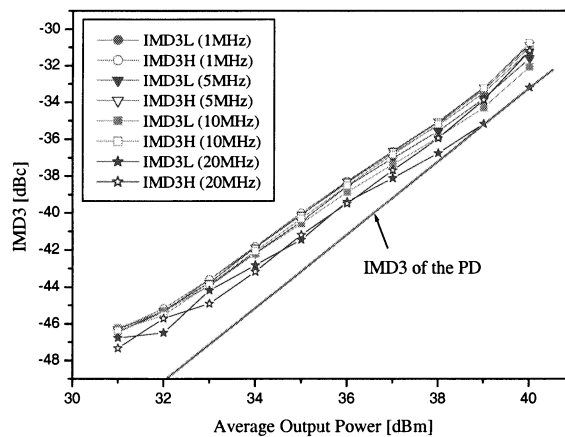
Fig. 10. Bias circuits for reduction of memory effects. (a) Gate and (b) drain bias circuits.

bandwidth by adding several capacitors in parallel on the gate and drain bias lines, as shown in Fig. 10 [16].

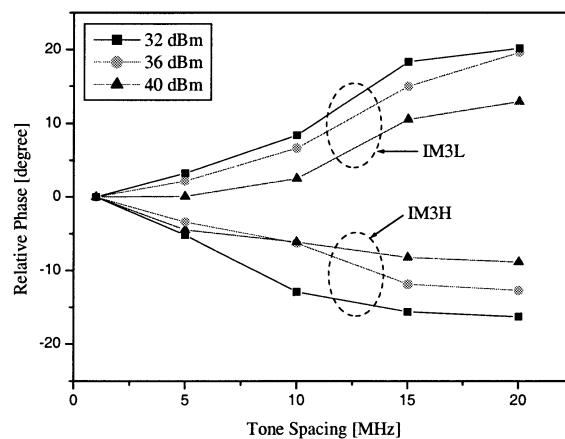
To find IM3 responses with memory effects, we have employed a two-tone test signal with varying tone spacing. Fig. 11 shows the IM3 characteristics of the amplifier according to tone spacing. Throughout the total power ranges considered in this paper, amplitude deviations caused by different tone spacings are less than 2 dB, as shown in Fig. 11(a). Fig. 11(b) shows the phase deviations for several power levels including the average power level (36 dBm), which have been measured relatively to the predistorter phase. The phase differences between the two third harmonics for 20 MHz spacing reach approximately 21.7° and 36.5° for 32- and 40-dBm output powers. Those are the minimum and maximum values within the swept power range.

B. Quantitative Analysis and Test Results for the Performance Degradation

Here, we have calculated the performance degradation caused by the memory effects. The suitable position of the IMD3 curve of the predistorter should be selected using inequality (28). For this purpose, inequality (28) is plotted in Fig. 12 as a function of IMD3 of the amplifier for several values of E_A and $\tau = -48.3$ dBc. For the IMD3 range we are considering, the



(a)



(b)

Fig. 11. Measured IM3 characteristics of the amplifier according to tone spacings. (a) IMD3. (b) Phases.

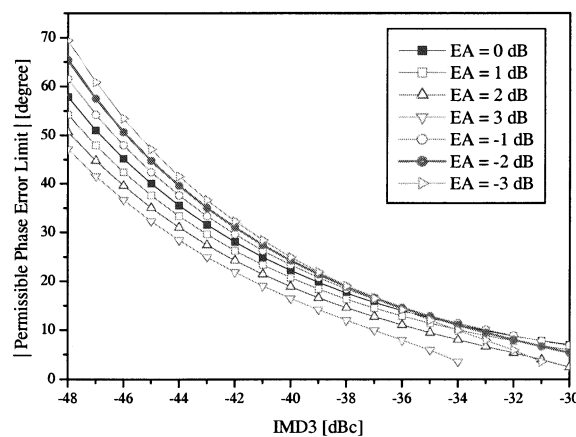


Fig. 12. Permissible phase-error limit represented as function of IMD3 of the amplifier for several values of E_A and $\tau = -48.3$ dBc.

deviation of $-2-0$ dB is nearly optimum, providing the wider permissible phase-error range than the normally considered deviation range of $-1-1$ dB. These trends have already been predicted in Section II. For optimum operation, the predistorter is adjusted to have the worst case amplitude deviation of -2 dB at 40-dBm output power, as shown in Fig. 11(a). The amplitude errors are applied to inequality (28) to extract the permissible phase-error values according to the power levels. From the data,

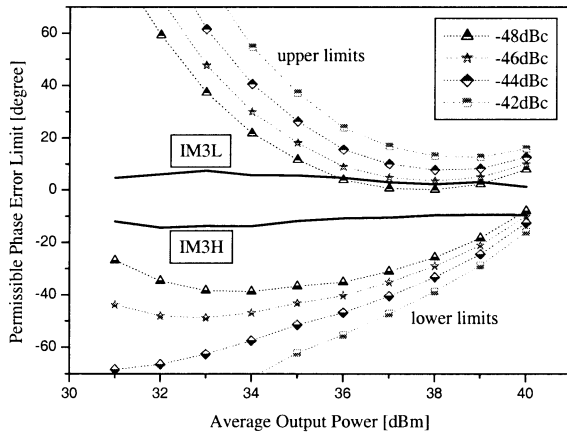


Fig. 13. Permissible range for the phase error caused by memory effects.

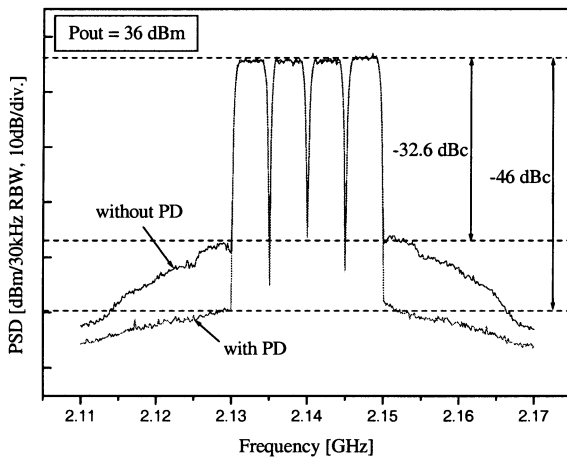


Fig. 14. Linearized spectrum for a four-carrier WCDMA signal at 36 dBm.

the permissible range for the phase errors caused by the memory effects for different linearity targets are depicted in Fig. 13.

To predict an accurate linearity of the amplifier for a four-carrier WCDMA signal, we must know the IM characteristic according to the signal power distribution with the instantaneous bandwidth. In fact, the occurrence rate of IM3 terms at the larger offset frequency is lower than that at a smaller offset frequency. The tone spacings that should be considered are different according to the respective offset positions. For example, the IM3 term on a 5-MHz offset frequency from the center frequency of the closing WCDMA carrier is affected by tone spacings between 2.5–11.25 MHz. On the other hand, the IM3 term on a 22.5-MHz offset frequency is affected by 20-MHz tone spacing only.

Since our purpose is to predict linearity for a WCDMA signal with simple two-tone tests, we have assumed that the probability distribution function (pdf) of the signal according to the instantaneous bandwidth is uniform and the occurrence rate of IM3 is still different according to offset frequencies, and lower at a high offset frequency. To accommodate the behavior, we have applied average values of the phase errors caused by memory effects for all offset frequencies.

The average phase errors for IM3L and IM3H caused by different tone spacings are also shown in Fig. 13 (solid lines). The

curves are the averaged phase errors of 1-, 5-, 10-, 15-, and 20-MHz tone spacings in Fig. 11(b). We have experienced less memory effects at a high power level where a tighter permissible phase error is required. For a desired linearity target, the average phase curves should be within the permissible range of phase errors caused by memory effects. By adjusting the vector modulator, the average phase-error curves for IM3L and IM3H in this figure are shifted 4° downward for better cancellation. The permissible phase-error range shown in this figure indicates that the linearity of -46 dBc can be achievable. Fig. 14 shows the measured power spectral densities of the amplifier with/without a predistortion linearizer (PD) at an average output power of 36 dBm for a four-carrier WCDMA signal. As expected, the amplifier was linearized to below -46 dBc for an offset frequency over 5 MHz by the predistorter, which is a cancellation of 13.4 dB at 5-MHz offset. The drain efficiency of the amplifier is 17.2% at the average output power.

V. CONCLUSIONS

For a linear RF power amplifier with a third-order predistorter, we have analyzed the three basic performance degradation factors using a two-tone signal. The factors include the IMD5 level of the amplifier, and the amplitude and phase errors for the IM3 terms. The IMD5 level limits linearization performance. We have quantitatively derived the allowable amplitude error without any phase error, the permissible phase-error range with a given amplitude error, and the optimum amplitude error for a given phase error.

To validate the analyses experimentally, we have implemented a simple predistorter and power amplifier at 2.14 GHz using Motorola's MRF21030 LDMOSFET with a 30-W PEP. For CDMA applications, a two-tone signal response has been swept for several power levels near the average output power. To satisfy the permissible error levels for predistortion according to the power levels, we have optimized the amplifier as well as the predistorter.

For a IS-95 CDMA signal with a large PAR, we have presented the method for optimum design of a power amplifier with the general third-order predistorter. As a result of the optimum design, the predistortive amplifier has showed an ACLR of -48.4 dBc at a 885-kHz offset, which has a cancellation of 14 dB.

In order to hold a good cancellation performance for a four-carrier WCDMA signal with a 20-MHz signal band, we have tried to reduce the memory effects of the amplifier. We have also shown the way to accommodate the memory effects for a linearity target. A proper design of the gate- and drain-bias circuits gives an amplitude error less than 2 dB and an average phase-error difference less than 21° between lower and upper IM3s over the considered total power range. These additional errors caused by memory effects have slightly degraded the linearization performance for a four-carrier WCDMA signal. The predistortion power amplifier has displayed an ACLR of -46 dBc with 13.4-dB cancellation at 5-MHz offset. We expect that our analysis will assist for a design of the predistortion power amplifier.

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