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SYNTHESIS AND IMPLEMENTATION INTEGRATED CIRCUITS OF SOLID STATE MICROWAVE SWITCHES WITH A CONTROLLED LEVEL OF NONLINEAR DISTORTION IN THE DECIMETER AND CENTIMETER WAVELENGTH RANGES

Specialty 05.12.04- Radio engineering, including systems and television devices

ABSTRACT

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Scientific Secretary of the Dissertation Committee

Professor, doctor of Technical Sciences, Alexander S. Korotkov

GENERAL CHARACTERISTICS OF THE WORK

Relevance of the research topic

Microwave switches are part of the equipment of communication, radar, navigation, and control systems. Currently, the following parameters of microwave switches have been achieved in the decimeter/centimeter wavelength ranges: in the 6-10 GHz range, the insertion loss is up to 1.2 dB, the decoupling reaches 28 dB, and the compression power per 1dB is 25-34 dBm. Further development of microwave switches occurs in three directions: increase of operating frequencies to tens of gigahertz or more, integration of microwave switches into more complex microwave monolithic integrated circuits (MMIC), development of new MMIC manufacturing technologies.

Currently (2020) most of the publications dedicated to innovation in silicon transceiver (T/R) modules 5-th generation, it is emphasized that most of the area of the MMIC is microwave switches; it is argued that a significant part of the components of the intermodulation distortion create a microwave switch; it is recognized that the dynamic range of a pair of "gallium arsenide microwave switch/low noise amplifier" wider dynamic range similar pairs, made on technology "silicon-on-insulator". The authors recognize that the transmitting part of the (T/R) modules, made on semiconductors of the A3B5 group of materials (GaAs and GaN), will remain inaccessible in terms of radiated power density for the "silicon-on-insulator" technology.

Every year, about two billion 4th-generation smartphones are sold in the world. It is assumed that the smartphone sales of the 5th generation will be even higher. Even with such huge production volumes, the cost of the microwave part of the smartphone is from 12 to 15 dollars. It is expected that the cost of the microwave part of the smartphone of the 5th generation will be from 18 to 20 dollars. It is obvious that the need for receiving and transmitting modules of radar systems is much less than the need for smartphones (which increases the cost of production), but the requirements for dynamic range and transmitted power are significantly higher. To resolve this contradiction allow the technology based on semiconductors of A3B5 group. Thus, the problem of designing and manufacturing the input/output part (i.e. the antenna switch) of microwave MMIC transceiver modules of decimeter and centimeter wavelength ranges remains relevant at the present time.

Existing methods of synthesis (design) of microwave switches are based on the representation of switching elements as discrete components with parasitic (inductive/capacitive) connections. Methods for the synthesis of monolithic integrated circuit switches based on the representation of switching elements in the form of integrated components are not developed, including for MMIC switches based on semiconductors of the A3B5 group. This does not allow us to consider the known solutions optimal, and the problem of synthesizing microwave switches is completely solved.

Purpose of work

The purpose of the dissertation is to develop a synthesis method and practical implementation of integrated circuits of solid-state microwave switches with a controlled level of nonlinear distortion for use in receiving and transmitting modules of decimeter and centimeter wavelength ranges.

To achieve this goal, you need to solve the following tasks:

1) Develop a methodology for the synthesis of microwave switch based on semiconductors of A3B5 group.

2) Develop a generalized (linear and nonlinear) model of a field-effect transistor designed to solve the problem of synthesizing microwave switches.

3) Develop a method for evaluating the nonlinear parameters of the MMIC switch based on the nonlinear properties of field-effect transistors of the A3B5 group.

4) Synthesize and manufacture integrated circuits of microwave switches based on A3B5 group semiconductors.

5) Conduct experimental studies, compare the theoretical and measured characteristics of implemented microwave switches based on A3B5 semiconductors.

Scientific novelty of the results of the dissertation work

1) Proposed to consider a microwave switch as an equivalent scheme of a parametric (switchable) frequency filter, which allows using methods of frequency filter synthesis for the synthesis of microwave switches.

2) Proposed to characterize the reactive elements of the model of the MOSFET, designed to solve the problem of synthesis of microwave switches using the specific values of inductance drain-source of the open transistor and the capacitance drain-source gated transistor, which allows to calculate the transistor according to the results of the synthesis solution according to the amounts of inductance or capacitance of the filter prototype.

3 Proposed to carry out the synthesis of the microwave switch using the theory of synthesis of frequency-selective devices based on a common low-pass filter (LPF) prototype for two modes of operation "on"/" off " of the microwave switch.

4) Proposed to use for the synthesis of the prototype microwave switch approximates the function of a Butterworth normalized not by the cutoff frequency but maximum operating

frequency of the microwave switch when the permissible unevenness in frequency response in the passband of the prototype, equal to the minimum decoupling of the microwave switch.

5) Proposed to introduce new specific nonlinear parameters of field-effect transistors that do not depend on the gate width of the transistor, which are used to estimate the intersection point of the 3rd-order intermodulation components of the synthesized microwave switch.

Theoretical significance of the results of the dissertation work

1) Generalized compact model of a field-effect transistor for MIS synthesis of a microwave switch has been developed, which allows evaluating the required isolation, insertion losses and intermodulation distortions during the synthesis of a microwave switch, performing parametric optimization.

2) Method for synthesizing the MMIC of a microwave switch has been developed to achieve maximum decoupling at controlled insertion losses, VSWR, and 1 dB compression input power.

3) Method of synthesis of MMIC microwave switch is developed to achieve minimum insertion losses at controlled insertion losses, VSWR and input compression power at 1 dB.

4) Procedure for evaluating the intermodulation distortion of the MIS microwave switch as a step in the synthesis of a microwave switch has been developed.

Practical significance of the results of the dissertation work

1) The parameters of a generalized compact model of a field-effect transistor based on PDK manufactured by JSC "Svetlana-Rost" and WIN Semiconductors were identified.

2) Synthesized and manufactured MMIC SPDT microwave switch C frequency range by a DpHEMT05 technology of JSC "Svetlana-Rost".

3) MMIC SPDT microwave switch X frequency range was synthesized and manufactured using WIN_PD2500 technology with multi-gate transistors from WIN Semiconductors.

Research methodology and methods

Methods of analysis and synthesis of linear and nonlinear electrical circuits were used to solve the tasks. Calculations and simulations were performed on a computer using software packages included in the NI AWR MWO CAD system (the University has license agreements for these software packages).

Provisions for protection

1) Synthesis of the microwave switch is advisable to carry out using the method of synthesis of frequency filters on a common LPF-prototype for both modes "on"/"off" of the microwave switch.

2) To use the methods of frequency filter synthesis for the synthesis of microwave switches, it is necessary to develop a compact model of a field-effect transistor and express the parameters of transistors in the "on"/"off" state in terms of R, L, C parameters of this model.

3) To solve the problem of approximation in the synthesis of low-pass prototype need to use the approximating function, not the normalized cutoff frequency but maximum operating frequency of the microwave switch when the permissible unevenness in frequency response in the passband, equal to the minimum decoupling of the microwave switch.

4) To reduce the insertion loss of the microwave switch in the "on" mode, it is necessary to expand the element base of the structural synthesis of the MMIC microwave switch by introducing additional reactive L and C elements that minimize the reflection losses that are caused by the reactive components of the open/closed transistor impedances.

5) To assess the nonlinear properties of field-effect transistors should be two parameters IIP3 (the intersection point intermodulation distortion third order): $IIP3_{on}$ for the transistor in the "on" state, and $IIP3_{off}$ for the transistor in the off state, and to calculate the parameters of $IIP3_{on}$ and $IIP3_{off}$ must enter the invariant of the width of the gate of the transistor parameters, namely: specific parameters $\sqrt{IP3_{on\_ud}}\ \left[\frac{mW^{\frac{1}{2}}}{mm}\right]$ and $\sqrt{IP3_{off\_ud}}\ \left[mW^{1/2} \times mm\right]$ that allow evaluating the IIP3 of a microwave switch without using CAD packages.

Degree of reliability and testing of results

The accuracy of the results and validity of scientific findings is confirmed by the correspondence of the presented analytical calculations and the results of structural, topological and parametric synthesis of microwave switches with experimental data obtained on modern equipment (network analyzer R&S ZVA-67 with the expansion unit ZVAX-TRM50, a signal and spectrum analyzer R&S FSVA30), and nonlinear data analysis was performed using the software package APLAC HB, part of the CAD NI AWR MWO.

The main results of the work were reported and discussed at the following scientific and technical conferences: The VI international conference "Electronics and applied physics" October, 20-23, 2010, Kyiv, Ukraine; The 19th international scientific and technical conference "Modern television and radio electronics", March 15-16, 2011, Moscow; The 2nd scientific conference

"Integrated circuits and microelectronic modules", September 26-30, 2016, Republic of Crimea, Alushta.

11 publications were published on the topic of the dissertation, including 3 articles published in journals included in the list of THE HIGHER ATTESTATION COMMISSION, 2 articles published in the journal included in the Scopus database, 6 articles published in journals included in the RSCI database, 1 patent and 1 state registration of integrated circuit topology was obtained.

Structure and scope of the dissertation

The dissertation consists of an introduction, four chapters, conclusion, two appendices, and a list of references. The total volume of the dissertation work is 131 pages, including 112 pages of the main text, 64 figures, 12 tables, a list of literature of 139 titles on 11 pages.

Author's contribution to the problem development

The main scientific provisions, theoretical conclusions, practical recommendations, calculations, modeling and experimental results in the dissertation work are developed and performed by the author independently.

SUMMARY OF THE WORK

The introduction shows the relevance, scientific novelty and practical significance of the work, formulated the purpose and objectives of the study, set out the provisions to be submitted for protection.

The first section provides an overview of the physical principles of operation, manufacturing technology, circuitry and applications of solid-state microwave switches on field-effect transistors. Considered: basic information about the theory of microwave switches, types of solid-state microwave switches, manufacturing technologies and circuitry of solid-state microwave switches, application and prospects of application of solid-state microwave switches. Based on the review, the purpose and objectives of the dissertation work are outlined.

In the second section, the main research directions are formulated that led to the development of a method for the synthesis of MMIC microwave switch on field-effect transistors of the A3B5 group. Classification of synthesis methods (structural, parametric and structural synthesis), classification of models of electronic components (physical, compact, functional models) are given. The necessity of creating a new compact model of a field-effect transistor (FET) is justified, for this purpose, the properties of frequency filters and the properties of microwave switches were compared (table 1).

Table 1 Comparison of frequency filter properties and microwave switch properties

Filter properties/parameters	**Switch properties/parameters**
Structure is a ladder diagram	Structure is a ladder diagram
Filters are divided into reflective and absorbing. Reflective filters return microwave energy back to the generator outside of the bandwidth. Absorbing filters dissipate microwave energy inside the filter at frequencies outside the bandwidth.	Switches are divided into reflective and attenuator switches. Reflective microwave switches return microwave energy back to the generator in "off" mode. Attenuator microwave switches dissipate microwave energy inside the switch in "off" mode.
Elementary filter cells are two-port components that are used to create microwave energy distributors in the frequency domain: selective circuits	Unit cells of switches represent two-port components, from which microwave energy distributors are created in the time domain: channel switches
Filters are characterized by the main parameters: insertion loss, VSWR, channel isolation.	The switches are characterized by key parameters: insertion loss, VSWR, isolation between the channels.

The comparison allows us to imagine a microwave switch as a switchable (parametric) frequency filter, which, depending on the parameter – its internal impedance – represents either a low-pass filter (LPF) in ON mode (enabled), or a high-pass filter (HPF) in OFF mode (disabled). In this regard, for the synthesis of microwave switches, it is proposed to use classical methods of synthesis of frequency filters. To use frequency filter synthesis methods for the synthesis of microwave switches, you must convert existing models into compact models based on elements of the R, L, C combinatorial space that is used for the synthesis of frequency filters (see figure 1).

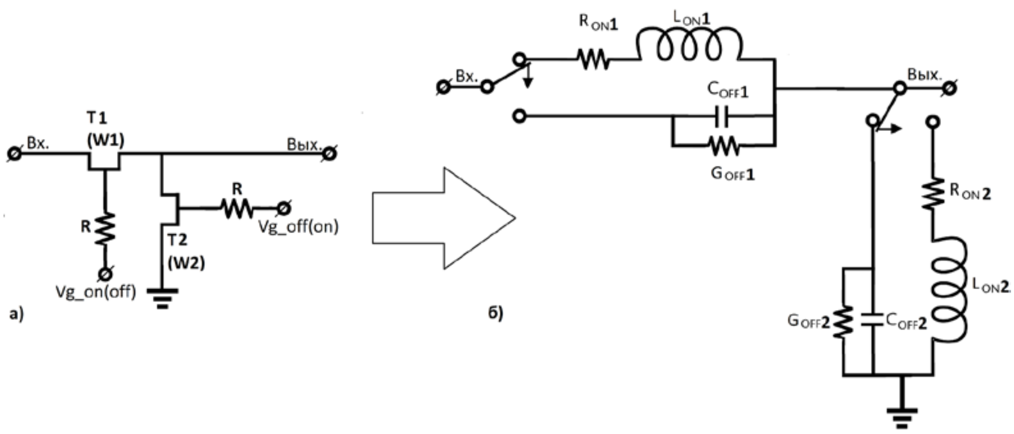


Figure 1. a) Schematic diagram of the L-shaped microwave switch on the FET;

b) representation of the L-shaped microwave switch through the main parameters of the elements of the compact model FET (without taking into account the elements of the control circuit R)

Table 2 shows the parameters of the compact FET model for the pHEMT05 technology of JSC "Svetlana-Rost". The main parameters (FET parameters with a gate width equal to 1 mm) are directly related to the values of the elements shown in figure 1 (with a gate width of W1 and W2). the derived parameters are used to calculate the prototype filter elements.

Table 2. Parameters of the compact FET model for pHEMT05 technology

Main parameters				Derived parameters			
Ron_ud	Lon_ud	Goff_ud	Coff_ud	$Q = \frac{1}{R_{on\_ud}}\sqrt{\frac{L_{on\_ud}}{C_{off\_ud}}}$	$\rho_X = \sqrt{\frac{L_{on\_ud}}{C_{off\_ud}}}$	$f_r = \frac{1}{2\pi\sqrt{L_{on\_ud}C_{off\_ud}}}$	$K = \frac{2\pi f_{p\_max}}{2\pi f_r}$
1.575 Ω*mm	0.046 nH* mm	8.16×10^{-5} 1/(Ω * mm)	0.332 pF/ mm	Q=7.47	ρ_X =11.771 Ω	Fr=40.726 GHz	f_{p_max}=3 GHz K=0,07366

It is shown that according to the normalized values of LC elements of the LPF-prototype with unit resistances of the generator and load, for example, for the 3rd order (L1 = g1, C2 = g2, L3 = g3), a microwave switch is synthesized both in on and off mode. Since it is important to ensure the monotony of the frequency response and the linearity of the frequency response of microwave switches, approximations of the smoothest possible frequency response of the Butterworth filter and the linear frequency response of the Bessel filter were considered. Taking into account the need to provide the required decoupling, the Butterworth transfer function is finally selected as the approximating function. Synthesis of the microwave switch was carried out according to the value of the required decoupling, since the required insertion losses can be provided with a sufficiently "wide" serial transistor T1 (W1), (figure 1).

It is proposed to use an approximating Butterworth function for the synthesis of a prototype of a microwave switch, normalized not by the cutoff frequency, but by the maximum operating frequency of the microwave switch with an acceptable unevenness of the frequency response in the prototype bandwidth equal to the minimum decoupling (A_{off_min} [dB]) of the microwave switch. As a result, using the procedure for decomposing a fractional-rational function into elementary fractions, we find the normalized inductance $g_1$and the capacitance g_2 of the LPF-prototype:

$$g_1 = \sqrt{2\varepsilon_p} \quad (1a) \quad g_2 = \sqrt{2\varepsilon_p} \qquad (1b)$$

where $\varepsilon_p = \sqrt{10^{A_{off\_min}[\text{дБ}]/10} - 1}$ is the coefficient of unevenness, which corresponds to the value of the required decoupling (A_{off_min} [dB]). Knowing the values g_1 and g_2 we find

$$W_1[\text{мм}] = \frac{1}{K\frac{Z_0}{\rho_X} g_1} \quad (2) \quad W_2 = \frac{g_2 R_{on\_ud}\sqrt{1+K^2Q^2}}{Z_0} \quad (3)$$

The synthesis procedure is illustrated by an example using the parameter values from table 2. Let us synthesize a SPST microwave switch that provides a frequency f_{p_max}=3GHz decoupling equal to or greater than A_{off_min} [dB]=30 dB.

1) Find the LPF-prototype of the Butterworth filter, i.e. for the required decoupling A_{off_min} [dB]=30 dB, find the normalized inductance and capacitance according to (1a), (1b):

$$g_1 = g_2 = \sqrt{2\varepsilon_\text{p}} = \sqrt{2\sqrt{10^{A_{off\_min}[\text{дБ}]/10} - 1}} = \sqrt{2\sqrt{999}} = 7{,}95.$$

2) Find the geometric dimensions of the serial FET (the gate width of the pHEMT transistor) according to (2):

$$W_1 = \frac{1}{K\frac{Z_0}{\rho_X} g_1} = \frac{1}{0{,}07366\frac{50}{11.771}7{,}95} = 0{,}402\ mm.$$

3) Find the geometric dimensions of the parallel FET (the gate width of the pHEMT transistor) according to (3):

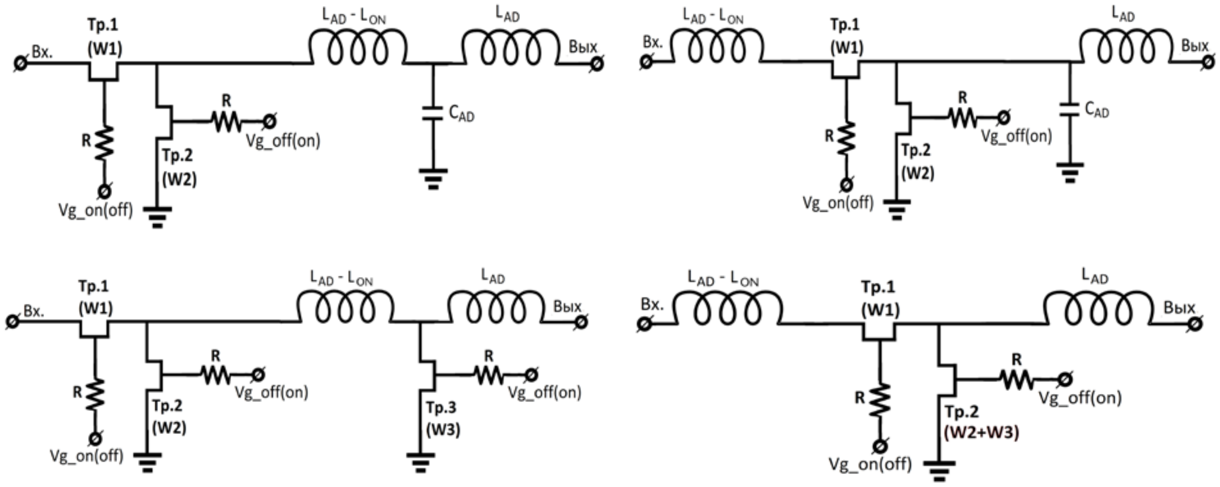
$$W_2 = \frac{g_2 R_{on\_ud}\sqrt{1+K^2Q^2}}{Z_0} = \frac{7{,}95*1{,}575*1.141}{50} = 0{,}286\text{mm}.$$

Knowing $W_1$and W_2, figure 1, we find the insertion loss (A_{on_max} [dB]). Repeating steps 1-3 for different values of A_{off_min} [dB], we will build table 3.

Table 3. Main parameters of synthesized microwave switches

A_{off_min}[dB]	W_1[mm]	W_2[mm]	A_{on_max}[dB]
20	0,716	0,160	0,196
30	0,402	0,286	0,343
40	0,226	0,508	0,616
50	0,127	0,904	1,121
60	0,071	1,607	2,108

Table 3 shows that the more decoupling is required, the "narrower" the serial transistor will be. A "narrow" serial transistor leads to large insertion losses (large R_{on}), and to an increase in the voltage standing wave coefficient (VSWR) both at the input and output of the microwave switch. Therefore, it is necessary to make an additional step at the stage of structural synthesis by adding elements of matching L_{AD} and C_{AD} (L_{ON} – inductance of the transistor Tp.1). Consider two options for structural synthesis: option a) with a T-shaped *L-C-L* circuit at the output of the microwave switch, (figure 2 a), and option b) *L-C-L* circuit in combination with the internal reactivity of transistors, (figure 2 b).



a) T-shaped matching b) Γ-shaped matching

Figure 2. Matching circuits of microwave switch

If the capacity of C_{AD} in the matching scheme is replaced with a closed transistor, then in the OFF mode of the microwave switch, we get an additional increase in the decoupling. An additional increase in the decoupling allows you to reduce the original requirement for the decoupling value (A_{off_min} [dB]) by the resulting excess value and repeat the synthesis procedure for the adjusted value (A_{off_min} [dB]). This completes the synthesis of the MMIC SPST switch.

Synthesis of the SPnT microwave switch, where n is the number of outputs of the switch, is carried out by parallel connection to the input of the SPST switch in the ON state (n-1) SPST switches in the OFF state. The input impedance of the SPST switch in the OFF state represents the capacitance with losses (the main part of the capacitance is provided by a serial closed transistor, the main part of the loss is provided by a parallel open transistor). Reactive losses (n-1) of SPST switches are compensated by adding a series inductor to the input of the microwave switch. Active losses (n-1) of SPST switches in the OFF state lead to an increase in insertion losses in the n-th SPST switch in the ON state. At this point, the theoretical part of the method of synthesis of MMIC microwave switches on field-effect transistors of the A3B5 group is considered complete.

In the third section, the synthesis method proposed in the second section is supplemented by a method for evaluating the nonlinear parameters of the MMIC microwave switch based on FET group A3B5. As an indicator of the nonlinearity of microwave devices, the IIP3 parameter was selected (the intersection point of 3rd-order intermodulation distortions at the input). The method of calculating the IIP3 parameter for a chain of 4-pole conductors with known transmission coefficients and IIP3 parameters is shown. It is proposed to use this technique to evaluate the IIP3 parameter of a microwave switch based on known insertion losses and IIP3 FET parameters in the open (ON) and closed (OFF) States. For why the linear FET model, figure 1, is replaced by a nonlinear compact FET model, figure 3.

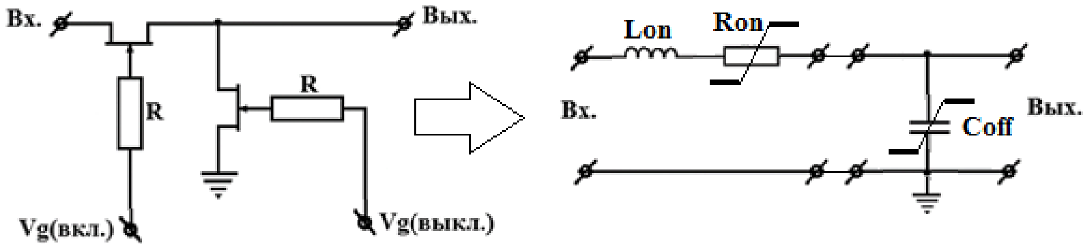


Figure 3. Representation of a microwave switch as a nonlinear system consisting of a 4-pole serial connection

To model a transistor in the ON state, we will use the power series method, namely, the decomposition of a nonlinear transfer function into a Taylor series. Figure 4 shows the application of a frequency-selective circuit with sequential nonlinearity to model a serial transistor in the ON state. Here, $V_S(t)$ represents the signal voltage at the inductor input $L_{on} = \frac{L_{on\_ud}}{W}$, *V(t)* – the signal voltage drop on the nonlinear resistor $R_{on} = \frac{R_{on\_ud}}{W}$, *i(t)* – the low-signal component of the transistor drain current, which can be decomposed into a Taylor series around the offset point on the transistor drain in the ON state.

$$f(v) = F(V_{d0} + v) - F(V_{d0}) = \frac{dF}{dV}\Big|_{V=V_{do}} v + \frac{1}{2}\frac{d^2F}{dV^2}\Big|_{V=V_{do}} v^2 + \cdots \frac{1}{n!}\frac{d^nF}{dV^n}\Big|_{V=V_{do}} v^n$$

where $V = V_{d0}$ is the offset on the transistor drain in the ON state, usually $V_{d0} = 0$V. Rewrite the resulting expression as:

$$f(v) = a_1 v + a_2 v^2 + \cdots a_n v^n$$

We obtained a procedure for extracting system parameters using n-th order derivatives:

$$a_1 \equiv \frac{dF}{dV}\Big|_{V=V_{do}};\ a_2 \equiv \frac{1}{2}\frac{d^2F}{dV^2}\Big|_{V=V_{do}};\ \ldots;\ a_n \equiv \frac{1}{n!}\frac{d^nF}{dV^n}\Big|_{V=V_{do}}$$

as well as the connectivity of the model, i.e. a smooth transition from a nonlinear model to a linear one when the input signal amplitude decreases.

To construct the dependence of the value of the IIP3 parameter of a serial transistor in the ON state (4-pole containing L_{on} *and* R_{on}, figure 3) on the gate width of the transistor W, substitute the expression for the nonlinear resistor $R_{on} = \frac{R_{on\_ud}}{W}$ into a nonlinear function *f(v)*. We get an expression for the current of a weak signal at the output of a 4-pole conductor:

$$i(v) = a_1 v + a_2 v^2 + \cdots a_n v^n = \frac{1}{W}\left[\frac{d(R_{on_{ud}})}{dv} v + \frac{1}{2}\frac{d^2(R_{on_{ud}})}{dv^2} v^2 + \cdots + \frac{1}{n!}\frac{d^n(R_{on_{ud}})}{dv^n} v^n\right]$$

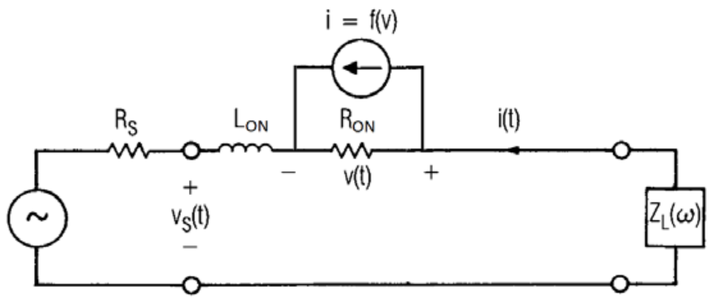


Figure 4. Model of a serial transistor in the ON state (frequency-selective circuit with serial nonlinearity)

Hence, 1/W is the scaling factor for both the square root of power at the main frequency and the square root of power at intermodulation frequencies. This makes it possible to identify the intersection points of intermodulation distortions of the IPN orders of interest on a transistor of known width W at a given offset (state ON) and bring the results to a transistor of 1 mm width. We obtained a new parameter $\sqrt{IPN_{on\_ud}}\ [W^{1/2}/mm]$, we call it the specific intersection point of n-th order intermodulation distortion (the wider the transistor, the closer it is to the linear resistor), which allows us to calculate the intermodulation distortion of the transistor in the ON state with a given gate width.

To model a transistor in the OFF state (4-pole containing C_{off}, figure 3), we use the expansion of the nonlinear transfer function into a Volterra series. In the analysis of nonlinear capacity $C_{off} = C_{off\_ud}\,W$ we take advantage of the fact that the Volterra series method is a Taylor power series for inertial systems (systems with memory). We apply the same approach that was used when analyzing a transistor in the ON state. Find the change in charge *q* on the plates of the capacitor (transistor in the OFF state, connected in parallel to the load):

$$q = f_Q(V_0 + v) - f_Q(V_0) = \frac{d}{dV} f_Q(V)\,|_{V=V_0} v + \frac{1}{2}\frac{d^2}{dV^2} f_Q(V)\,|_{V=V_0} v^2 + \cdots \frac{1}{n!}\frac{d^n\left(f_Q(V)\right)}{dV^n}\,|_{V=V_0} v^n$$

This implies that the charge value depends on the time *q (t).* Then, the current of the weak signal in the nonlinear capacitance will be equal to:

$$i = \frac{dq}{dt} = \frac{d}{dV} f_Q(V)\,|_{V=V_0} \frac{dv}{dt} + \frac{d^2}{dV^2} f_Q(V)\,|_{V=V_0} v \frac{dv}{dt} + \cdots \frac{1}{(n-1)!}\frac{d^n\left(f_Q(V)\right)}{dV^n}\,|_{V=V_0} v^{(n-1)} \frac{dv}{dt}$$

Rewrite the resulting expression as:

$$i = [C_1(V_0) + C_2(V_0)v + C_3(V_0)v^2 + \cdots]\,\frac{dv}{dt},$$

which represents a series expansion of the differential capacity. In the case under consideration, this will be the drain-source capacity at the offset on the gate providing the OFF state:

$$C_1(V_0) \equiv C_{off} = C_{off\_ud}\,W$$

$$C_n(V_0) \equiv \frac{1}{(n-1)!}\frac{d^n(C_{off})}{dV^n} = \frac{W}{(n-1)!}\frac{d^n(C_{off\_ud})}{dV^n}.$$

We found that for a transistor in the OFF state, the gate width W is a scaling factor for both the square root of power at the main frequency and the square root of power at intermodulation frequencies. This fact makes it possible to identify the intersection points of intermodulation distortions of the IPN orders of interest on a transistor of known width W at a given offset (OFF state) and bring the results to a transistor of 1 mm width. Got a new parameter $\sqrt{IPN_{off\_ud}}\ [mW^{1/2} * mm]$], which allows us to estimate the intermodulation distortion of a transistor with a given gate width W in the OFF state (the wider the transistor, the greater the value of the nonlinear currents generated in it).

Identification (determination of values) of the proposed nonlinear specific parameters was carried out using the manufacturer's PDK using the APLAC HB software package, which is part of the NI AWR MWO CAD. Combining linear and nonlinear models of FET, we obtained a generalized compact model of FET (table 4).

Table 4 Parameters of the generalized compact FET model for WIN_PD2500 technology

Main parameters				Nonlinear parameters	
Ron_ud	Lon_ud	Goff_ud	Coff_ud	$\sqrt{IP3_{on\_ud}}$	$\sqrt{IP3_{off\_ud}}$
1.785 Ω*mm	0.128 nH* mm	2.78x10^{-4} 1/(Ω * mm)	0.117 pF/ mm	876,92 $\frac{mW^{\frac{1}{2}}}{mm}$	568,35 $mW^{1/2} * mm$

Thus, after calculating the numerical values of the transistor gate width (W [mm]), the following main parameters of the microwave switch circuit are estimated (without a complete circuit construction): the level of intermodulation distortion of the microwave switch, the level of required decoupling, the level of insertion losses. The proposed approach allows parametric optimization of the scheme according to a given criterion. For example, to minimize the level of nonlinear distortion at a controlled level of insertion loss and decoupling without conducting a circuit simulation using CAD.

The fourth section presents experimental results. MMIC SPDT microwave switch C frequency range was synthesized and manufactured using DpHEMT05 technology of JSC "Svetlana-Rost" (figure 5).

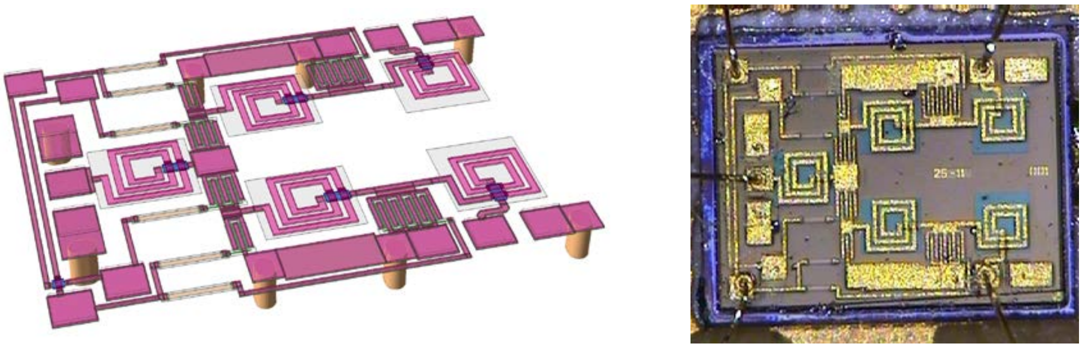


Figure 5. Topology and photo of a microwave MMIC SPDT switch crystal for C frequency range.

This MIS demonstrates the capabilities of the synthesis procedure to achieve a maximum decoupling of 53 dB, with acceptable insertion losses of 0.8 dB, VSWR≤1.2, and compression power of 1dB 27 dBm. In terms of maximum decoupling of 53 dB, the synthesized MMIC SPDT microwave switch exceeds known foreign analogues, which is the result of targeted synthesis to achieve maximum decoupling.

MMIC SPDT microwave switch X frequency range was synthesized and manufactured using WIN_PD2500 technology with multi-gate transistors from WIN Semiconductors (figure 6).

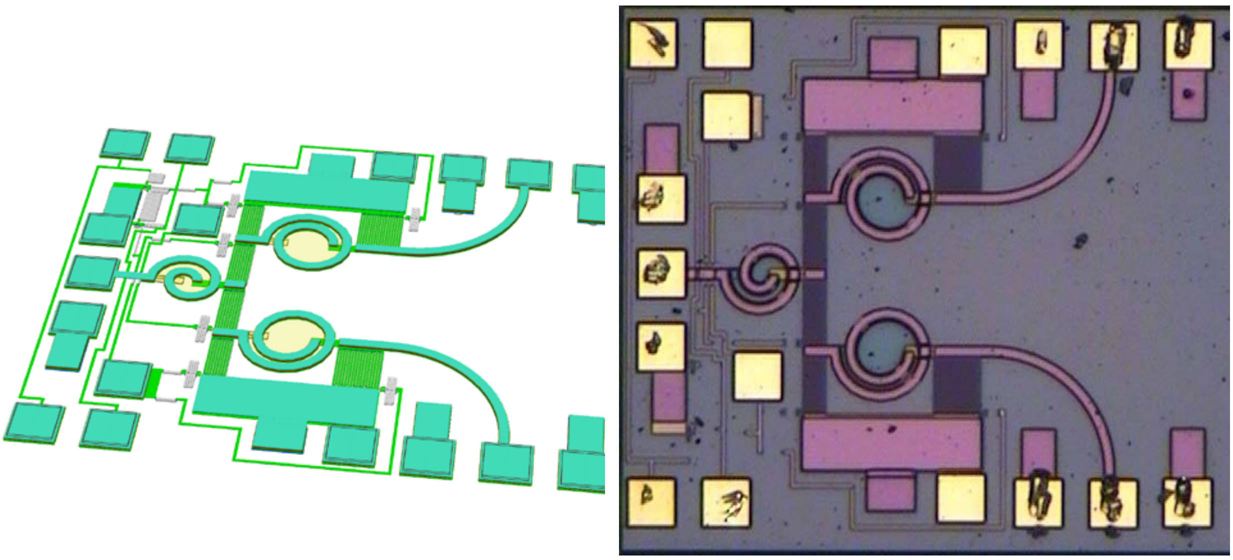


Figure 6. Topology and photo of the microwave MMIC SPDT switch crystal for X-band frequency synthesized on the basis of WIN_PD2500 technology

This MIS demonstrates the capabilities of the synthesis procedure to achieve a minimum insertion loss of 0.8 dB, with an acceptable decoupling of 33 dB, VSWR≤1.5, and compression power of 1dB - more than 30 dBm. In terms of insertion losses, the synthesized MMIC SPDT microwave switch exceeds known foreign analogues, which is the result of targeted synthesis to achieve minimal insertion losses.

In conclusion, the following conclusions on the dissertation work are formulated.

1) The method of synthesis of MMIC microwave switch on A3B5 group semiconductors, which is based on the theory of structural and parametric synthesis of frequency-selective filter circuits, has been developed. When solving the problem of structural synthesis, it is proposed to expand the element basis of switch circuits by introducing an additional element, namely, inductance. This made it possible to reduce the problem to parametric synthesis of the switch circuit with a known solution of the structural synthesis problem. The proposed method is implemented in two versions: the method of synthesis of the microwave switch, aimed at achieving the maximum isolation (at a given level of insertion losses); the method of synthesis of the microwave switch, aimed at achieving the minimum insertion losses (at a given level of isolation). During the synthesis process, the level of nonlinear distortion in both versions is controlled by the IIP3 parameter.

2) Developed a methodology for estimating non-linear parameters of MMIC microwave switch based on nonlinear parameters of field-effect transistors of the group A3B5, in which the technique has been developed for analysis of nonlinear distortion of microwave switch, in particular, the calculation of this parameter is IIP3, based on the submission of each switching element in the structure of the microwave switch as quasilinear 4-pole. As a result of this representation, a circuit is formed whose IIP3 parameter is equal to the IIP3 parameter of the microwave switch. This approach made it possible to express the nonlinear parameters of a microwave switch through the nonlinear parameters of its switching elements (transistors).

3) Synthesized and manufactured two integrated circuits of microwave switches:

MMIC SPDT switch with frequency range (synthesized to achieve maximum decoupling) based on GaAs pHEMT technology of JSC " Svetlana-Rost»;

MMIC SPDT switch X frequency band (synthesized to achieve minimum insertion loss) based on GaAs pHEMT technology WIN Semiconductors.

4) Experimental studies were carried out, in which the theoretical and measured characteristics of microwave switches manufactured MMIC were compared:

MMIC SPDT switch from the frequency range using DpHEMT05 technology of JSC "Svetlana-Rost" demonstrates the capabilities of the synthesis procedure to achieve a maximum decoupling of 53 dB at controlled insertion losses of 0.8 dB, VSWR≤1.2, and compression power of 1dB 27 dBm. The synthesized MMIC SPDT microwave switch exceeds the known foreign analogues by at least 20 dB, which is the result of synthesis according to the criterion of achieving the maximum decoupling;

MMIC SPDT microwave switch X frequency range using WIN_PD2500 technology with multi-gate transistors from WIN Semiconductors demonstrates the capabilities of the synthesis procedure to achieve a minimum insertion loss of 0.8 dB, with a controlled decoupling of 33 dB, VSWR≤1.5, compression power of 1dB - more than 30 dBm. In terms of insertion losses, the synthesized MMIC SPDT microwave switch exceeds known foreign analogues by at least 0.4 dB, which is the result of synthesis according to the criterion of achieving minimum insertion losses.

PUBLICATIONS ON THE TOPIC OF THE DISSERTATION

1. Berezniak, A.F., Korotkov, A.S. Solid-state microwave switches: Circuitry, manufacturing technologies and development trends. Review (Part 1). Radioelectron.Commun.Syst. 56, 159–177 (2013). https://doi.org/10.3103/S0735272713040018 (Scopus, RSCI, THE HIGHER ATTESTATION COMMISSION)

2. Berezniak, A.F., Korotkov, A.S. Solid-state microwave switches: Circuitry, manufacturing technologies and development trends. Review (Part 2). Radioelectron.Commun.Syst. 56, 213–226 (2013). https://doi.org/10.3103/S0735272713050014 (Scopus, RSCI, THE HIGHER ATTESTATION COMMISSION)

3. Guk V. G., Filaretov G. A., Kalinin B. V., Berezniak A. F., Krasovitsky D. M. Three-electrode high-frequency semi-conducting instrument, Patent of the Russian Federation No. 2354010, 27.04.09.

4. Bereznyak A. F., Korotkov A. S., Balashov E. V. Transformation of the synthesis of frequency filters for the synthesis of solid-state microwave switches, 2nd scientific conference "Integrated circuits and microelectronic modules" Collection of reports, Alushta, September 26-30, 2016, Pp. 427-432.

5. Berezniak A. F., Guk V. G., Pechenkin I. V., Konkov Yu. V., Filaretov G. A., Experimental research and calculation of microwave characteristics of gallium arsenide field-effect transistors with a Schottky barrier // Questions of Radioelectronics, Series: General questions of Radioelectronics, issue 2, 1989, Pp. 93-101. (RSCI)

6. Berezniak A. F., Korotkov A. S., Balashov E. V. Transformation of the synthesis of frequency filters for the synthesis of solid-state microwave switches // NANOINDUSTRY, 2017, Volume 74 (special Issue), Pp. 427-432. http://elibrary.ru/item.asp?id=29871688 (RSCI)

7. Berezniak A. F. AlGaN/GaN heterojunction quality monitoring with large-area heterostructure field-effect transistor // St. Petersburg Polytechnic University Journal - Physics and Mathematics, 2009, 1(73), Pp. 43-48. (RSCI)

8. Bereznyak A. F., Determination of parameters for technical requirements of monitoring technology, Proceedings of the VI international conference “Electronics and applied physics” October 20-23, 2010, Kyiv, Ukraine, p. 85-86.

9. Berezniak A. F., the Use of test structures in the interaction of the developer and manufacturer of specialized integrated circuits, 19th international scientific and technical conference "Modern television and radio electronics", March 15-16, 2011, Moscow, P. 304-307.

10 Berezniak A.F., Korotkov A.S. Design method and manufacturing monolithic microwave integrated circuit switches on GaAs pHEMT. St. Petersburg State Polytechnical University Journal. Computer Science. Telecommunications and Control Systems, 2019, Vol. 12, No. 4, Pp. 84—96. DOI: 10.18721/JCSTCS.12407 (THE HIGHER ATTESTATION COMMISSION, RSCI)

11. Balashov E. V., Berezniak A. F., Korotkov A. S., Shubarov A.V. Crystal Modulator. State registration of integrated circuit topology no. 2018630116, 16.07.2018, bul. no. 7.