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INTL JOURNAL OF ELECTRONICS AND TELECOMMUNICATIONS, 2011, VOL. 57, NO. 1, PP. 103–108
Manuscript received January 19, 2011; revised February 2011. DOI: 10.2478/v10177-011-0015-x

27 dBm Microwave Amplifiers with Adaptive Matching Networks

Dawid Rosolowski, Wojciech Wojtasiak, and Daniel Gryglewski

***Abstract*—The paper describes adaptive amplifier design with varactors and pin diodes as regulators of matching networks. As examples the two amplifiers with SHF-0189 HFET transistor and different matching sections were designed and manufactured. The output power level of 27 dBm and gain higher than 13 dB within L and S-band have been achieved. The amplifier design methodology is based on the small-signal approach and DC characteristics of transistors and regulators. Amplifier adaptivity allows us to remotely control the chosen parameters such as: frequency range, output power level, gain and etc.**

***Keywords*—Adaptive Power Amplifiers (APAs), components for Software Defined Radio, multi-band & multi-mode devices, RF adaptivity, tunable matching networks.**

I. INTRODUCTION

RECENTLY wireless communication has come into public use, therefore there is urgent and intensified need of implementation of several telecommunication standards in one device, e.g.: GSM, Wireless LAN, GPS, Bluetooth or HDTV. Such "services integration" is typically performed by application of standard oriented transceivers which operate in one band with fixed modulation scheme [1]. Implementation of several standards using separate dedicated devices is non-economical, because these devices include a lot of identical components. More convenient solution for designing of multi-mode and multi-standard devices can be made by using of SDR (*Software Defined Radio*) [2] idea with DiCon (Direct Conversion) architecture [3]. The concept requires implementation of two mechanisms: baseband block reconfigurability and RF Front-End adaptivity. Since digitally realized reconfigurability is relatively simple and well-known, the main problem lies in RF blocks adaptivity. Application of DiCon architecture minimizes a number of conversion stages (no IF standard-oriented filters required), simplifies design process and brings the designer closer to building reconfigurable systems. However, due to the lack of appropriate tunable elements, adaptive amplifiers and filters operating in wide frequency range are still not mature enough. In the absence of an alternative solution, modern multi-band and multi-standard systems are based on integrating DiCon architecture and baseband block reconfigurability with switched amplifiers and filters. Front-End modules adaptivity can be also achieved by more complicated devices, e.g. simultaneously multi-band (from 2 to 3 bands) filters and amplifiers. The issue of designing and implementing of fully-reconfigurable wireless devices remains open and is a challenge for designers of the next generation of radio systems.

In the paper, the concept and design of APA for wireless communication is presented. The amplifier architecture with adaptive matching networks is briefly described in Section II. The review of microwave tuning components is included in Section III. In Section IV amplifier design based on small-signal analysis is briefly presented. Section V describes prototyping process of two example medium power amplifiers operating over frequency range of 1.3 GHz to 2.6 GHz and 0.7 GHz to 2.8 GHz, respectively. Each of them provide power gain exceeding 13 dBm and is characterized with input matching $|\Gamma_{IN}| \leq 0.3$. Simulation and experimental results for both amplifiers are compared in Section VI. The conclusions are given in section VII.

II. CONCEPT OF THE ADAPTIVE POWER AMPLIFIER

Adaptive Power Amplifier (APA) may be considered as an enhanced classic, "fixed" RF amplifier structure with reconfigurable functionality. As result, the amplifier should be capable of changing of its fundamental parameters, e.g. operating frequency range, gain and output power level or content of intermodulation products, depending on the user requirements. The reconfiguration process consists in adaptation of matching networks to signal parameters at the amplifier input. APA can be also equipped with active bias or dynamic load mechanism for efficiency improvement and increasing versatility. To provide optimal performances at varying load impedance (variation of antenna parameters in different condition) the output matching network of APA can be also dynamically controlled.

Basic block diagram of APA with reconfigurable matching networks and active bias is shown in Fig.1.

The signals p_1, p_2 control reconfiguration process in input and output matching networks. Similarly, voltages u_1, u_2 determine operating point of an active element. Adaptation process can be static or dynamic. The static reconfiguration is performed only once, when the system comes into use. This process can be supervised by micro-controller due to the non real-time operation. The dynamic adaptation process consists in correction of matching network control signals preceded by tracking of the input signal in order to achieve the desired parameters. Such operation requires the use of fast DSP processor or FPGA to perform the algorithm in real-time. The control algorithms used to optimize the performance of adaptive amplifiers are considered in [4].

This work was supported by the Ministry of Science and Higher Education for the years 2008-2010 as development project.

The authors are with Institute of Radioelectronics, Warsaw University of Technology, Nowowiejska 15/19, 00-665 Warsaw, Poland (e-mails: {drosolow, W.Wojtasiak, D.Gryglewski}@ire.pw.edu.pl).

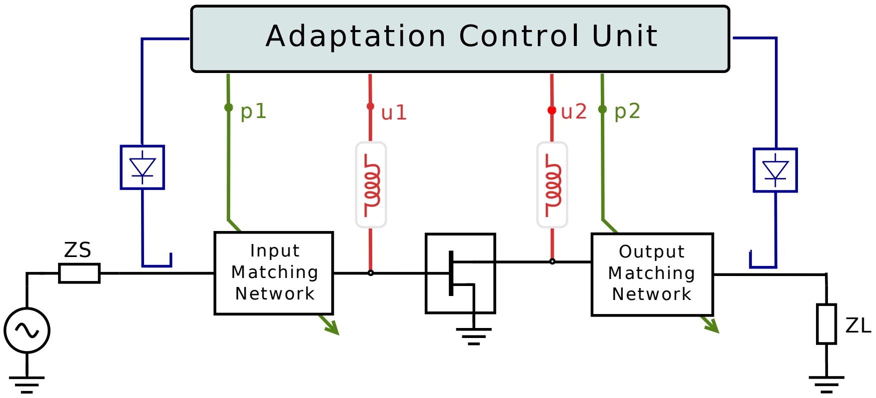

Fig. 1. Block diagram of Adaptive Power Amplifier.

Irrespective of the adaptation performing methods, the capability to shape the amplifier characteristics without hardware modification is a very interesting concept, and changes the perception of RF amplifiers.

III. REGULATORS = TUNABLE ELEMENTS

The APA reconfigurability can be performed using reactance-controlled components and switches, called regulators in matching networks. It seems that in order to one must take into account following parameters:

- frequency range,
- power handling,
- insertion loss,
- linearity,
- brake-down voltage,
- continuous and fast tunability,
- dc power consumption during change of state and its upholding,
- size and easy assembling,
- low cost.

Most of variable microwave devices such as varactors, pin diodes, MEMS (*Micro Electro-Mechanical Systems*), BST capacitors or microstrip lines on the substrate with voltage variable dielectrics exhibit numerous advantages and drawbacks at the same time. Due to the availability, simple control, as well as easy assembly and low cost the classical p-n varactors and pin diodes have been taken into consideration. Despite promising features the other mentioned above variable elements were rejected, because of non-standard processing, packaging techniques or the control voltage of more than 100 V.

The regulators applied as elements of reconfigurable matching networks should be able to achieve wide tuning frequency range and insert very low losses. The large-signal behaviour of variable components is especially important for power amplifier design. It is necessary to determine the range of RF signals for which the parameters of regulators are constant or their changes can be neglected. Otherwise, the matching network can be de-tuned by RF signals turning those components into sources of distortions i.e. unwanted products. In the case of varactor its capacitance is modulated by even small RF signal compared to the bias voltage. Finally the amplifier will reduce transmission performance despite the output power level is below the 1dB gain compression point. To limit this effect, the regulators should be weakly coupled with matching section elements or anti-serial or anti-parallel configurations of varactors can be used [5].

IV. APA DESIGN

Proposed APA design is based on the small-signal approach and the following assumptions:

- operating class of transistor: A or AB,
- output power level of amplifier: below 1dB gain compression point,
- voltage-current analysis of regulators,
- non-linear effects - negligible,
- a number of regulators reduced a priori up to 3 varactors and 4 pin diode per matching section

The APA design comes down to the search for optimal structures of matching networks for desired adaptation criteria. The amplifier design algorithm can be outlined as follows:

1) Modelling of Chosen Components: The measured S-parameters of transistor, varactors and pin diodes are used to extract the parameters of models i.e. the equivalent circuits' values of components [6]. To improve modelling accuracy, the S-matrix measurements are performed for a lot of transistor operating points and regulators' biases. The transistor is modelled using S-parameters measured for three operating states: pinch-off (Off-state), saturation (On-state) and normally biased transistor (Nb-state). The transistor model parameters are determined by a fitting of measured and simulated characteristics. Similar procedure is used for modelling of regulators.

2) Transistor Stability Problem: The most of microwave transistors usually exhibit conditional stability i.e. stability factor $K > 1$ and $det[S] < 1$, especially in low frequency range. Therefore during amplifier design it is necessary to stabilize transistor unconditionally in whole frequency range, both within desired band and out of it. The transistor stability can be achieved by means of losses located either in the input biasing circuit or into input matching section and biasing circuit. The first solution is possible only for transistor instability over a low frequency range, far from the operating band. The instability within or close to the operating frequency range must be removed by inserting resistors in the input matching section.

3) Input Matching Network: The amplifier input matching network is directly designed using the S-parameters of normally biased transistor according to the following condition:

$$|\Gamma_{IN}(p_i, f_i)| \leq \Gamma_{LIM}, \ and \quad f_{i-1} < f_i \tag{1}$$

where p_i is the state of input regulators, i defines the number of adaptation state. It is assumed that the reflection coefficient value Γ_{LIM} less than 0.3 is acceptable. Due to the adaptation methods used for re-tuning of narrowband matching characteristic at the amplifier input, the Γ, T and Π matching section structures are suggested. On the basis of simulations it can be assumed that the simplest structures with only one regulator allows achieving relative band up to 50%, whereas quasi Π and T structure give approximate octave-width band.

4) Output Matching Network: The output matching network of an amplifier is optimized for maximum output power in given frequency range. For this purpose the admittance condition (Equation 2) defined in Fig.2 is used to determine the matching section structure.

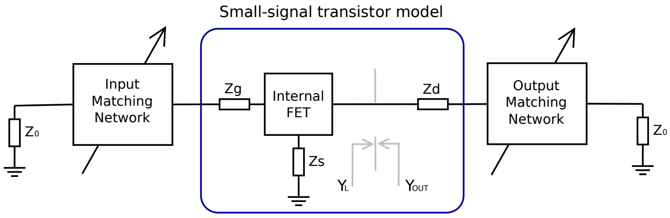

Fig. 2. Block scheme for optimal load analysis.

$$Y_L = \frac{1}{R_{opt}} - jIm(Y_{out}) = G_{opt} - jB_{opt} \tag{2}$$

The optimal load resistance R_{opt} is derived from a DC I-V characteristics of transistor operating in A-class. Imaginary part of load admittance is directly obtained from the S-parameters measured for Nb-state of transistor.

5) Iterative Synthesis of the Input and Output Matching Network: Because of the finite isolation of transistor ($s_{12} \neq 0$) the output circuit affects the input matching section. Therefore the both matching networks are separately optimized in iterative process.

V. AMPLIFIER DESIGN EXAMPLES

As example two APAs optimized for maximum output power level and tuned over a wide frequency range are designed and manufactured. To design both amplifier the SHF-0189 HJFET transistors and semiconductor tunable devices (varactors and pin diodes) are used. The APAs should fulfil the following parameters:

- operating class: A,
- tunable frequency range from 1.5 GHz to 2.5 GHz,
- output power level $P_{OUT} > 27$ dBm,
- $|\Gamma_{IN}| < 0.3$,
- gain $G = 14 \pm 1dB$.

Design process was performed using Agilent ADS (Advanced Design System) microwave circuits simulator.

A. APA1 and APA2 Design

To investigate adaptive performances, the two amplifiers with different matching section structures were designed.

As shown in Fig.3 APA1 includes two independently reconfigurable networks. The input network is made as quasi-Π structure with on MA46H202 varactors, which are simultaneously controlled by the V1 voltage. The two diodes enable the tuning range to expand approximately by factor of 2. Simulated $|S_{11}|$ characteristics vs frequency for a few states of input network of transistor under matching conditions at its output are presented in Fig.4.

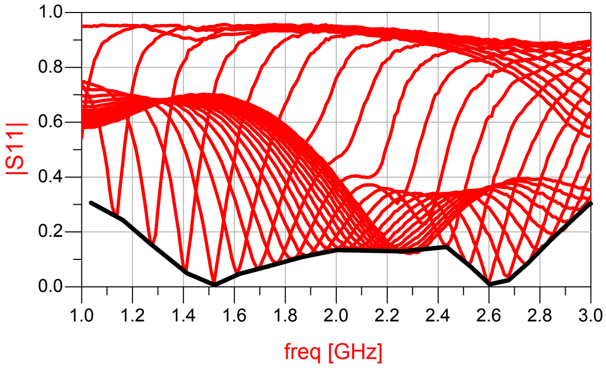

Fig. 4. Simulated $|S_{11}|$ for V1 voltage in the range from $0V$ to $22V$.

The output conductance G_{OPT} is calculated from DC-IV SHF-0189 characteristics as follows:

$$G_{OPT} = \frac{I_{Nb}}{U_{Nb} - U_k} = 18.8mS \tag{3}$$

where: I_{Nb}, U_{Nb} - transistor normal bias point, U_k is the knee voltage from the DC I-V characteristic of the transistor. The imaginary part of the output admittance of the internal FET is determined from simulation of the circuit including input matching network and part of the transistor as shown in Fig.2. Referring to Equation (2) the optimal susceptance B_{opt} (red circles) depending on frequency for all of the control states under condition that $|\Gamma_{IN}|$ is lower than 0.3, as presented in Fig.6. The trend black line was used as criterion for output network design.

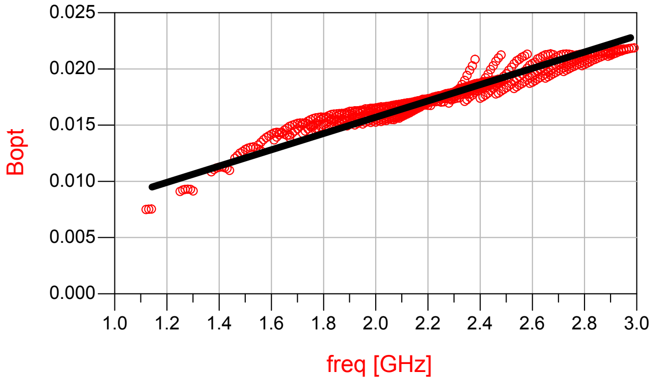

Fig. 6. Simulated susceptance at the output of internal FET.

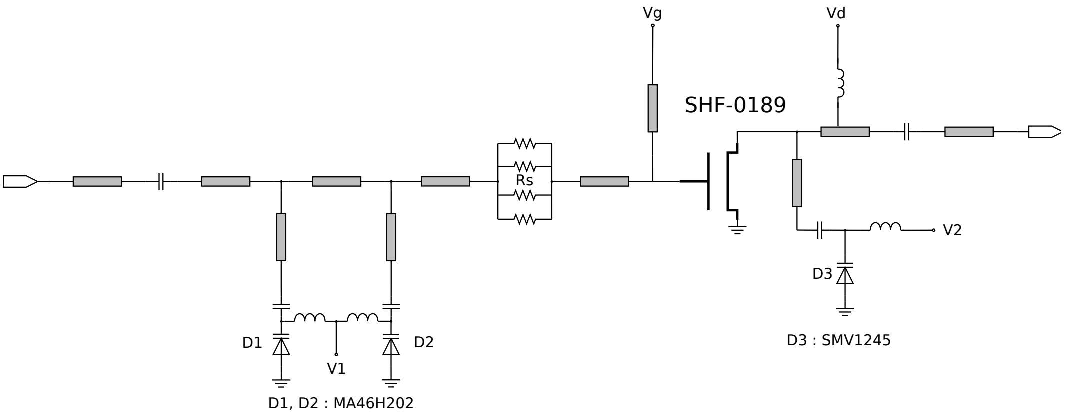

Fig. 3. Schematic diagram of APA1.

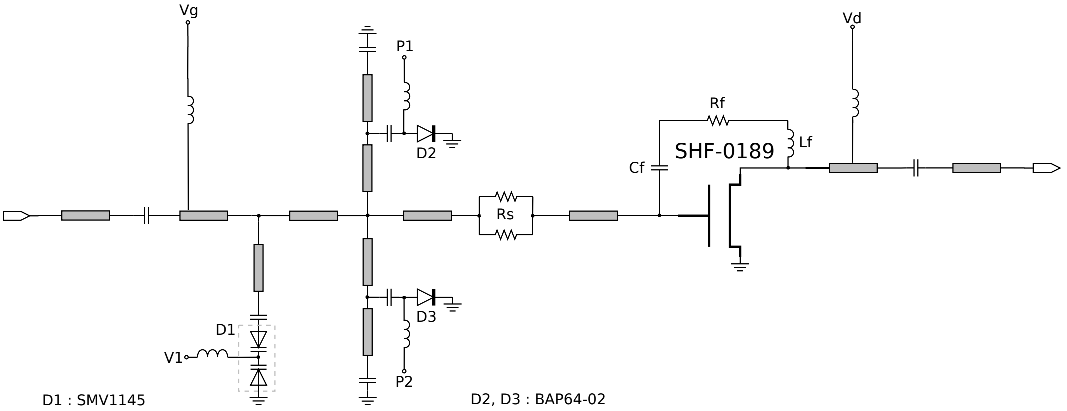

Fig. 5. Schematic diagram of APA2.

In the APA2 the shunt feedback technique is used to increase frequency range, especially below 1 GHz. As shown in Fig.5, the feedback characteristic is determined by the values of C_f, R_f and L_f. Input network reconfigurability is performed within three bands using pin diodes switches for controlling of stubs' lengths. Fine tuning is achieved by the varactors in anti-serial configuration to reduce non-linear distortions. Maximum tuning range of APA2 can be found from $|S_{11}|$ simulations as shown in Fig.7.

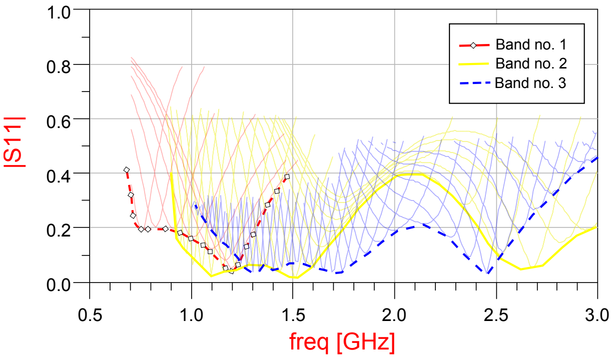

Fig. 7. Simulated $|S_{11}|$ for the three states of pin diodes (Band1: D2=off & D3=off, Band2: D2=on & D3=off, Band3: D2=on & D3=on).

The optimal load admittance is realized by fixed output matching network optimized only within the lowest band. To improve the output power and gain characteristics for the remaining bands the feedback technique is used.

B. Small-Signal Models

The model of SHF-0189 transistor was extracted using S-matrices measured at three operating points, i.e. Nb-state: $U_{DS} = 9V, I_D = 0.15A$, Off-state: $U_{GS} = -5V, U_{DS} = 9V$, On-state: $U_{GS} = 0V, U_{DS} = 1V$. The equivalent circuit of the SHF0189 HFET is presented in Fig.8.

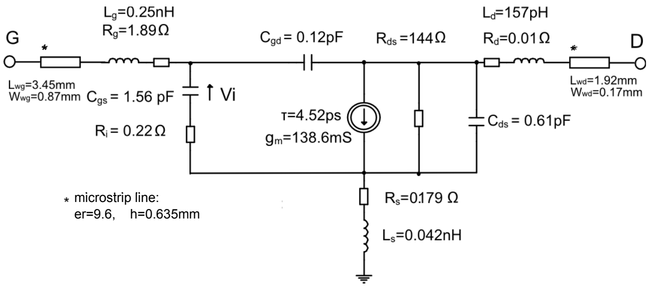

Fig. 8. Equivalen circuit of the SHF0189 HFET transistor.

The BAP64-02 pin diode, as well as, MA46H202, SMV1245 and SMV1135 varactors were modelled based on DC characteristics and S-Parameters obtained for chosen biases.

C. APAs' Realization

The proposed adaptive power amplifiers have been manufactured on Taconic RF 3.5 and Rogers RO4003 substrates with a dielectric constant of 3.5 and thickness of 0.505 mm housed on brass heat sinks for APA1 and APA2, respectively. The views of the devices are shown in Fig.9 and Fig.10. All the elements used to APAs manufacture are commonly available.

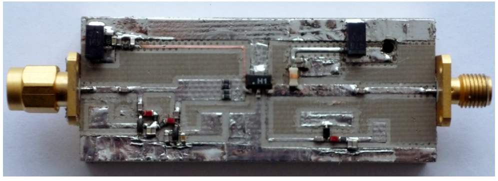

Fig. 9. Photograph of the fabricated APA1.

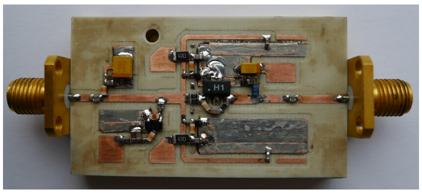

Fig. 10. Photograph of the fabricated APA2.

VI. SIMULATIONS AND EXPERIMENTAL RESULTS

The simulated or measured parameters of the amplifiers depend on the chosen states of the regulators. Thus it's strongly recommended to define how to interpret simulated and measured data in aspect of adaptation process. An example algorithm of data extraction can be performed as follows:

- choice of adaptation criteria for regulators' pre-sets (e.g. maximization of output power level or gain),
- adaptation process and data acquisition for chosen criteria,
- extraction of desired characteristics from collected data.

The amplifiers were adapted for the criteria of the output power level higher than 27 dBm at the gain flatness and input matching better than 0.3.

The simulated and measured magnitude of reflection coefficient and gain of the APA1 are respectively compared in Fig.11. The input network control voltage was swept from 0 V to 22 V with 2 V step. To bias of the output network constant 22 V voltage was used.

The magnitude of reflection and gain vs frequency of APA2 for a few chosen regulators' states are shown in Fig.12.

The good agreement between simulated and measured characteristics has been achieved. The discrepancies can be interpreted as inaccuracy of the models, simulations and measurements, as well as precision of assembling.

Measured output power and gain characteristics vs frequency, and output power vs input power level Pout = f(Pin) for APA1 and APA2 are presented in Fig.13, Fig.14, Fig.15 and Fig.16, respectively.

The influence of the regulators' non-linearity, especially varactors, on the overall amplifiers' linearity was investigated by

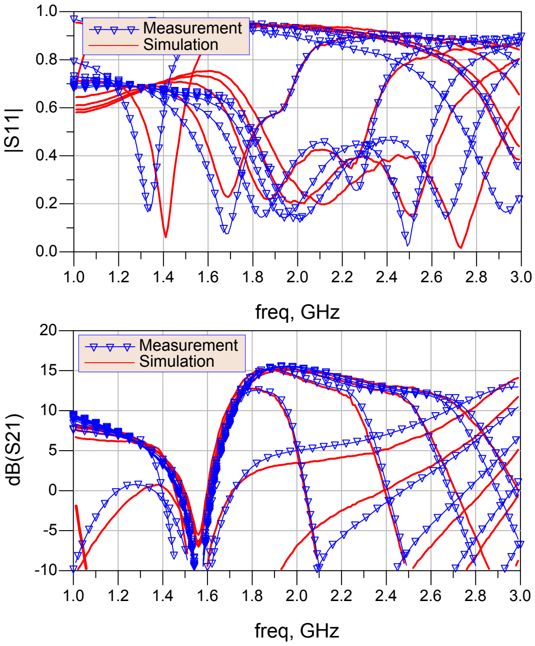

Fig. 11. Simulated and measured characteristics of $|S_{11}|$ and gain for APA1.

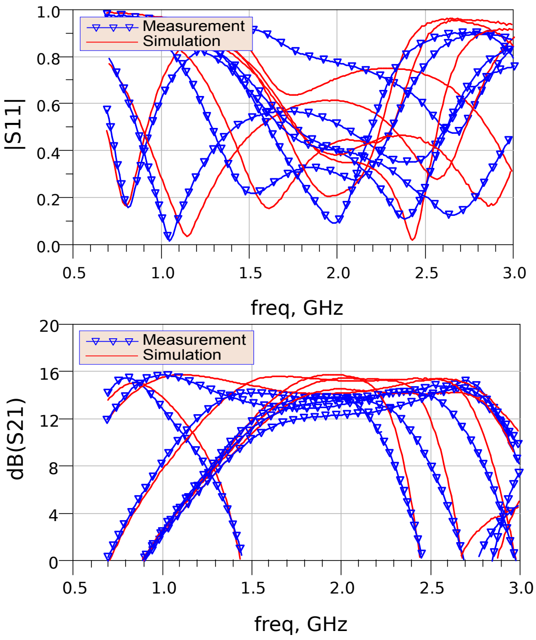

Fig. 12. Simulated and measured characteristics of $|S_{11}|$ and gain for APA2.

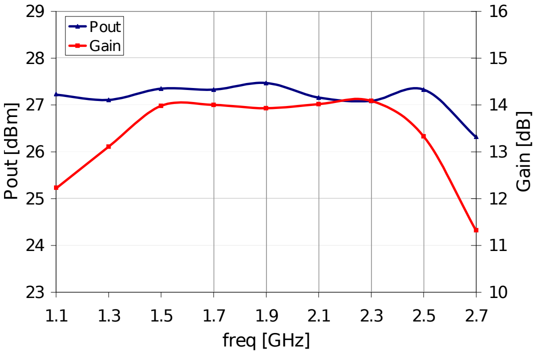

Fig. 13. Measured P_{out} and gain vs frequency for APA1.

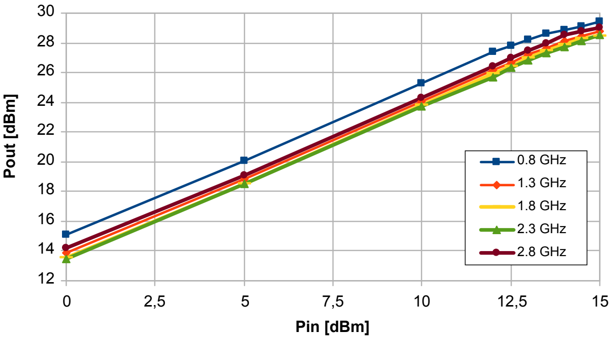

Fig. 16. APA2 characteristics of P_{out} vs P_{in}.

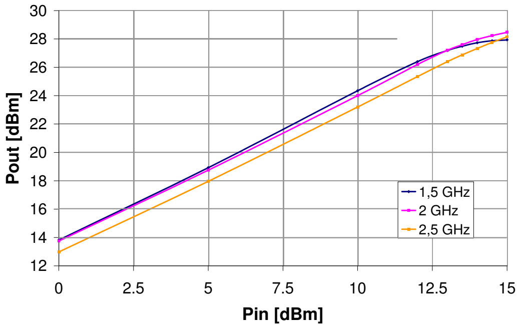

Fig. 14. APA1 characteristics of P_{out} vs P_{in}.

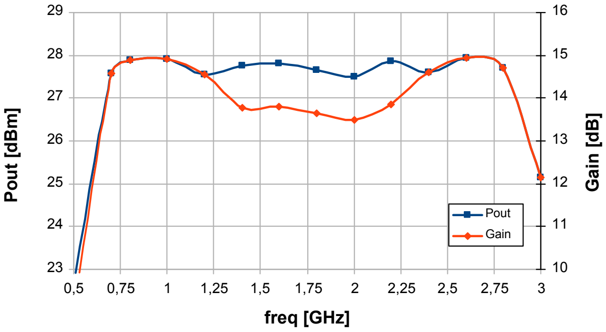

Fig. 15. Measured P_{out} and gain vs frequency for APA1.

measuring intermodulation products. The third order intercept point was determined by two tone excitation method (Δf = 200 kHz) for 2 GHz and output power level of 17 dBm. OIP3 is better than 34 dBm and 42 dBm, respectively for APA1 and APA2.

The measured parameters of developed adaptive power amplifiers are summarized in Tab.I.

TABLE I
MEASURED PARAMETERS OF THE AMPS OPTIMIZED FOR $P_{OUT} > 27dBm$ AND GAIN FLATNESS

Parameter	APA1	APA2
Frequency range	1.3 GHz ÷ 2.6 GHz	0.7 GHz ÷ 2.8 GHz
Pout	$\geq$ 27 dBm	
Gain	$\geq$ 13.5 dB	
Bandwidth	100 MHz ÷300 MHz	100 MHz ÷300 MHz *
OIP3	$\geq$ 34 dBm	$\geq$ 42 dBm
Input ctrl params no.	1	3
Output ctrl params no.	1	0
DC supply	9V / 0.15 A	

* for each band

VII. CONCLUSION

The adaptive amplifier design using small-signal approach to the transistor and regulators modelling has been presented. As examples the two amplifiers with HFET transistor and varactors and pin diodes were designed and manufactured. The APAs achieve output power level higher than 27 dBm and gain higher than 13 dB within frequency range from 1.3 GHz to 2.6 GHz and from 0.7 GHz to 2.8 GHz, respectively. The performances of amplifiers are optimized by controlling of the varactors bias and the states of pin diode switches. Apart from frequency adjustment and output power optimization, reconfiguration of matching networks may also reduce out-of-band higher order intermodulation products or in-band distortions. Due to parameters and functionality, the APA1 and APA2 can be used in multi-band and multi-standard applications (1.8GHz GSM, UMTS, WLAN), e.g. in modern SDR transceivers.

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