New Predistortion Method Using Phase Modulation with Envelope Signal

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***Abstract* — A new predistortion method using phase modulation technique is proposed. The phase modulator is adopted for generating predistortion signal. The phase of input signal is modulated with the envelope signal from the envelope detector then the IMD components are generated. Each coefficient of the 3rd and 5th order intermodulation distortion (IMD) is optimized to improve the linearity of the power amplifier. The amplitude and phase of IMD components are controlled in RF carrier band. This makes it possible to overcome several drawbacks of the envelope control methods such as difficulties in controlling the phase of baseband signal, narrow bandwidth, and delay variation at the low frequency circuits. The experimental results show the sufficient improvements in two-tone and multi-carrier CDMA test over the broad dynamic range.**

I. Introduction

More and more complex modulation methods are used in modern communication systems for high spectral efficiency and the linearity specifications become tighter than those of the 1st and 2nd generation wireless systems. It demands the highly linear amplifiers to reduce the adjacent channel interferences effectively and offer a high quality service.

So, many techniques of the linearization methods are investigated [1]-[4]. The feedforward method, which has the best linearization performance, is still used in base station and satellite. However, it has some drawbacks such as size, cost, complexity and efficiency. To solve these problems, several predistortion methods which are simple, more compact and efficient but provide good performance, have been suggested.

In this paper, a new type predistorter is presented. This method uses the phase modulation with envelope signal to generate the predistorted 3rd and 5th IMD components. The envelope signal and the squared envelope signal are generated in the envelope detector. With the automatic level control (ALC) circuit, these components are generated stably [4].

Compare to other conventional polar or Cartesian modulation schemes [1]-[3], it just uses IMD components after modulation process with envelope signal. This circuit consists of the phase modulators with balanced structure. With this balanced structure, no additional cancellation loop is required for eliminating residual carrier.

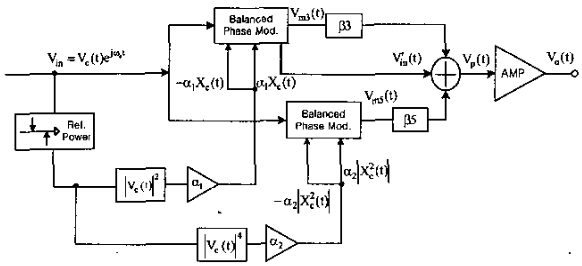

Fig. 1. The block diagram of the proposed predistorter

The amplitude and phase of the generated IMD components are controlled in the RF carrier band. It is possible to overcome several drawbacks in the envelope control technique such as difficulties in controlling the phase of base band signals, narrow bandwidth, and delay variation at the low frequency circuits.

Numerical analysis is presented in section II and III. The validity of this circuit has been verified with multi-carrier CDMA IS-95 signal having 11dB peak-to-average ratio at 0.01% probability of CCDF in section IV.

II. Analysis And Theory

Fig. 1 shows the block diagram of the proposed predistorter. If an input signal is $V_{in}(t) = V_c(t)e^{j\omega_c t}$, we can define the envelope signal as $X_c(t) = |V_{in}(t)|^2 = |V_c(t)|^2$ which is generated in the envelope detector. The main signal $V_{in}(t)$ is phase modulated, then $V_m(t) = V_{in}(t)e^{jf(X_c(t))}$, where $f(X_c(t))$ is the modulation function having modulation index $X_c(t)$. This modulated signal generates the 3rd and 5th IMD signals. Variable phase shifter is used for the phase modulation and the output phase varies linearly in proportion to the control signal. So, modulation function is expressed like $f(X_c(t)) = k\,X_c(t)$.

In the results, the phase modulation signal is expressed as $V_m(t) = V_{in}(t)e^{jkX_c(t)} = V_c(t)e^{j\omega_c t}e^{jkX_c(t)}$ and from the Bessel function definition, the each modulated signal of the balanced modulator in the fig. 2 can be written as [5]

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$$
\begin{aligned}
V_{m31}(t) &= \gamma_3 V_c(t) e^{j\omega_c t} e^{j\alpha_1 k X_c(t)} \\
&= \gamma_3 V_c(t) e^{j\omega_c t}\left(J_o(\alpha_1 k X_c(t)) + 2jJ_1(\alpha_1 k X_c(t))\right) \\
&= \gamma_3 V_c(t) e^{j\omega_c t}\left(1 + j\alpha_1 k X_c(t)\right) \\
&= \gamma_3 V_c(t) e^{j\omega_c t} + jk\alpha_1\gamma_3 V_c(t) e^{j\omega_c t} X_c(t)
\end{aligned} \tag{1}
$$

$$
\begin{aligned}
V_{m32}(t) &= \gamma_3 V_c(t) e^{j\omega_c t} e^{-j\pi/2} e^{-j\alpha_1 k X_c(t)} \\
&= \gamma_3 V_c(t) e^{j\omega_c t} e^{-j\pi/2}\left(J_o(-\alpha_1 k X_c(t)) + 2jJ_1(-\alpha_1 k X_c(t))\right) \\
&= \gamma_3 V_c(t) e^{j\omega_c t} e^{-j\pi/2}\left(1 - j\alpha_1 k X_c(t)\right) \\
&= \gamma_3 V_c(t) e^{j\omega_c t} e^{-j\pi/2} - jk\alpha_1\gamma_3 V_c(t) e^{j\omega_c t} e^{-j\pi/2} X_c(t)
\end{aligned}
$$

where γ_3 is a linear coefficient.

Equation (1) shows only generated 3rd IMD signals in each phase modulators, as shown in III. A. proposed balanced phase modulator. The generated signals at each port of the balanced phase modulators can be expressed as

$$
\begin{aligned}
V'_{in}(t) &= V_{m31}(t) e^{-j\pi/2} + V_{m32}(t) \\
&= 2\gamma_3 V_c(t) e^{j\omega_c t} e^{-j\pi/2} = \alpha_0 V_{in}(t)
\end{aligned} \tag{2}
$$

$$
\begin{aligned}
V_{m3}(t) &= V_{m31}(t) e + V_{m32}(t) e^{-j\pi/2} \\
&= \gamma_3 V_c(t) e^{j\omega_c t} + jk\alpha_1\gamma_3 V_c(t) e^{j\omega_c t} X_c(t) \\
&\quad + \gamma_3 V_c(t) e^{j\omega_c t} e^{-j\pi} - jk\alpha_1\gamma_3 V_c(t) e^{j\omega_c t} e^{-j\pi} X_c(t) \\
&= 2jk\alpha_1\gamma_3 V_c(t) X_c(t) e^{j\omega_c t} = \alpha_3 V_{in}(t) X_c(t)
\end{aligned} \tag{3}
$$

The equation (2) is the pure main signal component and the equation (3) expresses the generated 3rd IMD signal component with the balanced structure. From same method, the predistorted 5th IMD signal component can be expressed as

$$
\begin{aligned}
V_{m5}(t) &= V_{m51}(t) e + V_{m52}(t) e^{-j\pi/2} \\
&= 2jk\alpha_2\gamma_5 V_c(t) X^2{}_c(t) e^{j\omega_c t} = \alpha_5 V_{in}(t) X^2{}_c(t)
\end{aligned} \tag{4}
$$

In the end, the power amplifier input signals $V_P(t)$ consist of the individually controlling 3rd and 5th predistorted signals and pure main signal.

The input signals $V_P(t)$ of the power amplifier are expressed as

$$
\begin{aligned}
V_p(t) &= V'_{in}(t) + \beta_3 V_{m3}(t) + \beta_5 V_{m5}(t) \\
&= \alpha_0 V_{in}(t) + A_3 e^{j\phi_3} V_{m3}(t) + A_5 e^{j\phi_5} V_{m5}(t)
\end{aligned} \tag{5}
$$

General power amplifier characteristics can be expressed as power series like equation (6).

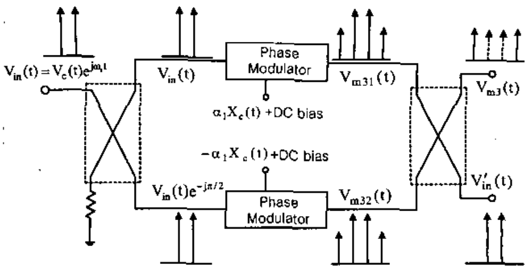


Fig. 2. A proposed balanced phase modulator

$$
A(X(t)) = g_1 X(t) + g_3 X^3(t) + g_5 X^5(t) + \cdots\cdots \tag{6}
$$

If we consider only 3rd and 5th degree nonlinear components of the test power amplifier, the output signals of power amplifier having input signal $V_P(t)$ can be expressed as

$$
\begin{aligned}
V_o(V_p(t)) &= A(V_p(t)) = g_1 V_p(t) + g_3 V_p^3(t) + g_5 V_p^5(t) \\
&= \alpha_o g_1 V_{in}(t) + [\alpha_3 g_1 \beta_3 + g_3 \alpha_0{}^3] V_{in}(t) X_c(t) \\
&\quad + [\alpha_5 g_1 \beta_5 + g_5 \alpha_0{}^5] V_c(t) X_c^2(t)
\end{aligned} \tag{7}
$$

Compare to other predistorter using quadrature modulators [1]-[3], α_1, α_2 are fixed at optimum phase modulation point. Then the control coefficients β_3, β_5 are adjusted for 3rd and 5th IMD cancellation. In equation (7), by proper selection of the β_3 (A_3, ϕ_3) and β_5 (A_5, ϕ_5) coefficients, we can use the second and third polynomial terms to reduce the 3rd and 5th order IMD generated by the power amplifier. If the relatively small component $\alpha_3\beta_3 V_c(t) X_c(t)$ has the only linear gain g_1, the proposed predistorter cancels the 3rd and 5th IMD signals individually.

III. Implementation Of The Circuits

In this section, the numerical analyses of the each circuit implemented are derived.

A. Proposed balanced phase modulator

Fig. 2 is the detailed circuit of the proposed balanced phase modulator to generate the distortion functions.

If the main carrier signal is $V_{in}(t)$, the phase-modulated signal $V_m(t)$ having the modulation index $\alpha X_c(t)$ can be written as

$$
\begin{aligned}
V_m(t) &= V_{in}(t) e^{jf(\alpha X_c(t))} \approx V_{in}(t) e^{jk\alpha X_c(t)} \\
&= V_{in}(t)\left(\cos(k\alpha X_c(t)) + j\sin(k\alpha X_c(t))\right)
\end{aligned} \tag{8}
$$

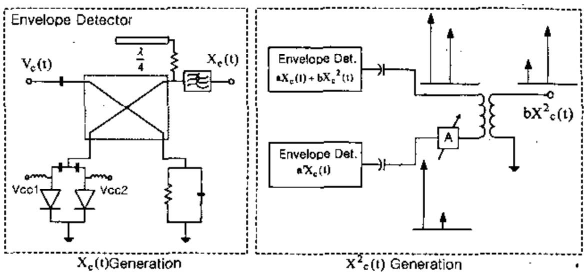


Fig. 3. A new envelope detector

From the trigonometric expansions and the series representations of the Bessel functions, the parenthesis of the equation (8) are expressed as [5]

$$\begin{aligned}&\cos(k\alpha X_c(t)) + j\sin(k\alpha X_c(t))\\ &= J_o(k\alpha X_c(t)) - 2J_2(k\alpha X_c(t)) + \cdots\\ &+ 2j\{J_1(k\alpha X_c(t)) - J_3(k\alpha X_c(t)) + \cdots\}\end{aligned} \tag{9}$$

The required signals from the distortion function generator are the main signal and the first side frequency pair that is the 3rd or 5th IMD component.

Under the assumption that the phase modulation index $\alpha X_c(t)$ is very small, we consider only $J_0(k\alpha X_c(t))$ and $J_1(k\alpha X_c(t))$ spectral components.

The power series of the Bessel functions are written as

$$\begin{aligned}J_0(k\alpha X_c(t)) &= 1 - \frac{k\alpha X_c^{\,2}(t)}{2^2} + \frac{k\alpha X_c^{\,4}(t)}{2^2 * 4^2} + \cdots\cdots\\ J_1(k\alpha X_c(t)) &= \frac{k\alpha X_c(t)}{2} - \frac{k\alpha X_c^{\,3}(t)}{2^2 * 4} + \frac{k\alpha X_c^{\,5}(t)}{2^2 * 4^2 * 6} + \cdots\end{aligned} \tag{10}$$

Due to $k\alpha X_c(t) \approx$ very small, we consider only each first term of the equation (10)

$$J_0(k\alpha X_c(t)) = 1 \quad , \quad J_1(k\alpha X_c(t)) = \frac{k\alpha X_c(t)}{2} \tag{11}$$

Hence, we can define the phase modulation as

$$\begin{aligned}V_m(t) &= V_{in}(t)e^{jk\alpha X_c(t)}\\ &= V_{in}(t)(J_0(k\alpha X_c(t)) + 2jJ_1(k\alpha X_c(t)))\\ &= J_0(k\alpha X_c(t)V_{in}(t) + 2jJ_1(k\alpha X_c(t))V_{in}(t)\\ &= V_{in}(t) + jk\alpha X_c(t)V_{in}(t)\\ &= V_c(t)e^{j\omega_c(t)} + jk\alpha X_c(t)V_c(t)e^{j\omega_c(t)}\end{aligned} \tag{12}$$

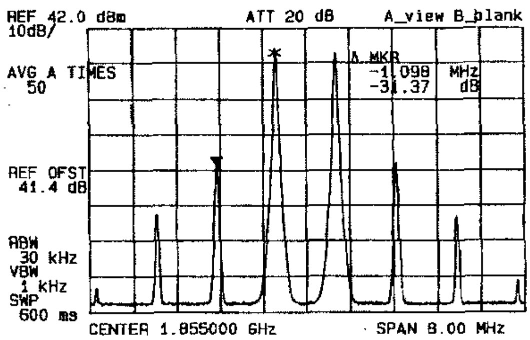
From (12), IM component for predistortion is generated by phase modulation. With the proposed balanced phase modulator, we can separate pure signal and the predistorted 3rd, 5th IMD products.

B. New envelope detector

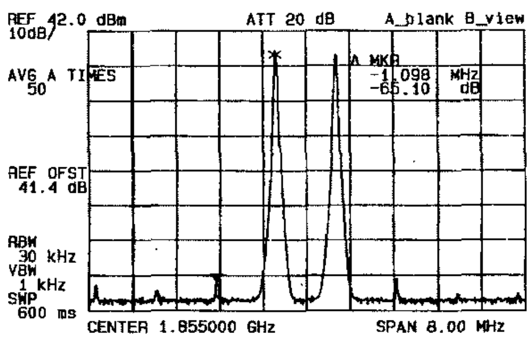
Fig. 3 shows a structure of the proposed envelope detector [4]. It is reflection type and has two bias voltage controllers and two different characteristic diodes biased separately to generate pure envelope signal. Due to the individual controlling DC voltage of the two diodes, the two diodes are biased at proper operation points and also it is easy to generate the multiplied envelope signal $X^2{}_c(t)$. The right side of the fig. 3 is the detailed circuit that generates the signal $X^2{}_c(t)$. It has the merits that minimize the additional signal delay time and the signal distortion of the conventional multiplier generating the multiplied signal $X^2{}_c(t)$ and generate only pure signal $X^2{}_c(t)$. This implies that more accurate distortion functions can be generated for the improvement of the IMD products.

IV. Experimental Results

The power amplifier (STA1800-37, 10Watts) for experiments has 50dB gain and is developed for the Personal Communication Service (PCS) Tx. Band (1840MHz-1870MHz) in Korea.



(a)



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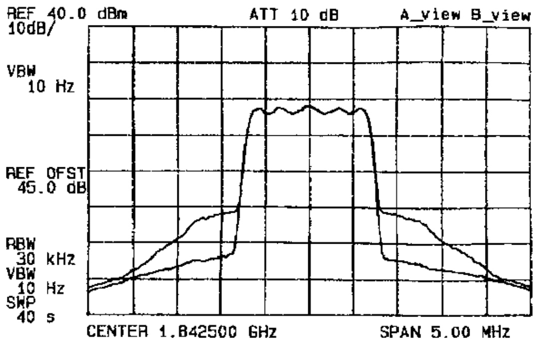
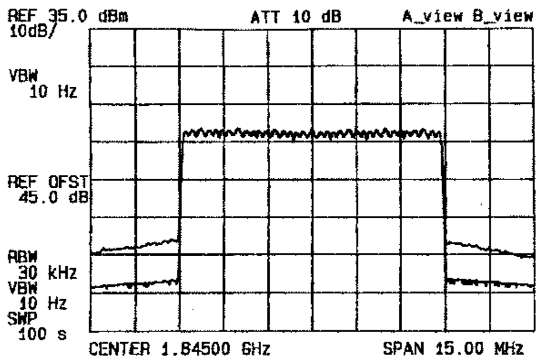


(c)



(d)

Fig. 4. (a) Two tone output (PA) @Po=37dBm
(b) Two tone output (LPA) @Po=37dBm
(c) CDMA 1FA output (PA, LPA) @Po=35.4dBm
(d) CDMA 7FA output (PA, LPA) @Po=34dBm

The low frequency circuits including the envelope detector and gain controller etc. are designed to have at least 30MHz bandwidth for broadband linearization in Korea PCS Tx. band.

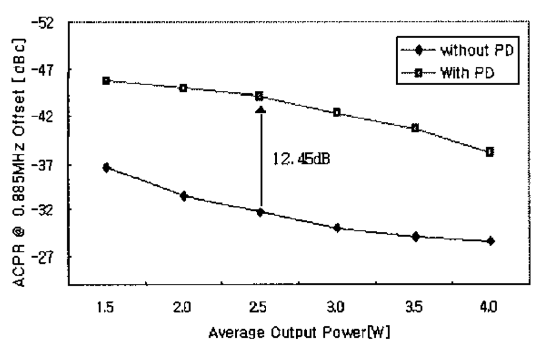


Fig. 5. The improvements of the ACPR versus output power

Fig. 4 shows experimental results. Fig. 4 (a) and (b) illustrate the performance of the proposed method for two-tone case with an RF amplifier driven into biased class AB. The IM3 and IM5 components are improved by more than 30dB and 20dB respectively. Fig. 4 (c) shows the performance for IS-95 CDMA 1FA signal case and fig. 4 (d) shows the performance for broad IS-95 CDMA 7FA signal case with 11dB peak-to-average ratio at 0.01% probability of CCDF. Fig. 5 plots the improvements of the ACPR versus the output power in CDMA 1FA case.

V. Conclusions

In this paper, a new predistortion method has been presented. The numerical analyses of the predistortion, detailed circuits and the experimental results have also been presented in section II, III and IV.

The new envelope detectors that easily generate the envelope signal $X_c(t)$ and the multiplied envelope signal $X^2{}_c(t)$ are also proposed. This method controls the 3rd and 5th IMD components individually. The method using balanced phase modulators has low gain losses and need not additional cancellation loops for main carrier.

The proposed predistortion method compensates for input-output nonlinearities and effectively cancels the 3rd and 5th order intermodulation distortions. For the verification of the proposed method, experiments are performed for two-tone signals and multi FA CDMA signals. That shows the sufficient improvements over the wide dynamic ranges.

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