Improved Second Harmonic Linearization Technique for Multichannel Amplifiers with Enhancement Reducing in Intermodulation Distortion

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Abstract - **A linearization technique for reducing third-order intermodulation distortion that uses the injection of the fundamental signal second harmonics together with the fundamental signals at the amplifier input has been improved in this paper. The procedure proposed introduces phase correction of the fundamental signals according to the differences in phase of the second harmonics. Linearization technique has been applied on an muliichannel amplifier with four analog signals at input. As the result, the improvement in third-order intermodulation power level is 40 dB.**

Key words – **amplifier, intermodulation distortion, linearization technique.**

I. Introduction

In telecommunications systems, the intermodulation (IM) especially the third-order (IM3) generated in-band, has always been of concern, particularly when many channels are simultaneously processed. Many different techniques for IM distortion reduction can be found in literature such as predistortion, feedforward, feedback and combination of them. However, the application of these techniques requires the circuitry that may be complex, expensive and large in size. The effects of carriers' second harmonics to the third-order distortion in a microwave power amplifier have been investigated and applied so far in few works [1-3]. The published results are based on a power amplifier design with additional second harmonics that are either generated out of the amplifier and injected together with fundamental signals [1] or extracted from the output and led through the feedback loop to the amplifier input [2,3]. Additionally, the influence of the second harmonics as well as other second-order IM products (sum of pairs of the fundamental signals) to the first and second kind of IM3 appearing for more then two fundamental signals, has been considered as well [4]. Proposed techniques were verified for analog as well as digitally modulated signal at the amplifier input. However, these approaches are very sensitive to the different phases of the second harmonics (mean second harmonics and sum of pairs of fundamental signals).

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For instance, if the injected fundamental signals as well as their second harmonics have equal amplitudes and phases (ideal case), the reducing of IM3 power level will be about 40 dB [1]. Even though the condition of equal amplitudes is expected in reality, it is not the case with their phases. Namely, the components in the second harmonics path (bandpass filter, attenuator, phase shifter) may have a certain slope of phase characteristic. Only few degrees different phases of the second harmonics lead to considerably lower reduction in IM3 power level [2-4].

In this paper, the fundamental signals injected at the amplifier input pass trough component that has phase characteristic with the same slope as the second harmonics have across their whole path. This approach provide reducing in IM3 as in the ideal case with the equal phases of the second harmonics.

Improved second harmonic linearization technique has been tested for four carriers at the amplifier input. In comparison with earlier applied second harmonic linearization techniques [1-4], this approach makes the reducing in IM3 power level more flexible to the phases of the second harmonics.

A theoretical description of this linearization technique is given in the section II. A designing procedure of the power amplifier and the additional components (phase shifters, variable attenuator, bandpass filter, power combiner) as a hybrid microwave integrated circuit is described in the section III. The simulated results relating to the improvement in IM3 power levels obtained by this linearization technique are represented in the section IV.

II. Analysis

The proposed technique uses the amplifier non-linear characteristic to generate an additional third-order distorted signal that is used to cancel the original third-order intermodulation products generated by the cubic term in the amplifier characteristic.

An expression for the non-linearity of the active device (MESFET) is represented by a three term Taylor's series connecting the input voltage, v_{in} with the output current, i_{out} and the transconductance, g_m regarded as the dominant non-linearity:

$$i_{out}(t) = g_{m_1} v_{in}(t) + g_{m_2} v_{in}^2(t) + g_{m_3} v_{in}^3(t) \tag{1}$$

with $g_{m_1} = \dfrac{dI_{out}}{dV_{in}}$, $g_{m_2} = \dfrac{d^2 I_{out}}{dV_{in}^2}$ and $g_{m3} = \dfrac{d^3 I_{out}}{dV_{in}^3}$.

A three-tone injection of the fundamental signals at the frequencies ω_1, ω_2 and ω_3 with amplitudes V_{ω_1}, V_{ω_2}, V_{ω_3} and phases φ_1, φ_2, φ_3, respectively, together with their second harmonics at the frequencies $2\omega_1$, $2\omega_2$ and $2\omega_3$ with amplitudes $V_{2\omega_1}$, $V_{2\omega_2}$, $V_{2\omega_3}$ and phases $\varphi_{2\omega_1}$, $\varphi_{2\omega_2}$, $\varphi_{2\omega_3}$ can be expressed as:

$$\begin{aligned} V_{in} &= V_{\omega_1} Cos(\omega_1 t + \varphi_1) + V_{\omega_2} Cos(\omega_2 t + \varphi_2) \\ &+ V_{\omega_3} Cos(\omega_3 t + \varphi_3) + V_{2\omega_1} Cos(2\omega_1 t + \varphi_{2\omega_1}) \\ &+ V_{2\omega_2} Cos(2\omega_2 t + \varphi_{2\omega_2}) + V_{2\omega_3} Cos(2\omega_3 t + \varphi_{2\omega_3}). \end{aligned} \quad (2)$$

The source signals and their second harmonics interact as the result of amplifier non-linearity. All relevant frequency components at the output of the amplifier can be obtained by substituting Eq. (2) into Eq. (1). The expression valid for the first kind of IM3 product at the frequencies $2\omega_i$-ω_j, i,j=1,2,3 is:

$$\begin{aligned} I_{out(2\omega_i - \omega j)} &= \frac{3}{4} V_{\omega_i}^2 V_{\omega_j} g_{m3} Cos(2\omega_i t - \omega_j t + 2\varphi_i - \varphi_j) \\ &+ V_{\omega_j} V_{2\omega_i} g_{m2} Cos(2\omega_i t - \omega_j t + \varphi_{2\omega_i} - \varphi_j). \end{aligned} \quad (3)$$

The first term in Eq. (3) relates to the third-order IM product caused by the interaction between fundamental signals. The interaction between the fundamental signals and second harmonics results in the additional signals at the output of the amplifier at the third-order IM frequencies, (the second term in Eq. (3)). Therefore, by a proper selection of phase and amplitude of the second harmonics, it is possible to make the third-order IM products produced by the second harmonics out of the phase and equal in the amplitude with the original third-order products. For fundamental signals with equal amplitudes and phases and for the second harmonics with the same conditions, the maximum reduction in all IM3 products can be accomplished, simultaneously. The equal amplitudes of fundamental signals as well as second harmonics is real to expect. But, in contrast to this, the different phases of the second harmonics are unavoidable. If $\varphi_{2\omega_1} \neq \varphi_{2\omega_2} \neq \varphi_{2\omega_3}$, it is obvious that there is no possibility to obtain maximum reducing in all IM3 frequencies with the same adjustment of phase in the second harmonic path.

However, if $\varphi_1 \neq \varphi_2 \neq \varphi_3$ the relations between phases of the fundamental signals can be written as follows:

$$\begin{aligned} \varphi_2 &= \varphi_1 - \Delta, \\ \varphi_3 &= \varphi_2 - \Delta_1. \end{aligned} \quad (4)$$

For i=1, j=3, according to Eq. (3), the maximum reducing of $2\omega_1$-ω_3 is obtained adjusting phase $\varphi_{2\omega_1}$ of $2\omega_1$ to 180º. Using the relations (4), the phases of $2\omega_2$ and $2\omega_3$ can be expressed as follows:

$$\begin{aligned} \varphi_{2\omega_2} &= \varphi_{2\omega_1} - 2\Delta, \\ \varphi_{2\omega_3} &= \varphi_{2\omega_2} - 2\Delta_1. \end{aligned} \quad (5)$$

In the case of such relations between phases of the fundamental signals and their second harmonics, it is possible to adjust all second harmonics with only one value of phase (180º) to achieve maximum reduction in all IM3 products, simultaneously. Therefore, the slope of the phase characteristic in fundamental signal path should be the same as for their second harmonics, having in mind that differences between second harmonic frequencies are twice more then between fundamental ones.

The analysis applied in [4] shows that the injection of the second harmonics reduces the first kind of IM3 and the injection of the sum of pairs of the fundamental signal frequencies reduces the second kind of IM3.

The expression for the injection of these second-order IM signals together with the fundamental signal frequencies is:

$$\begin{aligned} V_{in} &= V_{\omega_1} Cos(\omega_1 t + \varphi_1) + V_{\omega_2} Cos(\omega_2 t + \varphi_2) \\ &+ V_{\omega_3} Cos(\omega_3 t + \varphi_3) + V_{\omega_{12}} Cos(\omega_1 t + \omega_2 t + \varphi_{\omega_{12}}) \\ &+ V_{\omega_{23}} Cos(\omega_2 t + \omega_3 t + \varphi_{\omega_{23}}) + V_{\omega_{13}} Cos(\omega_1 t + \omega_3 t + \varphi_{\omega_{13}}), \end{aligned} \quad (6)$$

where the injected signals (ω_1+ω_2), (ω_2+ω_3) and (ω_1+ω_3) have amplitudes $V_{\omega_{12}}$, $V_{\omega_{23}}$ and $V_{\omega_{13}}$ and phases $\varphi_{\omega_{12}}$, $\varphi_{\omega_{23}}$ and $\varphi_{\omega_{13}}$, respectively. The additional signals at the second kind IM3 frequencies at output of the amplifier are the results of interaction between the source signals (ω_1,ω_2 and ω_3) and the injected IM2 signals. The second kind IM3 products at frequencies (ω_i+ω_j-ω_k) i,j,k=1,2,3 can be expressed as given in Eq. (7) where the first term relates to the interaction between fundamental signals only.

$$\begin{aligned} & I_{out(\omega_i + \omega_j - \omega_k)} = \\ & \frac{3}{2} V_{\omega_i} V_{\omega_j} V_{\omega_k} g_{m3} Cos(\omega_i t + \omega_j t - \omega_k t + \varphi_i + \varphi_j - \varphi_k) \\ & + \frac{3}{2} V_{\omega_k} V_{\omega_{ij}} g_{m3} Cos(\omega_i t + \omega_j t - \omega_k t + \varphi_{\omega_{ij}} - \varphi_k). \end{aligned} \quad (7)$$

The original signals and the injected second-order IM signals interact and produce additional third-order term of the second kind. Therefore, a complete elimination of a particular second kind IM3 product can be achieved by a proper selection of phase and amplitude of appropriate injected signal. As the injected signals have almost equal amplitudes and different phases, it is difficult to obtain a maximal reduction in all second kind IM3 products with the same value of the amplitude and phase adjustment.

Using Eq. (4), the phases of the second-order IM products $\varphi_{\omega_{ij}}$ are expressed as given by Eq. (8). If relations between second-order non-linear products (second harmonics and sum of pairs of the fundamental signals) given by Eqs. (5) and (8) respectively, are established, it will be possible to reduce all IM3 products (first and second kinds) with same value of phase in the second harmonic path (means second harmonics and sum of pairs of the fundamental signal frequencies in further text).

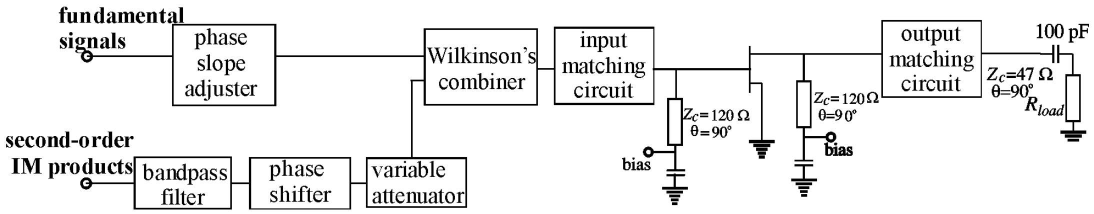

Fig. 1. Amplifier with injection of the second harmonics

This condition will be satisfied if the slope of phase characteristic of the fundamental signals is the same as of the second harmonics.

i=1, j=2 and k=3

$$\varphi_{\omega_{12}} = \varphi_{2\omega_1} - \Delta$$

i=1, j=3 and k=2

$$\varphi_{\omega_{13}} = \varphi_{\omega_{12}} - \Delta_1$$

i=2, j=3 and k=1

$$\varphi_{\omega_{23}} = \varphi_{\omega_{13}} - \Delta \,. \tag{8}$$

III. DESIGNING PROCEDURE

The power amplifier (Fig. 1) including the additional components (phase shifter, variable attenuator, bandpass filter, power combiner) was designed as a hybrid microwave integrated circuit by using program ADS. A design was applied on the substrate characterized by following parameters ε_r=4.3, H=0.635 mm, t=0.004 mm.

In the CAD simulation, non-linear Curtice's cubic model was used for MESFET modeling.

With the aim to select only second harmonics from the output of non-linear signal sours, the bandpass filter is used. The bandpass filter that can be conveniently fabricated in microstrip is the capacitive-gap coupled resonator filter designed at 5 GHz center frequency with 20% bandwidth and 0.5 dB equal-ripple response, with 3 sections.

For the phase shifter in second harmonics path, a broadband reflection and analog type circuit was designed [5]. This is the dual–varactor reflection circuit with Lange coupler at input. Since 120^o phase shift was obtained in simulation for this kind of phase shifter, two circuit are connected in cascade [6] to achieve 240^o phase shift in broadband frequency range 4-16 GHz. A broadband operation of the phase shifter is required to achieve a greater flatness of the phase characteristic over second harmonic frequencies. Two types of hyperabrupt tuning varactor diodes with capacitances ration 3:1 were used for simulation. Varying the controlled voltage between 0 and 10 V, a full phase shift of 240^o is achieved at the frequencies of the fundamental signal second harmonics.

PIN diode attenuator accomplishes an appropriate adjustment of the second harmonic amplitudes. For simulation purposes, HP hermetic PIN diode for microstrip attenuators was used. Changing a diode forward current from 0.01 to 100 mA, the resistance of the intrinsic region of the diode is varied, providing the control of attenuation with the bias point.

The second harmonics are combined with fundamental signals at amplifier input by Wilkinson's combiner.

A component that can involve different phases of fundamental signals with the same slope of phase characteristic as in the second harmonic path was included in the amplifier (Fig. 1) and denoted as phase slope adjuster. An ideal element with possibility to vary a slope of phase characteristic was used from ADS library. Instead of this, the bandpass filter that precedes the amplifier circuit in order to pass only fundamental signals trough can be designed with appropriate phase characteristic.

IV. SIMULATED RESULTS

Four input fundamental signals at frequencies 2.5, 2.51, 2.522 and 2.531 GHz at input power levels –5 dBm were chosen at the amplifier input. The spectrum for the bias point V_{gs}=-0.4 V and V_{ds}=3 V, obtained at the amplifier output without applying our technique is shown in Fig. 2. It includes fundamental signals, the first kind of the third-order IM products at 2.469, 2.478, 2.489, 2.49, 2.498, 2.513, 2.52, 2.534, 2.540, 2.544, 2.552 GHz and 2.562 and the second kind IM3 products at 2.479, 2.488, 2.491, 2.501, 2.509, 2.512, 2.519, 2.521, 2.532, 2.541, 2.543, and 2.553 GHz. The results obtained by applying linearization technique without additional component in fundamental signal path for phase slope adjustment are presented in Fig. 3. Achieved improvement in IM3 is up to 18 dB only. If we include appropriate component in fundamental signal path that provides a difference in phases between two adjacent frequencies so that it is a half of ones between their second harmonics, results are shown in Fig. 4. The IM3 signal power levels are reduced by 40 dB for the optimized values of the phase shifter and variable attenuator. This result is comparable with ones obtained for an ideal case with equal phases of the second harmonics.

Varying phase shifter characteristics for ±10°, the improvement in IM3 power is reduced to 18 dB. This suits to the results achieved without phase slope adjustment. However, in the case without phase slope adjustment, deviation in the phase of the second harmonics from optimal value deteriorates result more. Therefore, the approach proposed in this paper makes the linearization technique not only insensitive to the different phases of the second harmonics but also provide satisfied results for a deviation of second harmonic phase from optimal value.

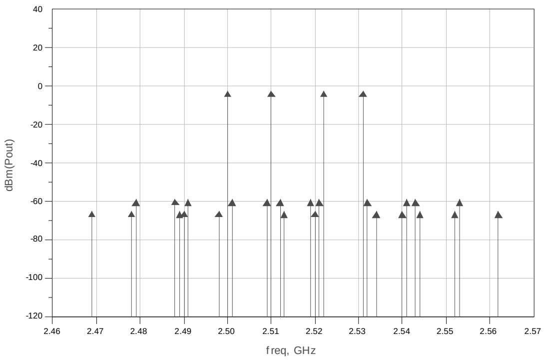

Fig. 2. The simulated fundamental powers and third-order IM powers before employing the technique.

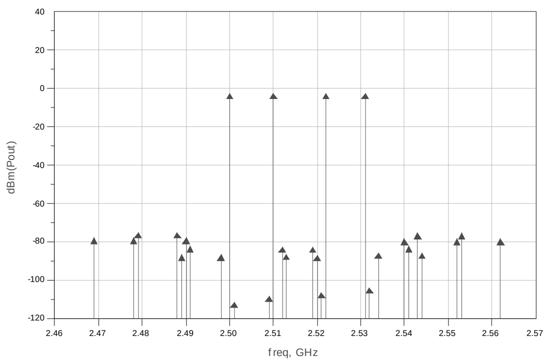

Fig. 3. The simulated fundamental powers and third-order IM powers after employing linearization technique without phase slope adjustment.

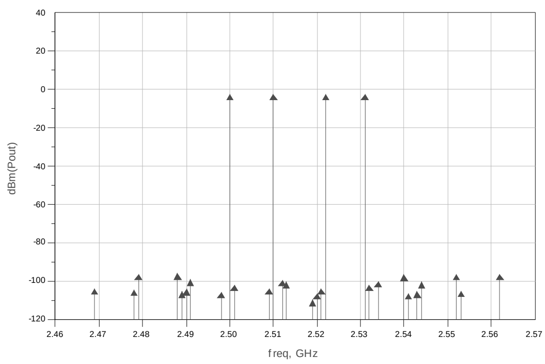

Fig. 4. The simulated fundamental powers and third-order IM powers after employing linearization technique with phase slope adjustment.

V. CONCLUSION

A linearization technique for reducing the third-order distorted signals, with the injection of the fundamental signal second harmonics was improved in this paper lowering the sensitivity to phase differences of injected second harmonics. The amplifier circuit with all additional components that proposed linearization technique was designed as hybrid microwave integrated circuit. The improvement in IM3 power level is approximately 40 dB achieved in simulation for four signals at amplifier input. Additionally, proposed procedure provides that it is possible to obtain 18 dB improvement for ±10° variation of appropriate phase in the second harmonic signals that is result obtained for no phase slope adjustment but for appropriate phase of second harmonics. This approach makes the improvement in intermodulation more flexible to the different phases of second harmonics allowing variation in the phase shifter characteristic from an optimal value with satisfied results.

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