A Simple Mixer for Generating the 3^{rd}-Order Intermodulation Products Used for HPA Predistortion

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Abstract — **This paper proposes to use nonlinear mixer circuits to generate the intermodulation (IM) products for high-power amplifier (HPA) predistortion using the difference-frequency technique. The design of a 3^{rd}–order nonlinear circuit is used for illustration purpose. The circuit employs two mixers using Schottky diodes as non-linear devices to generate the difference-frequency signals. The circuit has a simple structure, requires no DC bias or additional filters, and is easy to fabricate and low cost. Simulation and measurement results show that the design has a low conversion loss and a low-frequency spurious.**

I. INTRODUCTION

Mixers are highly nonlinear devices which can be used in different applications. In wireless communication systems, mixers are crucial for up-converting and down-converting the signals in the transmitters and receivers [1]. In some systems, the nonlinear effects can also be used to counteract the nonlinearity [2].

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 have broadband and linear amplification. Unfortunately, the amplification processes are always nonlinear. Thus some methods are needed to be used to linearize the HPAs or to reduce the intermodulation (IM) distortion effects. Among these methods, the difference-frequency technique is an efficient one which generates the in-band intermodulation (IM) products and then adds them to the original signal at the input of the HPA [3, 4].

Different ways have been studied to generate the IM products in the difference-frequency technique. In [5], the IM products were obtained directly from the HPA (which is a non-linear device) and fed to the input of the HPA. The method combines feedback with feedforward and has the advantages of no gain loss and 20 dB improvement in the 3^{rd}-order intermodulation distortion products (IMDP3). However, the disadvantages are 1) the circuit complexity, 2) the narrow bandwidth, and 3) potentially unstable [5].

The nonlinear characteristics of a diode or transistor can also be used to generate the IM products. In [6], a diode connected with an MOSFET was used as a nonlinear circuit to generate the IM products. The circuit is simple, small, and effective in the low-gain (10dB) amplifiers, but its linearity improvements for the HPAs are limited because it also generates many other spurious frequencies and causes gain losses even for the low-power amplifiers [6].

In this paper, we propose a design for a nonlinear mixer circuit to generate the IM products for RF HPA predistortion using the difference-frequency technique. For illustration purpose, we design and describe a nonlinear circuit to generate the 3^{rd}–order intermodulation products (IM3) for use in the predistorter to reduce the IMDP3. The nonlinear circuit employs two mixers: a single-balanced mixer to obtain the down converted difference-frequency signals and a single-ended mixer to generate the wanted IM3. Studies of the circuit have been performed by using Agilent ADS and measuring the actual circuit implemented.

II. MIXER CIRCUITS DESIGN

The basic concept of using two mixers to generate the IM3 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.

To generate the IM3, 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 signal, $\cos(\omega_2-\omega_1)t$ and other unwanted signals at the output port IF#1. The direct current (DC) component is blocked by a capacitor and the unwanted signals are removed. So the signal, $\cos(\omega_2-\omega_1)t$, from the output port IF#1 becomes the input signal 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

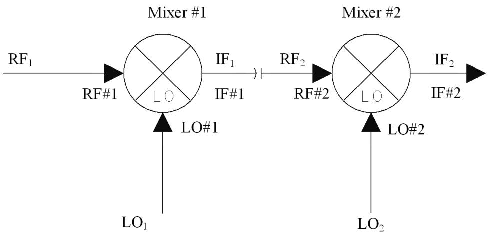

Fig. 1 Block diagram of the IM3 generator

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$\cos(\omega_2-\omega_1)t$ in Mixer #2 to generate the wanted IM3 $\cos(2\omega_1-\omega_2)t+\cos(2\omega_2-\omega_1)t$ at the output port IF#2. In addition to the wanted signal, other unwanted signals are also generated but removed as described later.

The circuits proposed for Mixer #1 and Mixer #2 are shown in Fig. 2 and Fig. 3, respectively. Mixer #1 is a single-balanced mixer, where C_1 and C_2 are filter capacitors used to block DC component, and T_1 and T_2 are 50-Ohm transmission lines with equal lengths. The input ports RF#1 and LO#1 are fed with the signals RF_1 and LO_1, respectively. 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 90^0 hybrid coupler (H_1) has a 90^0 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 180^0 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 180^0 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 open circuit by the signals RF_1 and LO_1 which are fed to the diodes for mixing. Note 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 short-circuits. T_5 is a quarter-wave open-circuited transmission line also at the frequency of RF_1, so point C is seen as 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 [7].

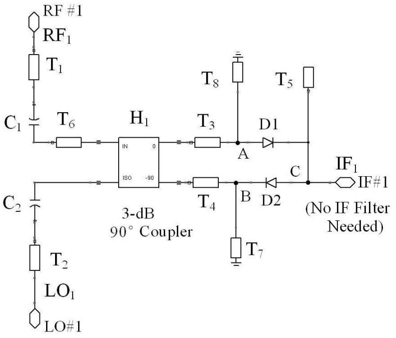

Fig. 2 Mixer #1: a single-balanced mixer

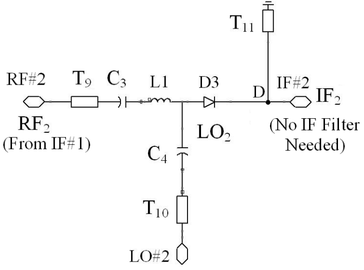

Fig. 3 Mixer #2: a single-ended mixer

Mixer #2 is a single-ended mixer as shown in Fig. 3. The output signal IF_1 from Mixer #1 is fed via T_9 to the input port RF#2 of Mixer #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 open-circuit and by the low-frequency signal RF_2 as short-circuit. At the frequency of the second harmonic of LO_2, which is the dominant spurious at IF #2, T_{11} is a half-wave short-circuited line, thus the spurious frequency is also short-circuited at point D.

Note that the circuit does not need any DC supply, nor does it need any additional filters for both RF and IF signals. So it is simple, low cost and easy to implement.

III. SIMULATION AND MEASUREMENT RESULTS

Harmonic-balance simulation tests using the Agilent's Advanced Design Systems 2006A (ADS 2006A) has been used to assess the performance of the IM3 generator using the mixer circuits as shown in Fig. 2 and Fig. 3. The same IM3 generator has also been fabricated on a PCB using Roger's RO4005C where the 3-dB 90° hybrid coupler is Anaren's model JP503S and the Schottky diodes are Avago-tech's HSMS 282X. The chip capacitors C_1, C_2, C_3 and C_4 have values of 100pf, 100pf, 10nf, 100pf, respectively, and a mounting size of 0603 (60 mil x 30 mil). The inductor L_1 has a value of 100nH and mounting size of 0805 (80 mil x 50 mil). Since the IM3 generator is designed for HPA predistortion using the difference-frequency technique, the unwanted spurious frequencies generated from the circuit will affect the performance of the predistorter. The conversion loss will determine whether the IM3 generated are large enough to be applicable. Thus 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 both simulation and measurements.

In the single-tone test for Mixer #1, the signals RF_1 and LO_1 had the powers of -10dBm and 5dBm, respectively, and the corresponding frequencies of ω_1 = 2.21GHz and ω_2 = 2.2GHz, resulting in a wanted difference-frequency signal IF_1 at a frequency of ($\omega_1-\omega_2$) = 10 MHz.

The simulation result on the IF_1 signal spectrum of Mixer #1 is shown in Fig. 4a. The experimental measured result of the same signal for the actual circuit is shown in Fig. 4b. The power levels of different output tones in both tests are shown in Table 1 for comparison. It can be seen that the wanted difference-frequency signal at 10 MHz has a simulated power level of -15.6dBm and measured power level of -16.83dBm. The conversion loss is therefore 5.6dB in simulation and 6.83dB in measurement. Taking into account the cable loss of about 1dB, the actual conversion loss in the measured circuit is

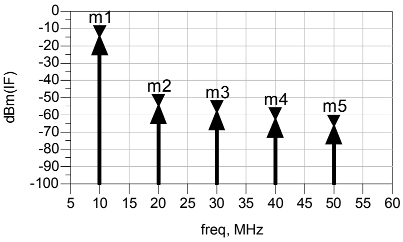

Fig. 4a Simulated IF_1 output signal spectrum from Mixer #1 in single-tone test

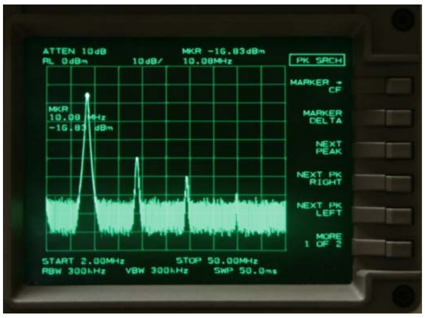

Fig. 4b Measured IF_1 output signal spectrum from Mixer #1 in single-tone test

TABLE 1 SIMULATED AND MEASURED IF_1 OUTPUT POWERS FROM MIXER #1 IN SINGLE-TONE TEST

Frequency (MHz)	Simulated power (dBm)	Measured power (dBm)
m1, 10	-15.618	-16.83
m2, 20	-54.090	-52.04
m3, 30	-60.323	-61.07
m4, 40	-62.237	-70.13
m5, 50	-66.838	Noise Floor

in fact about 5.83dB. The optimum conversion loss of passive mixers is 3.92 dB [1], so our Mixer #1 has a small additional conversion loss of about 2dB more than that of an optimum mixer. Table 1 shows that the unwanted spurious are more than 40 dB below that of the wanted signal power at 10 MHz.

In the single-tone test for Mixer #2, the output signal IF_1 at 10 MHz from Mixer #1 was applied to RF#2. The signal LO_2 applied to LO#2 had a frequency of 2.2 GHz with 5dBm power. The expected difference signals IF_2 are 2.2±0.01 GHz.

Figures 5a and 5b show the simulated and measured signal spectra, respectively. Table 2 lists the simulated and measured powers of different tones in the output signal IF_2 of Mixer #2. In simulation, the input signal RF_2 was -15.6dBm. The output wanted difference-frequency signals at 2.21GHz and 2.19 GHz had the powers of -25.4dBm and -25.17dBm, respectively, leading to the conversion losses of 9.8dB and 9.57dB. In measurement, the input signal RF_2 was -16.83dBm. The output wanted signals at 2.21GHz and 2.19 GHz were at the power levels of -25.1dBm and -26dBm, respectively. Taking into account the 1dB cable loss, the corresponding conversion losses of Mixer #2 were 8.27 dB and 9.17dB, which are within about 1.5 dB of the simulated values. The strongest spurious frequencies are at 2.18 GHz and 2.22GHz 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. 5b.

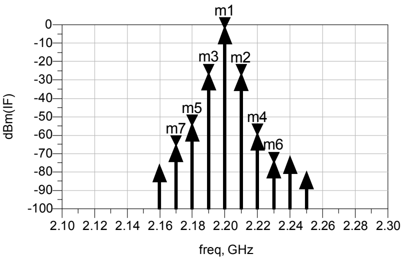

Fig. 5a Simulated IF_2 output signal spectrum from Mixer #2 in single-tone test

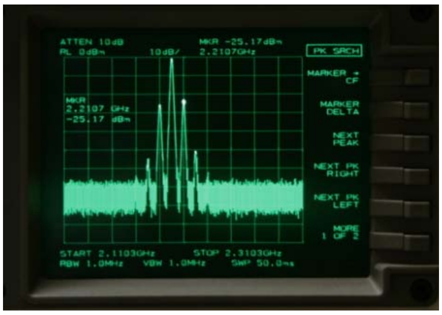

Fig. 5b Measured IF_2 output signal spectrum from Mixer #2 in single-tone test

TABLE 2 SIMULATED AND MEASURED IF_2 OUTPUT POWERS FROM MIXER #2 IN SINGLE-TONE TEST

Frequency(GHz)	Simulated power (dBm)	Measured power (dBm)
m1, 2.2	-3.105	-3.57
m2, 2.21	-25.432	-25.17
m3, 2.19	-25.271	-26.00
m4, 2.22	-50.848	-51.50
m5, 2.18	-48.950	-58.37
m6, 2.23	-73.984	-65.18
m7, 2.17	-65.622	-68.42 (noise floor)

A two-tone test was used to study the performance, in terms of generating the IM products, of the generator. In the two-tone test, a two-tone signal, consisting of two tones 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 the generator. 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 ($2\omega_2 - \omega_1$ and $2\omega_1 - \omega_2$) from IF#2 should be at 2.19 and 2.22 GHz.

The simulated and measured results are shown in Figs. 6a and 6b, respectively. Table 3 lists the signal powers of the IM products. It can be seen that the IM3 at 2.19 GHz and 2.22 GHz have power 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

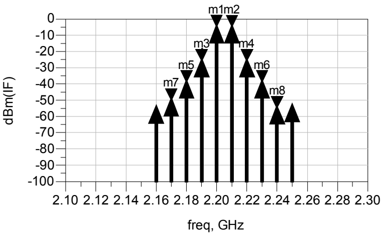

Fig. 6a Simulated IF_2 output signal spectrum from the generator in two-tone test

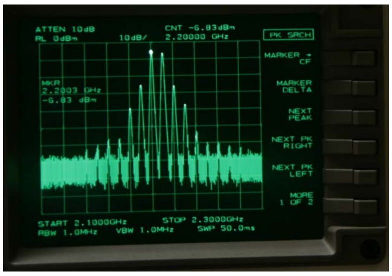

Fig. 6b Measured IF_2 output signal spectrum from the generator in two-tone test

TABLE 3 SIMULATED AND MEASURED IF_2 OUTPUT POWERS FROM IM3 GENERATOR IN TWO-TONE TEST

Frequency(GHz)	Simulated (dBm)	Measured (dBm)
m1,2.20	-5.089	-6.83
m2,2.21	-5.147	-6.83
m3,2.19	-26.173	-24.10
m4,2.22	-26.026	-24.33
m5,2.18	-39.126	-39.67
m6,2.23	-39.208	-37.50
m7,2.17	-50.208	-57.03
m8,2.24	-55.157	-52.67

power of RF_1 was -10dBm, the conversion losses were 13.1 dB and 13.33dB at 2.19 GHz and 2.22 GHz, respectively.

The IM3 generator also generates higher-order IM products, such as the 5th- and 7th-order IM products, i.e., IM5 and IM7. Table 3 shows that the IM5 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 the IM7 at $4\omega_2 - 3\omega_1$ =2.17GHz and $4\omega_1 - 3\omega_2$ =2.24GHz, have the powers of about 30 dB lower than that of IM3. The remaining spurious, are merely several dB higher than the noise floor.

Our nonlinear generator produces the output signal IF_2 which contains the fundamental signals at ω_1 and ω_2 and the IM3 at $2\omega_2 - \omega_1$ and $2\omega_1 - \omega_2$ so it can be used in the difference-frequency technique for HPA predistortion. The amplitudes and phases of the IM3 generated can be adjusted before feeding to the HPA for predistortion. Our measurement results have shown that this method can achieve a 15-dB two-tone IMDP3 improvement for the HPA. Experimental verification of the proposed mixer circuits has also been done using a practical HPA and results have shown a 15 dB HPA adjacent channel power ratio (ACPR) improvement for a CDMA IS-95 input signal.

IV. CONCLUSIONS

This paper has proposed the design of a nonlinear circuit using mixers to generate the IM products for HPA predistortion utilizing the difference-frequency technique. An IM3 generator, employing a balanced mixer and a single-ended mixer using Schottky diodes as nonlinear devices, has been studied. Results have shown that the circuit has a low conversion loss of less than 15dB, low spurious components, and the advantages of simple structure, no DC bias and no additional filters requirement.

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