Linearization of Two-way Doherty Amplifier by Using Second and Fourth Order Nonlinear Signals

Aleksandar Atanasković and Nataša Maleš-Ilić

***Abstract*—In this paper, a two-way Doherty amplifier with the additional circuit for linearization has been realized in order to experimentally verify the linearization influence of the fundamental signals' second harmonics and fourth-order nonlinear signals to the third- and fifth-order intermodulation products. The signals for linearization-second harmonics and fourth-order nonlinear signals are extracted at the output of the peaking cell, adjusted in amplitude and phase and injected at the input of the carrier cell in Doherty amplifier. Additionally, the linearization effects of three variants of the linearization approach have been analyzed by Advance Design System simulator: one that was tested experimentally, the case when the signals for linearization are injected only at the carrier amplifier output and when they are put simultaneously at the input and output of the amplifier.**

***Index Terms*—Doherty amplifier, linearization, second harmonics and fourth-order nonlinear signals, intermodulation products.**

I. Introduction

WITH the advent of spectrally efficient wireless communication systems, linearization techniques for nonlinear microwave power amplifiers have gained significant interest. Demanding requirements of new systems (CDMA2000, W-CDMA, OFDMT etc.), in order to meet both linearity and high power efficiency present a serious task for transmitter designers. The Doherty amplifier is capable of achieving a high efficiency of power amplifiers in base station. Different linearization methods exist with the aim to reduce nonlinear distortions while keeping power amplifier in a nonlinear and efficient mode. The various linearization methods of Doherty amplifier have been reported: post-distortion-compensation [1], the feedforward linearization technique [2], the predistortion linearization technique [3] and combination of those two linearization techniques [4].

The linearization effects of the fundamental signals' second harmonics (IM2) and fourth-order nonlinear signals (IM4) at frequencies that are close to the second harmonics to the standard (two-way, three-way and three-stage) Doherty amplifiers were investigated in [5] for LDMOSFETs in carrier and peaking amplifiers with the same periphery and in [6] for periphery relations 1:2.5:2.5. We applied the approach where IM2 and IM4 signals are injected together with the fundamental signals into the carrier amplifier input and put at its output [7]. In addition, three-stage Doherty amplifier was loaded with harmonic control circuit (HCC), which represents an optimal impedance for the second harmonics and either an open or short circuit for the third harmonics at the output of cells. Various configurations of loading were considered for the case of the same transistors in amplifying cells [8], [9] and with the transistor size ratio 1:2.5:2.5 [10]. Analysis of the linearization of Doherty amplifiers was carried out for sinusoidal signals and digitally modulated signals through the simulation process by ADS software.

In this paper, two-way Doherty amplifier with the additional circuit for linearization is realized. The effects of linearization are verified by measurements. The linearization technique applied utilizes the second harmonics and fourth-order nonlinear signals at frequencies close to the second harmonics, which are generated at the output of the peaking cell. They are adjusted in amplitude and phase through the linearization branch and run at the carrier amplifier input over frequency diplexer. Also, the results of simulation that refer to the linearization approach tested in experiment, the linearization when the signals for linearization are led only at the carrier amplifier output and the linearization with the signals that are fed at the input and output of the amplifier are given in parallel.

II. Theoretical Analysis of Linearization Technique Applied in Experiment

Theoretical analysis of the proposed linearization approach is based on the nonlinearity of the drain-source current of LDMOSFET in amplifier circuit which is expressed by a polynomial model [11], [12] under the assumption of neglecting a memory effect, as represented by (1).

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$$
\begin{aligned}
&i_{ds}\left(v_{gs}, v_{ds}\right) = \\
&K_{10} v_{gs}(t) + K_{20} v_{gs}^2(t) + K_{30} v_{gs}^3(t) + K_{40} v_{gs}^4(t) + K_{50} v_{gs}^5(t) + \\
&+ K_{11} v_{gs}(t) v_{ds}(\mathrm{t}) + K_{21} v_{gs}^2(t) v_{ds}(t) + K_{12} v_{gs}(t) v_{ds}^2(t) + \dots
\end{aligned} \tag{1}
$$

The spectrum of a digitally modulated fundamental signal is given by the expression: $V_B(j\omega) \otimes \frac{1}{2}\delta(\omega \pm \omega_0)$, where $V_B(j\omega)$ represents a baseband spectrum.

Equation (1) connects the nonlinearity of the drain-source current i_{ds}, in reference to the voltage v_{gs} between gate and source, which is represented by the coefficients K_{10} to K_{50}. Higher order nonlinear terms K_{40} and K_{50} are included into the equation according to the analysis performed in [12] that favours the terms of output current as function of v_{gs} up to the fifth-order. The nonlinearity of drain-source current in terms of the voltage between drain and source, v_{ds}, which is expressed by the coefficients K_{01} to K_{03}, is assumed to have a negligible contribution to the intermodulation products according to [11] and [12], so that they are omitted from the equation. However, the equation encompasses "mixing" terms K_{11}, K_{12} and K_{21}.

The drain-source current at IM3 and IM5 frequencies can be written by (2) and (3), where $\left(\rho_2^{(i)}, \varphi_2^{(i)}, \rho_4^{(i)} \text{ and } \varphi_4^{(i)}\right)$ stand for the amplitudes and phases of the IM2 and IM4 signals put at the amplifier input, whereas $\rho_2^{(o)}$, $\varphi_2^{(o)}$, $\rho_4^{(o)}$ and $\varphi_4^{(o)}$ are amplitudes and phases of IM2 and IM4 signals that exist at the amplifier output due to both an inherent nonlinearity of transistor and transferred signals from the input.

The signal distorted by the cubic term of the amplifier, K_{30}, is included into analysis by (2) as the first term. The cubic term is considered as a dominant one according to [11] and [12] in causing IM3 products and spectral regrowth. The term K_{20} (second term) is created by the gate-source voltage of fundamental signal and voltage of second harmonic fed at the amplifier input. The mixing product of the fundamental signal and second harmonic appearing at the amplifier output is expressed as the third term. Additionally, the fundamental signal at the output of amplifier mingles with the second harmonic injected at the amplifier input generating the fourth term. The amplitude of output voltage at the fundamental signal frequency that is 180° out of phase in reference to the input signal is denoted as ρ_1. The third and fourth terms can be neglected for lower signal power. In case of higher power, they may reduce each other. The mixing terms between drain and gate, K_{12} and K_{21}, produce drain-source current at IM3 frequencies with the opposite phases, so that they reduce each other [11].

$$
\begin{aligned}
&I_{ds}(j\omega)\big|_{IM3} \approx \left\{\left[\frac{3}{4}K_{30} + \frac{1}{4}K_{20}\rho_2^{(i)} e^{-j\varphi_2^{(i)}} + \right.\right. \\
&\left. + \frac{1}{4}K_{11}\rho_2^{(o)} e^{-j\varphi_2^{(o)}} - \frac{1}{4}K_{11}\rho_1 \rho_2^{(i)} e^{-j\varphi_2^{(i)}} \right] \\
&\left.\left(V_B(j\omega) \otimes V_B(j\omega) \otimes V_B(j\omega)\right)\right\} \otimes \frac{1}{2}\delta(\omega \pm \omega_0)
\end{aligned} \tag{2}
$$

According to the previous analysis, it is possible to reduce spectral regrowth caused by the third-order distortion of fundamental signal by choosing appropriate amplitude and phase of the second harmonics ($\rho_2^{(i)}$ and $\varphi_2^{(i)}$).

The first term in (3) expressing the drain-source current of the fifth-order intermodulation products (IM5) is formed from the fundamental signals due to an amplifier nonlinearity of the fifth-order, K_{50}. The second term is the mixing product between the fundamental signal at amplifier input and IM4 signal inserted to its input, too. Therefore, the original IM5 product (the first term) can be reduced by adjusting the amplitude and phase of IM4 signals that are injected at the amplifier input. The IM5 products are also expressed in terms of K_{30} coefficient-the third term in (3) made by reaction between two IM2 signals and fundamental one at the amplifier input. Also, the fundamental signal at the amplifier output reacts with the IM4 signal at the amplifier input over K_{11} term producing IM5 product (fourth term). The fifth term is made between the input fundamental signal and IM4 signals at the amplifier output. All mixing terms which stand by K_{12} and K_{21} in (3) are generated due to reaction between two second harmonics and fundamental signal. The signals taken in consideration are observed at the input and output of the amplifier. The K_{12} and K_{21} terms produce current at the frequencies of IM5 products with the opposite phases, so that they reduce each other. Consequently, their influence to the power of IM3 and IM5 products can be cancelled.

$$
\begin{aligned}
&I_{ds}(j\omega)\big|_{IM5} \approx \\
&\left\{\left[\frac{5}{8}K_{50} + \frac{1}{4}K_{20}\rho_4^{(\mathrm{i})} e^{-j\varphi_4^{(\mathrm{i})}} + \frac{1}{8}K_{30}{\rho_2^{(i)}}^2 e^{-j2\varphi_2^{(i)}}\right.\right. \\
&- \frac{1}{4}\rho_1 K_{11}\rho_4^{(i)} e^{-j\varphi_4^{(i)}} + \frac{1}{4}K_{11}\rho_4^{(o)} e^{-j\varphi_4^{(o)}} \\
&+ \frac{1}{8}K_{12}{\rho_2^{(o)}}^2 e^{-j2\varphi_2^{(o)}} - \frac{1}{8}K_{12}\rho_1\rho_2\rho_2^{(o)} e^{-j\left(\varphi_2^{(i)} + \varphi_2^{(o)}\right)} \\
&\left. + \frac{1}{8}K_{21}\rho_2^{(i)}\rho_2^{(o)} e^{-j\left(\varphi_2^{(i)} + \varphi_2^{(o)}\right)} - \frac{1}{8}K_{21}\rho_1{\rho_2^{(i)}}^2 e^{-j2\varphi_2^{(i)}} \right] \\
&\left. V_B(j\omega) \otimes V_B(j\omega) \otimes V_B(j\omega) \otimes V_B(j\omega) \otimes V_B(j\omega)\right\} \\
&\otimes \frac{1}{2}\delta(\omega \pm \omega_0)
\end{aligned} \tag{3}
$$

As in the case of IM3 products, third to fifth terms have negligible impact for lower power of the fundamental signals, while in case of higher power, it can be assumed that fourth and fifth terms cancel each other. However, for higher power, the mixing K_{30} term (the third term in (3)) may increase IM5 products if IM4 signals injected at the amplifier input do not have enough power against the K_{30} term to control it.

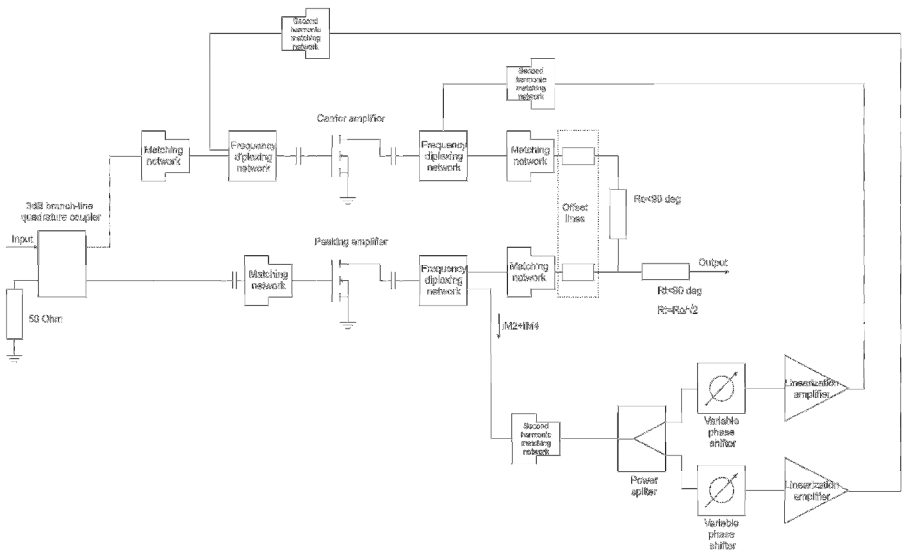


Fig. 1. Schematic diagram of two-way Doherty amplifier with additional circuit for linearization.

III. DESIGN OF AMPLIFIER AND LINEARIZATION CIRCUITS

Agilent Advanced Design System-ADS software has been used for the design of conventional two-way Doherty amplifier, which schematic diagram is shown in Fig. 1.

Two-way Doherty amplifier was designed in standard configuration [1], [2], [4], [5]. The carrier and peaking amplifiers have input and output matching circuits, which transform the input impedance of the device to 50Ω and the optimum load impedance Z_{opt} to 50Ω. In low-power region, the peaking amplifier should be an open circuit and load impedance of the carrier amplifier should be doubled to $2Z_{opt}$ by a quarter-wave impedance transformer with the characteristic impedance R_0=50Ω. Also, the quarter-wave transmission line with the characteristic impedance $R_t = R_0\sqrt{2}$ transforms 50Ω to 25Ω that is a load impedance of the output combining circuit when the peaking amplifier is turned on in higher power region. Phase difference of 90° is required at the inputs of the carrier and peaking amplifier to compensate for the same phase difference between those two amplifiers caused by the quarter-wave impedance transformer at the output.

The output impedance of the LDMOSFET is strongly reactive with low resistance so in low-power region considerably power leaks from the carrier amplifier to the peaking amplifier. The output impedance seen at the output of the peaking transistor is transformed to the open by the output matching circuit and the proper offset line.

The carrier and peaking cells were designed using Freescale’s MRF281S LDMOSFET which non-linear MET model is incorporated in ADS library.

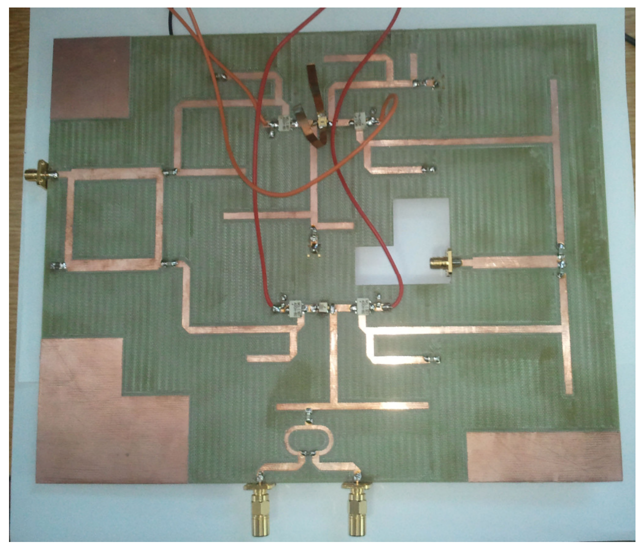


Fig. 2. Realized two-way Doherty amplifier.

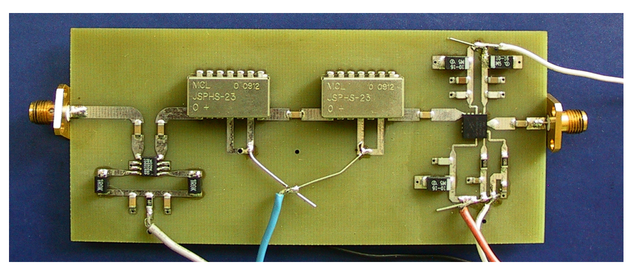


Fig. 3. Realized linearization circuit.

The transistor shows a 4-W peak envelope power. The matching impedances for source and load at 1GHz are Z_S=5.5+j15Ω and Z_L=12.5+j27.5Ω, respectively. These impedances were obtained by using load-pull and source-pull analysis in ADS. The matching impedances for the second harmonics at 2GHz for source and load are Z_S=3.1-j2.4Ω and Z_L=12.5+j9.2Ω, respectively. These impedances are taken from the authorized Freescale catalogue.

The carrier amplifier is biased in class-AB (V_D=26V, V_G=5.1V (13.5%IDSS)), whereas the peaking amplifier operates in class-C (V_D=26V, V_G=3.6V).

In simulation of two-way Doherty amplifier, ideal elements from ADS library was utilized for the linearization circuit components. The linearization circuit fabricated for the experiment comprises from M/A-COM PIN diode variable attenuator MA4VAT2007-1061T, two Mini-Circuits 180° voltage variable phase shifters JSPHS-23+ to provide phase shift of 360° and Skyworks high linear 2W power amplifier-SKY65120. The second harmonics, IM2, and fourth-order nonlinear signals at frequencies close to the second harmonics, IM4, which are generated at the output of the peaking amplifier, are extracted through the diplexer circuit [5] that was designed to separate the fundamental signals and signals for linearization matched to the impedance for their adequate power level. The linearization circuit adjusts IM2 and IM4 signals in amplitude and phase before they are inserted at the carrier amplifier input over the frequency diplexer designed with the independent matching circuits for the fundamental and signals for linearization. Linearization branch can vary power of the signals for linearization from -10dB to 7dB in reference to the generation point at the peaking amplifier output.

Both, two-way Doherty amplifier (Fig. 2) and linearization circuit (Fig. 3) are realized on FR4 substrate with 1.55 mm thickness and 17.5µm metallization layer. The printed circuit boards for the circuits were manufactured on LPKF ProtoMat S100 in laboratory.

IV. Simulated and Measured Results

S-parameters of Doherty amplifier obtained by ADS simulator as well as the measured parameters are shown in Fig. 4. The figure compares the characteristics achieved in the case of the ideal lossless amplifier circuit (dashed line) and in the case when losses and discuntinuity effects of tee-sections and banded microstrip lines are included into the analysis. One can notice that the amplifier operational frequency is shifted from the design frequency of 1GHz to 1.006GHz in the fabricated amplifier.

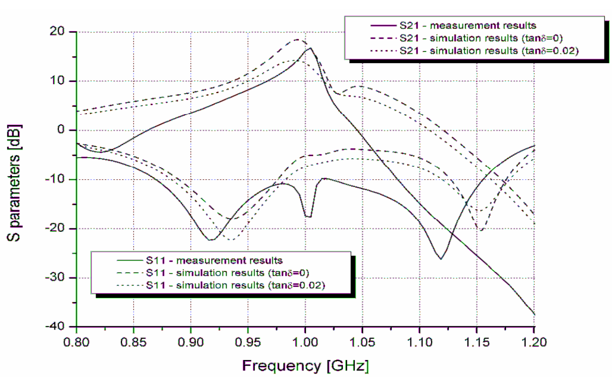
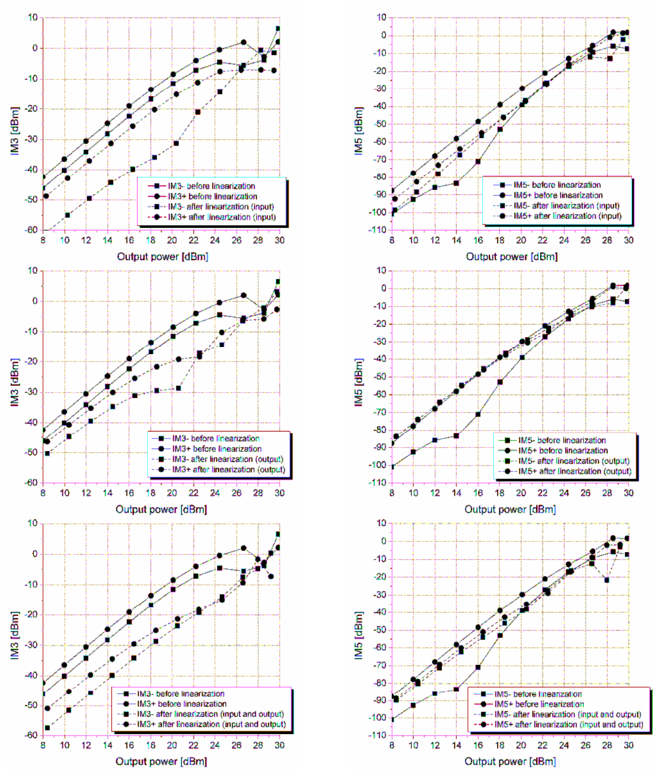


Fig. 4. S-parameters of two-way Doherty amplifier.

The results before and after linearization for two-tone test of two-way Doherty amplifier at frequencies 988MHz and 990GHz are given in Fig. 5 for the range of fundamental signal output power (8dBm-30dBm). These figures compare the linearization effects for three cases of linearization depending on whether the signals for linearization are injected at: 1. the amplifier input, 2. the amplifier output and 3. the amplifier input and output. Denotation in the figures is as follows: IM3- at 986MHz, IM3+ at 992MHz, IM5- at 984MHz and IM5+ at 994MHz. In the lower power range (8dBm-24dBm), the presented results relate to the case when the amplitudes and phases of IM2 and IM4 signals are adjusted on the optimal values at 22dBm output power where IM3 products are suppressed for 14dB and 7dB in the first case, 10dB and 12dB in the second and 12dB and 14dB in the third case. The IM5 products are more asymmetrical before linearization, so that at 22dBm IM5- product is kept almost the same to the level before linearization in all cases considered, whereas IM5+ is lessened by 6dB in the first and 8dB in the third case and deteriorates by 3dB in the second case. In case of higher power (24dBm-30dBm) the amplitude and phases of the signals for linearization were adjusted on the optimal values for each single power level. As far as the whole power range is observed the best reduction of IM3 products was achieved by the injection of the signals for linearization at the input and output, whereas the injection only at the carrier amplifier input bring slightly better suppression of IM5 products.



a) b)

Fig. 5. Simulated intermodulation products before and after linearization of two-way Doherty amplifier for a power range: a) third-order; b) fifth-order products.

The measured output spectra of Doherty amplifier before and after applying the linearization for two sinusoidal signals at 8dBm input power at frequencies 1.0065GHz and

1.0075GHz are compared in Fig. 6. The fundamental signal output power is about 19.96dBm before and 19.35dBm after the linearization. The third-order intermodulation products at frequencies 1.0055MHz and 1.0085GHz are lowered by linearization from -8dBm to -16dBm and -13dBm, respectively. The fifth-order intermodulation products are reduced by around 6dB at frequencies 1.0045MHz and 1.0095GHz.

The results from Fig. 7 show the effects of two-way Doherty amplifier linearization accomplished for the output power ranging from 10dBm to 26dBm (upper signal power is constrained by the laboratory equipment capability to the power that is 10dB below the maximal catalogue power level of the transistor applied). These results are compared to the case when linearization is not carried out. Fig. 7a) relates to the power reduction of IM3 at 1.0055GHz (IM3-) and 1.0085GHz (IM3+), whereas Fig. 7b) shows results connected to the IM5 products at 1.0045GHz (IM5-) and 1.0095GHz (IM5+).

It is evident from these figures that the linearization with the proposed approach gives satisfactory results in improvement of IM3 products for the power range up to approximately 18dBm and becomes asymmetrical at higher power. However, IM5 products decrease slightly at lower power levels, whereas they get worse at higher power range considered, still retained below the levels of the linearized IM3 products. According to (2) and (3), IM2 and IM4 signals can reduce both IM3 and IM5 products that depends on the relations between amplitudes as well as phases of the IM2 and IM4 signals generated at the peaking amplifier output. However, when the required relations are not fulfilled, only one kind of the intermodulation products can be reduced sufficiently.

Doherty amplifier drain efficiency (DE) obtained in simulation for ideal circuit case without losses, the simulated characteristic gained for the loss microstrip circuit with included discontinuities and the measured values are compared in Fig. 8. The good agreement can be observed between the curves relating to the real simulated Doherty amplifier and experimental results up to 34dBm power that is maximal level that can be reached by the available laboratory equipment. At this power level, there is a maximal discrepancy between the simulated and measured result of 5%. The maximal efficiency achieved by the realized circuit is 32.7%.

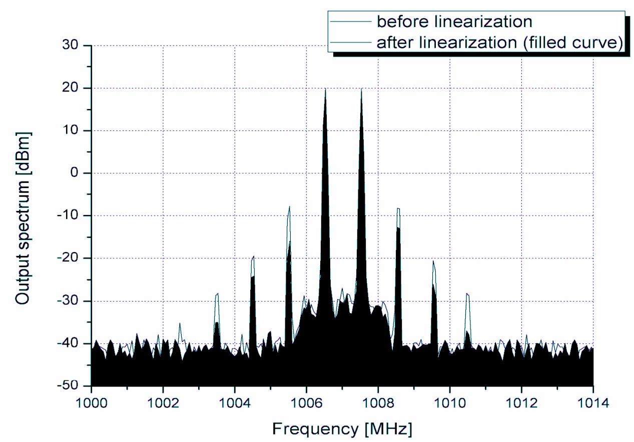
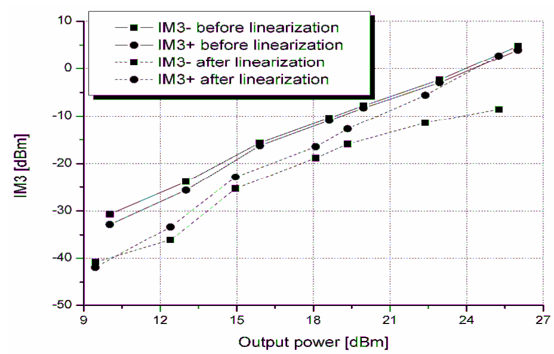
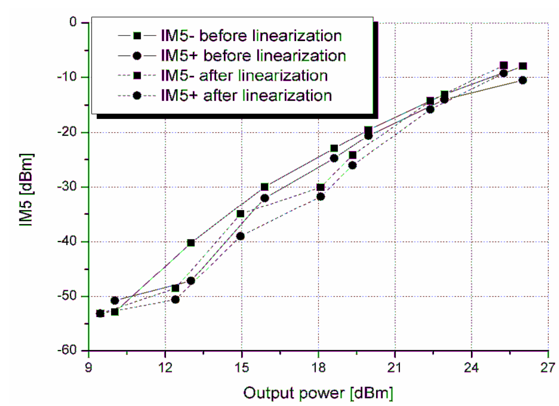


Fig. 6. Measured output spectra for 8dBm input power of fundamental signals; before and after linearization (filled curve).



a)



b)

Fig. 7. Measured intermodulation products before and after linearization of two-way Doherty amplifier for a power range: a) third-order; b) fifth-order products.

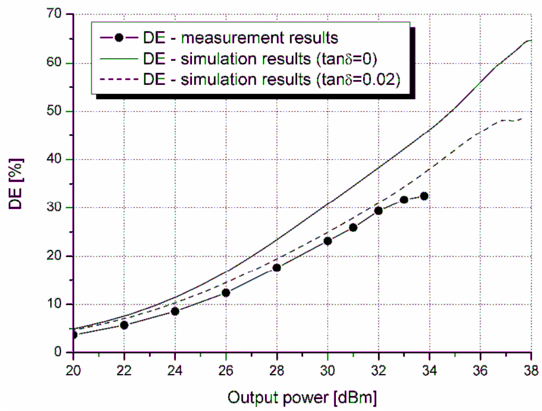


Fig. 8. Drain efficiency of two-way Doherty amplifier.

V. CONCLUSION

This paper presents for the first time the experimental verification of two-way Doherty amplifier linearization by simultaneous injection of the second harmonics and fourth-order nonlinear signals at the input of carrier amplifier. The linearization approach achieves very good results in a reduction of the third-order intermodulation products, even for a wider power range. When the fifth-order intermodulation products are concerned, the mild suppression is observed at low- power levels, however these products deteriorate at high-power range. Measurements are constrained by the laboratory equipment to the lower power that is 10dB below the maximal available power of transistors utilized. Additionally, the results of simulation obtained by Advance Design System program are introduced in the paper for three variances of the linearization approach concerning the injection point of the signals for linearization: 1. input, 2. output, and 3. input and output of the carrier amplifier. It can be observed the similar behaviour of the designed and realized two-way Doherty amplifier in linearization process.

We would like to point out that the crucial matter in the linearization approach used for Doherty amplifier linearization is the possibility to exploit the peaking amplifier as a source of signals for linearization and therefore avoid the necessity for additional nonlinear sources that will increase the circuit complexity and total energy consumption.

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