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An intermodulation products generator for predistortion of base station HPAs

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Abstract — This paper presents the design of an intermodulation (IM) products generator for predistortion of high-power amplifiers (HPAs) used in the base stations of cellular mobile systems. The IM products generator composes of two simple mixers constructed with Schottky diodes, has a simple structure and requires no external dc bias voltage. Simulation and measurement results show that the generator has a low conversion loss and low spurious frequency components. Studies of the IM3 generator for predistortion of a practical base station HPA are also carried out by simulation and measurements. Measurement result of a two-tone test shows that the predistorter can suppress the 3rd intermodulation distortion (IMD) products by 15 dB.

Index terms — High Power Amplifier, Intermodulation distortion, Intermodulation products generator, Mixer, RF Analog Predistortion

I. INTRODUCTION

Analog RF predistortion has the advantages of simple and low cost to implement and has a much wider bandwidth than digital predistortion, so it is more suitable for HPAs in the base stations of cellular mobile system. An RF predistorter has a 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 intermodulation (IM) products [5-9]. The harmonic-frequency technique has an advantage of low insertion loss [4], but the bandwidth of the HPA will block the high-order harmonic-frequency signals, making the technique impractical to use 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 the microwave frequency systems, the difference-frequency signal with a relatively low frequency will be blocked by the HPAs. The sum-frequency signal with twice of the maximum frequency is not an easy-to-handle signal, particularly when generating IM products with higher orders for intermodulation distortion (IMD) products cancellation.

This paper proposes to use an IM products generator composing of two mixers to avoid the mentioned problems for RF HPA predistortion. The mixers are constructed with Schottky diodes: a single-balanced mixer to obtain the down converted difference-frequency signals and a single-ended mixer to generate the wanted IM3 products. Simulation and measurement results on single tone tests show that the mixers

have low conversion losses and low spurious frequency components. RF predistortion usually assumes a real polynomial expression to model the HPA. In this paper, a complex polynomial is used to model the HPA and a quadrature predistorter is used for predistortion. Studies are carried out using simulation and measurements. Experimental results using a practical HPA show that, for a two-tone signal, the predistorter can suppress the 3rd-intermodulation distortion (IMD) products by 15 dB.

II. MODEL OF HIGH-POWER AMPLIFIER (HPA)

The nonlinear process of an HPA can be represented by:

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

where x is the input signal, y is the output signals, $A(\cdot)$ and $\phi(\cdot)$ 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:

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

where $a_1, a_2, a_3, b_1, b_2, b_3$ are the coefficients of the complex polynomial. Since the even-order terms produce IM products which are outside the HPA operating frequency band and do not contribute to the inband distortion, we can consider only the odd-order terms in (2).

III. INTERMODULATION PRODUCTS GENERATOR

Here, we describe how 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. Figure 1 shows our proposed IM3 generator, consisting of 2 mixers, where RF#1, LO#1, RF#2 and LO#2 are input ports, IF#1 and IF#2 are output ports, and RF₁, LO₁, IF₁, RF₂, LO₂ and IF₂ are the signals in these ports respectively.

To generate the IM3 signals, $\cos(2\omega_2 - \omega_1)t$ and $\cos(2\omega_1 - \omega_2)t$, a two-tone signal, $\cos(\omega_1t) + \cos(\omega_2t)$, is used to feed to the input ports, RF#1 and LO#1, of Mixer #1 to generate the 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 low-pass 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.

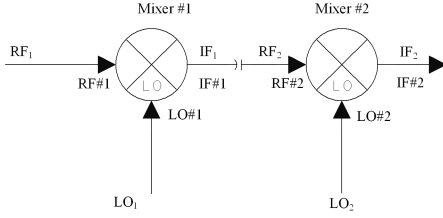


Fig. 1 IM3 generator using mixers

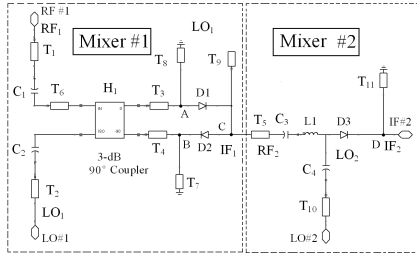


Fig. 2 Circuit of IM3 generator

The actual circuit of the IM3 generator is shown in Fig. 2. 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 D1 and D2 (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 D1 and D2. The signal IF_1 , being at a much lower 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 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 D1 and D2, 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 tuned circuit to block the DC signal and pass the RF_2 signal to diode D3. The tuned 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.

IV. QUADRATURE PREDISTORTER

The wanted IM3 signals from Mixer #2 are fed to a 90° 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 $C_1 \dots C_4$ 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 .

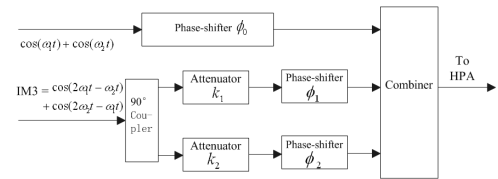


Fig. 3 Attenuators and phase shifters of predistorter

V. RESULTS AND DISCUSSIONS

5.1 IM3 generator

The IM product generator has 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).

Since the IM3 generator is designed for HPA predistortion, the unwanted spurious frequencies generated will degrade the performance of the predistorter and the conversion loss will determine whether the IM3 signals generated are large enough for use. A single-tone test and a two-tone test have been used to study the performances, in terms of conversion loss and unwanted spurious frequencies, of the IM3 generator using simulation and measurements.

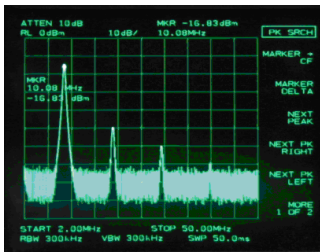


Fig. 4 Measured signal spectrum at IF#1 of Mixer #1 in single-tone test

| Frequency (MHz) | Simulated power (dBm) | Measured power (dBm) |
|-----------------|-----------------------|----------------------|
| 10 | -15.618 | -16.83 |
| 20 | -54.090 | -52.04 |
| 30 | -60.323 | -61.07 |
| 40 | -62.237 | -70.13 |
| 50 | -66.838 | Noise Floor |

Table 1 Tone signal powers at IF#1 of Mixer #1 in single-tone test

In the single-tone test for Mixer #1, the signal powers of RF_1 and LO_1 were set at -10dBm and 5dBm, respectively, and the corresponding frequencies were $\omega_1 = 2.21$ GHz and $\omega_2 = 2.2$ GHz, resulting in a difference-frequency signal IF_1 at a frequency of $(\omega_1 - \omega_2) = 10$ MHz. The measured signal spectrum at IF#1 is shown in Fig. 4 which indicates that IF_1 has a power of -16.83dBm, leading to a conversion loss of 6.83 dB. Taking into account the cable loss of about 1 dB, the actual conversion loss is in fact about 5.83 dB. The optimum conversion loss of passive mixers is 3.92 dB [11], so our Mixer #1 has a slightly additional conversion loss of about 2dB more than that of an optimum mixer. Simulation using Agilent ADS 2006A has also been carried out on the mixer. For comparison purpose, the power levels of the output tones at different frequencies in both simulation and measurement are shown in Table 1. It can be seen that at the frequencies of 10, 20 and 30 MHz, the differences between the simulation and measurement results are less than 2 dB. The measurement

results show that the unwanted spurious frequencies are more than 35 dB below that of the wanted tone at 10 MHz.

In the single-tone test for Mixer #2, the signal IF_1 with a power of -16.83 dBm at 10 MHz from Mixer #1 was fed to RF_2 of Mixer #2. The tone signal LO_2 at LO_2 had a frequency of 2.2 GHz and power of 5 dBm. The expected difference signal IF_2 was 2.2 ± 0.01 GHz. The measured spectrum at the output IF_2 of Mixer #2 is shown in Fig. 5. It can be seen that the output wanted signals at 2.21 GHz and 2.19 GHz have the power levels of -25.1 dBm and -26dBm, respectively. Taking into account the 1 dB cable loss, the corresponding conversion losses of Mixer #2 were 8.27 dB and 9.17 dB. Table 2 shows the simulated and measured powers of different tones in IF_2 of Mixer #2. It can be seen that the differences between the measured and the simulation results of the wanted tones are all within 1.5 dB. The measured results show that the strongest spurious frequencies are at 2.18 GHz and 2.22 GHz and both are about 25-30 dB lower than the wanted frequencies. The remaining spurious frequencies are close to the noise floor as shown in Fig. 5.

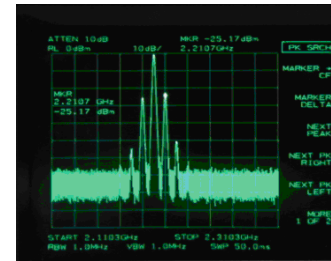


Fig. 5 Signal spectrum from IF#2 of Mixer #2 in single-tone test

| Frequency (GHz) | Simulated (dBm) | Measured (dBm) |
|-----------------|-----------------|----------------------|
| 2.2 | -3.105 | -3.57 |
| 2.21 | -25.432 | -25.17 |
| 2.19 | -25.271 | -26.00 |
| 2.22 | -50.848 | -51.50 |
| 2.18 | -48.950 | -58.37 |
| 2.23 | -73.984 | -65.18 |
| 2.17 | -65.622 | -68.42 (noise floor) |

Table 2 Tone signal powers at IF#2 of Mixer #2 in single-tone test

A two-tone test was used to study the performance of the generator on generating the IM products. In the test, a two-tone signal at the frequencies of 2.21 GHz (ω_1) and 2.2 GHz (ω_2) with equal amplitude was used as the input signals to LO_1 , LO_2 and RF_1 of Mixer #1. The signals LO_1 and LO_2 at LO_1 and LO_2 had a power of 5dBm, while the signal RF_1 at RF_1 had a power of -10dBm. The wanted IM3 signals at the frequencies of $2\omega_2 - \omega_1$ and $2\omega_1 - \omega_2$ from IF_2 should be at 2.19 and 2.22 GHz. The measured signal spectrum is shown in Fig. 6. Table 3 shows the measured and simulated IMD products at different frequencies. It can be seen that the IM3 signals at 2.19 GHz and 2.22 GHz have the powers of -24.1dBm and -24.33dBm, respectively. Again, taking into account the 1-dB cable loss, the actual output power are -23.1dBm and -23.33dBm. Since the input power of RF_1 was -

10dBm, the conversion losses are 13.1 dB and 13.33dB at 2.19 GHz and 2.22 GHz, respectively.

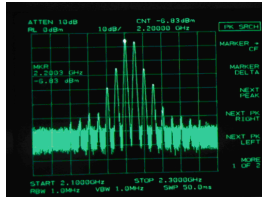


Fig. 6 Signal spectrum from IM products generator in two-tone test

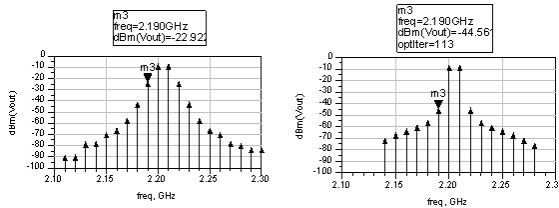
It can be seen in Fig. 6 that the generator also generates other higher-order IMD products, such as the 5th- and 7th-order IMD products, i.e., IM5 and IM7. Table 3 shows that IM3 at $3\omega_2 - 2\omega_1 = 2.18$ GHz and $3\omega_1 - 2\omega_2 = 2.23$ GHz have the powers of about 15dB less than that of IM3. While IM7 at $4\omega_2 - 3\omega_1 = 2.17$ GHz and $4\omega_1 - 3\omega_2 = 2.24$ GHz, have the powers of about 30 dB lower than that of IM3. The remaining spurious are merely several dB higher than the noise floor.

| Frequency(GHz) | Simulated (dBm) | Measured (dBm) |
|----------------|-----------------|----------------|
| 2.20 | -5.089 | -6.83 |
| 2.21 | -5.147 | -6.83 |
| 2.19 | -26.173 | -24.10 |
| 2.22 | -26.026 | -24.33 |
| 2.18 | -39.126 | -39.67 |
| 2.23 | -39.208 | -37.50 |
| 2.17 | -50.208 | -57.03 |
| 2.24 | -55.157 | -52.67 |

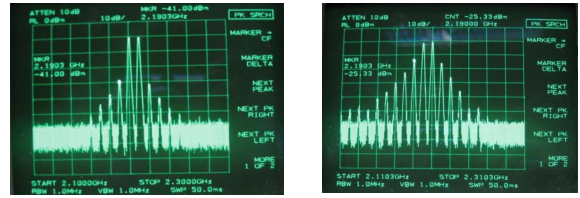
Table 3 Tone signal powers from IM products generator in two-tone test

5.2 Predistorter

Simulations using Agilent ADS 2006A and measurement tests have been used to assess the performance of the IM product generator for predistortion of a practical base station HPA. The characteristic of a practical base station HPA, HW-1900-40 manufactured by Bravotech Inc, China, was modeled by the complex polynomial in (2) and used in ADS 2006A. The simulated and measured results of the predistorter using the IM products generator are shown in Fig. 7 and Fig. 8. In the measurement, the output powers from the HPA in these two tests were kept the same at 30W (14.8 dBW) and the spectra with and without the predistorter were obtained via a 40-dB coupler. It can be seen from Fig. 7 that the quadrature predistorter can suppress the 3rd-order IMD output power by more than 20 dB, compared with no predistortion. The measured result in Fig. 8 has also shown a similar improvement of 15 dB suppression in the 3rd-order IMD products.



(a) without predistortion (b) with predistortion
Fig. 7 Simulated two-tone signal spectra from HPA



(a) without predistortion (b) with predistortion
Fig. 8 Measured two-tone signal spectra

V. CONCLUSIONS

This paper has presented the design of an IM products generator using simple mixers constructed with Schottky diodes for predistortion of HPAs. Simulation and measurement results have shown that the IM products generator has a low conversion loss and low spurious components, coupling with the advantages of simple structure, no DC bias and no additional filters requirement. Simulation and experimental tests on a practical HPA operating at 2.2 GHz with an output power of 30 W (14.8 dBW) have shown that, for a two-tone test, the predistorter can reduce the 3rd IMD products by 15 dB.

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