A Simple and Effective RF Predistorter for Use in the HPAs of Base Stations in Cellular Mobile Systems

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***Abstract* —This paper presents the design of using a simple mixer circuit, constructed with Schottky diodes as the nonlinear device, to generate the intermodulation (IM) products for predistortion of high-power amplifiers (HPAs) in the base stations of cellular mobile systems. The design has a simple structure and requires no external dc bias voltage. A complex polynomial is used to model the characteristic of the HPA and the predistorter generates the in-phase and quadrature components of the intermodulation distortion (IMD) products for predistortion of the HPA. Experimental results using a practical HPA show that, for a modulated CDMA (IS-95) signal, the predistorter can reduce the adjacent-channel-power ratio (ACPR) by 15 dB.**

Index terms —Adjacent-channel-power ratio (ACPR), High Power Amplifier, Inter-modulation, Mixer, RF Analog Predistorter.

I. INTRODUCTION

The current mobile radio systems such as the GSM-EDGE, CDMA (IS-95) and 3G require the RF high power amplifiers (RF HPAs) in the base stations to be broadband and have linear amplification. However, due to the inherent nature of RF HPAs (even with class-A or class-AB configurations), the amplification processes are always nonlinear, so some sorts of linearization techniques need to be used in the base station HPAs of these mobile systems. Analog RF predistortion is simple, low cost to implement and having a much wider bandwidth, so it is more suitable than digital predistortion for base station HPAs. An RF predistorter has a distortion characteristic complementary to that of the RF HPA [1, 2] and can be implemented by generating either the harmonic-frequency signals [1, 3, 4] or the inband intermodulating (IM) products [5-9] and then adding to the original signal at the input of the HPA. The harmonic-frequency technique has an advantage of low insertion loss [4], but the bandwidth of the HPA may block the high-order harmonic-frequency signals, making the technique less useful for high frequency systems. In general, there are two ways, i.e. using the difference-frequency signal or the sum-frequency signal, to generate the inband IM products for HPA predistortion [5, 6]. In [5], a diode was used as a nonlinear device to generate the difference-frequency signal. However, for HPAs operating in the microwave frequency band, the difference-frequency signal will be out of the HPA operation frequency band and thus blocked. In [6], two wideband double-balanced mixers capable of operating at twice of the maximum frequency were used to generate the sum-frequency signal in order to generate the IM3 signals. But it is not easy to handle signals with such high frequency, particularly when generating the IM products with higher orders for intermodulation distortion (IMD) products cancellation.

This paper proposes to use mixers as the nonlinear devices to generate the inband IM products for RF HPA predistortion and presents the design of a simple mixer circuit to generate the 3rd–order intermodulation (IM3) products for 3rd–order IMD cancellation. The mixer circuit employs two mixers constructed with Schotty diodes: a single-balanced mixer to obtain the down converted difference frequency signals and a single-ended mixer to generate the wanted IM3 products. RF predistortion usually assumes a real polynomial expression to model the HPA. In this paper, a complex polynomial is used to model the HPA. Experimental results using a practical HPA show that, for a modulated CDMA (IS-95) signal, the predistorter can reduce the adjacent-channel-power ratio (ACPR) by 15 dB.

II. MODEL OF HIGH-POWER AMPLIFIER (HPA)

The nonlinear process of an HPA can be written as:

$$y = A(x)e^{j\phi(x)} = A(x)\cos(\phi(x)) + jA(x)\sin(\phi(x)) \qquad (1)$$

where x is the input signal, y is the output signals, $A(.)$ and $\phi(.)$ are the amplitude-amplitude (AM-AM) and amplitude-phase (AM-PM) distortion effects, respectively, of the HPA. Using a 3rd-order polynomial representation, (1) can be approximated by:

$$y = (a_1x + a_2x^2 + a_3x^3) + j(b_1x + b_2x^2 + b_3x^3) \qquad (2)$$

where a_1, a_2, a_3 and b_1, b_2, b_3 are the coefficients in the real and imaginary parts, respectively, of the polynomial. The even-order terms produce IM products which are outside the HPA operation frequency band and do not contribute to inband distortion, so we can consider only the odd-order terms in (2).

III. PREDISTORTER CIRCUITS DESIGN

Here, we demonstrate how to use simple mixers to generate the 3rd–order intermodulation (IM3) signals to suppress the 3rd-order intermodulation distortion (IMD) products introduced by an HPA. The approach can be extended to suppress higher order IMD products. The basic idea of using two mixers to generate the IM3 signals is shown in Fig. 1, where RF#1, LO#1, RF#2 and LO#2 are input ports, IF#1 and IF#2 are output ports, and RF_1, LO_1, IF_1, RF_2 , LO_2 and IF_2 are the signals in these ports.

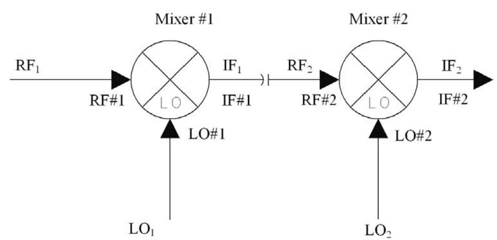
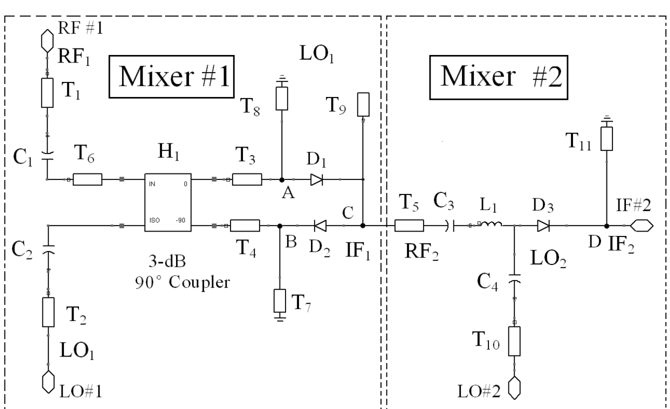
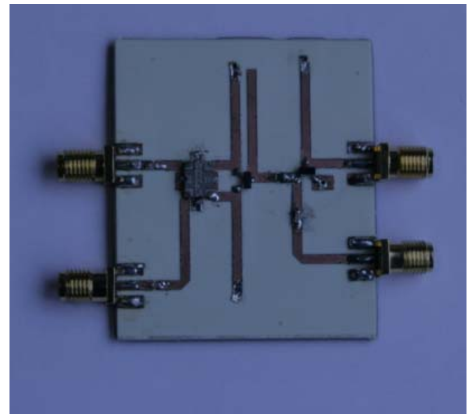


Fig. 1 IM3 generation using mixers

To generate the IM3 signal, a two-tone signal, $\cos(\omega_1 t)+\cos(\omega_2 t)$, is applied to the input ports, RF#1 and LO#1, of Mixer #1 to generate the wanted difference-frequency signal, $\cos(\omega_2-\omega_1)t$, and other unwanted signals at the output port IF#1. The direct current (dc) component and the unwanted signals are blocked by a capacitor and lowpass filter, respectively. The signal, $\cos(\omega_2-\omega_1)t$, from the output port IF#1 is fed to the input port RF#2 of Mixer #2. The input port LO#2 is fed with the same two-tone signal $\cos(\omega_1 t)+\cos(\omega_2 t)$ which is mixed with $\cos(\omega_2-\omega_1)t$ in Mixer #2 to generate the wanted IM3 signal, $\cos(2\omega_1-\omega_2)t+\cos(2\omega_2-\omega_1)t$, at the output port IF#2. In addition to the wanted signal, the unwanted signals are also generated but easily removed as described later.



(a)



(b)

Fig. 2 IM3 generator
(a) Circuit diagram (b) Hardware implementation

The actual circuit of the IM3 generator is shown in Fig. 2. In Fig. 2 (a), Mixer #1 is a single-balanced mixer. C_1 and C_2 are the filter capacitors used to block the dc component, and T_1 and T_2 are 50-Ohm transmission lines with equal length serving as the input ports, RF#1 and LO#1, to which the signals RF_1 and LO_1, respectively, are fed. T_6 is a quarter-wave transmission line at the frequency of RF_1, so the signal RF_1 at the input of the 3-dB 90° hybrid coupler (H_1) has a 90° phase delay. At the balanced ports of the coupler, the signals RF_1 and LO_1 have the same phase in T_4, but a phase difference of 180° in T_3. An antipodal diode pair, using Schottky diodes D_1 and D_2 (as the mixing elements), is connected to the outputs of the coupler. The mixing IF components in each diode element with equal phase are combined together to form the output signal IF_1 and those with a phase difference of 180° are cancelled off. T_7 and T_8 are quarter-wave short-circuited lines at RF_1 frequency. Assuming that the frequencies of RF_1 and LO_1 are close to each other, so points A and B are seen as an open circuit by the signals RF_1 and LO_1 which are fed to the diodes for mixing. It is noted that the dc signal produced by the mixing process is used to bias the diodes D_1 and D_2. The signal IF_1, being at a much low frequency, sees points A and B as a short circuit. T_9 is a quarter-wave open-circuited transmission line also at the frequency of RF_1, so point C is also seen as a short circuit for signals RF_1 and LO_1. T_3 and T_4 are transmission lines used for soldering components. In addition, T_3 & T_8 and T_4 & T_7 also form the matching networks for diodes D_1 and D_2, respectively, to reduce the mixer's conversion loss [10].

Mixer #2 is a single-ended mixer. The output signal IF_1 from Mixer #1 is fed via T_5 to the input port RF#2 and becomes the input signal RF_2. The capacitor C_3 and inductor L_1 form a tune circuit to block the dc signal and pass the RF_2 signal to diode D_3. The tune circuit also blocks the high-frequency signals LO_2 and IF_2. The transmission line T_{10} and capacitor C_4 form a high-pass filter to pass the signal LO_2 and block the low-frequency signal RF_2. T_{11} is a 50-Ohm quarter-wave short-circuited transmission line at IF_2 and so point D is seen by the signal IF_2 as an open circuit and by the low-frequency signal RF_2 as a short circuit. This mixer circuit does not need any dc supply, so it is simple, low cost and easy to implement. Figure 2 (b) shows the actual hardware implementation of the IM3 generator.

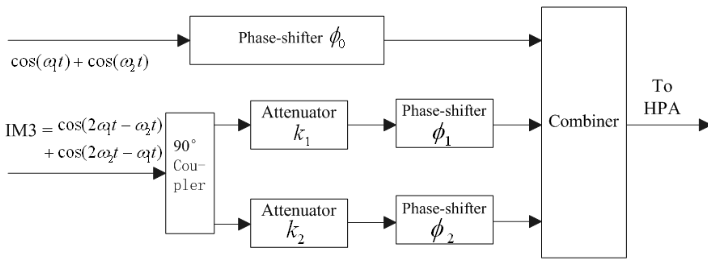


Fig. 3 Attenuators and Phase Shifters of Predistorter

The wanted IM3 signals from Mixer #2 are fed to a 90^0-coupler, as shown in Fig. 3, to produce an in-phase and quadrature-phase signals of $[\cos(2\omega_2-\omega_1)t+\cos(2\omega_1-\omega_2)t]$ and $j[\cos(2\omega_2-\omega_1)t+\cos(2\omega_1-\omega_2)t]$, respectively. The amplitudes and phases of the IM3 signal and the original two-tone signal $\cos(\omega_1 t)+\cos(\omega_2 t)$ are adjusted using the corresponding attenuators and phase-shifters. The two signals are then combined to produce:

$$\begin{aligned}&\cos(\omega_1 t+\phi_0)+\cos(\omega_2 t+\phi_0)\\&+k_1[\cos((2\omega_2-\omega_1)t+\phi_1)+\cos((2\omega_1-\omega_2)t+\phi_1)]\\&+jk_2[\cos((2\omega_2-\omega_1)t+\phi_2)+\cos((2\omega_1-\omega_2)t+\phi_2)]\end{aligned} \quad (3)$$

where k_1, k_2 and ϕ_0, ϕ_1, ϕ_2 are the adjusted amplitudes and phases, respectively, of the corresponding signal components. The resultant signal of (3) is fed to the HPA. Assume that we adjust the phase shifters such that $\phi_0=\phi_1=\phi_2$, then substituting (3) into (2) gives the 3rd–order IMD at the HPA output:

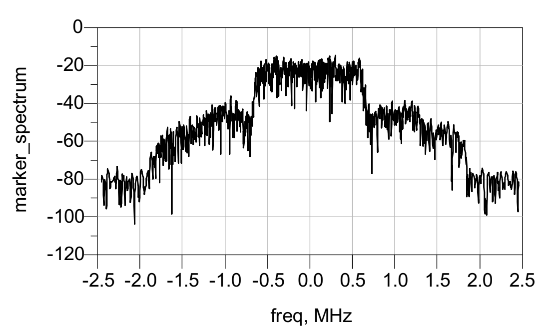
$$\begin{aligned}IMD(t)=&(C_1+jC_2)\cos((2\omega_1-\omega_2)t+\phi_0)\\&+(C_3+jC_4)\cos((2\omega_2-\omega_1)t+\phi_0)\end{aligned} \quad (4)$$

where $C_1 \ldots C_4$ are functions of k_1 and k_2. Thus the powers of the IMD products can be minimized by adjusting k_1 and k_2.

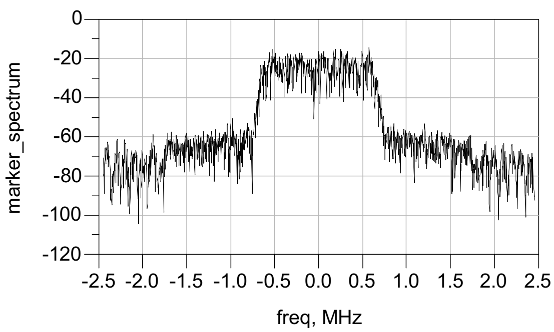
IV. RESULTS

Simulation tests using Agilent ADS 2006A have been used to assess the performance of the predistorter on a practical base station HPA. The characteristic of a practical base station HPA, HW-1900-40 manufactured by Bravotech inc, China, was modeled using a complex polynomial and used in ADS 2006A. A two-tone signal at the frequencies of 2.2 and 2.21 GHz was first used to obtain the correct settings for the phase shifters and attenuators as follows. The two-tone signal was applied to the inputs of the predistorter. The phase shifters and attenuators were adjusted to minimize the powers of the 3rd-IMD products at the HPA output. With the settings of the phase shifters and attenuators unchanged, an IS-95 CDMA signal was applied to the input of the predistorter. The results on the HPA out signal spectra with and without the predistorter are shown in Fig. 4, which indicates that the predistorter has significantly reduced the adjacent channel power ratio (ACPR) suppression by 17 dB at the band edge of 0.8 MHz.

The predistorter has also been fabricated on a PCB using Roger's RO4005C. The 3-dB 90° hybrid coupler used was Anaren's model JP503S and the Schottky diodes were Avago-tech's HSMS 282X. The chip capacitors C_1, C_2, C_3 and C_4 had values of 100 pf, 100 pf, 10 nf, 100 pf, respectively, with a mounting size of 0603 (60 mil x 30 mil). The inductor L_1 had a value of 100 nH with a mounting size of 0805 (80 mil x 50 mil). To assess the predistortion performance of our hardware design, the same practical base station HPA, HW-1900-40 manufactured by Bravotech inc. China, was used with an IS-95 CDMA signal as the input. Before measurement was taken, a two-tone signal was again used to obtain the correct settings for the phase shifters and attenuators. In the two-tone test, two tone signals of 2.2 and 2.21 GHz were generated using two signal generators and applied to the inputs of the predistorter. The phase shifters and attenuators were adjusted manually to minimize the powers of the 3rd-IMD products. Then an IS-95 CDMA signal was fed to the input of the predistorter. The output powers from the HPA in these two tests were kept the same at 30W (14.8 dBW). The measurement results of the spectra obtained via a 40-dB coupler, with and without the predistorter, are shown in Fig. 5. The predistorter has achieved a 15 dB ACPR suppression at the band edge of 0.8 MHz

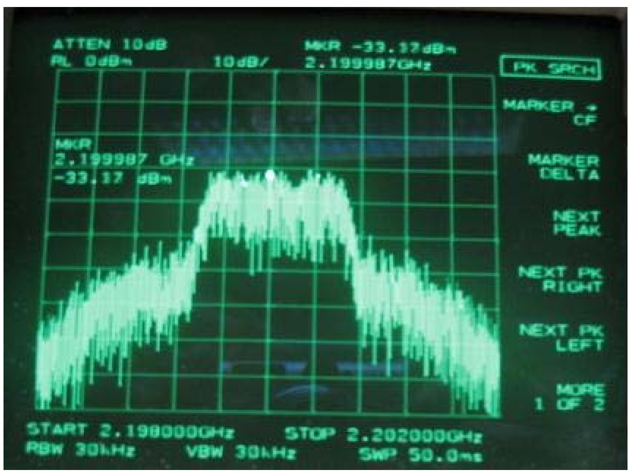


(a)



(b)

Fig. 4 Simulated IS-95 signal spectra from the HPA with (a) no predistortion and (b) predistortion



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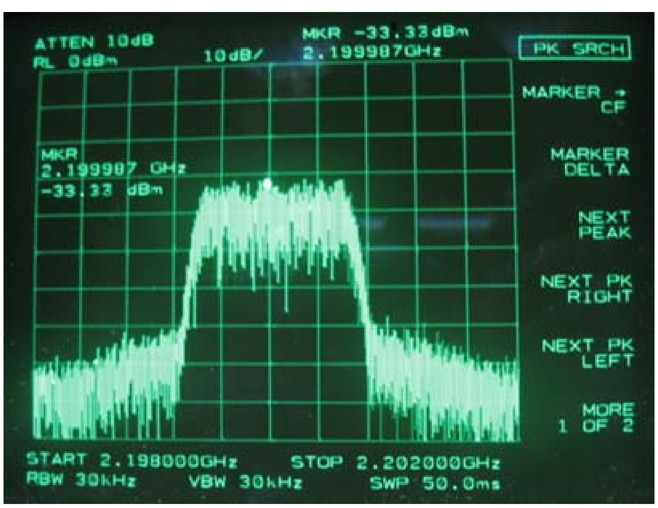

(b)

Fig. 5 Measured IS-95 signal spectra with (a) no predistortion and (b) predistortion

V. CONCLUSIONS

This paper has presented the design of using simple mixers as the nonlinear circuit to generate the IM products for predistortion of HPAs. An IM3 product generator, employing a balanced mixer and a single-ended mixer constructed with Schottky diodes, has been studied and used to generate the real and imaginary parts of the IM3 signals. The IM3 product generator has the advantages of simple structure, no dc bias and no additional filters requirement. Experimental results on a practical HPA operating at 2.2 GHz and an output power of 30 W (14.8 dBW) have shown that, for an input of a modulated CDMA signal, the predistorter can reduce the adjacent-channel-power ratio (ACPR) by 15dB.

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