Linearization of Multichannel Amplifiers with the Injection of Second Harmonics into The Amplifier and Predistortion Circuit

Djuradj Budimir[1], Natasa Males-Ilic[2], Bratislav Milovanovic[2], Milan Tomic[3]

***Abstract* — A linearization technique that uses the injection of the fundamental signal second harmonics together with the fundamental signals at the amplifier input has been extended in this paper by introducing the injection the second harmonics into nonlinear microwave amplifier and so-called predistortion circuit. Predistortion circuit produces the third-order intermodulation signals that are injected at the amplifier input together with the second harmonics making the linearization procedure more independent on the phase variation of the second harmonics. In addition, a considerably better improvement is attained for the power of fundamental signals close to 1-dB compression point by applying the linearization technique proposed in this paper in comparison to the linearization with the injection of the second harmonics merely in the nonlinear amplifier.**

Keywords – **intermodulation distortion, linearization technique, second harmonics, sensitivity to phase variation.**

I. INTRODUCTION

The influences of carriers' second harmonics to the third-order intermodulation products in microwave power amplifiers have been investigated and applied in few works [1-5]. The linearization for more than two fundamental signals at amplifier input achieved by the injection of the second harmonics and signals at frequencies that are the sum of the fundamental signals (all together denoted as IM2 signals) has been proposed in [3]. The linearizatoin effect was achieved by adjusting amplitude and phase of the IM2 signals, which are injected together with the fundamental signals at the amplifier, on optimal values. However, this approach is very sensitive to the IM2 signal's phase characteristic. For instance, the change in the phase of IM2 signals by ±5º leads to the 5 dB lower reducing in the third-order intermodulation products (IM3).

Two different approaches for reducing the sensitivity to the variation of the phases of the IM2 signals from the optimal value in the linearization with the injection of the second harmonics have been proposed in [4], [5].

In the first approach [4], the IM2 signals are injected together with fundamental signals at the amplifier input and feedforwarded at the amplifier output. The desired improvement is achieved by adjusting only amplitudes of the IM2 signals over two paths for a certain degree in deviation of their phase characteristics. The proposed correction procedure in the second approach [5] combines the IM2 signals (main and corrective) with 90º differences in phases at the amplifier input. The adjustable parameters are only amplitudes of the injected IM2 signals in two paths.

Another approach that can correct deviation from an optimal phase of the IM2 signals is proposed in this paper. The IM2 signals are involved into a nonlinear microwave amplifier and so-called predistortion circuit. Predistortion circuit is consisted of a nonlinear component that produces IM3 signals. These signals are injected at the amplifier input together with the IM2 signals. Applying this linearization technique, the phases of the injected IM2 signals over so-called direct injection path can vary from the optimal values for a certain phase in the injection path of IM2 signals into predistortion circuit (corrective path). Furthermore, this linearization approach can be used for the higher power of fundamental signals that is closer to 1-dB compression point.

II. THEORETICAL ANALYSIS

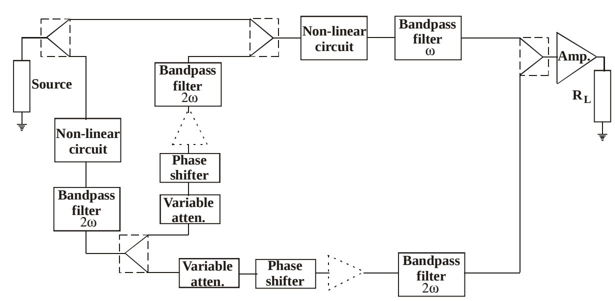


Fig. 1. Amplifier circuit with the injection of the second harmonic into the amplifier and predistortion circuit

New procedure with the injection of the IM2 signals together with fundamental signals and third-order intermodulation products obtained as output of the predistortion circuit is proposed as shown in Fig. 1. In simulation, the broadband single-stage amplifier designed as described in [2] was used for a nonlinear amplifier denoted as Amp. Components denoted as non-linear circuits are designed as amplifiers biased at appropriate operating point to provide required degree of nonlinearity. The ideal elements from ADS (Advanced design system) were used for other

[1]Djuradj Budimir is with University of Westminster, Department of Electronic Systems, 115 New Cavendish Street, London W1W 6UW, UK, E-mail: d.budimir@westminster.ac.uk

[2]Natasa Males-Ilic, Bratislav Milovanovic are with University of Nis, Faculty of Electronic Engineering, Beogradska 14, 18000 Nis, Serbia and Montenegro, E-mail:natasam@elfak.ni.ac.yu

[3]Milan Tomic is with 063 MOBTEL, Bulevar umetnosti 16a, 11070 Novi Beograd

components (bandpass filters, phase shifters, variable attenuators, power combiners and dividers). The bandpass filter in the injection path of the fundamental signals was selected to have the same slope of the phase characteristics as the IM2 signals have throughout the injection path in order to compensate differences in phases of the injected IM2 signals and provide the same reducing rate for all IM3 products of the certain kind as depicted in [6]. The amplifiers in the injection paths of the IM2 signals into the main amplifier and predistortion circuit are required if the power levels of IM2 signals generated are not sufficient to carry out the linearization and correction of variation from an optimal phase.

The injection of two fundamental signals at the frequencies ω_1 and ω_2 with amplitudes V'_{ω_1} and V'_{ω_2} respectively, together with their second harmonics at the frequencies $2\omega_1$ and $2\omega_2$ with amplitudes $V'_{2\omega_1}$ and $V'_{2\omega_2}$ and phases $\varphi'_{2\omega_1}$ and $\varphi'_{2\omega_2}$ into the predistortion circuit can be expressed as:

$$\begin{aligned} v_{in} &= V'_{\omega_1}\cos(\omega_1 t) + V'_{\omega_2}\cos(\omega_2 t) + \\ &+ V'_{2\omega_1}\cos\left(2\omega_1 t + \varphi'_{2\omega_1}\right) + V'_{2\omega_2}\cos\left(2\omega_2 t + \varphi'_{2\omega_2}\right) \end{aligned} \quad (1)$$

The output current of the predistortion circuit at frequency $2\omega_2$-ω_1 can be expressed as follows:

$$\begin{aligned} i'_{out(2\omega_2-\omega_1)} &= \frac{3}{4}V'^2_{\omega_2}\,V'_{\omega_1}\,g'_{m3}\cos(2\omega_2 t - \omega_1 t) + \\ &+ V'_{\omega_1}\,V'_{2\omega_2}\,g'_{m2}\cos\left(2\omega_2 t - \omega_1 t + \varphi'_{2\omega_2}\right) + \\ &+ \frac{3}{2}V'_{\omega 1}\,V'_{2\omega_1}\,V'_{2\omega_2}\,g'_{m3}\cos\left(2\omega_2 t - \omega_1 t + \varphi'_{2\omega_2} - \varphi'_{2\omega_1}\right) \end{aligned} \quad (2)$$

The third term can be neglected for lower power of input signals.

The output voltage of the predistortion circuit can be expressed as $v'_{out} = \alpha' i'_{out}$ where α' is transformation coefficient. Phase and amplitude of voltage v'_{out} are controlled by the phase and amplitude of the second harmonics injected into predistortion circuit. Then, the voltage at the input of main amplifier can be written as:

$$\begin{aligned} v_{in} &= V_{\omega_1}\cos(\omega_1 t) + V_{\omega_2}\cos(\omega_2 t) + v'_3 + \\ &+ V_{2\omega_1}\cos\left(2\omega_1 t + \varphi_{2\omega_1}\right) + V_{2\omega_2}\cos\left(2\omega_2 t + \varphi_{2\omega_2}\right) \end{aligned} \quad (3)$$

where V_{ω_1} and V_{ω_2} are amplitudes of the fundamental signals at the input of the main amplifier after they pass through predistortion circuit. The amplitudes and phases of the second harmonics injected at the main amplifier input are $V_{2\omega_1}$, $V_{2\omega_2}$, $\varphi_{2\omega_1}$ and $\varphi_{2\omega_2}$ respectively. Voltage v'_3 corresponds to the first term in Eq. (2) as well as the second term that is controlled by the phase and amplitude of the appropriate second harmonic injected into the predistortion circuit. Then, the current at the output of the main amplifier relating to ($2\omega_2$-ω_1) IM3 product can be written by Eq. (4). The first term is linearly amplified IM3 product of the predistortion circuit. The second is IM3 product evolves due to cubic nonlinearity in the amplifier circuit. The first term should be negligible in comparison to the power of the main amplifier IM3 component (the second term). The second-order nonlinearity of the main amplifier generates the third term that is the mixing product of the fundamental signal and second harmonic injected directly into the main amplifier. Finally, the output of the predistortion circuit that is result of the second-order nonlinearity is linearly amplified (the fourth term). The last term is g_{m3} mixing product between fundamental signal and injected second harmonics into main amplifier and can be neglected for lower power of input signals.

$$\begin{aligned} i_{out(2\omega_2-\omega_1)} &= \\ & g_{m1}\frac{3}{4}V'^2_{\omega_2}\,V'_{\omega_1}\,g'_{m3}\cos(2\omega_2 t - \omega_1 t + \varphi'_1) + \\ &+ \frac{3}{4}V^2_{\omega_2}V_{\omega_1}g_{m3}\cos(2\omega_2 t - \omega_1 t + \varphi''_1) + \\ &+ V_{\omega_1}V_{2\omega_2}g_{m2}\cos(2\omega_2 t - \omega_1 t + \varphi_2) + \\ &+ g_{m1}V'_{\omega_1}\,V'_{2\omega_2}\,g'_{m2}\cos(2\omega_2 t - \omega_1 t + \varphi_3) + \\ &+ \frac{3}{2}V_{\omega 1}V_{2\omega_1}V_{2\omega_2}g_{m3}\cos(2\omega_2 t - \omega_1 t + \varphi_4) \end{aligned} \quad (4)$$

Observing the output voltage as $v_{out} = \alpha i_{out}$, the representation using phasor diagram given in Fig. 2 depicts clearly the correction procedure and role of the predistortion circuit.

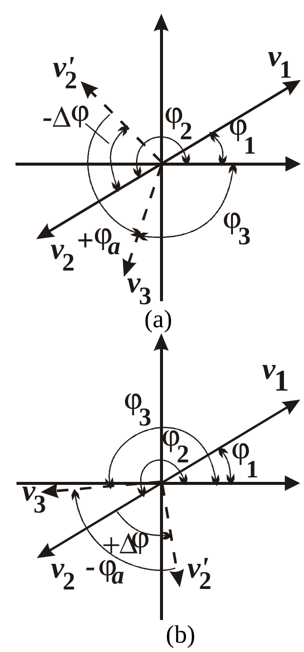


Fig. 2. Phasor diagram relates to: (a) minus; (b) plus deviation from optimal phase of the second harmonics

The first and second terms in Eq. (4) are the contribution to the IM3 products yielded due to the cubic nonlinearity of the predistorter and main amplifier and those terms at the output voltage are denoted as v_1 with phase φ_1. The third term in Eq. (4) for maximally attenuated the fourth term is represented with v_2 and phase φ_2 that are treated as optimal values. Deviation in the phase φ_2 for $\pm\Delta\varphi$ can be annulated by introducing corrective voltage v_3 with phase φ_3 that corresponds to the fourth term in Eq. (4). It is possible to alter the phase of the voltage v_3 by tuning the phase of the second harmonics injected into the predistortion circuit. Voltage v'_2 is the term in IM3 product that is influenced by the second harmonic injected into the main amplifier when its phase is shifted by $\pm\Delta\varphi$. In that case, the phase of v'_2 is φ'_2. This corrective procedure can be described by following expressions:

$$\text{if } \varphi'_2 = \varphi_2 + \Delta\varphi \;\Rightarrow\; \varphi_3 = \varphi'_2 - \varphi_a\,,$$

$$\text{if } \varphi'_2 = \varphi_2 - \Delta\varphi \;\Rightarrow\; \varphi_3 = \varphi'_2 + \varphi_a \qquad (5)$$

For a certain deviation of $+\Delta\varphi$ or $-\Delta\varphi$ from optimal value of v_2, the correction can be achieved easily by adjusting amplitudes of v'_2 and v_3 on proper values.

The fifth term in the expression for the output current, Eq. (4), contributes to the overall IM3 power level for the higher input power. The power of the second harmonics injected directly into main amplifier is then required to be higher in order to increase third term in Eq. (4) and thus reduce rising power of IM3 products. Consequently, the fifth term in Eq. (4) is gained additionally rising IM3 power furthermore. Apparently, the injection of the second harmonics can not reduce IM3 products. However, the fourth term in Eq. (4) can be added to the third term by adjusting phase and amplitude of the injected second harmonic into predistortion circuit and thus helps in reducing IM3 power.

Phasor diagram that corresponds to this action is shown in Fig. 3 under assumption that φ_1=0 and consequently φ_4≈0.

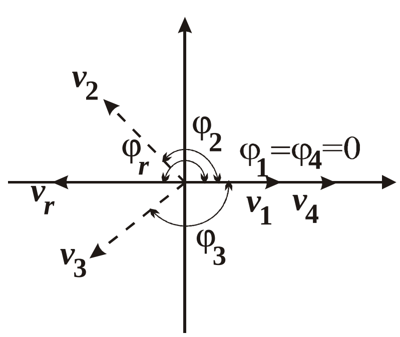
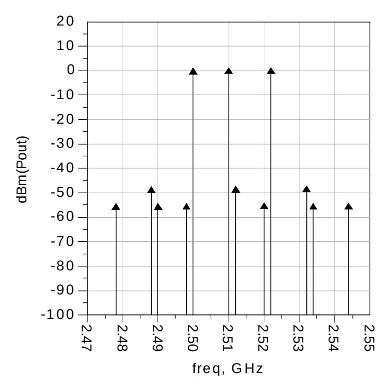


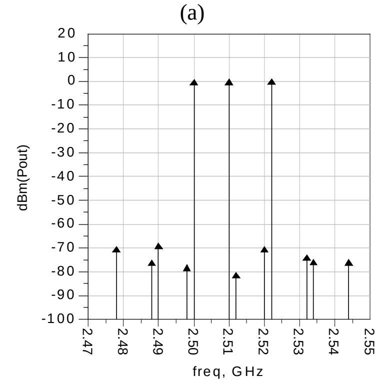
Fig. 3. Phasor diagram

III. Simulated Results

The output spectrum for three fundamental signals at amplifier input at frequencies 2.5 GHz, 2.51 GHz and 2.522 GHz at power level -4 dBm at amplifier input without employing linearization is presented in Fig. 4(a). This spectrum is consisted of fundamental signals, and third-order IM products of the first and second kinds [3]. According to the Fig. 1, input signals are injected into direct path and path for generation of the appropriate IM2 signals (second harmonics and signals at frequencies that are the sum of pairs of fundamental signals as defined in [3] for three and more fundamental signals). The output signals of the non-linear circuit in this path are filtered out in order to extract only IM2 signals. Filtered IM2 signals are led to two paths. In one, the amplitudes and phases of the IM2 signals are adjusted to influence IM3 products at main amplifier output in the manner already described in literature [3], as the linearization techniques with the injection of IM2 signals. The other path called corrective path serves to inject IM2 signals into the predistortion circuit. Optimizing phase shifter and variable attenuator parameters, over the direct injection path for maximally attenuated IM2 signals in the corrective path the first kind of IM3 products is reduced by approximately 15 dB and second kind by 23 dB. The variety in the reducing rate of the first and second kinds is due to the differences in phases and amplitudes of generated second harmonics that influence the first kind of IM3 and other IM2 products that have an impact to the second kind of IM3. Varying the value of the phase shifter that gives those results for +10° the reducing in IM3 power level is impaired so that the IM3 product at frequency 2.49 GHz is reduced by 4 dB only. The non-linear predistortion circuit is with the low nonlinearity that provides low IM3 predistortion products generated originally as a consequence of the third-order nonlinearity Thus, they have negligible influence to the IM3 products at the output of the main amplifier.



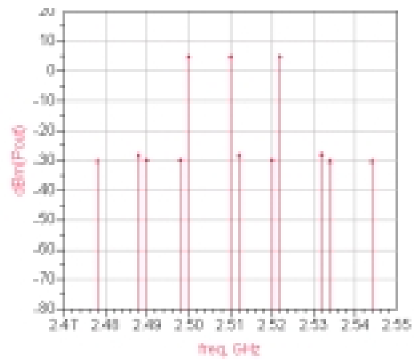
(a)



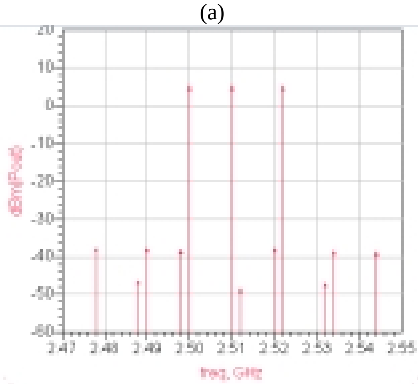
(b)

Fig. 4. Output spectrum: (a) without applying linearization technique; (b) after correction of -40° deviation from optimal phase in the main injection path of IM2 signals

The variation from an optimal value of the phase in the direct injection path of the IM2 signals into the main amplifier is corrected by setting phases of the IM2 signals injected into predistortion circuit on appropriate value. The value of the phase shifter in the injection path into the predistorter is 90º shifted for +Δφ deviation from the value required for -Δφ deviation. Correction is performed by adjusting amplitudes of IM2 signals through two injection paths. The result achieved for -40º deviation from the optimal value is shown in Fig. 4(b). The same result was obtained for +40º deviation. From Fig. 4 follows that approximately same reducing in IM3 products is accomplished by applying correction technique as for the optimal case. Additionally, the results obtained with correction of ±60º deviation from the optimal phase in IM2 injection path into the main amplifier are only 5 dB worse than in previous case. The value of phase in the IM2 injection path in the predistortion circuit can vary approximately ±20º from prescribed value.



(a)



(b)

Fig. 5. The simulated output power of fundamental signals and IM3 products for three analog signals at input power 5 dB below 1-dB compresion point: (a) without applying the linearization technique; (b) with applying linearization technique.

Applying the proposed approach to the higher power of fundamental signals, the result of simulation for three fundamental signals at 0 dBm power level at input of the main amplifier that is 5 dB below 1-dB compression point is illustrated in Fig. 5. It indicates that the first kind IM3 is reduced by 8 dB and the second kind by 18 dB. It turns out that reducing in IM3 products enabled for higher power of fundamental signals by applying the linearization with the injection of appropriate IM2 signals into the predistortion circuit and directly into the main amplifier is remarkable result in comparison to 2 dB reducing with the injection of the IM2 signals only into the main amplifier circuit.

IV. CONCLUSION

The correction procedure presented in this paper provides that the linearization technique is less troublesome to the variation in phases of the injected second harmonics. The phase of the second harmonics in the main injection path can vary for ±40º with the results that are comparable to the reducing in IM3 products achieved for optimal phase. The reducing rate in IM3 power levels with applying corrective approach depends on the deviation grade from the optimal phase. The value of phase in the second harmonic injection path in the predistortion circuit can vary ±20º from prescribed value.

A complex linearization circuit is required in described approache for reducing the sensitivity of the second harmonic linearization technique to the variation of second harmonic phase from the optimal value but the reducing in IM3 products is more flexible to phase values in both paths. Also, possibility to adjust optimal amplitude of the second harmonic across two paths offers greater freedom in choice of amplitude values of the second harmonics in two independent paths.

REFERENCES

[1] C. S. Aitchison, M. Mbabele, M. R. Moazzam, Dj. Budimir, and F. Ali, "Improvement of third order intermodulation products of RF and microwave amplifiers by injection", *IEEE MTT Transactions on Microwave Theory and Techniques,* Vol.49, pp.1148-1154, June 2001.

[2] N. Males-Ilic, B. Milovanovic, Dj. Budimir, "Amplifiers with improved IMD performance for multi-channel wireless systems", *Proc. Int. Conf. European Microwave Conference*, September 2002, Milan, Italy.

[3] N. Males-Ilic, B. Milovanovic, Dj. Budimir, "A multicarrier amplifier design linearized trough second harmonics and second-order IM feedback", *Facta Universitatis, Series: Electronics and Energetics*, 2001, Vol. 14, pp.243-252.

[4] Dj. Budimir, N. Males-Ilic, B. Milovanovic, "A New Low Intermodulation Amplifier Using Simultaneous Injection and Feedforwarding of Second Harmonics', *Proc. Int. Conf. Mediterranean Microwave Conference*, Jun 2002, Caceres, Spain.

[5] N. Males-Ilic, B. Milovanovic, Dj. Budimir, "Diminished Sensitivity to Phase Variation in Injected Second Harmonic Linearization Technique for Multychannel Amplifiers", *Proc. of Int. Conf. Asia Pacific Microwave Conference*, November 2002, Kiotto, Japan.

[6] N. Males-Ilic, B. Milovanovic, Dj. Budimir, "Improvement in "Second Harmonics" Linearization Technique for Multichannel Amplifiers", *Microwave and Optical Technology Letters*, Vol.38. No.2, July 2003, pp.150-153.