New Linearization Technique for Third- and Fifth-Order Intermodulation Products in Multichannel Amplifiers

Jovana Ranđelović, Natasa Maleš-Ilić, Bratislav Milovanović

Abstract — **New linearization technique that reduces the third and fifth-order intermodulation products is proposed in this paper. It introduces two independent sources in the linearization circuit from which one produces the second harmonics (IM2) and the other generates both the second harmonics and fourth-order nonlinearities of the fundamental signals (IM2+IM4). 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 1dB compression point. Also, proposed linearization technique enables that the phases of the injected signals do not need to be set on the optimal values and can fluctuate within appropriate range.**

Keywords – **Third- and fifth- order intermodulation products, linearization technique**

I. INTRODUCTION

The third-order intermodulation products are the major concern in microwave amplifiers in base stations of wireless communications systems. Besides the IM3 products, the fifth-order intermodulation products (IM5), that are the results of microwave amplifier nonlinearity as well, should be considered. The effects of fundamental signals' second-order nonlinear products, IM2, to the IM3 products in multichannel microwave amplifiers have been investigated and applied so far [1-4]. The IM2 term relates to the second harmonics at frequencies $2\omega_i$ and products at frequencies that are the sum of pairs of the fundamental signal frequencies, $\omega_i+\omega_j$. The linearization technique with the injection of IM2 signals decreases IM3 power levels without affecting the power levels of the fundamental signals but the reduction of the fifth-order intermodulation cannot be accomplished using this technique.

The linearization method described in [5] has opportunity to lower both the IM3 and IM5 products. It uses the IM2 signals and the fourth-order nonlinear signals of the fundamental ones (IM4), which are brought into the amplifier through the two different paths. However, the linearization circuit of the amplifier is far more complex than in the case when only the IM2 signals are led into the amplifier.

The linearization of the third- and fifth-order intermodulation products proposed in this paper exploits the IM2 signals in one injection path and the IM2 together with the IM4 signals (IM2+IM4) in the other. These signals are generated independently at the outputs of two nonlinear components at which inputs are the fundamental signals. Thus, this approach simplifies the linearization circuit of the microwave amplifier in comparison with the linearization technique proposed in [5].

II. ANALYSIS

The nonlinear transfer characteristic of the active component, MESFET, can be represented by a five term Taylor's series by introducing higher order nonlinearities up to fifth-order. The relation between the input voltage and output current is expressed as follows if transconductance is considered as a dominant nonlinearity.

$$i_{out}(t)=g_{m_1}v_{in}(t)+g_{m_2}v_{in}^2(t)+g_{m_3}v_{in}^3(t)+g_{m_4}v_{in}^4(t)+g_{m_5}v_{in}^5(t) \qquad (1)$$

Two sinusoidal fundamental signals at the frequencies ω_i (i=1,2) with amplitudes V_{ω_i}, and phases φ_{ω_i}, are driven into the amplifier together with their second harmonics (IM2 signals) at the frequencies $2\omega_i$, with amplitudes $V_{2\omega_i}$, and phases $\varphi_{2\omega_i}$ which are put into the amplifier through one path. The IM2 and IM4 signals at frequencies $2\omega_i$, and $3\omega_i$-ω_j, $i\neq j \in(1,2)$, respectively, are injected through the other path. The amplitudes and phases of IM2 signals from the second path are $V'_{2\omega_i}$, and $\varphi'_{2\omega_i}$, whereas the IM4 signals' amplitudes and phases are $V_{\omega_{3i-j}}$, and $\varphi_{\omega_{3i-j}}$. Therefore, the input voltage can be written as:

$$v_{in}=\sum_{i=1}^{2}V_{\omega_i}\cos(\omega_i t)+\sum_{i=1}^{2}V_{2\omega_i}\cos\left(2\omega_i t+\varphi_{2\omega_i}\right)+\sum_{i=1}^{2}V'_{2\omega_i}\cos\left(2\omega_i t+\varphi'_{2\omega_i}\right)+\sum_{\substack{i=1\\ i\neq j}}^{2}\sum_{\substack{j=1\\ j\neq i}}^{2}V_{\omega_{3i-j}}\cos\left(3\omega_i t-\omega_j t+\varphi_{\omega_{3i-j}}\right) \qquad (2)$$

Substituting Eq. (2) into Eq. (1) all IM3 and IM5 products can be calculated. The output current of the IM3 products at frequencies $2\omega_i$-ω_j ($i\neq j$=1,2) are expressed by Eq. (3) including nonlinear mixing products that are the results of square, g_{m2}, and cubic, g_{m3}, terms in the amplifier transfer characteristic. The first term in Eq. (3) relates to the

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interaction between fundamental signals. The second term is dominant in reduction of the original IM3 product (the first term) by adjusting the appropriate IM2 signal in case when the linearization is performed by injection of only the IM2 signals. The influence of the injected IM2 signals to the IM3 product has been considered in [1-4].

$$\begin{aligned}
I_{out\left(2\omega_i-\omega_j\right)} &= \frac{3}{4}V_{\omega_i}^2 V_{\omega_j} g_{m3} \cos\left(2\omega_i t - \omega_j t\right) \\
&\quad + V_{\omega_j} V_{2\omega_i} g_{m2} \cos\left(2\omega_i t - \omega_j t + \varphi_{2\omega_i}\right) \\
&+ V_{\omega_j} V'_{2\omega_i} g_{m2} \cos\left(2\omega_i t - \omega_j t + \varphi'_{2\omega_i}\right) \\
&+ V_{\omega_{3i-j}} V_{\omega_i} g_{m2} \cos\left(2\omega_i t - \omega_j t + \varphi_{\omega_{3i-j}}\right) \\
&+ \frac{3}{2} V_{2\omega_i} V_{2\omega_j} V_{\omega_j} g_{m3} \cos\left(2\omega_i t - \omega_j t + \varphi_{2\omega_i} - \varphi_{2\omega_j}\right) \\
&+ \frac{3}{2} V'_{2\omega_i} V'_{2\omega_j} V_{\omega_j} g_{m3} \cos\left(2\omega_i t - \omega_j t + \varphi'_{2\omega_i} - \varphi'_{2\omega_j}\right) \\
&+ \frac{3}{2} V_{2\omega_i} V'_{2\omega_j} V_{\omega_j} g_{m3} \cos\left(2\omega_i t - \omega_j t + \varphi_{2\omega_i} - \varphi'_{2\omega_j}\right) \\
&+ \frac{3}{2} V'_{2\omega_i} V_{2\omega_j} V_{\omega_j} g_{m3} \cos\left(2\omega_i t - \omega_j t + \varphi'_{2\omega_i} - \varphi_{2\omega_j}\right) \\
&+ \frac{3}{2} V_{\omega_{3i-j}} V_{2\omega_i} V_{\omega_i} g_{m3} \cos\left(2\omega_i t - \omega_j t + \varphi_{\omega_{3i-j}} - \varphi_{2\omega_i}\right) \\
&+ \frac{3}{2} V_{\omega_{3i-j}} V'_{2\omega_i} V_{\omega_i} g_{m3} \cos\left(2\omega_i t - \omega_j t + \varphi_{\omega_{3i-j}} - \varphi'_{2\omega_i}\right) \quad (3)
\end{aligned}$$

The third term is the consequence of the injection of IM2 signals from IM2+IM4 source and square nonlinearity. The fourth term is the result of interaction between fundamental and appropriate IM4 signal. The linearization approach proposed in this paper suggests that the g_{m2} mixing products (second, third and fourth terms in Eq. (3)) be combined to cancel the original IM3 products. Additionally, there are terms at IM3 frequencies that are the results of the cubic nonlinearity in the amplifier characteristic. These products are generated by mixing the fundamental signal and two IM2 signals as well as the fundamental, IM2 and IM4 signals. The IM2 and IM4 signals can originate from the same source (fifth, sixth and tenth terms) or from the independent sources (seventh, eightieth and ninth terms).

In Eq. (4) the first term expressing the output current of the IM5 products at frequencies $3\omega_i$-$2\omega_j$ is formed due to the existence of fundamental signals and amplifier nonlinearity of the fifth-order. The second term is the mixing product between the fundamental signal and the injected IM4 signal at frequency $3\omega_i$-ω_j. 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 in terms of g_{m3} mixing terms made by reaction between the two IM2 signals and fundamental one.

All mixing terms which stand by g_{m3} in Eqs. (3) and (4) can be neglected for lower power of the fundamental signals, up to approximately 10 dB back off from 1-dB compression point. In the case of higher power of the input signals those terms affect the power of IM3 and IM5 products depending on the phases of the injected IM2 and IM2+IM4 signals. Accordingly, if the IM2 signals injected through two different paths have opposite phases (or that they differ in phases for more than 90°) the seventh term in Eq. (3) will decrease the fifth term, the eightieth term will reduce the sixth term and the last two will influence each other. It is obvious from Eq. (4) that the g_{m3} mixing terms behave exactly the same.

$$\begin{aligned}
&I_{out\left(3\omega_i-2\omega_j\right)} = \\
&\frac{5}{8} V_{\omega_i}^3 V_{\omega_j}^2 g_{m5} \cos\left(3\omega_i t - 2\omega_j t\right) \\
&+ V_{\omega_j} V_{\omega_{3i-j}} g_{m2} \cos\left(3\omega_i t - 2\omega_j t + \varphi_{\omega_{3i-j}}\right) \\
&+ \frac{3}{2} V_{2\omega_i} V_{2\omega_j} V_{\omega_i} g_{m3} \cos\left(3\omega_i t - 2\omega_j t + \varphi_{2\omega_i} - \varphi_{2\omega_j}\right) \\
&+ \frac{3}{2} V_{2\omega_i} V'_{2\omega_j} V_{\omega_i} g_{m3} \cos\left(3\omega_i t - 2\omega_j t + \varphi_{2\omega_i} - \varphi'_{2\omega_j}\right) \\
&+ \frac{3}{2} V'_{2\omega_i} V_{2\omega_j} V_{\omega_i} g_{m3} \cos\left(3\omega_i t - 2\omega_j t + \varphi'_{2\omega_i} - \varphi_{2\omega_j}\right) \\
&+ \frac{3}{2} V'_{2\omega_i} V'_{2\omega_j} V_{\omega_i} g_{m3} \cos\left(3\omega_i t - 2\omega_j t + \varphi'_{2\omega_i} - \varphi'_{2\omega_j}\right) \quad (4)
\end{aligned}$$

III. AMPLIFIER DESIGN

The amplifier with the additional circuitry for the injection and adjustment of IM2 as well as IM2+IM4 signals is represented in Fig. 1. The broadband single-stage amplifier designed as described in [3] has been used for the nonlinear amplifier denoted as Amp.

The fundamental signals are led to the inputs of two components with high-order and low–order non-linear characteristics. Therefore, in the point denoted as P1, Fig.1, both IM2 and IM4 signals are generated with high power and IM2>IM4, while at the point P2, the IM2 signals have sufficient power levels, and IM4 can be neglected. The IM2 and IM2+IM4 signals obtained at points P2 and P1, respectively, are adjusted in amplitudes and phases through two separated paths. They are combined with the fundamental signals at the amplifier input (P3). The phase shifters, variable attenuators, power combiners/splitters, bandpass filters are additional components included in the injection paths of the IM2 and IM2+IM4 signals.

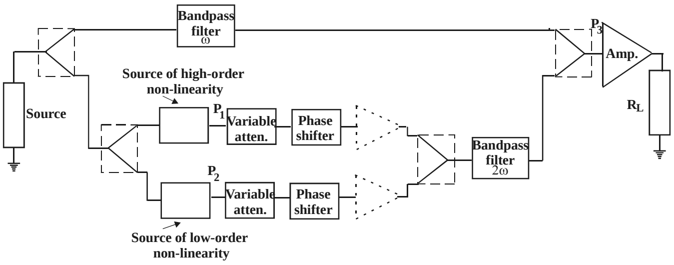

Fig 1. Amplifier with the circuit for linearization

The design of the amplifier with the linearization circuit has been carried out by the program named Advance Design System (ADS). In simulation the ideal elements from the library of this software have been used for the linearization circuit's components. For the components denoted as nonlinear sources with low and high-order nonlinearity, the amplifier designed and supplied with different biases has been used in simulation.

IV. SIMULATED RESULTS

The designed amplifier with the additional circuit for the linearization has been tested for three sinusoidal fundamental signals at frequencies 2.5 GHz, 2.51 GHz and 2.522 GHz for two signals' power levels, –6 dBm and -1 dBm that is 5 dB below 1-dB compression point. The results for IM3 products (the first and second kind) at frequencies 2.478 GHz and 2.488 GHz, as well as IM5 products at frequencies 2.456 GHz, 2.466 GHz 2.468 GHz are shown in Table I. Column (d) shows the results obtained by the linearization approach presented in this paper when the IM2 and IM2+IM4 signals are adjusted on optimal amplitudes and phases. The achieved results are compared with the IM power levels without applying linearization technique (col. a), after linearization with the injection of only IM2 signals (col. b), and after linearization attained by using IM2 and IM4 signals, [5], (col. c).

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 32 dB for input power level –6 dBm. The reduction rate is descending with the higher input power, so that the IM3 products of the first and second kinds are reduced by approximately 11 dB at -1 dBm input power. If the results referring to all IM5 products are concerned then the improvements are 10 dB for –6 dBm up to 3 dB for -1 dBm input power for ($3\omega_i-2\omega_j$) kind of the IM5 products. The IM5 products at frequencies ($2\omega_i+\omega_j-2\omega_k$) are lowered by 11 dB for both power levels, while the IM5 products at frequencies ($3\omega_i-\omega_j-\omega_k$) are decreased by 13 dB for -6 dBm and by 2 dB for -1 dBm.

It follows from the simulated results that considerably greater reduction of IM5 power levels are obtained by the injection of IM2 and IM2+IM4 signals than in the linearization with the IM2 signals only. Also, it is clear that at the input power level -1 dBm the reduction of IM3 products is negligible by applying merely the IM2 signals' injection. In contrast to this, all IM3 products are suppressed by 11 dB by using the linearization technique suggested in this paper. The results relating to the IM3 products is better in the proposed technique than in the case when the IM2 signals are put into amplifier through one path and IM4 signals are injected through the other path. Additionally, the linearization circuit of the latter linearization approach contains four components (variable attenuator, phase shifter, power splitter and combiner) more than in the circuit shown in Fig.1 that suits the linearization technique proposed in this paper.

Additionally, the linearization approach presented in this paper allows that the IM2 signals from one injection path can have the phases from the range of 80^0 while the phase of IM2+IM4 signals in the other injection path can vary in the range of $\Delta=20^0$ as displayed in Fig. 2 for the input power level -6 dBm. The output spectra containing the fundamental signals, IM3 and IM5 products before (dashed lines) and after the linearization (solid lines) for -20° deviation from the optimal phase in the injection path of the IM2 signals are shown in Fig.3.

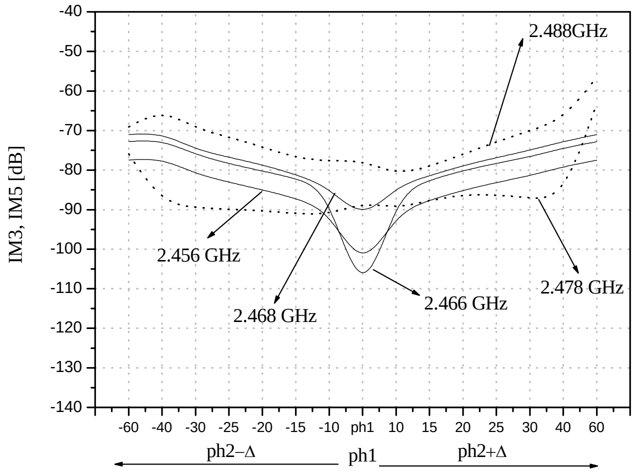

Fig 2. IM3 and IM5 products after linearization for various phases of IM2 and IM2+IM4 signals in case of -6 dBm input power

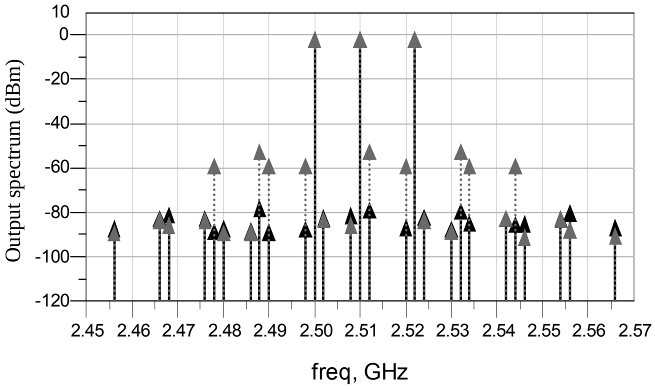

Fig 3. Output spectrum for -6 dBm input power of fundamental signals; before (dashed line) and after linearization (solid line) for -20^0 deviation from the optimal phase.

When the output power is -1 dBm, the fluctuation of the IM2 signals' phases in one injection path is limited to the range of 30° while the same parameter should stay within $\Delta'=15°$ range in the other injection path as illustrated in Fig. 4. Fig. 5 shows the output spectrum for -15^0 variation from the optimal phase in the injection path of IM2 signals.

Viewing the results one can notice nearly the same power of the IM3 products in case when phases in two injection paths take values from appropriate range as achieved for the optimal case. The IM5 products become worse for a few decibels than they had been before linearization for -6 dBm input power. In the case of -1 dBm input power the IM5 products are lowered, with the exception at 2.456 GHz frequency, in comparison with the state before linearization. The rate of reduction is slightly less than in the optimal case and depends on the frequencies. All the more remarkable is that the IM5 products in the considered power range of the input signals are kept either lower than the reduced IM3 products or nearly equal to them.

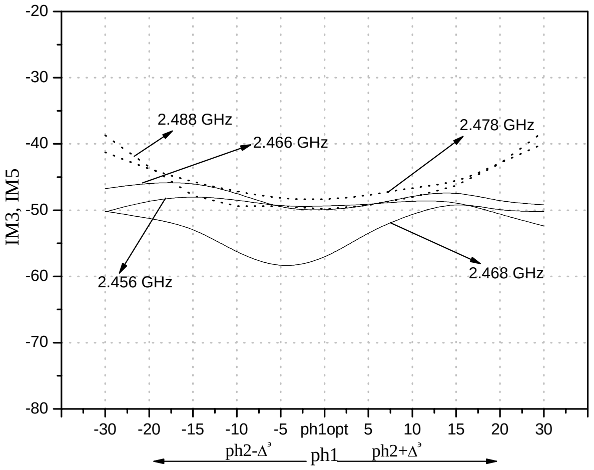

Fig. 4. IM3 and IM5 products after linearization for various phases of IM2 and IM2+IM4 signals in case of -1 dBm input power

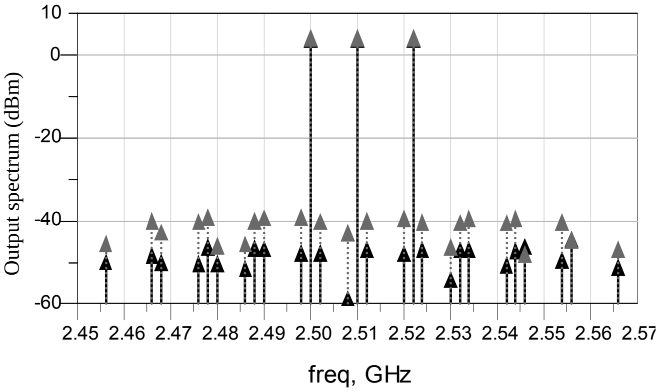

Fig 5. Output spectrum for -1 dBm input power of fundamental signals; before (dashed line) and after linearization (solid line) for $+15^0$ deviation from the optimal phase.

V. 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 through the two separated paths. The proposed technique gives good results in reduction of the IM3 and IM5 products for lower power of the fundamental signals of up to 10 dB back off from 1-dB compression point. Also, satisfactory decrease of the IM3 power levels can be achieved for the higher power of fundamental signals near 1-dB compression point. Those results are nearly the same as in the case when the IM2 signals are driven through one path, while only the IM4 signals are injected through the other path, but considerably better than in the linearization with only the IM2 signals. Quite the most important fact is that the linearization circuit is not as complex as in the linearization with the IM2 and IM4 signals. On the top of that, the phases in two different injection paths are not constrained on optimal values and can fluctuate within appropriate range.

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TABLE I: THE POWER LEVELS OF IM3 AND IM5 PRODUCTS WITHOUT APPLYING LINEARIZATION (COL. A)), WITH THE INJECTION OF IM2 SIGNALS (COL. B)), WITH THE INJECTION OF IM2 AND IM4 SIGNALS (COL. C)), AND WITH THE INJECTION OF IM2 AND IM2+IM4 SIGNALS (COL. D))

	2.456 $3\omega_i-2\omega_j$				2.466 $2\omega_i+\omega_j-2\omega_k$				2.468 $3\omega_i-\omega_j-\omega_k$				2.478 $2\omega_i-\omega_j$				2.488 $\omega_i+\omega_j-\omega_k$			
Pwr. [dBm]	a)	b)	c)	d)	a)	b)	c)	d)	a)	b)	c)	d)	a)	b)	c)	d)	a)	b)	c)	d)
-6	-87	-91	-110	-102	-81	-84	-100	-93	-83	-87	-91	-102	-57	-85	-83	-89	-50	-81	-81	-82
-1	-44	-44	-48	-49	-39	-39	-49	-50	-41	-43	-53	-58	-38	-40	-47	-48	-39	-41	-44	-50