The Non-Linear Signals for Linearization for Nonlinear Baseband Signals

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ABSTRACT: *To produce digital baseband domain, it is important to consider the non-linear signals for linearization. We in this work have processed the second and fourth order linearization signals and processed the amplitude and phase. We used the modulate carrier second harmonic which is further utilized for amplifier transistor. We studied the effects of the proposed linearization method are evaluated on a single stage power amplifier for simulated QAM digitally modulated signal characterized with frequency spacing between spectral components up to 20 MHz for different input power levels.*

Keywords: Linearization, Amplifier, Baseband Signal, Second Harmonics, Second- and Fourth-order Nonlinearity

Received: 19 November 2020, Revised 12 March 2021, Accepted 29 March 2021

DOI: 10.6025/ijwa/2021/13/2/37-44

1. Introduction

The power amplifiers need to support good linearity and high power efficiency in order to meet requirements of processing high rate non-constant envelope signals. For achieving high power efficiency, the power amplifier should operate around its compression region which distorts the linearity of the output signals; therefore a significant effort has been devoted for development of the linearization techniques for the nonlinear RF and microwave power amplifiers. Different linearization methods for minimizing the nonlinear distortions of the power amplifiers have been proposed [1]- [6]: feedback, feedforward, predistortion, technique that utilizes the even-order nonlinear signals processed in analogue domain, etc.

In the analysis carried out in [7]-[10] the proposed linearization method applies a digital processing of the baseband signal to generate the linearization signals of the second-order in order to suppress the intermodulation products of the third-order in the nonlinear amplifier. The adequately modified baseband signals formed and processed in the digital domain modulate the second harmonic of the fundamental carrier after they had been appropriately set in amplitude and phase. The linearization effects of the proposed technique have already been analysed for the single stage PA and the Doherty configurations in [8]-[10], as well as for the mixer [11].

The linearization approach presented in this paper extends the linearization method based on a baseband signal for linearization of the second-order so that the exploitation of the signals for linearization of the second and fourth-order that modulate the fundamental carrier second harmonics is suggested. The digital linearization signals are generated and processed in amplitude and phase in the baseband. The modulated signals at the second harmonic are then injected at the input of the amplifier transistor together with the fundamental signal or inserted at the transistor output in order to reduce the intermodulation products of the third and fifth-order. The injected signals for the linearization and the fundamental signal are mixed due to the second order nonlinearity of the transistor generating additional third-order and fifth-order nonlinear products that may suppress the original intermodulation products caused by the transistor nonlinear characteristic.

The effects of the proposed linearization method are estimated on a single stage power amplifier for the QAM signals wherein I and Q components are single tones with frequency spacing of spectrum components from 2 MHz to 20 MHz at different input power levels. The obtained results are compared for two cases: when the second- and fourthorder nonlinear signals for the linearization are inserted only at the input of the amplifier transistor (first case) and when the second- and fourth-order nonlinear signals for the linearization are injected only at the output of the amplifier transistor (second case).

2. Analysis

Theoretical analysis of the linearization approach is based on the current nonlinearity at the transistor output in the amplifier circuit, [7]-[9], which can be represented by a Taylor-series polynomial model [11]-[13].

The digitally modulated signal is characterized by the magnitude $c(t)$, phase $\varphi(t)$ and carrier frequency ω_0, as:

$$\begin{aligned} v_{gs}(t) &= c(t)\cos(\omega_0 t + \varphi(t)) \\ &= c(t)\cos(\varphi(t))\cos(\omega_0 t) - c(t)\sin(\varphi(t))\sin(\omega_0 t) \\ &= v_s(I\cos(\omega_0 t) - Q\sin(\omega_0 t)) \end{aligned} \tag{1}$$

where I and Q are the in-phase and quadrature-phase components of the baseband signal.

The second-order nonlinear signal of the digital signal expressed by equation (1) comprises the DC signal and signal at the second harmonic of the fundamental carrier. The I and Q components of the baseband signal required for the linearization that modulate the carrier second harmonic have the forms $I_{IM2} = (I^2 - Q^2)$ and $Q_{IM2} = 2IQ$, respectively.

When the nonlinear system of the fourth-order nonlinearity is driven by the input signal expressed by equation (1), the output signal consists of DC signal, the signal components at the carrier second harmonic as well as the components at carrier fourth harmonic. The in-phase and quadrature-phase components of this fourth-order nonlinear signal at the carrier second harmonic, which is needed for the linearization, have the forms: $I_{IM2} = (I^4 - Q^4)$ $Q_{IM4} = 2IQ(I^2 + Q^2)$, respectively.

Figure 1 shows the block diagram of the amplifier with the linearization circuit that forms, processes and directs the carrier second harmonic, modulated by the modified baseband signals of the second- and fourth-order nonlinearities, at the amplifier transistor input and output.

The desired signals for linearization of the second-order, I_{IM2} and Q_{IM2} signals, are multiplied by $a_{\{i|o\}}$ for amplitude tuning and adjusted in phase by $\theta_{\{i|o\}}$. Also, the amplitude and phase tuning of the fourth-order nonlinear signals for linearization, I_{IM4} and Q_{IM4}, is performed by the coefficients $b_{\{i|o\}}$ and $\varphi_{\{i|o\}}$. Indexes i and o in subscript are related to the signals prepared for the injection at the input and output of the amplifier transistor, respectively. The second and fourth-order signals processed and prepared for the linearization are injected at IQ modulators with carrier frequency $2\omega_0$ -fundamental carrier second harmonic.

After that, the modulated signals (denoted as the IM2 and IM4 signals for linearization) are fed through the bandpass filter, which is characterized by the centre frequency of $2\omega_0$, at the amplifier transistor input together with the fundamental signal, (equation (2)) or at the output of the amplifier transistor, (equation (3)), where $v_o\,(I\cos(\omega_0 t) - Q\sin(\omega_0 t))$ is the output signal at fundamental frequency.

$$\begin{aligned} v_{gs}(t) &= v_s\left[I\cos(\omega_0 t) - Q\sin(\omega_0 t)\right] + \\ &+ a_i e^{-j\theta_i}\frac{1}{2}\left[\left(I^2 - Q^2\right)\cos(2\omega_0 t) - 2IQ\sin(2\omega_0 t)\right] + \\ &+ b_i e^{-j\varphi_i}\frac{1}{2}\left[\left(I^4 - Q^4\right)\cos(2\omega_0 t) - 2IQ\left(I^2 + Q^2\right)\sin(2\omega_0 t)\right] \end{aligned} \tag{2}$$

$$\begin{aligned} v_{ds}(t) &= v_o\left[I\cos(\omega_0 t) - Q\sin(\omega_0 t)\right] + \\ &- a_o e^{-j\theta_o}\frac{1}{2}\left[\left(I^2 - Q^2\right)\cos(2\omega_0 t) - 2IQ\sin(2\omega_0 t)\right] + \\ &- b_o e^{-j\varphi_o}\frac{1}{2}\left[\left(I^4 - Q^4\right)\cos(2\omega_0 t) - 2IQ\left(I^2 + Q^2\right)\sin(2\omega_0 t)\right] \end{aligned} \tag{3}$$

The distorted current observed at the output of the amplifier when the signals for linearization of the second- and fourth order are inserted at the amplifier transistor input can be expressed by equation (4) if the third-order intermodulation products are concerned and by equation (5) in case of the fifth-order intermodulation products.

$$\begin{aligned} i_{ds}(t)\Big|_{IM3}^{lin\_i} &= \Bigg(\frac{3}{4}v_s^3 g_{m3} + \frac{1}{2}a_i e^{-j\theta_i} v_s g_{m2} + \\ &+ \frac{3}{4}v_s v_o^2 g_{m1d2} + \frac{3}{4}v_s^2 v_o g_{m2d1} + \\ &+ \frac{1}{4}a_i e^{-j\theta_i} v_o g_{m1d1}\Bigg)\left(I^2 + Q^2\right)\left(I\cos(\omega_0 t) - Q\sin(\omega_0 t)\right) \end{aligned} \tag{4}$$

$$\begin{aligned} i_{ds}(t)\Big|_{IM5}^{lin\_i} &= \Bigg(\frac{5}{8}v_s^5 g_{m5} + \frac{1}{2}b_i e^{-j\varphi_i} v_s g_{m2} + \\ &+ \frac{1}{4}b_i e^{-j\varphi_i} v_o g_{m1d1} + \frac{3}{8}a_i^2 e^{-j2\theta_i} v_s g_{m3} + \\ &+ \frac{1}{8}v_o a_i^2 e^{-j2\theta_i} g_{m2d1}\Bigg)\left(I^2 + Q^2\right)^2\left(I\cos(\omega_0 t) - Q\sin(\omega_0 t)\right) \end{aligned} \tag{5}$$

The equations (6) and (7) represents the amplifier output distorted current of the third- and fifth-order in case when the signals for linearization of the second- and fourth-order are inserted at the amplifier transistor output.

$$i_{ds}(t)\Big|_{IM3}^{lin\_o} = \left(\frac{3}{4}v_s^3 g_{m3} - \frac{1}{4}a_o e^{-j\theta_o} v_s g_{m1d1} + \right.$$
$$\left. + \frac{3}{4}v_s v_o^2 g_{m1d2} + \frac{3}{4}v_s^2 v_o g_{m2d1}\right)\left(I^2 + Q^2\right)\left(I\cos(\omega_0 t) - Q\sin(\omega_0 t)\right) \tag{6}$$

$$i_{ds}(t)\Big|_{IM5}^{lin\_o} = \left(\frac{5}{8}v_s^5 g_{m5} - \frac{1}{4}b_o e^{-j\varphi_o} v_s g_{m1d1} + \right.$$
$$\left. + \frac{1}{8}v_s a_o^2 e^{-j2\theta_o} g_{m1d2}\right)\left(I^2 + Q^2\right)^2\left(I\cos(\omega_0 t) - Q\sin(\omega_0 t)\right) \tag{7}$$

The first term in equations (4) and (6) represents the signal distorted by the cubic term of the amplifier ($gm3$), which is considered dominant in causing the third-order intermodulation products and spectral regrowth [12], [13]. The mixing products of the fundamental signal and IM2 signals supplied at the transistor input or output are expressed as the second and fifth terms in equation (4) and the second term in equation (6). The third and fourth terms in both equations (i.e., the mixed terms between drain and gate, g_{m1d2} and g_{m2d1}) produce the drain–source current at IM3 frequencies with opposite phases so that they may be considered to cancel each other partially [13]. According to the previous analysis, it is possible to reduce spectral regrowth caused by the third-order distortion of the fundamental signal by selecting the appropriate amplitude and phase of the IM2 signals which are injected at the input or output of the amplifier transistor. In the approach presented in this paper and [7]-[9] the amplitude and phase of the IM2 signals are set on the optimal values by using DSP.

The first term in equations (5) and (7) expresses the fifth-order intermodulation products of the drain-source current of amplifier transistor. It is formed due to the amplifier nonlinearity of the fifth-order, g_{m5}, when the fundamental signal is driven at the amplifier input. The second and third terms in equation (5) and the second term in equation (7) are the mixing products of the second order between the fundamental signal and IM4 signals fed at amplifier input or output. The fourth and fifth terms in equation (5) as well as third term in equation (7) are the mixing products of the fundamental signal and IM2 signal supplied at the amplifier transistor input or output. Therefore, according to equations (5) and (7), we may infer that the IM5 products are reduced by the IM4 signals generated and modified for linearization in baseband by digital signal processing.

3. PA Design

The broadband RF amplifier was designed in Agilent Advanced Design System-ADS by using Freescale's MRF281S LDMOSFET whose non-linear MET model is incorporated in ADS library, to operate over the frequency range 0.7 GHz-1.1 GHz, [6]-[8]. The amplifier circuit was designed at central frequency 1 GHz based on the source and load impedances $Z_s = (5.5 + j15)\ \Omega$ and $Z_l = (12.5 + j27.5)\ \Omega$, respectively, obtained by source-pull and load-pull analysis in ADS. The input and output matching circuits of the transistor are based on the filter structures with lumped elements and reference [6] offers a detailed insight in the design process of the amplifier broadband matching circuits.

The proposed technique requires generation of several linearization components: the in-phase and quadrature-phase signals of the second-order (I_{IM2} and Q_{IM2}), and also inphase and quadrature-phase signals of the fourth-order (I_{IM4} and Q_{IM4}), which modulate carriers at the second harmonic frequency of the fundamental signal carrier.

The additional modulated signals for linearization at the second harmonic are then injected at the input or output of the transistor in the amplifier circuit over the ideal bandpass filters characterized by 2 GHz centre frequency and 0.5 GHz frequency bandwidth (Figure 1).

4. Results

The described linearization technique was applied on the designed power amplifier for the QAM modulated signals whose spectrum contains two frequency components shifted in frequency by ±1 MHz, ±3 MHz, ±5 MHz and ±10 MHz in reference to the carrier frequency 1 GHz. Timed source component named QAM was used as a source of the signals. The analysis was carried out for different fundamental signal power levels at the amplifier input: 0 dBm, 3 dBm and 7 dBm. The results presented in this paper compare two cases: when the linearization was achieved by the injection of the secondand fourth-order nonlinear signals for linearization only at the input of the amplifier transistor (the curves that relate to this case are denoted with index *i*), and when the linearization was performed by the insertion of the second- and fourth-order nonlinear signals for linearization only at the amplifier output (the curves are marked with index *o*). The power levels of the third-order and fifth-order intermodulation products, before and after the linearization, in terms of the frequency interval between the spectral components of the QAM signal are presented in Fig. 3 and Fig. 4 for different input power levels. The Random optimization of the adjustable coefficients for amplitude and phase tuning of the linearization signals was carried out in ADS for each considered input signal power level with the aim to suppress the third-order intermodulation products and to restrain the fifth-order intermodulation products at the levels below the reduced IM3 products.

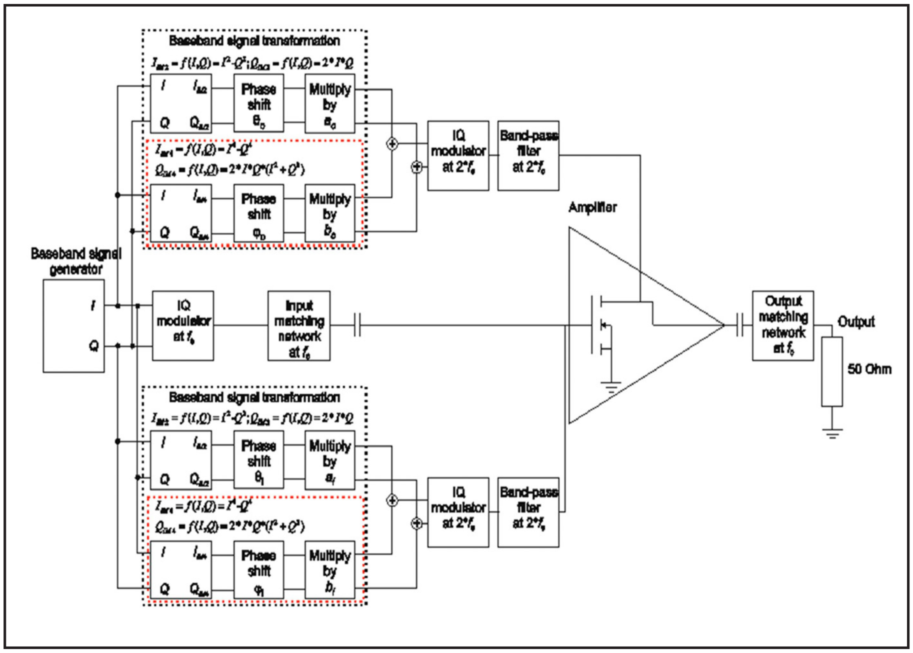


Figure 1. Block diagram of the amplifier linearized by the injection of the modified baseband signals processed in digital domain that modulate the carrier second harmonic

The simulation shows that the application of both linearization approaches has the similar effects on the IM3 products reduction. The IM3 products are lessened around 19 dB in the case of 0 dBm input power and 2 MHz frequency span when the first linearization case is applied, whereas for the application of the second case for the same conditions the accomplished suppression is around 22 dB. With the increase of the signal spacing to 10 MHz, the reduction of the IM3 products is around 8 dB for the feeding of the linearization signals at the amplifier input while they are decreased by 10 dB for the driving of the linearization signals at the amplifier output. The results obtained for the input power of 3 dBm and 2 MHz frequency spacing give almost the same decrease of IM3 products, around 20 dB, for both linearization approaches. When frequency span arises to 6 MHz, the IM3 products are lessened by 7 dB, when the first case is considered and by 9 dB for the second case, while at 20 MHz the first approach results in only 2 dB IM3 reduction, while the second one gives 3 dB better results. A general observation is that the simulations give a few decibels higher reduction of the IM3 products for all considered input power levels achieved by the insertion of the second- and fourth order nonlinear signals for linearization at the amplifier output. Such trend can also be observed from the results attained in the reduction of the IM3 products when input power is 7 dBm.

The simulation shows that both cases have the similar linearization effects on the IM5 products. They descend by 12 dB in case of 0 dBm input power and 6 MHz frequency spacing when the first linearization case is applied, whereas they decrease by 16 dB for the second case. As far as we analyse signal at 3 dBm input power, it can be noted that the IM5 product suppression is ranged from 16 dB for narrower spacing between signals to 3 dB at 20 MHz spacing in the first linearization case. The second case provides the drop of IM5 products from 23 dB to 4 dB that is for the widest spacing. When input power is 7 dBm, the second linearization approach delivers a few decibels greater suppression of the IM5 products than the first approach.

It should be indicate that the results obtained in this paper for the IM3 products by the injection of the signals for linearization of the second- and fourth-order at the amplifier transistor output are of the same order as achieved in [7] where the IM2 signals for linearization are simultaneously inserted at the amplifier transistor input and output. However, the higher suppression of the IM5 products is attained in this paper in relation to the approach presented in [7].

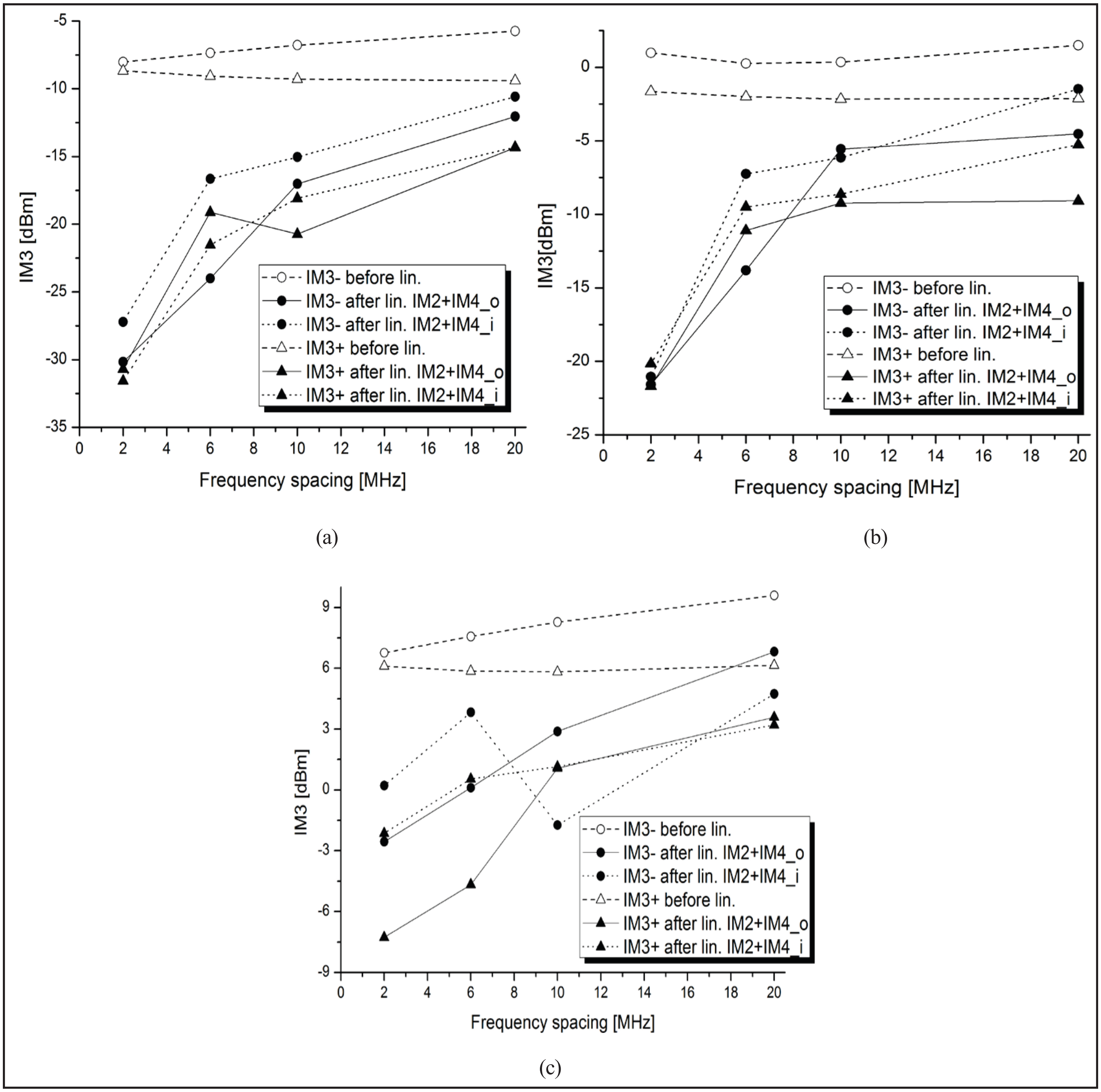
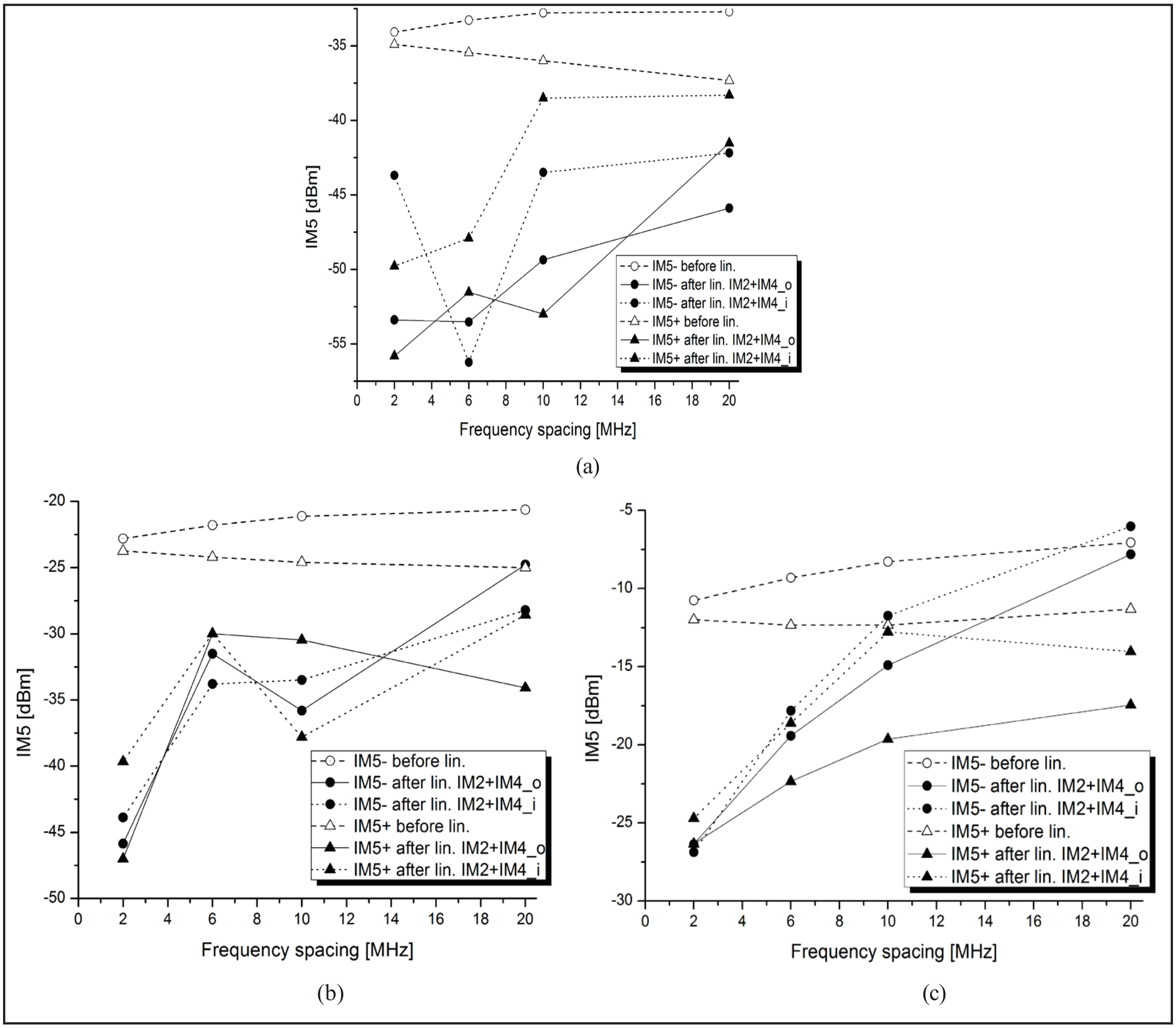


Figure 2. The third-order intermodulation products before and after linearization for the QAM signal for input power level: (a) 0 dBm; (b) 3 dBm; (c) 7 dBm



(a)

(b)

(c)

Figure 3. The fifth-order intermodulation products before and after linearization for the QAM signal for input power level: (a) 0 dBm; (b) 3 dBm; (c) 7 dBm

5. Conclusion

This paper presents the linearization technique of the power amplifier that uses the adequate nonlinear baseband signals of the second- and fourth-order to modulate the fundamental carrier second harmonics. The in-phase and quadrature-phase components of the baseband linearization signals are generated and processed in amplitude and phase in the digital domain and inserted into the input or output of the RF power amplifier transistor. The analysis of the impact of the proposed linearization technique on suppression of the intermodulation products is assessed for QAM signal by simulation in ADS. Two spectrum components of the QAM signal are separated by 2 MHz up to 20 MHz with centre frequency of 1 GHz and driven at the amplifier input or output for different power levels of the fundamental signal. The obtained results are compared for two cases: when the IM2 and IM4 signals for linearization are fed only at the amplifier input and when they are fed only at the amplifier output. It may be noted that the higher reduction grade regarding both, the IM3 and IM5 products, is obtained by supplying the linearization signals at the amplifier output. Additionally, better results in reducing the IM5 products are obtained when apart from the IM2 signals for linearization, the IM4 signals are inserted, especially at the amplifier transistor output.

Acknowledgement

This work was supported by the Ministry of Education, Science and Technological Development of Republic of Serbia; the project number III-44009.

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