FACTA UNIVERSITATIS
Series: **Electronics and Energetics** Vol. 29, N° 1, March 2016, pp. 127 - 138
DOI: 10.2298/FUEE1601127M

LINEARIZATION OF BROADBAND TWO-WAY MICROSTRIP DOHERTY AMPLIFIER

Nataša Maleš-Ilić[1], Aleksandra Đorić[2], Aleksandar Atanasković[1]

[1]Faculty of Electrical Engeneering, University of Niš, Serbia
[2]Innovation Center of Advanced Technologies, Niš, Serbia

Abstract. *The linearization of a broadband two-way microstrip Doherty amplifier designed for application in the frequency range 0.9-1.0 GHz is considered in this paper. The amplifier characterized by the maximum output power 8 W is designed in microstrip technique for broadband applications. For linearization purposes, the second- and fourth-order nonlinear signals are extracted at the output of the peaking cell, adjusted in amplitude and phase and fed at the input and output of the carrier transistor over the microstrip hairpin band-pass filters. The effects of the linearization are considered through the simulation for two sinusoidal signals with different frequency interval between them setting on from 5 MHz and going up to30 MHz at different input power levels up to saturation, as well as for an Orthogonal frequency division multiplexing (OFDM) digitally modulated signal.*

Key words: *Doherty amplifier, broadband, microstrip, OFDM signal, linearization, second- and fourth-order nonlinear signals, intermodulation products.*

1. INTRODUCTION

The Doherty amplifier topology enables high efficiency in a range of output power that represents one of the most attractive characteristic required in contemporary wireless communication systems; therefore its design is a subject of various researches and investigations for application as a power amplifier in transmitters that need to support multi-standard modulation schemes and to provide a high efficiency, wideband operation, and linear performance.

Significant efforts have been devoted to the development of the linearization techniques for suppression of the nonlinear distortions in a Doherty amplifier: the post-distortion-compensation [1], the feedforward linearization technique [2], the predistortion linearization technique [3] and their combination [4], as well as the digital predistortion [5]-[7].

The linearization effects of the fundamental signals' second- (IM2) and fourth-order nonlinear signals (IM4) at the frequencies of the second harmonics and around them on

Received January 17, 2015; received in revised form March 23, 2015
Corresponding author: Nataša Maleš-Ilić
Faculty of Electrical Engeneering, University of Niš, Aleksandra Medvedeva 14, 18000 Niš, Serbia
(e-mail: natasa.males.ilic@elfak.ni.ac.rs)

the standard (two-way, three-way and three-stage) Doherty amplifiers were investigated in simulation, [8]. We applied the approach where the IM2 and IM4 signals are injected together with the fundamental signals into the carrier amplifier input and fed at its output [9]. Additionally, the influence of IM2 and IM4 signals on Doherty amplifier linearity was verified experimentally on a standard symmetrical and asymmetrical two-way Doherty amplifier [9], [10] and [11].

A broadband two-way Doherty amplifier including an additional circuit for linearization was designed in configuration with ideal lumped elements in the input and output matching circuits [12]. Matching circuit design was based on the filter structures with lumped elements and adequate transformations such as Norton transformations, [13], [14]. After applying appropriate transformations on the lumped elements [15], we designed and analyzed Doherty amplifier whose matching circuits comprise the ideal transmission lines combined with the lumped elements [16]. In order to design a matching circuit realizable in microstrip technology, the microstrip lines are calculated starting from the ideal transmission lines and combined with the commercially available SMD (Surface Mounted Devices) components instead of the ideal lumped elements in the matching circuits [17]. Additionally, the impact of band-pass filters in the linearization circuit on the amplifier performance was analyzed for four different filter types: doubly and singly terminated ideal bandpass filters, hairpin microstrip band-pass filter and a combination of a singly terminated stop-band filter with a hairpin filter [16].

In this paper, a broadband two-way Doherty amplifier was designed in microstrip technology, so that the input and output matching circuits of the transistors were based on only microstrip lines. Different transformations [15] were applied on the starting lumped elements matching circuits of Doherty amplifier in order to achieve the adequite performance (gain, efficiency, linearity). The complete microstrip Doherty amplifier is to be simpler for realization and implementation, especially at higher frequencies, in comparison with the amplifier consisting of combined microstrip lines and lumped elements matching circuits [17]. Also, an additional circuit for linearization was included into the broadband Doherty amplifier which operates over the frequency range 0.9-1.0 GHz.

In the applied linearization method, the second- and fourth-order nonlinear signals are extracted at the output of the peaking transistor of Doherty amplifier, adjusted in amplitude and phase throughout two independent branches and inserted into the input and output of the carrier cell over the hairpin microstrip band-pass filters. The effects of linearization are considered for two tone signals separated by various frequency intervals from 5 MHz to 30 MHz at different input power levels commencing from 5 dBm and getting up to 15 dBm (total signal power is at 2 dB back-off level in relation to the maximal output power). Additionally, according to the authors knowledge, for the first time in this paper the broadband two-way Doherty amplifier linearization by the technique that exploites the second- and fourth-order nonlinear signals is analysed for OFDM digitally modulated signal. In the recent authors' work, the linearization for OFDM signal has been carried out on narrowband single-stage power amplifier for LTE application by the injection of only second-order nonlinear signals (second harmonics) as depicted in [18].

This paper is organized as follows: Section II relates to the design of broadband two-way Doherty amplifier and additional linearization circuit including the simulation results that refer to the main amplifier characteristics-gain and efficiency. The simulation results of linearization for two sinusoidal fundamental signals (two-tone) analyzed in the range of signal output power and various frequency intervals between two signals are included in section III. This section also represents the results of linearization in case of OFDM digitally modulated signal for a power range. The conclusions are reported in section IV.

2. Design and Characteristics of Broadband Doherty Amplifier

Advance Design System-ADS was utilized for the design of two-way Doherty amplifier in standard configuration [1], [2], [4], [5], (schematic diagram is shown in Fig. 1) characterized by two quarter-wave impedance transformers with the characteristic impedance R_0=50 Ω and $R_t = R_0/\sqrt{2}$ in the output combining circuits, as well as a 3 dB quadrature branch-line coupler at the input to compensate for the phase difference of 90° caused by the 50 Ω quarter-wave impedance transformer at the output. The offset line in the output of the peaking amplifier transforms its output impedance to an open circuit in a low power region to prevent current leakage from the carrier amplifier.

The carrier and peaking cells were designed using Freescale's MRF281S LDMOSFET showing 4-W peak envelope power. The carrier amplifier was biased in class-AB (V_D = 26 V, V_G = 5.1 V (13.5% of I_{DSS}-transistor saturation current)), whereas the peaking amplifier operates in class-C (V_D = 26 V, V_G = 3.6 V). The source and load matching impedances of carrier and peaking cells were determined by using source-pull and load-pull analysis; for the carrier cell they are $Z_s = (5.5 + \mathrm{j}15)\ \Omega$ and $Z_l = (12.5 + \mathrm{j}27.5)\ \Omega$, respectively, and for the peaking cell $Z_s = (3.55 + \mathrm{j}15.7)\ \Omega$ and $Z_l = (3.95 + \mathrm{j}30.85)\ \Omega$.

The broadband operation of the amplifier was achieved by using the input and output matching circuits of the transistors based on the filter structures with lumped elements. A detailed insight into the design process of the broadband matching circuits with lumped elements with all necessary transformations is given in [12]. The next step is a transformation of the lumped element matching circuits into the matching circuits with the transmission lines characterized by the appropriate characteristic impedances and electrical lengths. In this paper, the direct transformations of the resonant LC circuits into the appropriate transmission lines or stubs were applied; therefore the parallel LC circuit was approximated by an open quarterwave stub connected in parallel, the parallel L was replaced by a parallel short quarterwave stub, whereas the serial LC circuit, the serial L and the parallel C were replaced by an appropriate transmission line connected in series [15]. In order to design a matching circuit realizable in microstrip technology, all ideal transmission lines were transferred into the microstrip lines on substrate with parameters: dielectric constant ε_r = 2.2, substrate height h = 0.635 mm and metallization thickness t = 17 μm.

In order to prevent losses of the fundamental signals, the stabilization of the carrier and peaking amplifiers was performed by the resistances whose values were selected in the range between 300-600 Ω. These resistances were connected in parallel with RF chocks in DC power supply circuits of the carrier and peaking transistors and also posted parallel to the input matching circuit in carrier cell, as shown in Fig. 1.

The IM2 and IM4 signals generated at the output of peaking transistor were extracted through the band-pass filter (BPF1), characterized by the center frequency of the second harmonics to pass the signals for linearization (IM2 and IM4 signals). The linearization circuit consists of two independent linearization branches that include the variable attenuator, variable phase shifter and amplifier for the amplitude and phase adjustment of the IM2 and IM4 signals. The IM2 and IM4 signals, over the band-pass filters BPF2 and BPF3, are delivered to the carrier transistor input and output, respectively, as illustrated in Fig. 1.

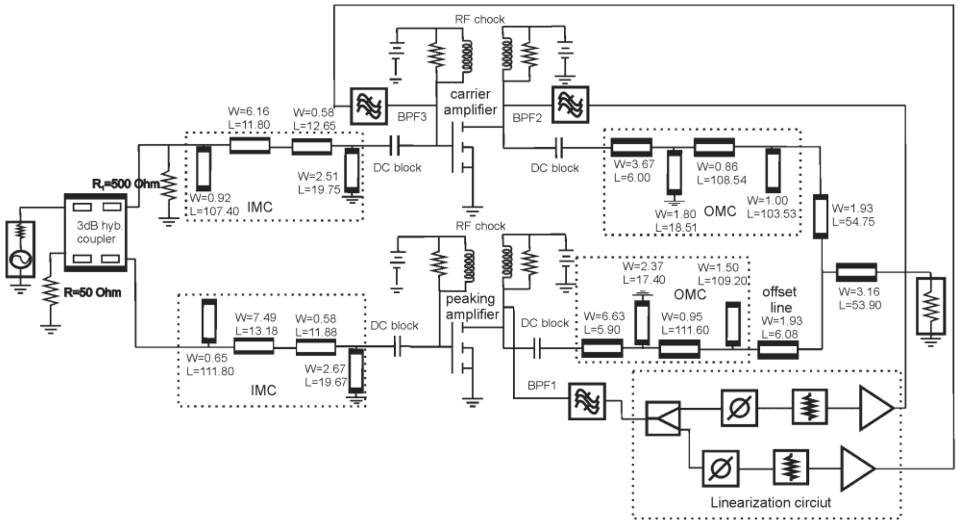

Fig. 1 Schematic diagram of broadband two-way microstrip Doherty amplifier with additional circuit for linearization (length (L) and width (W) are in millimeters).

Since the band-pass filters are directly connected to the gate and drain of the transistors in the Doherty amplifier they have the greatest influence on the amplifier behaviour. The band-pass filter was designed as a hairpin filter (HP) with three sections at the center frequency 1.9 GHz and 20% bandwidth on the microstrip substrate. Insertion of the linearization branches into the Doherty amplifier over the band-pass filters deteriorates the amplifier performance [16]. Accordingly, in order to correct the degradation and improve the amplifier characteristics, an additional optimization of the microstrip line parameters (length and width) in the input and output matching circuits of the carrier and peaking amplifiers was performed.

The output power, gain and drain efficiency, DE, of the Doherty amplifier as a function of the input power are shown in Fig. 2 for the frequencies 0.90 GHz, 0.925 GHz, 0.95 GHz, 0.975 GHz and 1.00 GHz of single-tone excitation. It can be noted that the maximal gain achieved is around 21 dB. The gain characteristics observed at the excitation signal frequencies vary in the range of approximately 2 dB up to approximately 15 dBm input signal power level. However, they differ less and less with the increase of the input power from 15 dBm to 20 dBm. In a low power range, the drain efficiency at denoted frequencies deviates from the DE at 0.95 GHz by maximum 5%, whereas differences at higher power range go up to 8% maximally. The drain efficiency attained at maximal output power of around 40 dBm is 53%.

The Doherty amplifier layout including the hairpin band-pass filters are illustrated in Fig. 3. Concerning the insertion of T-junctions for lines connection as well as necessary bending of microstrip lines required to achieve appropriate circuit placement on the substrate, the additional corrections of microstrip lines lengths were performed in comparison to the dimensions denoted in Fig. 1. It should be stressed that the large circuit board dimensions are expected for the operational frequency at L-band. Also, the additional circuit for linearization used for obtaining simulation results in this paper consists of the ideal elements from ADS library. A branch of the fabricated circuit for

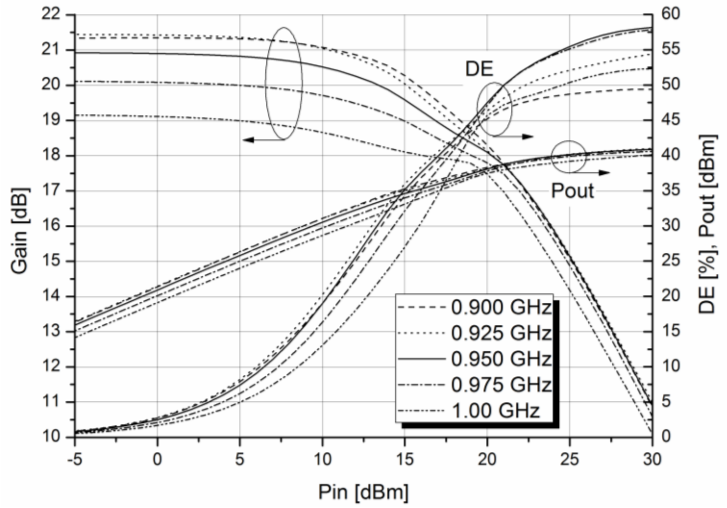

Fig. 2 Output power, gain and DE in terms of one-tone input power at 0.9 GHz, 0.925 GHz, 0.95 GHz, 0.975 GHz and 1.00 GHz.

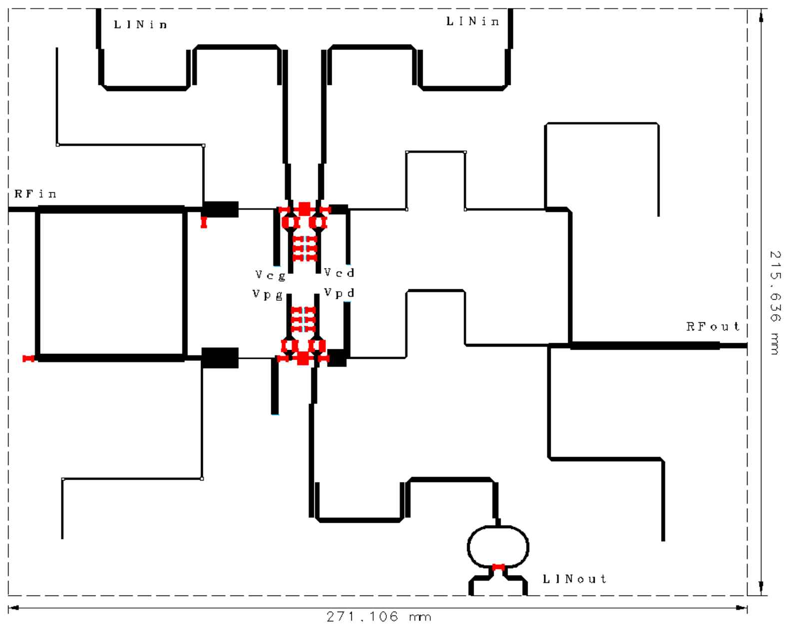

Fig. 3 Layout of broadband two-way microstrip Doherty amplifier including band-pass filters for extraction and injection of the signals for linearization.

linearization shown in Fig. 4 is planned to be used in further experimental verification of the linearization approach on microstrip broadband two-way Doherty amplifier. It comprises 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. This linearization circuit, which was already used in experiments performed for the linearization of narrowband amplifiers, [10], [11] satisfies the requirements for broadband applications.

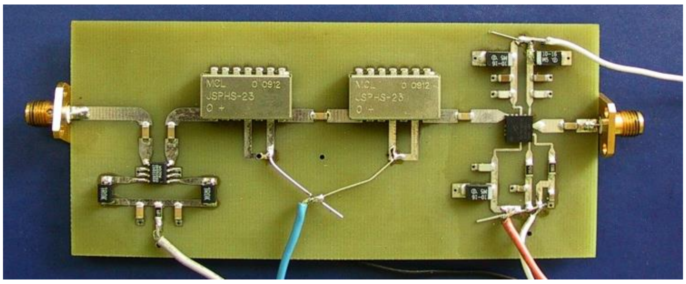

Fig. 4 Fabricated linearization circuit.

3. Linearization Results

In order to evaluate the impact of the proposed linearization technique on the designed microstrip Doherty amplifier, a two-tone test was carried out in ADS. One sinusoidal signal at frequency 0.95 GHz and the other shifted in frequency by 5 MHz to 30 MHz with an increment of 5 MHz were simultaneously driven at the amplifier input. The analysis was carried out for different input signal power levels. Power level of the third-order intermodulation products, before and after the linearization, in terms of the frequency interval between the signals is presented in Fig. 5 for the fundamental signal power levels at the amplifier input: 5 dBm, 8 dBm, 12 dBm and 15 dBm.

According to the theoretical analysis of the linearization approach given in [8]-[10], the linearization signals, IM2 and IM4, which are adjusted on the appropriate amplitudes and phases and injected at the input and output of the amplifier transistor, can reduce both the third- and fifth-order distortion of fundamental signal. However, the suppression grade depends on the relations between the amplitudes as well as phases of the IM2 and IM4 signals generated at the peaking amplifier output. Therefore, when the required relations between the amplitudes and phases are not fulfilled, only one kind of the intermodulation products can be lowered sufficiently.

In this paper the parameters of the linearization circuits were optimized to decrease the third-order intermodulation products while the fifth-order intermodulation products were required to retain at as low as possible power levels.

It can be noted that, after the linearization in the considered power range, a significant reduction of the IM3 products was attained. The suppression of the IM3 products is the highest, more than 40 dB, for the lower input power of 5 dBm. However, it is noticeable that the decreasing grade of intermodulation products descends when the power levels and interval between signals grow up; therefore it is seen that at the input power 8 dBm the

IM3 products are lessened by around 20 dB, whereas the increase of the input power to 15 dBm indicates around 10 dB reduction of the IM3 products.

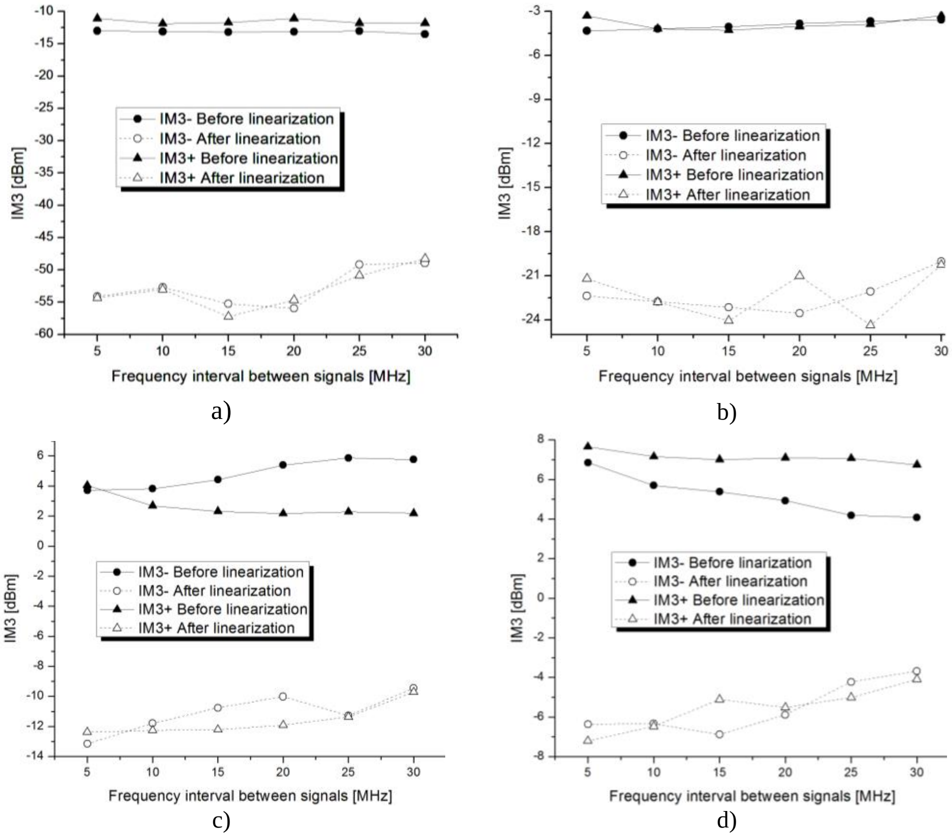

Fig. 5 Third-order intermodulation products of broadband microstrip Doherty amplifier at different input power levels: a) 5 dBm, b) 8 dBm, c) 12 dBm, d) 15 dBm.

The linearization results accomplished in this paper for the broadband Doherty amplifier incorporating the matching circuits that consist entirely of microstrip lines are very similar to the results that were achieved in the linearization of the broadband two-way Doherty amplifier designed in configuration with combined matching circuits comprising the microstrip lines and real SMD lumped elements, [17]. Suppressions of the IM3 products for all considered frequency intervals between signals up to 30 MHz for higher input power levels are approximately the same for both mentioned configurations; there is only difference at lower power levels where greter reduction of the IM3 products is obtained in case of a pure microstrip broadband Doherty configuration. Additionally, it should be indicated that, beside the comparable or better results of linearization, the broadband microstrip Doherty amplifier is simpler and less demanding for the realization comparing to the combined topology with SMD components, especially at higher frequencies. Moreover, microstrip amplifier enables the possibility for additional tuning of the width and length of the microstrip lines in the matching circuits if the correction of amplifier characteristics is required.

Additionally, the designed amplifier was tested for OFDM signal at 0.95 GHz carrier frequency, 17 MHz spectrum width for the range of signal power levels in order to access the impact of the proposed linearization technique on the microstrip broadband Doherty amplifier. The results of the analysis, the adjacent channel power ratio-ACPR before and after the linearization in terms of different average output power levels of fundamental signals are shown in Fig. 6. The parameters of the linearization circuits were optimized to suppress the third-order intermodulation products. The ACPR is observed at ±16 MHz offset from the carrier (the range of dominant third-order distortion) over the 0.32 MHz frequency span. It can be noted that the ACPR was improved by around 8 dB to 10 dB for the average output power levels of 20 dBm to 30 dBm. The ACPR decreases with output power rise, so that the improvement is around 3 dB at maximal observed power level.

The fifth-order intermodulation products are dominant at ±30 MHz offset from the centre frequency in the output spectrum. It follows from the Fig. 7 that the ACPR considered over the range of 0.32 MHz are retained on the power levels before the linearization at the lower output power levels up to approximately 26 dBm, while we notice the improvement of the parameter by maximum 8 dB for higher power.

It follows from the Fig. 8, which shows the average output power of fundamental signal for OFDM test, that the linearization method applied has the negligible influence of a few tenths of a dB on the output power of the fundamental signals. The fundamental signal power may be even increased after applying the proposed linearization techniques.

The output spectra for OFDM digitally modulated signal gained in simulation before and after the linearization for 12 dBm average input power level are given in Fig. 9. The average output power relates to the level around 8 dB back-off, but considering the 12 dB peak to average power ratio assigned to OFDM signal we may infer that the linearization results, which indicate the ACPR improvement of 11 dB for lower channel and 9 dB for higher channel, were achieved for the Doherty amplifier operating at high signal power going to the saturation.

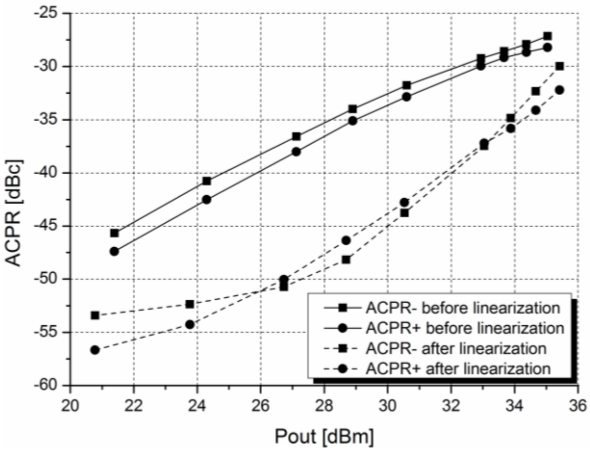

Fig. 6 ACPR before linearization (solid line) and after linearization (dashed line) at ±16 MHz offset from the carrier (the range of dominant third-order distortion) for OFDM signal in a range of average output power.

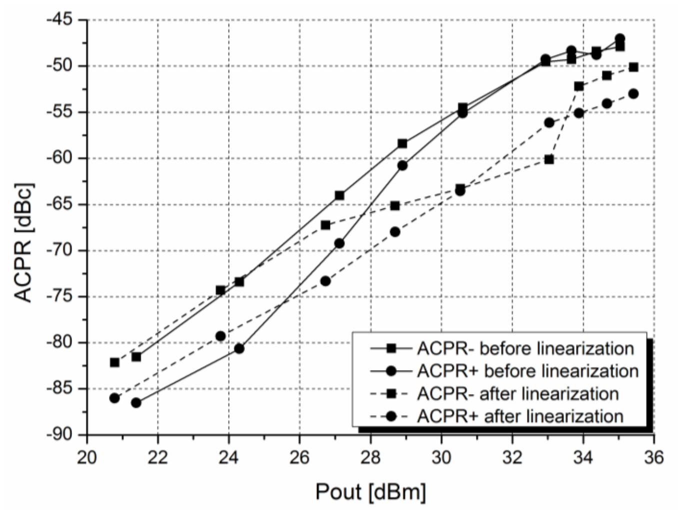

Fig. 7 ACPR before linearization (solid line) and after linearization (dashed line) at ±30 MHz offset from the carrier (the range of dominant fifth-order distortion) for OFDM signal in a range of average output power.

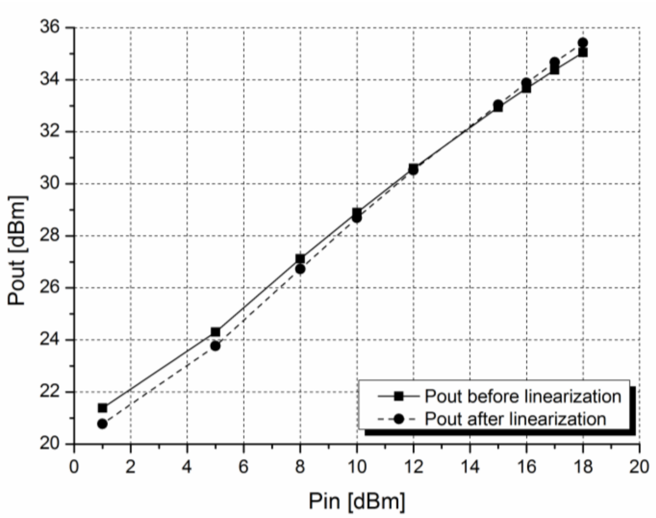

Fig. 8 Output power of OFDM signal before and after the linearization.

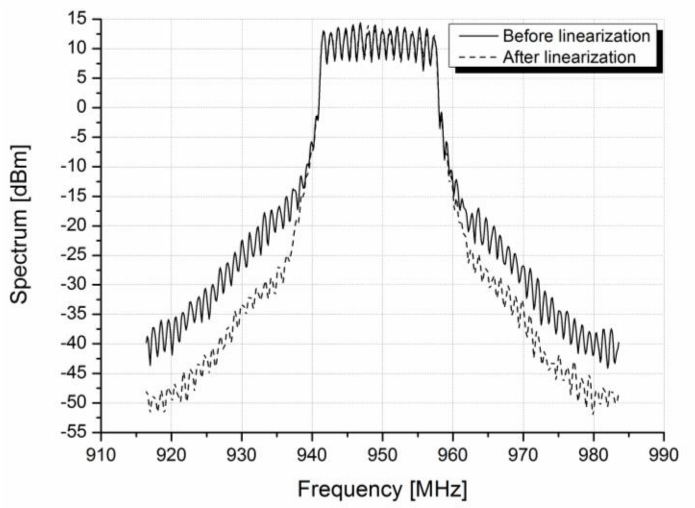

Fig. 9 Output spectra before and after linearization for OFDM signal at average input power of 12 dBm.

4. CONCLUSION

The effect of the linearization technique on the broadband two-way Doherty amplifier designed in microstrip technology is considered in this paper. A Doherty amplifier is designed to operate over the frequency range 0.9-1.0 GHz in configuration with matching circuits that consist of only microstrip lines. The applied linearization technique uses the even-order nonlinear signals, (IM2 and IM4) at frequencies of the second harmonics and around. These linearization signals, which are generated at the output of the peaking cell, are guided throughout two linearization branches. After being set in amplitude and phase on the appropriate values, the linearization signals are run at the carrier transistor input and output over the microstrip hairpin band-pass filters. The results attained in simulation for two-tone test indicate a satisfactory suppression of the IM3 products, even when the frequency interval between signals increases. However, with the growth of the power levels and interval between signals, the suppression results of the intermodulation products fall off. Moreover, in the case of broadband OFDM digitally modulated signal, the linearization method improves the ACPR in the range of dominant third-order intermodulation products and retains the fifth-order nonlinearities at sufficiently low power. The output power of useful fundamental signal is impaired negligibly or even it is augmented in case of higher power, which contributes to the efficiency of the amplifying system. It should be stressed that the amplifier designed completely as a microstrip circuit offers possibilities for simpler practical realization, especially at higher frequencies. Also, degradation of the amplifier performance, which appears when the commercially available SMD components are applied for lumped elements in the matching circuits, is evaded. Besides, the microstrip line dimensions may be trimmed additionally to improve the amplifier performance. It should be mentioned that dimensions of the microstrip two-way Doherty amplifier are expectedly large in the L frequency band of circuit operation. This paper aims to analyze the effects of the proposed linearization approach for application in broadband Doherty amplifier realizable in microstrip technique, while further intention will lead toward the design and linearization of amplifiers at higher frequencies where smaller circuit dimensions are expected.

Acknowledgement: *This work was supported by the Ministry of Education, Science and Technological development of Republic of Serbia, the project number TR-32052.*

REFERENCES

[1] K. J. Chao, W. J. Kim, J. H. Kim and S. P. Stapleton, "Linearity optimization of a high power Doherty amplifier based on post-distortion compensation", *IEEE Microwave and Wireless Components Letters*, vol.15, no.11, pp. 748-750, 2005.

[2] K. J. Cho, J. H. Kim and S. P. Stapleton, "A highly efficient Doherty feedforward linear power amplifier for W-CDMA base-station applications", *IEEE Trans., Microwave Theory Tech*., vol. 53, no. 1, pp.292-300, 2005.

[3] B. Shin, J. Cha, J. Kim, Y. Y. Woo, J. Yi, B. Kim , "Linear power amplifier based on 3-way Doherty amplifier with predistorter", In Proceedings of the IEEE MTT-S Int. Microw. Symp. Digest, 2004, pp.2027-2030.

[4] T. Ogawa, T, Iwasaki, H. Maruyama, K. Horiguchy, M. Nakayama, Y. Ikeda and H. Kurebayashi, "High efficiency feed-forward amplifier using RF predistortion linearizer and the modified Doherty amplifier", In Proceedings of the IEEE MTT-S Int. Microw. Symp. Digest, 2004, pp. 537-540.

[5] L. Piazzon, R. Giofre, P. Colantonio, and F. Giannini, "A wideband Doherty architecture with 36% of fractional bandwidth," *IEEE Microwave and Wireless Components Letters*, Vol. 23, No. 11, pp.626-628, Nov. 2013.

[6] David Yu-Ting Wu and Slim Boumaiza, A Modified Doherty Configuration for Broadband Amplification Using Symmetrical Devices, *IEEE Trans., Microwave Theory Tech*., vol. 60, no. 10, pp.3201-3213, 2012.

[7] Khaled Bathich, Georg Boeck, "Wideband Harmonically-Tuned GaN Doherty Power" Amplifier, In Proceedings of the IEEE MTT-S International Microwave Symposium Digest (MTT), 2012, Montreal, Canada, pp.1-3.

[8] A. Atanasković, N. Maleš-Ilić, B. Milovanović, "The linearization of Doherty amplifier", *Microwave review*, No.1, Vol. 14, pp. 25-34, September 2008.

[9] A. Atanasković, N. Maleš-Ilić, B. Milovanović: "Linearization of two-way Doherty amplifier", In EuMIC 2011 Proceedings, Conference Proceedings on CD, Manchester, UK, EUMA October 10-11, poster 01-17, pp.304-307, 2011.

[10] A. Atanasković, N. Maleš-Ilić, B. Milovanović: "Linearization of power amplifiers by second harmonics and fourth-order nonlinear signals", *Microwave and Optical Technology Letters*, vol. 55, Issue 2, pp. 425-430, February 2013.

[11] Aleksandar Atanasković, Nataša Maleš-Ilić, Bratislav Milovanović: "*Linearization of Symmetrical and Asymmetrical Two-Way Doherty Amplifier*", FACTA UNIVERSITATIS (NIS), Series: Electronics and Energetics, vol.25, no.2, pp.161-170, 2012,

[12] A. Đorić, N. Maleš-Ilić, A. Atanasković, B. Milovanović: "Linearization of Broadband Doherty Amplifier", " In TELSIKS 2013 Proceedings, Niš, Serbia, October 16-19, , Vol. 2, 2013, pp. 509-512,.

[13] G. Matthei, L. Zoung, and E. M. T. Jones, Microwave Filters, Impedance-Matching Networks, and Coupling Structures. Norwood, MA: Artech House, 1980.

[14] D. Dawson, "Closed-Form Solution for the Design of Optimum Matching Networks", *IEEE Trans. Microw. Theory Tech*., vol 57, no.1, pp. 121-129, 2009.

[15] R. W. Rhea, *HF Filter Design and Computer Simulation.* New York Noble, pp. 89, 1994.

[16] A. Đorić, N. Maleš-Ilić, A. Atanasković: "Analysis of Linearization Circuit Impact on Broadband Doherty Amplifier Performances", In Proceedings of the 1st International Conference on Electrical, Electronic and Computing Engineering, IcETRAN 2014, Vrnjačka Banja, Serbia, June 2-5, 2014, pp. MTI2.4.1-6.

[17] A. Đorić, N. Maleš-Ilić, A. Atanasković, "Broadband Microstrip Doherty Amplifier Design and Linearization", In ICEST 2014 Proceedings, Niš, Serbia, 25-27 June, 2014, pp. 131-134.

[18] Mijušković Jelena, Bukvić Branko, Nešković Nataša, Maleš-Ilić Nataša, Budimir Djuradj, "Compensation of Nonlinear Distortion in RF Power Amplifiers by Injection for LTE Applications", In Proceedings of the 22nd Telecommunications Forum- TELFOR2014 on CD, pp. 352-355, Belgrade, 2014.