A 3rd- and 5th-Order Intermodulation Products Generator for Predistortion of Base-Station HPAs

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***Abstract*—This paper presents the design of a circuit to generate 3rd- and 5th-order intermodulation (IM3 and IM5) products used for predistortion of base-station high power amplifiers (HPAs). The circuit employs a mixer constructed using two Schottky diodes as a nonlinear device to generate the IM3 products and another mixer of the same configuration to generate the IM5 products using the IM3 products generated. The circuit has been studied using a two-tone signal at a center frequency of 2.2GHz. The simulation and measured results show that the circuit can generate the IM3 and IM5 products effectively and suitable for use in predistortion of base-station HPAs.**

I. INTRODUCTION

In the rapid development of High-data-rate wireless communication systems, there are increasing demands for high-linearity high power amplifiers (HPAs) to minimize signal distortion and hence data errors. Unfortunately, the amplification processes of HPAs are highly nonlinear when the HPAs are operated at high output powers. HPAs can be operated at low output powers to avoid nonlinearities, but the price to pay is very low efficiency, i.e. a waste of the output power of HPAs. Therefore, linearity technologies such as predistortion, feed-forward or feed-back [1-4], have been developed to reduce the intermodulation distortion products (IMDPs) at the outputs of HPAs. Among these technologies, analog predistortion, which feeds the inband intermodulation (IM) signals [5-6], the difference-frequency signals [7] or the harmonic-frequency signals [8] of the fundamental signals to the HPAs to improve the linearity, is relatively low cost with reasonable linearity improvement. The injection of the difference-frequency or harmonic-frequency signals of the fundamental signals, known as the difference-frequency technique and harmonic-injection technique, respectively, generates some IM signals to suppress the unwanted IMDPs at the outputs of HPAs. However, these techniques cannot be used for narrowband HPAs which will block the injected signal. Therefore, the method of feeding the inband intermodulation (IM) signals is more practical [9]. When the HPA is operating in a more nonlinear region in order to obtain a higher output power, higher orders of the IM signals are needed to suppress the IMDPs at the output in order to maintain or obtain a better performance. Thus in using the inband-signal-injection method, a circuit to generate the higher order IM signals effectively is absolutely necessary. The circuit to generate the high order IM signals is complicated and very often also generates many unwanted spurious which will degrade the predistortion performance.

In this paper, we propose a simple circuit to generate the 3rd- and 5th-order intermodulation (IM3 and IM5) products using two identical mixers. The mixers employ two Schottky diodes as the nonlinear device and can be tuned to generate the IM3 or IM5 products with other unwanted signal suppressed. The Agilent's Advanced Design System 2009 (ADS2009) has been used to perform the design of the mixers circuit and assess the performances in a two-tone test at a center frequency of 2.2 GHz. For experimental verification, the circuit has been implemented and tested. The results show that the IM3 and IM5 products can be generated effectively using the two mixers.

II. MIXER CIRCUIT DESIGN

Fig. 1 shows the block diagram of our proposed mixer circuit which consists of a 3-dB 90° hybrid coupler, a pair of anti-parallel Schottky diodes (*D1* and *D2*), two varactors (*D3* and *D4*), an RF chock inductor *L*, a variable resistor *R* and a *λ/4*-length transmission line.

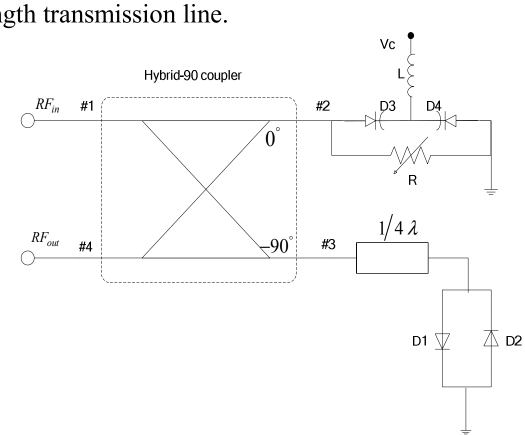

Fig. 1 Block diagram of proposed mixer

The nonlinear characteristics of the anti-parallel Schottky diodes, *D1* and *D2*, are used to generate the required IM products. The current flowing through *D1* and *D2* can be represented as (1):

$$\begin{aligned} I(t) &= I_s\{\exp[kV(t)]-1\} - I_s\{\exp[-kV(t)]-1\} \\ &= I_s\{2kV(t) + \frac{[kV(t)]^3}{6} + ... + \frac{[kV(t)]^{2n+1}}{(2n+1)!} + ...\} \end{aligned} \quad (1)$$

where *V(t)* is the signal across the anti-parallel Schottky diodes, *k* is a constant and I_s is the saturation current of the diodes.

In (1), when the power level of $V(t)$ is low, the 1st- and 3rd-order terms are dominant and other higher-order terms can be neglected, so the current can be approximated as:

$$I(t) \approx I_s\{2kV(t) + \frac{[kV(t)]^3}{6}\} \quad (2)$$

2.1 IM3 generation:

Assume the input signal, RF_{in}, fed to the input port, port #1, of the 3-dB 90° -hybrid coupler in Fig. 1 is a two-tone signal with equal amplitude and a small frequency separation. The 3-dB 90°-hybrid coupler divides the two-tone signal equally but with a 90°-phase difference at ports #2 and #3. The signal at port #3 undergoes a phase shift of 90° introduced by the $\lambda/4$-length transmission at the tone frequency before reaching the anti-parallel Schottky diodes, *D1* and *D2*, which, according to (2), generates a mixing product of the IM3 products (3rd-order term) and the two-tone signal. The mixing product is reflected back to port #3, with the two-tone signal undergoing a further phase shift of 90°. At port #4, the two-tone signal reflected from port #2 and the mixing products reflected from port #3 are summed together. Since the two-tone signals reflected from port #2 and port #3 have a phase difference of 180° and the variable resistor *R* can be used to make their amplitudes equal, the two-tone signals in port #4 can be canceled off. The anti-parallel Schottky diode circuit will have certain capacitive effects, causing a phase shift to the mixing product. The effects can be canceled off by tuning the bias voltage V_c at the varactors *D3* and *D4* to adjust the phase of the two-tone signal reflected from port #2.

2.2 IM5 generation:

We can generate the IM5 products using the same mixer circuit of Fig. 1. Here, we first combine the original two-tone signal and the IM3 products (with the generation described previously) to form the fundamental signal:

$$\begin{aligned} V_1(t) &= a(\cos\omega_1 t + \cos\omega_2 t) \\ &\quad + b\left[\cos(2\omega_1 - \omega_2)t + \cos(2\omega_2 - \omega_1)t\right] \end{aligned} \quad (3)$$

where *a* and *b* are the amplitudes of the two-tone signal and the IM3 products, respectively. Thus, the signal applied to *D1* and *D2*, which has a half power of (3), can be represented as:

$$V_2(t) = c\begin{Bmatrix} a\left(\cos\omega_1 t + \cos\omega_2 t\right) \\ +b\left[\cos(2\omega_1 - \omega_2)t + \cos(2\omega_2 - \omega_1)t\right] \end{Bmatrix} \quad (4)$$

Substituting (4) into (2) and expanding the 3rd-order term produce the two-tone signal, IM3, IM5, IM7 and IM9 products, respectively, as:

$$\frac{I_s \cdot k^3}{6}\left(\frac{9}{4}a^3c^3 + \frac{9}{4}a^2bc^3 + \frac{9}{2}ab^2c^3 + \frac{12}{k^2}ac\right)\left(\cos\omega_1 t + \cos\omega_2 t\right) \quad (5)$$

$$\frac{I_s \cdot k^3}{6}\begin{pmatrix} \frac{9}{4}b^3c^3 + \frac{3}{4}a^3c^3 \\ +\frac{9}{2}a^2bc^3 + \frac{12}{k^2}bc \end{pmatrix}\left[\cos\left(2\omega_1 - \omega_2\right)t + \cos\left(2\omega_2 - \omega_1\right)t\right] \quad (6)$$

$$\frac{I_s \cdot k^3 \cdot c^3}{6}\left[\frac{9}{4}(a^2b + ab^2)\right]\left\{\cos[(3\omega_1 - 2\omega_2)t] + \cos[(3\omega_2 - 2\omega_1)t]\right\} \quad (7)$$

$$\frac{I_s \cdot k^3 \cdot c^3}{6}\left(\frac{9}{4}ab^2\right)\left\{\cos[(4\omega_1 - 3\omega_2)t] + \cos[(4\omega_2 - 3\omega_1)t]\right\} \quad (8)$$

$$\frac{I_s \cdot k^3 \cdot c^3}{6}\left(\frac{3}{4}b^3\right)\left\{\cos[(5\omega_1 - 4\omega_2)t] + \cos[(5\omega_2 - 4\omega_1)t]\right\} \quad (9)$$

which are generated across the anti-parallel Schottky diode circuit. In (7)-(9), it can be seen that if *a* (the amplitude of the two-tone signal) is larger than *b* (the amplitude of the IM3 product), say, by 5 dB, then the IM5 product will have a much a higher power level than both the IM7 and IM9 products in (8) and (9), respectively, which therefore can be neglected. As a result, the mixing product then mainly consists of the two-tone signal, IM3 and IM5 products given by (5), (6) and (7), respectively, and is reflected to port #4 of the coupler. The $\lambda/4$-length transmission, bias voltage V_c and variable resistor R could be used to cancel either the two-tone signal or the IM3 products, as explained previously, but not both together, in port #3. Here, we choose these settings to suppress the IM3 products. To remove the original two-tone signal in port #3, we can simply use the two-tone signal with the same amplitude and 180° phase and add it to the mixing products, as described later. Thus the resultant signal mainly has the IM5 products.

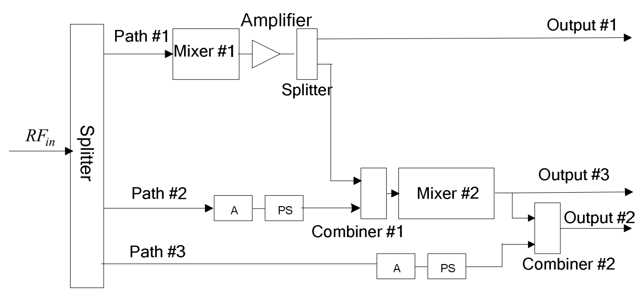

Fig. 2 Proposed IM5 and IM3 generation. A: attenuator; PS: phase shifter

Figure 2 shows the overall block diagram of the proposed circuit for generating the IM3 and IM5 products. The input two-tone signal is divided into three paths, Paths #1, #2 and #3, via a 3-way power splitter. Path #1 directs the signal to the input of Mixer #1 (with circuit shown in Fig. 1) to generate the IM3 products. The IM3 products generated are fed to a linear amplifier to obtain a proper power level and then to the power splitter. In Path #2, the amplitude and phase of the two-tone signal from the 3-way power splitter are adjusted by an attenuator and a phase shifter, and then combined with the IM3 products (from the splitter in Path #1) in combiner #1 to produce the fundamental signal given by (3). The fundamental signal is fed to Mixer #2 (which the same structure as Mixer #1) to generate the IM5 products. The values of *a* and *b* are adjusted so that *a* is large than *b* by

5 dB, for the reason described previously. (Simulation studies have shown that the difference of 2 to 8 dB is acceptable.) In Path #3, the amplitude and phase of the original two-tone signal are adjusted by another set of attenuator and phase shifter so that the adjusted two-tone signal can be used to remove the two-tone signal at the output of Mixer #2 using combiner #2. The required IM3 and IM5 products used for predistortion are therefore obtained at Output #1 and Output #2, respectively. Output #3 is a test port used to study the mixing product from Mixer #2 without removing the two-tone signal.

III. SIMULATION AND MEASUREMENT RESULTS

Computer simulation tests using the Advanced Design Systems 2009 (ADS2009) has been used to assess the performance of the proposed IM5 and IM3 generator circuit shown in Fig. 2. The circuit has also been implemented on a PCB, Roger's RO4005C. A two-tone signal with 2 MHz spacing at the center frequency of 2.2 GHz has been used in our studies.

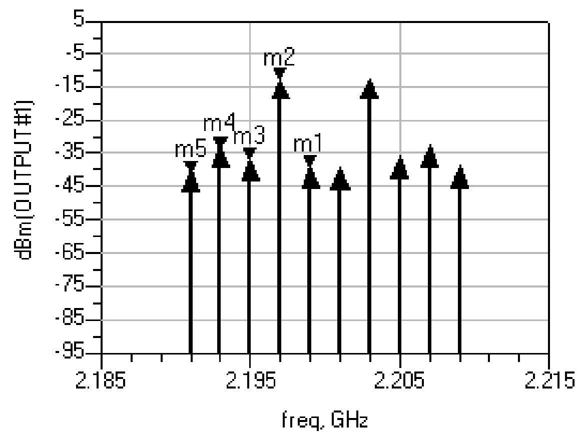

Fig. 3 Simulated signal spectrum at Output #1 in two-tone test

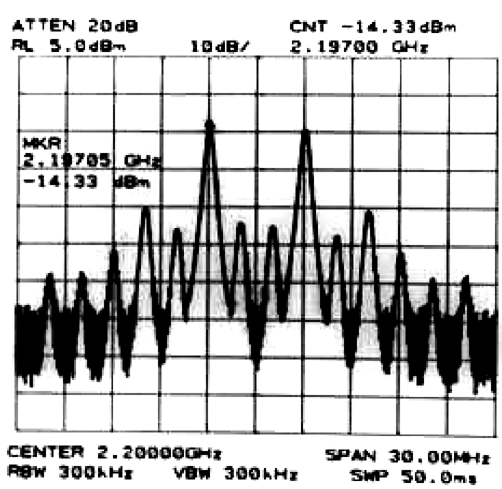

Fig. 4 Measured signal spectrum at Output #1 in two-tone test

Figures 3 and 4 show the simulation and measured spectra, respectively, at Output #1 of Fig. 2. For comparison, the power levels of different tones in the spectra are shown in Table I. The power level of the IM3 signal is more than 20 dB higher than that of the original two-tone signal and other intermodulation products of high orders.

TABLE I. SIMULATED AND MEASURED IM3 SIGNAL POWERS AT OUTPUT #1

Frequency (GHz)	*Simulated power (dBm)*	*Measured power (dBm)*
m1, 2.199	-39.7	-39.4
m2, 2.197	-13.1	-14.3
m3, 2.195	-37.2	-40.5
m4, 2.193	-33.5	-36.0
m5, 2,191	-40.9	-46.5

The simulated and measured spectra at test port Output #3 of Fig. 2 are shown in Figs. 5 and 6, respectively. The power levels of tones in these spectra are shown in Table II. The IM5 products are more than 10 dB higher than the other intermodulation products. However, the two-tone signal has even a higher power level, about 5 dB higher than that of the IM5 products and so must be suppressed.

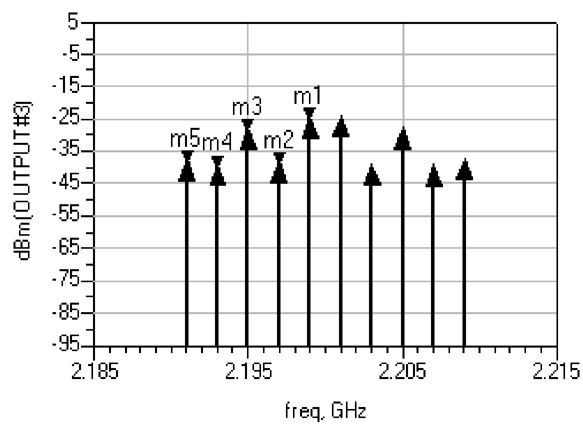

Fig. 5 Simulated signal spectrum at test port Output #3 in two-tone test

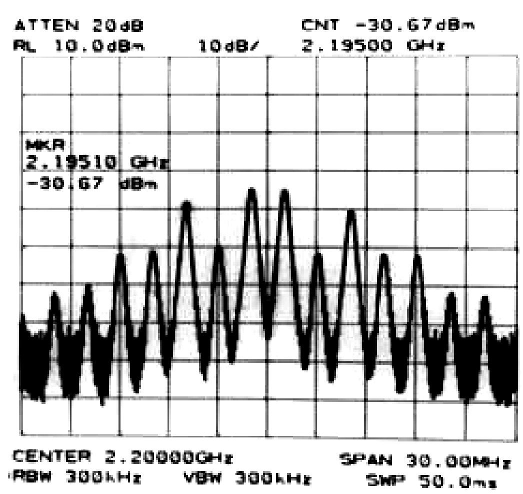

Fig. 6 Measured signal spectrum at test port Output #3 in two-tone test

TABLE II. SIMULATED AND MEASURED IM3 SIGNAL POWERS AT TEST PORT OUTPUT#3

Frequency (GHz)	*Simulated power (dBm)*	*Measured power (dBm)*
m1, 2.199	-25.2	-25.6
m2, 2.197	-39.0	-40.9
m3, 2.195	-28.6	-30.6
m4, 2.193	-39.9	-41.3
m5, 2,191	-38.6	-42.1

TABLE III. SIMULATED AND MEASURED IM3 SIGNAL POWERS AT OUTPUT#2

Frequency (GHz)	*Simulated power (dBm)*	*Measured power (dBm)*
m1, 2.199	-44.6	-43.5
m2, 2.197	-41.0	-43.0
m3, 2.195	-30.6	-32.3
m4, 2.193	-41.9	-42.9
m5, 2,191	-40.4	-43.6

Figures 7 and 8 show the simulated and measured spectra, respectively, of the IM5 products at Output #2 of Fig. 2. The power levels of the output tones are shown in Table III. Comparing the result in Fig. 6 with that in Fig. 8 shows that the two-tone signal is suppressed by nearly 18 dBm using Path #3 in Fig. 2. The IM5 product at Output #2 is more than 10 dB higher than the two-tone signal and the other intermodulation products.

The proposed IM5 and IM3 generator circuits have been tested for predistortion of a practical 10-W base-station HPA using a two-tone signal. Results have that the predistorter can reduce the IMDP3 and IMDP5 from 6.5 dBm and -8.5 dBm to -10.67 dBm and -19.5 dBm, respectively.

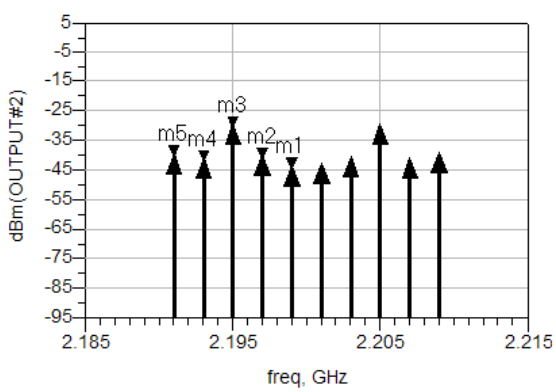

Fig. 7 Simulated signal spectrum at Output #2 in two-tone test

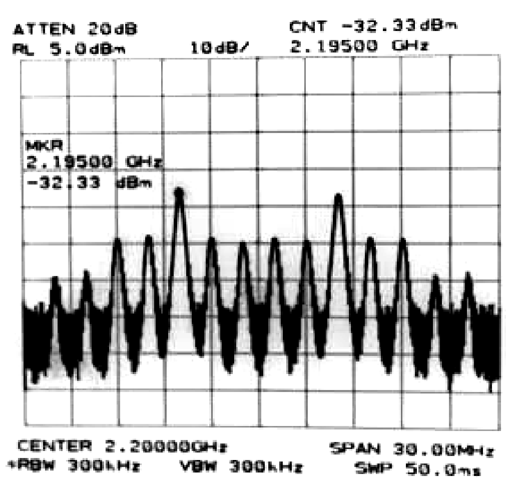

Fig. 8 Measured signal spectrum at Output #2 in two-tone test

IV. CONCLUTIONS

The design of a IM3 and IM5 order product generation circuit for predistortion of base station HPAs has been proposed, studied and implemented. Simulation and measured results have shown that the IM3 and IM5 products generated are 20 dB and 10 dB higher than other unwanted spurious. Tests have also shown that the design can suppress the IMDP3 and IMDP5 effectively in a practical base station HPA.

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