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METHOD OF SYNTHESIS OF MATCHING TELECOMMUNICATION DEVICES BASED ON THE METHOD OF REAL FREQUENCIES FOR 5G ANTENNAS IN A DISTRIBUTED ELEMENT BASIS

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Abstract. To solve the problem of synthesizing load matching circuits in a distributed element basis, the complex resistance of which has a non-stationary character in a wide band of operating frequencies, a new matching technique based on the sensitivity invariant apparatus in combination with the Richards and Kuroda transformation has been developed. The verification of the methodology was carried out on the example of matching the active element with the output and input loads in

Mitsubishi's LD-MOSRD07 power amplifiers. Radio engineering devices (RTU) are widely used in almost all spheres of human activity. In order for the RTU to provide maximum energy efficiency, and as a consequence, the maximum range of the radio line in various operating conditions, it is necessary that the elements of the radio engineering paths of both the transmitting and receiving devices, having their complex resistance (varying over time), be coordinated with each other. To perform this task, broadband matching devices (SHSU) are used, the synthesis methods of which do not take into account the variability of the load impedance caused by changes in operating conditions (temperature, vibration, various modes of operation of active elements, etc.). As a result, there is a need to develop a method for the synthesis of SHSU that provides a stable level of power transmission in conditions of varying load impedance. Such a need is relevant for RTU in both concentrated and distributed element basis. The paper proposes a method for the synthesis of matching devices for a distributed element basis. Geology is a multifaceted science that is classified into many areas, depending on the subject of research, analysis technology, subjects of study, theoretical calculations or the scope of application of knowledge obtained in the course of complex research. The most common aspects of geology as a science, their practical or applied application and benefits for humanity in modern life are described in detail below.

Keywords: 5G antenna, radio engineering device, load resistance, radio line, operating frequency

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ҮЛЕСТІРІЛГЕН ЭЛЕМЕНТ БАЗАСЫНДА 5 G АНТЕННАЛАР ҮШІН НАҚТЫ ЖИІЛІК ӘДІСІ НЕГІЗІНДЕ КЕЛІСЕТІН ТЕЛЕКОММУНИКАЦИЯЛЫҚ ҚҰРЫЛҒЫЛАРДЫ СИНТЕЗДЕУ ӘДІСТЕМЕСІ

Аннотация. Кешенді кедергісі жұмыс жиіліктерінің кең ауқымында стационарлық емес сипатта болатын үлестірілген элементтер базасында жүктемені үйлестіру схемаларын синтездеу мәселесін шешу үшін Ричардс пен Куродтың түрлендіруімен сезімталдыққа инвариантты аппаратқа негізделген сәйкестендірудің жаңа әдісі жасалды. Әдістемені тексеру Mitsubishi LD-MOSRD07 қуат күшейткіштеріндегі белсенді элементті Шығыс және кіріс жүктемелерімен үйлестіру мысалында жүргізілді. Радиотехникалық құрылғылар (RTU) адам қызметінің барлық салаларында кеңінен қолданылады. Өзінің кешенді кедергісі бар (уақыт бойынша өзгеретін) таратушы және қабылдаушы құрылғылардың радиотехникалық трактілерінің элементтері RTU максималды энергия тиімділігін және соның салдарынан әртүрлі пайдалану жағдайларында радиолиниялардың максималды диапазонын қамтамасыз ету үшін бір-бірімен келісілуі тиіс. Бұл тапсырманы орындау үшін синтездеу әдістері жұмыс жағдайларының (температура, діріл, белсенді элементтердің әртүрлі жұмыс режимдері және т.б.) өзгеруінен туындаған жүктеме кедергісінің өзгергіштігін ескермейтін кең жолақты келісу құрылғылары (ШСУ) қолданылады. Нәтижесінде жүктеменің өзгермелі кедергісі жағдайында қуат берудің тұрақты деңгейін қамтамасыз ететін CFC синтездеу әдісін әзірлеу қажет болады.. Бұл қажеттілік шоғырландырылған және үлестірілген элементтер базасындағы RTU үшін маңызды. Мақалада үлестірілген элементтер базасында тиісті құрылғыларды синтездеу әдісі ұсынылған. Геология-бұл кең Ғылыми тұжырымдама, оның құрамына қолданбалы қолдану саласы, теориялық есептеулер категориясы, төменде егжей-тегжейлі сипатталған зерттеу объектілерінің түрі бойынша ерекшеленетін көптеген бөлімдер кіреді.

Түйін сөздер: 5G антеннасы, радиотехникалық құрылғы, жүктеме кедергісі, радио желісі, жұмыс жиілігі

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МЕТОДИКА СИНТЕЗА СОГЛАСУЮЩИХ ТЕЛЕКОММУНИКАЦИОННЫХ УСТРОЙСТВ НА ОСНОВЕ МЕТОДА ВЕЩЕСТВЕННЫХ ЧАСТОТ ДЛЯ 5 G АНТЕНН В РАСПРЕДЕЛЕННОМ ЭЛЕМЕНТНОМ БАЗИСЕ

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Аннотация. Для решения задачи синтеза схем координации нагрузки на распределенной элементной базе, комплексное сопротивление которой носит нестационарный характер в широком диапазоне рабочих частот был разработан новый метод идентификации, основанный на аппарате, инвариантном к чувствительности, с преобразованием Ричардса и Курода. Проверка методики проводилась на примере согласования активного элемента в усилителях мощности Mitsubishi LD-MOSRD07 с выходными и входными нагрузками. Радиотехнические устройства (RTU) широко используются во всех сферах человеческой деятельности. Элементы радиотехнических трактов передающих и принимающих устройств со своим комплексным сопротивлением (изменяющимся во времени) должны быть согласованы друг с другом, чтобы обеспечить максимальную энергоэффективность RTU и, как следствие, максимальный диапазон радиолиний в различных условиях эксплуатации. Для выполнения этой задачи используются широкополосные согласующие устройства (ШСУ), методы синтеза которых не учитывают изменчивость сопротивления нагрузки, вызванную изменением условий работы (температуры, вибрации, различных режимов работы активных элементов и др.). В результате возникает необходимость разработки метода синтеза ХФУ, обеспечивающего стабильный уровень передачи мощности в условиях переменного сопротивления нагрузки. Эта потребность важна для RTU в консолидированной и распределенной элементной базе. В статье предлагается метод синтеза соответствующих устройств на распределенной элементной базе. Геология — это обширная научная концепция, которая включает в себя область прикладного применения, категорию теоретических расчетов, множество разделов, различающихся по типу объектов исследования, подробно описанных ниже.

Ключевые слова: антенна 5G, радиотехническое устройство, сопротивление нагрузки, радиолиния, рабочая частота

Introduction

A review and analysis of broadband matching methods have shown that it is advisable to use the method of real frequencies as a mathematical apparatus for the synthesis of a matching circuit (MC) with varying load impedance (Dubovik et al., 2021).

It is proposed to develop a method for the synthesis of BMD that provide the required level of power transmission under conditions of varying load impedance for RED in a distributed element basis based on the method of real frequencies in combination with the Richards and Kuroda transformation.

It should be noted that the spread of the nominal values of the BMD elements (in a distributed element basis, the dimensions, magnetic and dielectric permittivity of the substrates, etc.) and the load connected to it negatively affect the functioning of the RED in various operating conditions. The connection between the space of circuit parameters, analysis and optimization, including with adjustable (controlled) parameters, can be carried out using the sensitivity function. This function can contribute to solving a wide range of tasks related to the analysis of the impact of small changes in design parameters and external conditions on the operation of RED.

For the synthesis of the BMD, which allows to ensure the level of the power gain (PG) is not worse than required, in the presence of a changing load impedance, first of all it is necessary to assess the degree of influence of the load impedance variation on the PG level. Let's imagine the complex load resistance as a number of parameters (i = 1,2… M), on which a certain function describing the frequency response of the BMD (PG, group delay time, etc.) depends. The deviation of the function from the nominal value caused by a change in the parameter is determined by the corresponding Taylor series expansion. For the linearized case (we neglect the derivatives of the second and higher orders), the decomposition has the form

$$S_{x_i}^{D} = S\left\{D\left(x_i\right), x_i\right\} = \sum_{i=1}^{N} \frac{\partial D\left(x_i\right)}{\partial x_i} \tag{1}$$

where $S_{x_i}^{D} = S\left\{D\left(x_i\right), x_i\right\} = \sum_{i=1}^{N} \frac{\partial D\left(x_i\right)}{\partial x_i}$ - sensitivity of the function to parameter changes

- number of parameters;
- function deviation.

Expression (1) is used to describe the effect of small deviations, and it is based on mathematical analysis. Of particular interest in this expression is the sensitivity of the BMD characteristic, since a decrease in the value of this parameter leads to a decrease in the deviation of the BMD characteristic, and with its fixed (permissible) value increases the deviation , at which the required values of the BMD characteristic are preserved (Dedus et al., 2004).

To ensure the required level of PG in the presence of a changing load impedance, it is necessary that the synthesized BMD has the property of minimal sensitivity of the reflection coefficient function to changes in load parameters. To do this, it is necessary to solve a system of equations

$$\begin{cases} \int_{f_B}^{f_H} \left(K_{\text{треб}} - \left(1 - \left|S_{in}\left(f, Z_{\text{Н}}, Z_{\text{СЦ}}\right)\right|^2\right)\right)^2 df \le \varepsilon \\ \int_{f_H}^{f_B} \left|\operatorname{Re}\left\{R\left\{S_{in}\left(f, Z_{\text{Н}}, Z_{\text{СЦ}}\right)\right\}\right\}\right|^2 df \le \min \end{cases} \tag{2}$$

where K_{req} - required level of PG; $Z_{\text{Н}}(f)$ - complex payload resistance;
$Z_{\text{СЦ}}(f)$ - complex resistance of the matching circuit;

$R\left\{S_{in}\left(f,Z_{\text{Н}},Z_{\text{СЦ}}\right)\right\}=\dfrac{2\operatorname{Re}\left\{Z_{\text{СЦ}}(f)\right\}Z_{\text{Н}}(f)}{\left(Z_{\text{Н}}(f)+Z_{\text{СЦ}}(f)\right)\left(Z_{\text{Н}}(f)-Z_{\text{СЦ}}(-f)\right)}$ - invariant of the sensitivity of the reflection coefficient function to changes in payload parameters;

$S_{in}\left(f,Z_{\text{Н}},Z_{\text{СЦ}}\right)=\dfrac{Z_{\text{Н}}(f)-Z_{\text{СЦ}}(-f)}{Z_{\text{Н}}(f)+Z_{\text{СЦ}}(f)}$ - reflection coefficient function (mismatch coefficient); - permissible deviation of the PG level in the operating frequency range.

To determine the minimum value of the sensitivity invariant, it is proposed to use the expression 3.

$$\delta=\int_{f_B}^{f_H}\frac{\Delta\left|S_{in}\left(f,Z_{\text{Н}},Z_{\text{СЦ}}\right)\right|}{\left|S_{in}\left(f,Z_{\text{Н}},Z_{\text{СЦ}}\right)\right|}\left|\frac{Z_{\text{Н}}}{\left(\Delta\operatorname{Re}\left\{Z_{\text{Н}}\right\}+i\Delta\operatorname{Im}\left\{Z_{\text{Н}}\right\}\right)}\right|df \qquad (3)$$

where $\Delta\left|S_{in}\left(f,Z_{\text{Н}},Z_{\text{СЦ}}\right)\right|$ - permissible deviation of the reflection coefficient function module;

$\Delta\operatorname{Re}\left\{Z_{\text{Н}}\right\},i\Delta\operatorname{Im}\left\{Z_{\text{Н}}\right\}$ - permissible deviation of the real, imaginary part of the reflection coefficient function.

Thus, the system of equations is transformed to the form

$$\begin{cases}\displaystyle\int_{f_B}^{f_H}\left(K_{\text{треб}}-\left(1-\left|S_{in}\left(f,Z_{\text{Н}},Z_{\text{СЦ}}\right)\right|^2\right)\right)^2 df\le\varepsilon\\ \displaystyle\int_{f_H}^{f_B}\left|\operatorname{Re}\left\{R\left\{S_{in}\left(f,Z_{\text{Н}},Z_{\text{СЦ}}\right)\right\}\right\}\right|^2 df\le\delta\end{cases} \qquad (4)$$

where the initial data is given: the required deviation of the PG level, the permissible deviation of the modulus of the reflection coefficient function, the deviation of the complex load resistance ($\Delta\operatorname{Re}\left\{Z_{\text{Н}}\right\},\Delta\operatorname{Im}\left\{Z_{\text{Н}}\right\}$).

The system of equations can be used as an objective function (complex criterion) in combination with one of the existing numerical methods for the synthesis of BMD. It is proposed to use the method of real frequencies as a method of BMD synthesis. The main advantage of this method is that it does not require an approximation of the load impedance, and also that the PG function is represented as an analytical expression, while the ladder structure of the BMD is synthesized using iterative approaches to search for the real component of the resistance function of the BMD (Boykachev et al., 2012; Cherdyntsev et al., 2010). Thus, the combination of a complex criterion with the method of real frequencies 5G type of the real component of the resistance function allowed us to develop a method for the synthesis of matching devices for broadband radio engineering devices to a changing load impedance in a distributed element basis, which is shown in Fig. 1.

The developed methodology consists of seven stages:

To simplify the subsequent calculations, the input data (complex load resistance and frequency) is normalized, presented in the form of discrete samples. Based on the required level of PG and the permissible deviation of the load impedance in the operating frequency range, as well as the order of the electrical circuit;

The procedure for forming the form of the real component of the resistance function of the MC and the formation algorithm.

Formation of a complex representation of the function;

Calculation of the PG level taking into account the resistance function of the matching circuit;

Calculation of the sensitivity invariant of the reflection coefficient function module, as well as the minimum possible value of the sensitivity invariant in the operating frequency band;

Depending on the type of matching problem, one of the optimality criteria is calculated, according to the value of which a decision is made to recalculate the coefficients of the auxiliary polynomial. If the optimality criterion is met, proceed to the seventh stage of synthesis;

Formation of the complex resistance function of the MC with its subsequent transfer to the Richards (Fano et al., 1965; Orazbayev et al., 2012) space and synthesis of microstrip lines from the formed function;

Replacement of physically unrealizable elements with Kuroda elements (Filippovich et al., 1965; Filippovich et al., 2021)

The advantage of this approach lies in the absence of differentiation of the reflection coefficient function to find the sensitivity value. It is enough only to know the value of the SD impedance at a discrete range of frequencies in order to synthesize a BMD with minimal sensitivity to changes in the load impedance in a distributed element basis.

Analysis of quality indicators of the obtained mathematical model of adaptive matching device.

After the development of the BMD synthesis technique followed by the synthesis of the matching chain in combination with RFPA, Richards and Kuroda transformations, it is necessary to check the operability of this technique. To verify the presented methodology, it is proposed to develop a broadband impedance transformer based on it, designed for the Mitsubishi LD-MOSRD07 power amplifier. (Alekseeva et al., 1987; Moldasheva et al., 2022).

Synthesis of MC for Mitsubishi LD-MOSRD07 power amplifier.

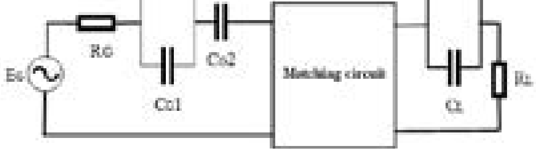

Fig. 1 The task of double matching of the LD-MOSRD07 power amplifier

Referring to Fig. 1, the impedance conversion filter is built between the generator R_G = 12 ohms (the output of the HF power amplifier, which is designed using Mitsubishi's LD-MOSRD07).

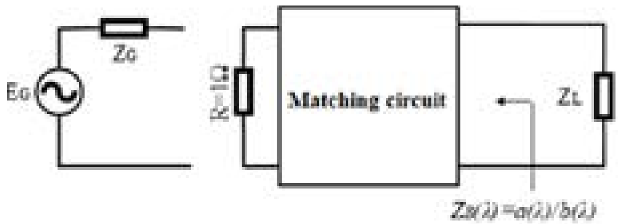

Fig. 2 Description of the matching network using the input resistance from the $Z_B(\lambda)$ side

Standard load R_L = 50 ohms in the range of 850-2100 MHz. On the oscillator side (12 ohms), the LG//CG1 resonant circuit introduces zero transmission at a frequency of 4200 GHz, which is the second harmonic at the upper end of the bandwidth. In addition, C_G2 introduces zero DC transmission. Similarly, on the load side, the LL//CL oscillatory circuit introduces zero transmission at the third harmonic (6300 MHz). Thus, Figure 2 shows the problem of double matching (complex resistance on both sides). The matching circuit must ensure coordination between the complex generator Z_G and the complex load Z_L.

Let's set the initial parameters of the loads R_G = 12 ohms, L_G = 0.947 nGn, C_G1 = 1.515 pF, C_G2 = 3.4 pF, C_L = 1.515 pF, L_L = 0.412 nGn, R_L = 50 ohms.

The matching circuit is synthesized, providing matching resistance from $Z_B(\lambda)$ using six commensurate transmission lines (n = 6). During the design, k = 4 (the total number of cascades) and q = 0 (without zero DC transmission) are selected, which, in turn, gives n ∞ = k − q = 2 transmission zeros at infinity.

The coefficients of the auxiliary polynomial are initialized. In addition, c0 is fixed equal to one (c0 = 1), so that the normalized terminal resistance R is set equal to one. Thus, a fractional rational function describing the resistance $Z_B(\lambda)$ obtained by the presented method will have the form:

$$Z_B(\lambda) = \frac{a(\lambda)}{b(\lambda)} = \frac{0\lambda^6+0.62\lambda^5+0.7259\lambda^4+0.2427\lambda^3+0.1717\lambda^2+0.0169\lambda+0.0036}{2.1530\lambda^6+2.5204\lambda^5+1.1745\lambda^4+0.9848\lambda^3+0.1634\lambda^2+0.0754\lambda+0.0036} \quad (5)$$

The coefficients are obtained as a result of optimization, and the coefficients of the numerator polynomial and the denominator polynomial are obtained using the Levenberg-Marquardt method (Yarman et al., 2010; Gorshelev et al., 1977).

Table 1. Calculation results

№	$c(\Omega)$, *100	$a(\lambda)$	$a(\lambda)$
	5,9257	0	2,1529
	6,0851	0,6200	2,5204
	-2,2964	0,7258	1,1744

	-2,3805	0,2426	0,9844
	0,1579	0,1717	0,1634
	0,1757	0,0168	0,0753
	0,010	0,0036	0,0036

After finding the function $Z_B(\lambda)$ with normalized parameters $R_0 = 1$, $f_0 = 1/(2\pi)$, perform the Richards transform.

The list of output vectors is shown in Table 2, and the final synthesis of $Z_B(\lambda)$ is shown in Figure 4.

Table 2. Synthesis results for the Richards transformation

№	Z_new	a_new	b_new	CT	CV
	0.2517	0	1.0000	8	7.5637
	1.8721	0.1322	1.1706	1	0.8542
	0.1245	0.1547	0.1547	9	0.9999
	1.536	-	–	–	–

where Z_new - normalized wave resistance; a_new, b_new — recalculated values of the coefficients of the numerator, denominator of the resistance function; CT is the type of connection of the MC cascade and the type of radio element (CT = 1 – serial Richards inductance, 8 – parallel Richards capacitance, 9 – resistor); CV — the remainder of the division.

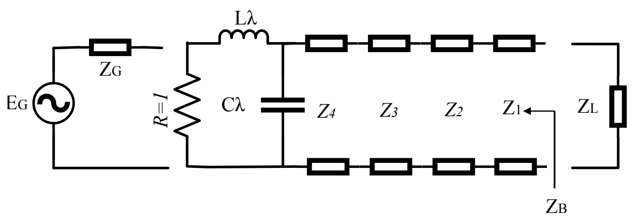

Fig. 3 – Results of the synthesis of MC from $Z_B(\lambda)$

Thus, the wave resistance in Fig. 3 is determined by the expression

$$Z_1 = 0.2517;\ Z_2 = 1.8721;\ Z_3 = 0.1246;\ Z_4 = 1.5364,$$

and the Richards components are listed as:

$$C = 7{,}5637;\ L = 0{,}8542.$$

When choosing the number of resistance normalization R_0 = 50 ohms, the actual values of the elements are determined as

$$Z\_new = [12{,}5850 \quad 93{,}6052 \quad 6{,}2297 \quad 76{,}8177];$$

The Richards capacitor C is made in the form of a shunting open loop with a reduced characteristic resistance Zcap = 1/C or with an actual wave resistance Zcap = R_0/C. Similarly, the Richards inductor L is implemented as a sequential short loop with a normalized characteristic resistance ZInd = L or with an actual characteristic resistance Zind = R_0L. Thus, it turns out that Zcap = R_0/C = 50/7,5 = 6.6105 ohms and Zind = R_0L = 42.7106 ohms. For the case under consideration, Z3-act = 6.2297 ohms and Zcap-act = 6.6 ohms are difficult to implement. As for practical implementation, we may prefer to use microstrip technology to implement ideal commensurate transmission lines. Richards shunt capacitors (i.e., open loops in a shunt configuration) can be easily implemented, but the implementation of Richards series inductors (i.e., short loops in a serial configuration) presents serious difficulties. However, the problems of physical implementation can be circumvented by using Kuroda identities (Abdukadyrov et al., 2023; Plotkin et al., 2021). In this regard, the sequential application of Kuroda identities removes consecutive short loops with shunting open loops (Yerzhan et al., 2023).

Identification of Kuroda 1:

According to Fig. 5, a transmission line with a capacitive load can be replaced by an equivalent line with an inductive load using the following set of equations:

$$Z_B = \frac{Z_A}{C_A Z_A + 1}, \qquad (6)$$

$$L_B = \frac{C_A Z_A^2}{C_A Z_A + 1}, \qquad (7)$$

In our case, the Richards capacitor and a pair of transmission lines {Cλ, Z4} = {Cλ = 7,5637λ, Z4 = 1,5364} can be replaced by a pair of transmission lines and Richards inductors {ZB1, LB1λ} so that

$$Z_{B1} = \frac{Z_A}{C_A Z_A + 1} = 0.1217, \qquad (8)$$

$$L_{B1} = \frac{C_A Z_A^2}{C_A Z_A + 1} = 1.4146, \qquad (9)$$

Thus, at the first stage, we used the Kuroda I identity and obtained the following chain topology.

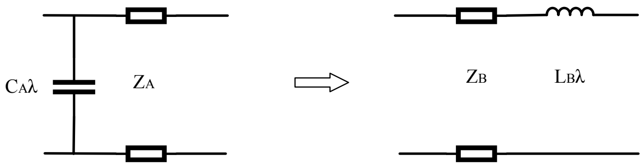

Fig. 4 - Identification of inductance using Kuroda identities

Identification of Kuroda 2

Referring to Fig. 4, the pairs {Lλ, ZB1} and {LB1, Z3} can be replaced by identical pairs using the Kuroda II identity, as shown in Fig. 5. The set of replacement equations is given by the expression

$$Z_B = Z_A + L_A, \tag{10}$$

$$C_B = \frac{L_A}{Z_A(Z_A+L_A)}, \tag{11}$$

In the second stage, the Kuroda II identity is applied twice. First, the pair {λ LB1, Z3} is replaced by

$$Z_{B3} = Z_3 + L_{B1} = 1.5393, \tag{12}$$

or is the actual value of ZB3 equal to ZB3-act =76 ohms.

$$C_{B3} = \frac{L_{B1}}{Z_{B1}(Z_{B1}+L_{B1})} = 7.37, \tag{13}$$

Similarly, the pair {Lλ, ZB1} is replaced by a new {ZB2, CB2} such that

$$Z_{B2} = Z_{B1} + L = 0.9759, \tag{14}$$

or is the actual value of ZB2 equal to ZB2-act =48.7974 ohms.

$$C_{B3} = \frac{L}{Z_{B1}(Z_{B1}+L)} = 7.1899, \tag{15}$$

Hence, we get Fig. 5 as the final synthesis of ZB2(λ)

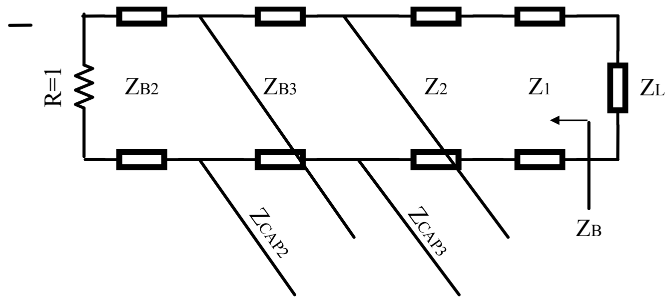

Fig.5 - Matching circuit for power amplifier LD-MOSRD07

The matching device is made on FR-4 with a dielectric constant of 4.3. The characteristics of the matched system are shown in Fig. 6.

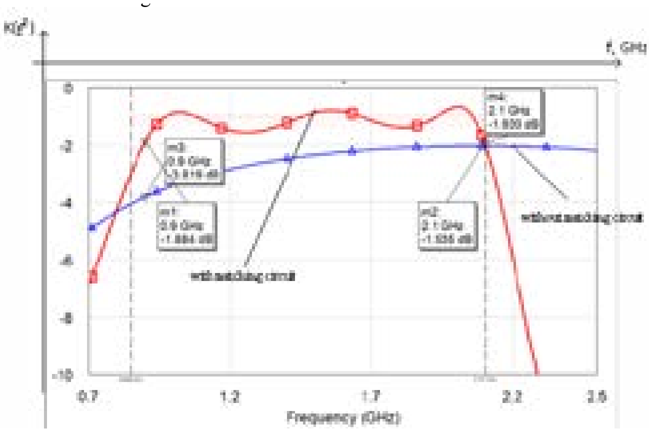

Fig. 6 - PG dependency with and without matching chain

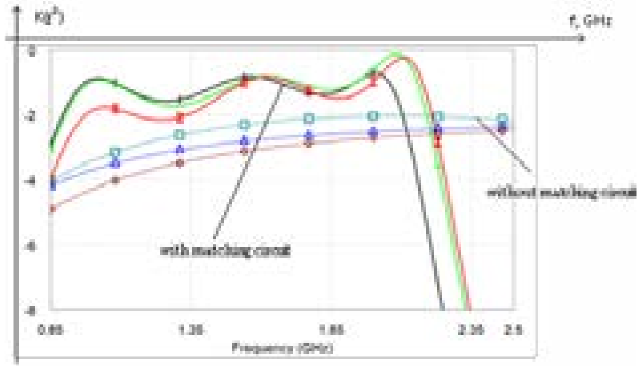

Fig. 7 - The dependence of the PG on the frequency of the amplifier with and without a matching circuit

Conclusions

In cases of instability of the amplifier parameters caused by various kinds of destabilizing factors, which led to a change in load parameters up to 25% of the nominal value, leads to a change in the PG in the bandwidth slightly when using a synthesized matching circuit (Fig. 7 – solid lines), unlike without it (Fig. 7 – dashed lines).

Based on the results obtained, it follows that the MD provides not only an improvement in PG in the frequency range from 0.9 to 2.1 GHz, but also has increased selectivity over the bandwidth. Thus, the obtained technique can be used for the synthesis of MD both in the concentrated element basis and in the microwave frequency range.

Geology is an extensive scientific concept, which includes many subsections that differ in the scope of application, category of theoretical calculations, type of research objects, described in detail below.

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