The Suppression of Intermodulation Products in Multichannel Amplifiers Close to Saturation

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Abstract: New linearization technique that reduces the third- and fifth-order intermodulation products is proposed in this paper. It suggests the injection of second harmonics (IM2) at the amplifier input whereas the IM2 signals and fourth-order nonlinear signals (IM2+IM4) are fed into the amplifier output. The reduction of the third- and fifth-order intermodulation products has been achieved by applying a new approach for a wide range of the fundamental signals' power going close to 1-dB compression point.

Key-Words: Amplifiers, Fourth-Order Nonlinear Signals, Intermodulation Products, Linearization, Saturation, Second Harmonics

1 Introduction

The linearization of multichannel amplifiers in base stations of wireless communication systems has always been of concern. The basic concept of the linearization technique that uses the second harmonics (IM2 signals) [1]-[4] gives good results in reduction of IM3 products up to the certain power of the fundamental signals that depends on load impedance [3]. However, the linearization approach does not reduce the fifth-order intermodulation products (IM5), which are the results of microwave amplifier nonlinearity and should be considered as well.

The linearization approach suggested in [5] injects the IM2 signals through one injection path and the IM2 together with fourth-order nonlinear signals (IM2+IM4) through the other at the input of the amplifier. However, the satisfactory results in reduction of IM3 and IM5 products can be obtained up to a certain power of fundamental signals that is approximately 5 dB below 1-dB compression point.

In the linearization approach proposed in this paper the IM2 signals are put at the amplifier input whereas the IM2+IM4 signals are driven at the amplifier output to suppress the third- and fifth-order intermodulation products.

A theory relating to the proposed linearization approach derived in this paper for digitally modulated signals is given in the section 2. The topology of the amplifier with the linearization circuit is described briefly in the section 3. The simulated results referring to the output spectra in case of three sinusoidal fundamental signals are represented in the section 4 for two input power levels. The influence of the proposed linearization approach to the IM3 and IM5 products for digitally modulated signal is shown in the same section.

2 Analysis

Theoretical analysis of the proposed linearization approach is based on the nonlinearity of drain-source current expressed by a polynomial model up to the third-order [6]. The expression for the nonlinearity of MESFET in amplifier circuit, under the assumption of neglecting the memory effect, is represented by eleven terms as given by (1). It connects the nonlinearity of the drain-source current i_{ds}, in reference to the gate-source voltage v_{gs}, which is represented by the coefficients K_{10} to K_{50}.

$$\begin{aligned}
&i_{ds}(v_{gs}, v_{ds}) = \\
&K_{10}v_{gs}(t) + K_{20}v_{gs}^2(t) + K_{30}v_{gs}^3(t) + \\
&+ K_{40}v_{gs}^4(t) + K_{50}v_{gs}^5(t) + \\
&+ K_{01}v_{ds}(t) + K_{02}v_{ds}^2(t) + K_{03}v_{ds}^3(t) + \\
&+ K_{11}v_{gs}(t)v_{ds}(t) + K_{21}v_{gs}^2(t)v_{ds}(t) + \\
&+ K_{12}v_{gs}(t)v_{ds}^2(t) + \ldots
\end{aligned} \tag{1}$$

The higher order nonlinear terms K_{40} and K_{50} are included into the analysis according to the analysis performed in [7] that favours the terms of drain-source current as a function of v_{gs} up to the fifth-order. The nonlinearity of drain-source current in terms of v_{ds} (voltage between drain and source of the transistor) is expressed by the coefficients K_{01} to K_{03}. Also, (1) encompasses "mixing" terms K_{11}, K_{12} and K_{21}.

The spectrum of IM2 signals, $V_{IM2}(j\omega)$, injected at the amplifier input can be represented by (2), where ρ_2 and φ_2 are the amplitude and phase of the IM2 signals. If the IM2 signals are fed into the drain together with fourth-order nonlinear signals, the drain voltage v'_{ds} can be written by (3), where v_{ds} is drain-source voltage before putting the IM2 and IM4 signals to the amplifier output. The term feedforwarding will be used hereafter for the latter operation.

$$V_{IM2}(j\omega)=\rho_2 e^{-j\varphi_2}\Big[V_B(j\omega)\otimes V_B(j\omega) \otimes \frac{1}{4}\big(\delta(\omega\pm 2\omega_0)\big)\Big] \tag{2}$$

$$\begin{aligned} V'_{ds}(j\omega)=V_{ds}(j\omega)- \\ -\Big\{\rho_2^{(F)}e^{-j\varphi_2^{(F)}}\left[V_B(j\omega)\otimes V_B(j\omega)\right]+\rho_4^{(F)}e^{-j\varphi_4^{(F)}} \\ \left[V_B(j\omega)\otimes V_B(j\omega)\otimes V_B(j\omega)\otimes V_B(j\omega)\right]\Big\} \\ \otimes\frac{1}{4}\big(\delta(\omega\pm 2\omega_0)\big) \end{aligned} \tag{3}$$

The amplitude and phase of the IM2 signal driven at the amplifier output are denoted as $\rho_2^{(F)}$ and $\varphi_2^{(F)}$, whereas $\rho_4^{(F)}$ and $\varphi_4^{(F)}$ relate to the same parameters when IM4 signal is considered.

The drain-source current distorted by the cubic term of the amplifier, K_{30}, is included into analysis by (4) as the first term. The cubic term is considered as a dominant one in causing IM3 products and spectral regrowth, [6], [7]. The mixing product of the fundamental signal and IM2 signal injected at the amplifier input is expressed as the second term. The third term exists due to the reaction between the fundamental signal and IM2 signal fed at the amplifier output. According to this, it is possible to reduce spectral regrowth caused by the third-order distortion of fundamental signal by choosing the appropriate amplitude and phase of both the injected IM2 signal (ρ_2 and φ_2) and feedforwarded IM2 signal ($\rho_2^{(F)}$ and $\varphi_2^{(F)}$).

The mixing term K_{11} analyzed is generated between gate-source voltage of the fundamental signal and drain-source voltage of the feedforwarded IM2 signal. The K_{11} term can be also produced by interaction between the fundamental signal at amplifier input and the IM2 signal appearing at its output before feedforwarding of the IM2 signal. Additionally, the fundamental signal at the amplifier output mingles with the IM2 signal that exists at the amplifier input generating K_{11} term. The amplitudes of former and latter K_{11} terms are less than that produced when the IM2 signals are led to the amplifier output. Consequently, feedeforwarded IM2 signals control in amplitude and phase the K_{11} terms mentioned above so that they are not included into the equations separately.

The nonlinearity of the drain-source conductance expressed by coefficients K_{01}, K_{02}, K_{03} is assumed to have a negligible contribution to the IM3 power levels according to [6] and [7]. The mixing terms between drain and gate, K_{12} and K_{21} produce drain-source current at IM3 frequencies with the opposite phase, so that they reduce each other [7].

$$\begin{aligned} I_{ds}(j\omega)\big|_{IM3}\approx \\ \Big\{\Big[\frac{3}{4}K_{30}+\frac{1}{4}K_{20}\rho_2 e^{-j\varphi_2}-\frac{1}{4}K_{11}\rho_2^{(F)}e^{-j\varphi_2^{(F)}}\Big] \\ \big(V_B(j\omega)\otimes V_B(j\omega)\otimes V_B(j\omega)\big)\Big\}\otimes\frac{1}{2}\delta(\omega\pm\omega_0) \end{aligned} \tag{4}$$

$$\begin{aligned} I_{ds}(j\omega)\big|_{IM5}\approx \\ \Big\{\Big[\frac{5}{8}K_{50}-\frac{1}{4}K_{11}\rho_4^{(F)}e^{-j\varphi_4^{(F)}}+\frac{1}{8}K_{30}\rho_2^2 e^{-j2\varphi_2}+ \\ +\frac{1}{8}K_{12}\rho_2^{(F)2}e^{-j2\varphi_2^{(F)}}+\frac{1}{8}K_{12}\rho_1\rho_2\rho_2^{(F)}e^{-j\left(\varphi_2+\varphi_2^{(F)}\right)}- \\ -\frac{1}{8}K_{21}\rho_2\rho_2^{(F)}e^{-j\left(\varphi_2+\varphi_2^{(F)}\right)}-\frac{1}{8}K_{21}\rho_1\rho_2^2 e^{-j2\varphi_2}\Big] \\ V_B(j\omega)\otimes V_B(j\omega)\otimes V_B(j\omega)\otimes V_B(j\omega)\otimes V_B(j\omega)\Big\} \\ \otimes\frac{1}{2}\delta(\omega\pm\omega_0) \end{aligned} \tag{5}$$

The first term in (5) that expresses the drain-source current of the IM5 products is formed due to the existence of fundamental signals and amplifier nonlinearity of the fifth-order K_{50}. The second term is the mixing product between the fundamental signal and IM4 signal fed to the amplifier output. Therefore, by adjusting the amplitude and phase of the appropriate IM4 signal the original IM5 product (the first term) can be reduced. The IM5 products are also expressed as a function of K_{30} mixing term made by reaction between two IM2 signals and fundamental one.

It is obvious that for the larger amplitudes of the fundamental signals the injected IM2 signals are supposed to have greater amplitudes as well according to (4). Since φ_2 is supposed to be equal to 180° to reduce IM3 products the phase of the K_{30} term in (5) is 360°. Accordingly, with the rise in amplitudes of IM2 signals, the third term in (5) starts increasing the power of IM5 spectrum. Due to the overlapping of IM3 and

IM5 spectra the power augmentation in the range of IM3 spectrum is unavoidable. That is why the power of IM2 signals run at the amplifier input should be kept at the reasonable level.

All mixing terms which stand by K_{12} and K_{21} in (5) are generated due to reaction between two IM2 signals and fundamental signal. The signals taken in consideration are observed at the input and output of amplifier. The amplitude of output voltage at fundamental signal frequency that is 180° out of phase in reference to the input signal is denoted as ρ_1. The K_{12} and K_{21} terms produce current at the frequencies of IM5 products with the opposite phases so that they reduce each other. Consequently, their influence to the power of IM3 and IM5 products can be cancelled. As a result, the IM2 and IM4 signals fed to the amplifier output are allowed to have power levels that are high enough to reduce IM3 and IM5 products.

3 Amplifier Design

The amplifier with the additional circuit for linearization is represented in Fig. 1. The broadband single-stage amplifier designed as described in [4] has been used for the nonlinear amplifier denoted as Amp. The design of the amplifier with the linearization circuit has been carried out by the program Advance Design System (ADS). It should be stressed that in a simulation process MESFET nonlinearity is modeled by Curtice-cubic model and Harmonic balance analysis is carried out.

The fundamental signals are led to the inputs of the amplifier and two nonlinear sources that are composed of MESFET transistors operating at various bias conditions. The IM2 source operates to produce a required power of IM2 signals retaining the power of IM4 signals sufficiently low. In the IM2+IM4 source a transistor is biased at either the pinch-off or saturation to enable simultaneously an enough power of both IM2 and IM4 signals. The amplitude adjustment of the fundamental signals is required at the inputs of the nonlinear sources.

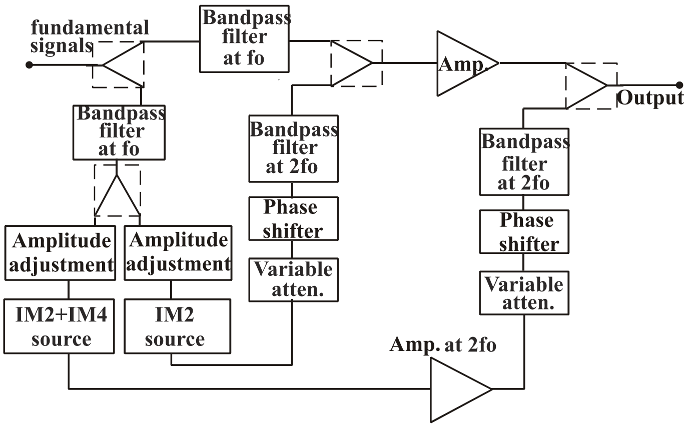

Fig 1. Amplifier with the circuit for linearization

The linearization procedure proposes the IM2 signals be led to the inputs of the amplifier and IM2 together with IM4 signals be directed to the output of the amplifier through two separated paths. The ideal elements from ADS have been used for components such as bandpass filters, phase shifters, variable attenuators, amplifier, power combiners and dividers.

4 Simulated Results

The designed amplifier with the additional circuit for linearization has been tested for three sinusoidal fundamental signals at frequencies 2.5 GHz, 2.51 GHz and 2.522 GHz. Two cases have been considered, when the power of fundamental signals at the input of amplifier is –9 dBm and -1 dBm that is 2 dB below 1-dB compression point.

The output spectra consisting of the fundamental signals, IM3 and IM5 products are compared in Fig. 2 and Fig. 3 for the cases before and after linearization. Various results are gained for different input power levels and kinds of IM3 and IM5 signals. For example, all IM3 products at frequencies $2\omega_i-\omega_j$ (the first kind) and $\omega_i+\omega_j-\omega_k$ (the second kind) $i\neq j\neq k \in(1,2,3)$ are approximately reduced by 23 dB for input power level –9 dBm. The reduction rate of IM3 products of the first and second kinds are approximately the same even in the case of higher input power at -1 dBm. If the IM5 products at frequencies $(3\omega_i-2\omega_j)$ are concerned then the results become better for 10 dB in reference to the case before linearization at –9 dBm input power. However, the improvement is only 3 dB for -1 dBm input power. The IM5 products at frequencies $(2\omega_i+\omega_j-2\omega_k)$ are lowered by 20 dB for both power levels, while the IM5 products at frequencies $(3\omega_i-\omega_j-\omega_k)$ are decreased by 13 dB for -9 dBm and by 15 dB for -1 dBm.

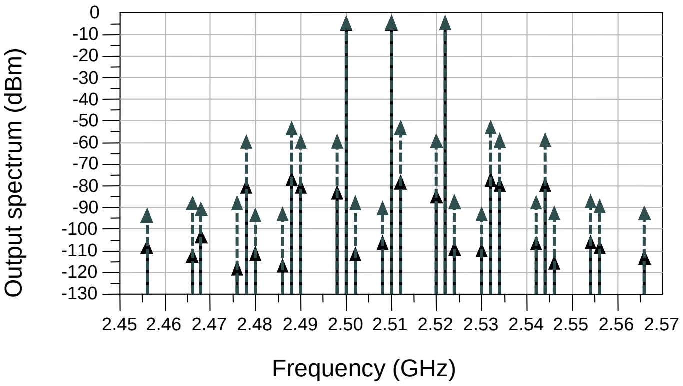

Fig. 2. Output spectrum for -9 dBm input power of fundamental signals; before (dashed line) and after the linearization (solid line)

Analyzing the results given in [5] which are gained when the IM2 signals are put into amplifier through one path and IM2+IM4 signals are injected through the other, one can notice pretty the same suppression of

IM3 and IM5 products as achieved herein in case of lower power of fundamental signals. In the case of higher power, the results relating to both the IM3 and IM5 products are much better in the new proposed linearization technique than the results achieved by the approach from [5] mentioned above.

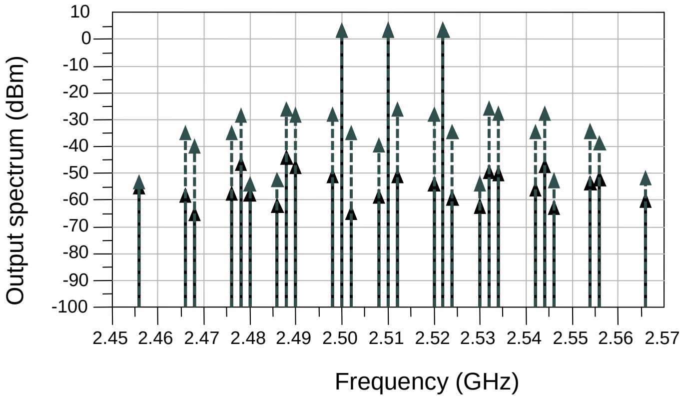

Fig. 3. Output spectrum for -1 dBm input power of fundamental signals; before (dashed line) and after linearization (solid line)

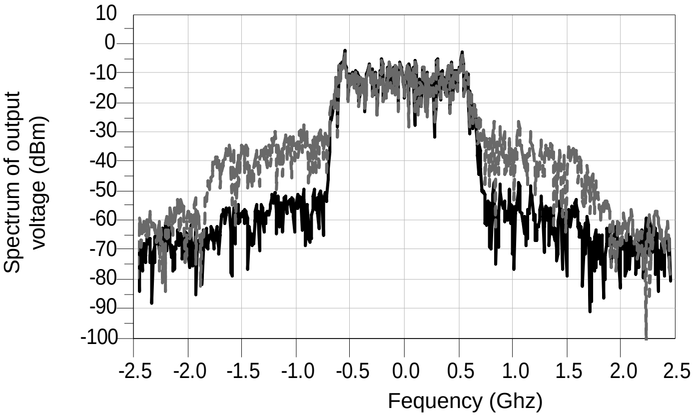

Fig. 4. Simulated spectrum of the output voltage for OQPSK digitally modulated signal before (dashed line) and after linearization (solid line) for 5 dBm carrier input power

Additionally, the amplifier has been simulated for OQPSK digitally modulated signals with 1.25 MHz spectrum width, carrier at frequency 2.5 GHz with input power 5 dBm. The input power level corresponds to the output power deep into saturation region taking into consideration 6 dB pick to average power ratio. The improvement in ACPR for ±900 kHz offset from carrier frequency over 30 kHz bandwidth gained by applying only the injection of the IM2 signals is approximately 2 dB. In the case of simultaneous injection of the IM2 signals and feedforwarding of the IM2+IM4 signals, 15 dB improvement of ACPR is obtained. The result can be seen from Fig. 4. which compares the output spectra before and after linearization. Also, the figure represents ACPR for 2.1-2.13 MHz offset, the range that belongs to the spectrum of IM5 products. The ACPR is improved by 7 dB at this offset by applying the procedure proposed in this paper.

5 Conclusion

The linearization approach proposed in this paper uses the IM2 signals generated at the output of a low-order nonlinear component and IM2+IM4 signals appearing as the output of a high-order nonlinear component. Those signals are adjusted and led to the amplifier input and output, respectively. The proposed technique gives good results in reduction of the IM3 and IM5 products for a wide range of the input power going to 1-dB compression point. Quite the most important fact is that the linearization is enabled at high power levels that was not possible to achieve by the injection of only the IM2 signals at the amplifier input. Additionally, the results got in this paper are much better for both kinds of IM products than in the case when IM2 and IM2+IM4 signals are put at the amplifier input.

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