Zbornik radova 49. Konferencije za ETRAN, Budva, 5-10. juna 2005, tom II
Proc. 49th ETRAN Conference, Budva, June 5-10, 2005, Vol. II

THE LINEARIZATION OF TWO MULTICHANNEL AMPLIFIERS CONNECTED IN CASCADE BY USING THE SECOND HARMONIC INJECTION

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Abstract — *The linearization of two amplifiers connected in cascade has been performed in this paper by the injection of the fundamental signals' second harmonics (IM2 signals) at the inputs of the amplifiers. The third-order intermodulation products have been reduced for wider power range of the fundamental signals going close to 1-dB compression point in comparison with the case when second harmonics are fed into only one amplifier. Also, the proposed linearization approach reduces the susceptibility of the linearization technique that drives the second harmonics at the input of a single amplifier to the amplitude and phase variation from the optimal values.*

1. INTRODUCTION

The intermodulation (IM) especially the third-order (IM3) generated in-band, has always been of concern, particularly when many channels are simultaneously processed in base station of wireless communication systems. The effects of carriers' second-order IM products, IM2, (second harmonics and products at frequencies that are the sum of pairs of the fundamental signal frequencies) to the IM3 products in multichannel microwave amplifiers have been investigated and applied so far in a few works [1-4]. The linearization technique with the injection of IM2 signals reduces IM3 power levels without affecting the power levels of the fundamental signals. The linearizatoin has been attained by adjusting the amplitudes and phases of the IM2 signals on the optimal values. However, this technique is constrained to the lower power levels of the fundamental signals, approximately 10 dB below 1-dB compression point. Also, this approach is very susceptible to the amplitude and phase characteristics of the IM2 signals.

In this paper IM2 signals are led at the inputs of two amplifiers connected in cascade. An independent control of their amplitudes and phases is carried out in order to reduce IM3 products. In this way, the phases of the IM2 signals in two paths do not have to be adjusted so strictly on optimal values. Therefore, the reduction of IM3 products is attained by tuning the amplitudes of the IM2 signals through two paths, whereas the phases can float in appropriate range. Also, the approach presented in this paper enables the linearization of two cascaded amplifiers for power of the fundamental signals approaching saturation.

2. ANALYSIS

In practice, the transmit path of RF signals is usually composed of a chain of cascaded amplifiers to achieve sufficient output power and signal gain. Fig. 1 shows the block diagram of the amplifying system under consideration (two amplifiers connected in cascade) including the additional circuitries for the injection and adjustment of the IM2 signals.

By introducing nonlinearities of up to fifth-order, the transfer characteristic of the active component, (MESFET in the amplifier), can be represented by a five term Taylor's series with transconductance dominant nonlinearity. This expression connects input voltage and output current and can be stated as:

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

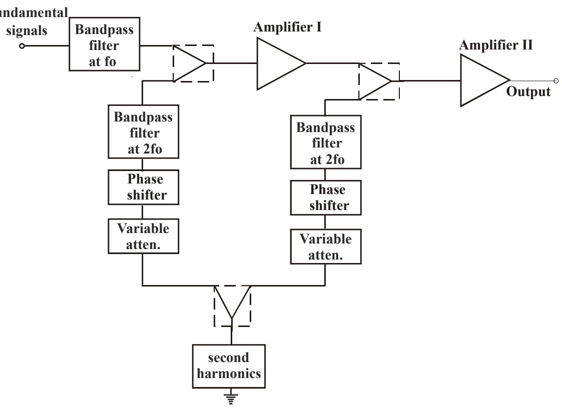

Fig. 1. *Amplifying system with the additional circuit for linearization with IM2 injection and adjustment*

The two-tones of the fundamental signals are introduced at the input of the first amplifier in cascade labeled as Amplifier I in Fig.1. Thus, the signals at frequencies ω_i with amplitudes V'_{ω_i} are driven into the amplifier together with their IM2 signals at frequencies $(\omega_i+\omega_j)$, with amplitudes $V_{\omega_{ij}}^{(1)}$, and phases $\varphi_{\omega_{ij}}^{(1)}$ for $i,j \in (1,2)$. Therefore, the input voltage is expressed as:

$$v_{in1} = \sum_{i=1}^{2} V'_{\omega_i} \cos(\omega_i t) + \sum_{i=1}^{2}\sum_{j=1}^{2} V_{\omega_{ij}}^{(1)} \cos\left(\omega_i t + \omega_j t + \varphi_{\omega_{ij}}^{(1)}\right) \qquad (2)$$

Substituting (2) into (1) all spectrum products at the output of Amplifier I can be calculated. Hence, the output current and voltage at the fundamental frequency ω_i can be expressed by:

$$I_{out1(\omega_i)} = \sum_{i-1}^{2} g_{m1} V'_{\omega_i} \cos(\omega_i t) + \\ + \sum_{i=1}^{2}\sum_{j=1}^{2}\left[g_{m2} V_{\omega_{ij}}^{(1)} V'_{\omega_j} \cos\left(\omega_i t + \varphi_{\omega_{ij}}^{(1)}\right) + \right. \qquad (3) \\ \left. + \frac{3}{4} g_{m3} V'_{\omega_i} V'^2_{\omega_j} \cos(\omega_i t) \right] \Rightarrow V_{in2(\omega_i)} = \sum_{i=1}^{2} V''_{\omega_i} \cos\left(\omega_i t + \varphi''_{\omega_i}\right)$$

Also, the output current, that is the voltage, at frequencies of the IM2 signals ($2\omega_1$, $2\omega_2$ and $\omega_1 + \omega_2$) is presented as follows:

$$I_{out1(\omega_i+\omega_j)} = \sum_{i=1}^{2}\sum_{j=1}^{2} g_{m1} V^{(1)}_{\omega_{ij}} \cos\left(\omega_i t + \omega_j t + \varphi^{(1)}_{\omega_{ij}}\right) +$$
$$+ \sum_{i=1}^{2}\sum_{j=1}^{2} g_{m2} V'_{\omega_i} V'_{\omega_j} \cos\left(\omega_i t + \omega_j t + \varphi'_{\omega_{ij}}\right)$$
$$\Rightarrow V_{in2(\omega_i+\omega_j)} = \sum_{i=1}^{2}\sum_{j=1}^{2} V''_{\omega_{ij}} \cos\left(\omega_i t + \omega_j t + \varphi''_{\omega_{ij}}\right) \qquad (4)$$

The current of the IM3 products at frequencies $2\omega_i$-ω_j ($i \neq j$=1,2) is expressed by (5). The first term exists due to mixing of the fundamental signals as a product of cubic nonlinearity of the amplifier, g_{m3}. The second term is a consequence of a square term g_{m2} that causes the reaction between injected IM2 signals and fundamental signals. Two products standing by g_{m3} nonlinear coefficient are results of stirring two IM2 signals and fundamental one. At the end, the voltage at IM3 frequencies appearing at the output of the first amplifier in cascade is given.

$$I_{out1(2\omega_i-\omega_j)} = \tfrac{3}{4} g_{m3} V'^{2}_{\omega_i} V'_{\omega_j} \cos\left(2\omega_i t - \omega_j t\right) +$$
$$+ g_{m2} V^{(1)}_{\omega_{ii}} V'_{\omega_j} \cos\left(2\omega_i t - \omega_j t + \varphi^{(1)}_{\omega_{ii}}\right) +$$
$$+ \tfrac{3}{2} g_{m3} V^{(1)}_{\omega_{ii}} V^{(1)}_{\omega_{jj}} V'_{\omega_j} \cos\left(2\omega_i t - \omega_j t + \varphi^{(1)}_{\omega_{ii}} - \varphi^{(1)}_{\omega_{jj}}\right) + \qquad (5)$$
$$+ \tfrac{3}{2} g_{m3} V^{(1)}_{\omega_{ij}} V^{(1)}_{\omega_{jj}} V'_{\omega_i} \cos\left(2\omega_i t - \omega_j t + \varphi^{(1)}_{\omega_{ij}} - \varphi^{(1)}_{\omega_{jj}}\right)$$
$$\Rightarrow V_{in2(2\omega_i-\omega_j)} = \sum_{i=1}^{2}\sum_{j=i+1}^{2} V''_{2\omega_i-\omega_j} \cos\left(2\omega_i t - \omega_j t + \varphi''_{2\omega_i-\omega_j}\right)$$

Moreover, the fourth-order nonlinear products (IM4) turn up at the amplifier output as a result of its nonlinear transfer characteristic. The output current of IM4 signals at the frequencies $3\omega_i$-ω_j ($i \neq j$=1,2) is expressed by (6). The fundamental signals mixed due to the fourth-order nonlinearity of the amplifier produce the first term in the equation. The other terms emerge as the results of interaction between either the two fundamental signals and the IM2 signal or the three IM2 signals. The output voltage at the IM4 frequencies is given in the same expression.

$$I_{out1(3\omega_i-\omega_j)} = \frac{1}{2} g_{m4} V'^{3}_{\omega_i} V'_{\omega_j} \cos\left(2\omega_i t - \omega_j t\right) +$$
$$+ \tfrac{3}{2} g_{m3} V^{(1)}_{\omega_{ii}} V'_{\omega_i} V'_{\omega_j} \cos\left(3\omega_i t - \omega_j t + \varphi^{(1)}_{\omega_{ii}}\right) + \qquad (6)$$
$$+ \tfrac{3}{2} g_{m3} V^{(1)}_{\omega_{ij}} V^{(1)}_{\omega_{ii}} V^{(1)}_{\omega_{jj}} \cos\left(3\omega_i t - \omega_j t + \varphi^{(1)}_{\omega_{ij}} + \varphi^{(1)}_{\omega_{ii}} - \varphi^{(1)}_{\omega_{jj}}\right)$$
$$\Rightarrow V_{in2(3\omega_i-\omega_j)} = \sum_{i=1}^{2}\sum_{j=i+1}^{2} V''_{3\omega_i-\omega_j} \cos\left(3\omega_i t - \omega_j t + \varphi''_{3\omega_i-\omega_j}\right)$$

It follows from (7) that the voltage at the input of the second amplifier in cascade (Amplifier II) contains the fundamental signals, IM2, IM3 and IM4 signals that are formed at the output of the first amplifier as well as the IM2 signals injected through the other path directly at the input of the second amplifier. The amplitudes and phases of latter IM2 signals are $V^{(2)}_{\omega_{ij}}$, and $\varphi^{(2)}_{\omega_{ij}}$ for $i,j \in (1,2)$.

$$v_{in2} = v_{in2(\omega_i)} + v_{in2(\omega_i+\omega_j)} + v_{in2(2\omega_i-\omega_j)} + v_{in2(3\omega_i-\omega_j)} +$$
$$+ \sum_{i=1}^{2}\sum_{j=1}^{2} V^{(2)}_{\omega_{ij}} \cos\left(\omega_i t + \omega_j t + \varphi^{(2)}_{\omega_{ij}}\right) \qquad (7)$$

The current of the IM3 products at frequencies $2\omega_i$-ω_j ($i \neq j$=1,2) at the output of the second amplifier is expressed by (8) where the coefficients h_{m1}, h_{m2} and h_{m3} represent the transconductance nonlinerities of the second amplifier. In the equation the first term relates to the IM3 products of the first amplifier linearly transmitted by the Amplifier II. The second term exists due to the cubic nonlinearity of the second amplifier that mingles fundamental signals only. The third term, together with the first one, takes part in reduction of the original IM3 product of the second amplifier (the second term) by adjusting the appropriate IM2 signal driven at the input of the first amplifier. By feeding IM2 signals at the input of the second amplifier through an independent path, there is the additional term at IM3 frequencies that is the result of mixing the fundamental and appropriate IM2 signal (the fourth term). The fifth term is the consequence of the square nonlinearity of Amplifier II (h_{m2}) and the existence of fundamental and IM4 signals formed at the output of the first amplifier. Furthermore, there are terms at IM3 frequencies that are the results of the cubic nonlinearity in the second amplifier characteristic (h_{m3}). These terms are generated by mixing the fundamental and two IM2 signals as well as the fundamental, IM2 and IM4 signals. The IM2 signals originating from the first amplifier form the sixth and seventh terms, whereas the IM2 signals injected directly into the second amplifiers generate the eightieth and ninth terms. Also, the IM2 signals from the first amplifier and ones put directly into the second amplifier react with the fundamental signals and produce tenth to thirteenth terms in (8). Additionally, the IM2 signals interact with the IM4 signals and fundamental signals making the last four terms. All those mixing terms that stand by h_{m3} can be neglected for lower power of the fundamental signals.

In case when the linearization is carried out by the injection of IM2 signals at the input of a single amplifier [1-4] the reduction of IM3 power levels can be reached by adjusting amplitudes and phases of the IM2 signals up to a certain value of fundamental signals' power. At the higher power levels of the input signals the h_{m3} mixing terms which do not affect the IM3 products in case of lower power of the input signals begin influencing them. Consequently, the tuning of IM2 signals cannot reduce IM3 products. This is conditioned by the fact that the h_{m3} mixing terms do not depend on IM2 signal phases due to nearly the same phases of the IM2 signals controlled over the same injection path.

The linearization approach proposed in this paper suggests that the h_{m2} mixing products (third, fourth and fifth terms in (8)) be combined to cancel the original IM3 products. In this way, the third and fifth terms can be set in amplitudes and phases through the injection path to the Amplifier I, whilst the third term is headed over the injection path to the second amplifier in cascade. Moreover, the h_{m3} terms made by reaction between IM2 signals or IM2 and IM4 signals directed through two different paths into the amplifying system can lower the h_{m3} products emerging as a result of mixing between those products led to the amplifiers through the same path. As a consequence of a descending influence of h_{m3} terms it is possible to decrease IM3 products for higher power levels of the fundamental signals going closer to 1-dB compression point in comparison with the linearization that exploits the IM2 signals put into only one amplifier.

$$
\begin{aligned}
I_{out2(2\omega_i-\omega_j)} &= h_{m1}V_{in2(2\omega_i-\omega_j)}+ \qquad (8)\\
&+\tfrac{3}{4}h_{m3}V_{\omega_i}^{''2}V_{\omega_j}^{''}\cos\left(2\omega_i t-\omega_j t+\varphi_{\omega_i}^{''}\right)+\\
&+h_{m2}V_{\omega_{ii}}^{''}V_{\omega_j}^{''}\cos\left(2\omega_i t-\omega_j t+\varphi_{\omega_{ii}}^{''}-\varphi_{\omega_j}^{''}\right)+\\
&+h_{m2}V_{\omega_{ii}}^{(2)}V_{\omega_j}^{''}\cos\left(2\omega_i t-\omega_j t+\varphi_{\omega_{ii}}^{(2)}-\varphi_{\omega_j}^{''}\right)+\\
&+h_{m2}V_{3\omega_i-\omega_j}^{''}V_{\omega_i}^{''}\cos\left(2\omega_i t-\omega_j t+\varphi_{3\omega_i-\omega_j}^{''}-\varphi_{\omega_i}^{''}\right)+\\
&+\tfrac{3}{2}h_{m3}V_{\omega_{ii}}^{''}V_{\omega_{jj}}^{''}V_{\omega_j}^{''}\cos\left(2\omega_i t-\omega_j t+\varphi_{\omega_{ii}}^{''}-\varphi_{\omega_{jj}}^{''}+\varphi_{\omega_j}^{''}\right)+\\
&+\tfrac{3}{2}h_{m3}V_{\omega_{ij}}^{''}V_{\omega_{jj}}^{''}V_{\omega_i}^{''}\cos\left(2\omega_i t-\omega_j t+\varphi_{\omega_{ij}}^{''}-\varphi_{\omega_{jj}}^{''}+\varphi_{\omega_i}^{''}\right)+\\
&+\tfrac{3}{2}h_{m3}V_{\omega_{ii}}^{(2)}V_{\omega_{jj}}^{(2)}V_{\omega_j}^{''}\cos\left(2\omega_i t-\omega_j t+\varphi_{\omega_{ii}}^{(2)}-\varphi_{\omega_{jj}}^{(2)}+\varphi_{\omega_j}^{''}\right)+\\
&+\tfrac{3}{2}h_{m3}V_{\omega_{ij}}^{(2)}V_{\omega_{jj}}^{(2)}V_{\omega_i}^{''}\cos\left(2\omega_i t-\omega_j t+\varphi_{\omega_{ij}}^{(2)}-\varphi_{\omega_{jj}}^{(2)}+\varphi_{\omega_i}^{''}\right)+\\
&+\tfrac{3}{2}h_{m3}V_{\omega_{ii}}^{''}V_{\omega_{jj}}^{(2)}V_{\omega_j}^{''}\cos\left(2\omega_i t-\omega_j t+\varphi_{\omega_{ii}}^{''}-\varphi_{\omega_{jj}}^{(2)}+\varphi_{\omega_j}^{''}\right)+\\
&+\tfrac{3}{2}h_{m3}V_{\omega_{ii}}^{(2)}V_{\omega_{jj}}^{''}V_{\omega_j}^{''}\cos\left(2\omega_i t-\omega_j t+\varphi_{\omega_{ii}}^{(2)}-\varphi_{\omega_{jj}}^{''}+\varphi_{\omega_j}^{''}\right)+\\
&+\tfrac{3}{2}h_{m3}V_{\omega_{ij}}^{''}V_{\omega_{jj}}^{(2)}V_{\omega_i}^{''}\cos\left(2\omega_i t-\omega_j t+\varphi_{\omega_{ij}}^{''}-\varphi_{\omega_{jj}}^{(2)}+\varphi_{\omega_i}^{''}\right)+\\
&+\tfrac{3}{2}h_{m3}V_{\omega_{ij}}^{(2)}V_{\omega_{ii}}^{''}V_{\omega_i}^{''}\cos\left(2\omega_i t-\omega_j t+\varphi_{\omega_{ij}}^{(2)}-\varphi_{\omega_{jj}}^{''}+\varphi_{\omega_i}^{''}\right)+\\
&+\tfrac{3}{2}h_{m3}V_{3\omega_i-\omega_j}^{''}V_{\omega_{ii}}^{''}V_{\omega_i}^{''}\cos\left(2\omega_i t-\omega_j t+\varphi_{3\omega_i-\omega_j}^{''}-\varphi_{\omega_{ii}}^{''}+\varphi_{\omega_i}^{''}\right)+\\
&+\tfrac{3}{2}h_{m3}V_{3\omega_i-\omega_j}^{''}V_{\omega_{ii}}^{(2)}V_{\omega_i}^{''}\cos\left(2\omega_i t-\omega_j t+\varphi_{3\omega_i-\omega_j}^{''}-\varphi_{\omega_{ii}}^{(2)}+\varphi_{\omega_i}^{''}\right)+\\
&+\tfrac{3}{2}h_{m3}V_{3\omega_i-\omega_j}^{''}V_{\omega_{ij}}^{''}V_{\omega_j}^{''}\cos\left(2\omega_i t-\omega_j t+\varphi_{3\omega_i-\omega_j}^{''}-\varphi_{\omega_{ij}}^{''}+\varphi_{\omega_j}^{''}\right)+\\
&+\tfrac{3}{2}h_{m3}V_{3\omega_i-\omega_j}^{''}V_{\omega_{ij}}^{(2)}V_{\omega_j}^{''}\cos\left(2\omega_i t-\omega_j t+\varphi_{3\omega_i-\omega_j}^{''}-\varphi_{\omega_{ij}}^{(2)}+\varphi_{\omega_j}^{''}\right)
\end{aligned}
$$

3. SIMULATED RESULTS

Advanced Design System-ADS software has been used for simulation. The nonlinear amplifier denoted as Amplifier I in Fig.1 has been designed as the broadband single-stage amplifier as described in [3]. In the CAD simulation, non-linear Curtice's cubic model was used for MESFET modeling. The small-signal gain of the amplifier is 6 dB.

The distributed amplifier in configuration of three cascaded single-stage distributed amplifier has been designed relying on amplifier design from [5]. The MESFET used in simulation and denoted as cf_nec_NE71000hi_19920211 is from ADS library. The small-signal gain of this amplifier is 19 dB at 2.5 GHz. Therefore, the amplifying system is characterized by small-signal gain of 26 dB around frequency 2.5 GHz while the input and output reflection coefficients are -17 dB and -8 dB, respectively.

The ideal elements from ADS have been used for other components (bandpass filters, phase shifters, variable attenuators, power combiners and dividers).

The designed amplifying system of two cascaded amplifiers 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. Two cases have been considered, when the power of fundamental signals at the amplifying system input is –25 dBm and -20 dBm that is 1 dB below 1-dB compression point of the second amplifier.

The results relating to the output spectra are shown in Fig.2 for the input power level -25 dBm. The figure compare the output spectra containing the fundamental signals, IM3 and IM5 products before (dashed lines) and after the linearization (solid lines). Various reducing levels are achieved for different kinds of IM3 signals. For example, IM3 products at frequencies $2\omega_i$-ω_j (the first kind) and ω_i+ω_j-ω_k (the second kind) $i \neq j \neq k \in (1,2,3)$ are approximately reduced by 24 dB and 30 dB, respectively. In case when the IM2 signals are injected only at the input of Amplifier I the same results as in this approach can be achieved for -25 dBm fundamental signals' power. However, the IM2 signals have to be adjusted on optimal amplitude and phase. In our approach, the IM2 signals in one injection path can take the value of phase from the range of 80° while the phase of the IM2 signals in the other injection path can vary in the range of 40°. The output spectra for -40° deviation from the optimal phase in the injection path of the first amplifier are illustrated in Fig.3.

The reducing rate is descending with the higher input power, so that the IM3 products of the first and second kinds are reduced by 10 dB and 14 dB at -20 dBm input power as shown in Fig.4. However, concerning the results obtained by the injection of IM2 signals only at the second amplifier that show 4 dB reduction of IM3 products, the sufficient improvement is attained by leading IM2 signals at the input of both amplifiers simultaneously. When the input power is -20 dBm, the fluctuation of the IM2 signals' phases is limited to the range of 40° for the phase in one injection path while the same parameter should stay within 20° range in the other injection path. Fig.5 shows the output spectrum for -20° discrepancy of the phase in the injection path of the first amplifier from the optimal value. Viewing the results one can notice nearly the same power of the IM3 products (exactly 3 dB higher) as they are shown in previous figure for the optimal case.

If the results referring to IM5 products are concerned then these products become worse for a few decibels than they had been before linearization for both values of the input power. Actually, the power of the IM5 products rises, yet stay either lower than the reduced IM3 products or nearly equal to them.

4. CONCLUSION

This paper presents for the first time the investigation of the linearization of two amplifiers connected in cascade based on the injection of the second harmonics (IM2 signals). The linearization procedure presented proposes the IM2 signals be fed at the inputs of two amplifiers connected in cascade that is usual amplifying configuration in RF transmit paths. The linearization approach achieves very good results in reduction of IM3 products for a wide range of the input power. Accordingly, better results in IM3 reduction can be accomplished for high power of fundamental signals near 1-dB compression point by combining amplitude and phase adjustment through two independent injection paths than by the linearization carried out through only one path. On the top of that, the phases of IM2 signals in two different injection paths are not constrained on optimal values and can fluctuate within appropriate range.

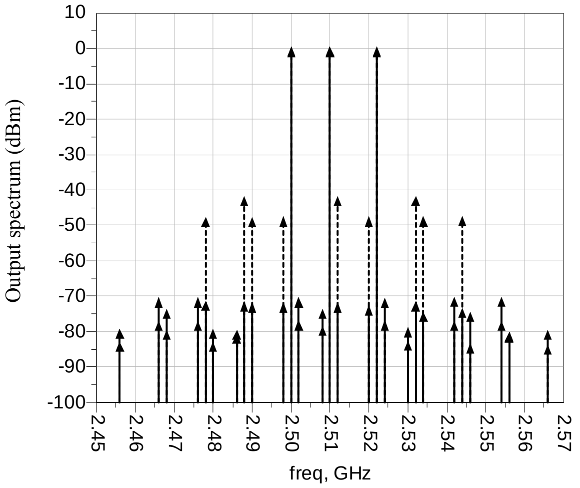

Fig. 2. *Output spectra for -25 dBm input power of fundamental signals; before (dashed line) and after the linearization (solid line)*

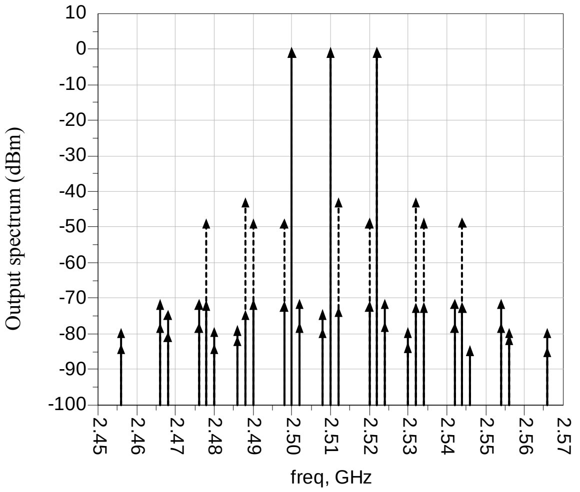

Fig. 3. *Output spectra for -25 dBm input power of fundamental signals before (dashed line) and after linearization (solid line) for -40° deviation from the optimal phase in the injection path of the first amplifier*

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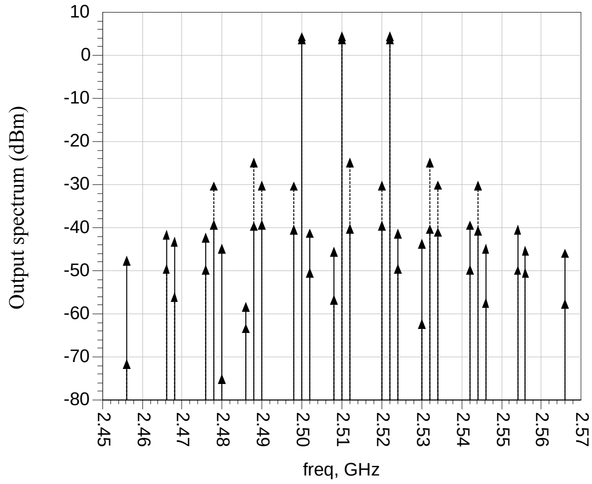

Fig. 4 *Output spectra for -20 dBm input power of fundamental signals; before (dashed line) and after the linearization (solid line)*

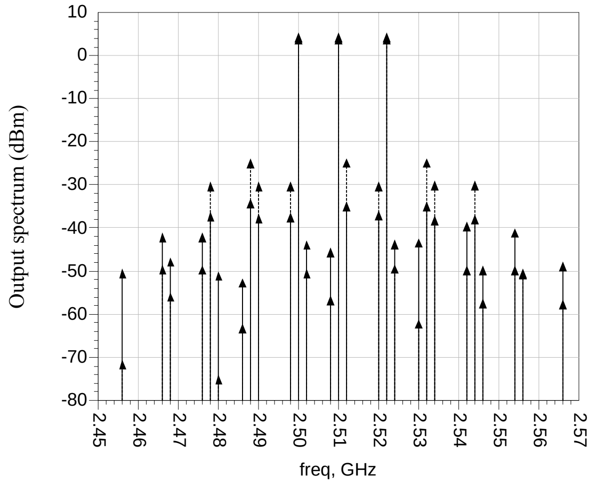

Fig. 5 *Output spectra for -20 dBm input power of fundamental signals; before (dashed line) and after the linearization (solid line) for -20° deviation from the optimal phase in the injection path of the first amplifier*

Abstract — *U ovom radu je izvršena linearizacija kaskadne veze dva pojačavača pomoću drugih harmonika osnovnih korisnih signala (IM2 signala) koji se ubacuju na ulaz svakog pojačavačkog stepena. Predloženi linearizacioni postupak je primenjena kako za niže tako i za više snage korisnih signala blizu 1-dB tačke kompresije. Postignuti su bolji rezultati u slučaju većih snaga u poređenju sa linearizacionom metodom koja ubacuje IM2 signale na ulaz samo jednog pojačavača. Takođe, predloženim postupkom smanjuje se osetljivost metode na promenu faza IM2 signala u odnosu na optimalne vrednosti.*

LINEARIZACIJA KASKADNE VEZE DVA POJAČAVAČA POMOĆU DRUGIH HARMONIKA

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