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ABSTRACT

In the work the non-standard system of w-parameters of the microwave quadripoles is proposed. a method of floating loads for the determination of w-parameters of microwave quadripoles is developed. the elements of the theory of the method of floating loads are proposed. new equations for determining the w-parameters of microwave quadripoles are obtained. the experimental setup for the determination of w-parameters of microwave quadripoles is developed. the results of experimental studies of w-parameters of the field transistor are obtained.

Keywords: microwave quadripole, W-parameters, non-standard system, floating loads, experimental equipment, short-circuit mode, idling mode

1. INTRODUCTION

To describe and define the parameters of radio-electronic devices in the microwave range, two systems of parameters of quadripoles are widely used: the system of parameters of the scattering matrix (*S*-parameters)[1], based on the representation of incident and reflected power waves, and the generalized W-parameters. There any of the four systems of parameters used in specific cases (*y*-, *z*-, *g*- and *h*-parameters)[2,14].

The advantage of the first system is the explicit physical content of its elements (coefficients of reflection and transmission), characteristic for schemes with distributed parameters, as well as simplicity and convenience of measurement in the microwave range using transmission lines with constant characteristic supports. To the disadvantages of this system of parameters can be attributed: the need to make measurements at coordinated loads (standing wave ratio < 1.05), which is practically not always possible to implement; growth of the measurement error in the determination of all parameters with the increase in the coefficient of standing wave of voltage in the measuring path[3]. The need for measurement of transmission and reflection arguments, which leads to the complication of the experimental installation. In addition, the calculated relations, expressed through *S*-parameters, are more complex and less visible than when using *W*-parameters.

In the microwave range, schemes with distributed parameters are predominantly used, but when designing, usually with certain assumptions, they are calculated as schemes with lumped parameters. This, on the one hand, simplifies the calculation, on the other hand, allows you to use the rich experience of designing low-frequency devices. In this case, the elements of the W-matrix[2] are used. The advantage of this matrix is the explicit physical content of its elements (*z* is resistance, *y* is conductivity), which is characteristic for schemes with lumped parameters. But for their measurement it is necessary to implement the short-circuit (SC) and idling (IM) mode, which is practically impossible to do in the microwave range due to the influence of parasitic reactive elements of the circuit.

In a detailed examination of these systems, one can conclude that their common disadvantage is the need for direct access to the investigated quadripole. This will not always be possible, in addition, the instability of the installation in the case of measuring the parameters of potentially unstable quadripole at frequencies that are usually unknown.

Based on the consideration of the advantages and disadvantages of the *S*- and *W*-parameters of the quadripole, one can formulate the requirements for a new system of parameters, which would have as much as possible the advantages of the *S*- and *W*-parameters and would not have their drawbacks. These requirements are as follows:

- the constituent elements of the new system must have an explicit physical content of the W-parameters;

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- the measurement error with increasing inconsistency of the quadripole with the measuring paths should be minimal;
- it measurement should be possible in the microwave range;
- the modes SC and IM should not be used for measurement;
- the measuring installation should have increased stability over a wide range of frequencies;
- calculated ratios for determining the required parameters should be as simple as possible.

This task can be solved by entering a new non-standard system of quadripole parameters. In microwave technology it is known to introduce non-standard parameters of quadripole systems. An example can be the non-standard system of *S*-parameters[3], through which the direct measurement of the coefficients of reflection of loads or complex-conjugate quantities with them. This eliminates the errors that arise in calculations with inaccurately measured standard *S*-parameters. This system, called the system of non-standard *S*-parameters (in the general case G_1, G_2, S_{12}, S_{21}), allows to carry out an unambiguous transition to the system of traditional *S*-parameters.

Non-standard parameters can be complete when their help is possible to identify all elements of the standard system of parameters, and partial (incomplete), when through them it is possible to express only a part of elements of the system of standard parameters. Not possessing the universality inherent in a complete system of non-standard parameters, the introduction of an incomplete system is appropriate in the case if it is sufficient for the calculation of a certain class of devices, while having significant advantages over the measurement of the complete system of parameters of the quadripole.

The main difficulty with the use of traditional *S*-parameters is that they are not measured with a sufficient degree of accuracy. Most of all, this is due to the lack of equipment, the inconsistency of the final loads, the presence of heterogeneous elements in the measuring path. Therefore, different system parameters can be uneven and the advantage must be given to one that guarantees the highest accuracy of the calculation. Systems of non-standard parameters, including directly the data necessary for design, are presented well-coordinated with the experiment and therefore it is expedient to use them.

2. DEVELOPMENT OF THE METHOD OF FLOATING LOADS

In the analysis of analytical expressions that determine the main low-signal parameters of broadband and frequency selective amplifiers (in the general case of quadripole) and used in the calculation, for example such parameters as working K_w and nominal $K_{w\cdot n}$ the coefficients of the forward and inverse power transmission, the invariant coefficient of stability of $K_{s.in}$, the immitations of the matching schemes of ReW_{go}, ImW_{go}, ReW_{no}, ImW_{no}, it is clear that they can be calculated if a known part of the elements of the standard system of the *W*-parameters of the matrix of the quadripole and their derivatives[4] is:

$$\mathrm{Re}(W_{12}W_{21}),\ \mathrm{Im}(W_{12}W_{21}),\ W_{11},\ W_{22},\ |W_{12}|,|W_{21}|. \quad (1)$$

It is proposed to be used as a system of non-standard parameters of the quadripole[5].

System elements (1) determine the dependence of the input W_{in} and the output W_{out} immitations of the quadripole on the reactive immitations connected according to its output of $\mathrm{Im}W_l$ or $\mathrm{Im}W_g$ input, and the maximum steady-state gain of the quadripole[6] is:

$$K_{mS}=|W_{21}/W_{12}|. \quad (2)$$

In accordance with the theory of conformal mappings[7,8], dependence W_{in}=f($\mathrm{Im}W_l$) (W_{out}=f($\mathrm{Im}W_g$)) is displayed on the plane $W_{out}(W_{in})$ with a circle with a radius is:

$$\rho=|W-W_O|, \quad (3)$$

where W_O - center coordinates of the imitative circle (Fig. 1).

Expressing the radiuses through the imitations of the quadripole, we get:

$$\begin{cases} \rho_{out} = \dfrac{|W_{12}W_{21}|}{2\operatorname{Re}W_{11}}, \\ W_{out0} = \dfrac{W_{22} - W_{12}W_{21}}{2\operatorname{Re}W_{11}}, \\ \rho_{in} = \dfrac{|W_{12}W_{21}|}{2\operatorname{Re}W_{22}}, \\ W_{in0} = \dfrac{W_{22} - W_{12}W_{21}}{2\operatorname{Re}W_{22}}, \end{cases} \tag{4}$$

where ρ_{out} is a radius of the outgoing circle; W_{out0} is a coordinate of the center of the outgoing circle; ρ_{in} is a radius of input circle; W_{in0} is a coordinate of the center of the input circle[11,19,20].

The coordinates of the centers of the circle are respectively determined by the expressions:

$$\begin{cases} \operatorname{Re}W_{out0} = \operatorname{Re}W_{22} - \dfrac{\operatorname{Re}(W_{12}W_{21})}{2\operatorname{Re}W_{11}}, \\ \operatorname{Im}W_{out0} = \operatorname{Im}W_{22} - \dfrac{\operatorname{Im}(W_{12}W_{21})}{2\operatorname{Re}W_{11}}, \\ \operatorname{Re}W_{in0} = \operatorname{Re}W_{11} - \dfrac{\operatorname{Re}(W_{12}W_{21})}{2\operatorname{Re}W_{22}}, \\ \operatorname{Im}W_{in0} = \operatorname{Im}W_{11} - \dfrac{\operatorname{Im}(W_{12}W_{21})}{2\operatorname{Re}W_{22}}. \end{cases} \tag{5}$$

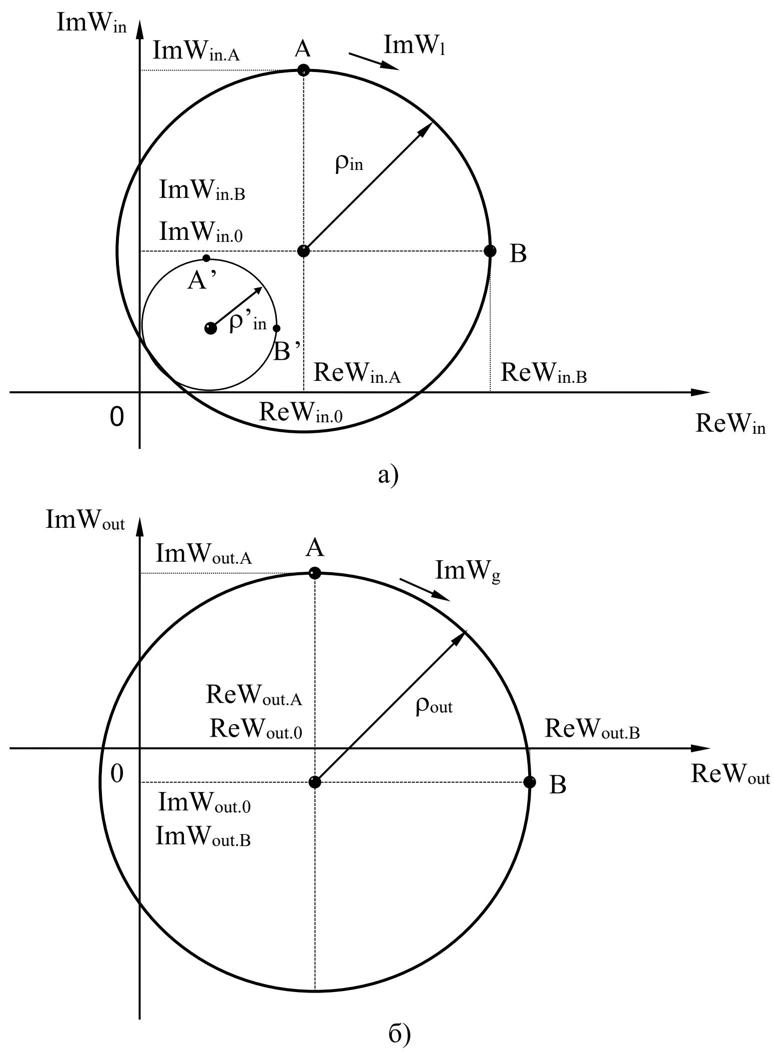

Figure 1. The dependences W_{in} = f(ImW_l) and W_{out} = f(ImW_g) on the complex plane.

Let Im$W_{in.A}$, Im$W_{out.A}$, Re$W_{in.B}$, Re$W_{out.B}$ define the coordinates of points A and B in the imitative circle corresponding to the maximum value of the components of the immittance of the quadripole. We express through these components the radii ρ_{in} , ρ_{out} and the coordinates of the centers of the circles (Fig. 1):

$$\begin{cases} \rho_{in} = \mathrm{Im}W_{in.A} - \mathrm{Im}W_{in.B} = \mathrm{Re}W_{in.B} - \mathrm{Re}W_{in.A}, \\ \rho_{out} = \mathrm{Im}W_{out.A} - \mathrm{Im}W_{out.B} = \mathrm{Re}W_{out.B} - \mathrm{Re}W_{out.A}, \\ \mathrm{Re}W_{in.0} = \mathrm{Re}W_{in.A}, \\ \mathrm{Re}W_{out.0} = \mathrm{Re}W_{\mathrm{out}.A}, \\ \mathrm{Im}W_{in.0} = \mathrm{Im}W_{in.\mathrm{B}}, \\ \mathrm{Im}W_{out.0} = \mathrm{Im}W_{out.\mathrm{B}}. \end{cases} \tag{6}$$

Systems of equations (24) and (35) are incomplete because

$$\frac{\mathrm{Re}W_{in.0}}{\rho_{in}} = \frac{\mathrm{Re}W_{out.0}}{\rho_{out}} = K_{s.\mathrm{in}}, \tag{7}$$

it does not allow to determine the parameters of the system (1). To find these parameters, we additionally connect to the output of the quadripole consecutive resistance W_g=Z_g or parallel conductivity W_g=Y_g. In this case, the dependence of the input immittance W'_{in} of the newly formed quadripole on the reactive load ImW_l is a circle with a radius[12,21,22]

$$\rho'_{in} = \frac{|W_{12}W_{21}|}{2\,\mathrm{Re}\left(W_{22}+W_g\right)}, \tag{8}$$

where is:

$$\rho'_{in} = ImW'_{in.A} - ImW'_{in.B} = ReW'_{in.B} - ReW'_{in.A}, \tag{9}$$

where $W'_{in.A}$, $W'_{in.B}$ is a coordinate of points A and B corresponding to the maximum value of the components of the immitance on the circle W'_{in} (Fig. 1).

With a certain meaning of the immitance W_g, solving system of equations (4, 5) with taking (6), find some elements of the system (1) parameters W- matrix.

$$\begin{cases}
\mathrm{Re}W_{22} = \dfrac{\rho'_{in}\,\mathrm{Re}W_g}{\left(\rho_{in}-\rho'_{in}\right)}, \\
\mathrm{Re}W_{11} = \dfrac{\rho_{in}}{\rho_{out}}\mathrm{Re}W_{22} = \dfrac{\rho_{in}\rho'_{in}}{\rho_{out}\left(\rho_{in}-\rho'_{in}\right)}\mathrm{Re}W_g, \\
|W_{12}W_{21}| = 2\rho_{in}\,\mathrm{Re}W_{22} = \dfrac{2\rho_{in}\rho'_{in}}{\left(\rho_{in}-\rho'_{in}\right)}\mathrm{Re}W_g, \\
\mathrm{Re}\left(W_{12}W_{21}\right) = 2\,\mathrm{Re}W_{22}\left(W_{11}-W_{in.A}\right), \\
\mathrm{Im}\left(W_{12}W_{21}\right) = \sqrt{|W_{12}W_{21}|^2 - \mathrm{Re}^2\left(W_{12}W_{21}\right)}, \\
\mathrm{Im}\left(W_{12}W_{21}\right) = |W_{12}W_{21}|\sin\left(\arccos\mathrm{Re}\left(\dfrac{\left(W_{12}W_{21}\right)}{|W_{12}W_{21}|}\right)\right), \\
\mathrm{Im}W_{11} = \mathrm{Im}W_{in.B} + \dfrac{\mathrm{Im}\left(W_{12}W_{21}\right)}{2\,\mathrm{Re}W_{22}}, \\
\mathrm{Im}W_{22} = \mathrm{Im}W_{out.B} + \dfrac{\mathrm{Im}\left(W_{12}W_{21}\right)}{2\,\mathrm{Re}W_{11}}.
\end{cases} \tag{10}$$

To find these parameters, there is no need to implement CS and IM modes and use a consistent load, - it is enough to measure the input and output immitances of the quadripole at extreme points A and B, which correspond to ImW_g and ImW_l reactive immitations that may remain uncertain. From the above analysis it is obvious that the actual constituents of extreme parameters in the study of potentially unstable quadrupole with $K_{s.in} < 1$ are always positive, which guarantees the stability of measurements.

To find the parameters $|W_{21}|$ i $|W_{12}|$ we use familiar expressions for direct $K_{w.l.1}$ and the inverse $K_{w.l.2}$ nominal transmission coefficients of the quadripole power[2,23] is:

$$K_{w.l.1} = \frac{4|W_{21}|^2\,\mathrm{Re}W_{oscill.}\,\mathrm{Re}W_l}{\left|\left(W_{11}+W_{oscill.}\right)\left(W_{22}+W_l\right)-W_{11}W_{22}\right|^2}, \tag{11}$$

$$K_{w.l.2} = \frac{4|W_{12}|^2\,\mathrm{Re}W_{oscill.}\,\mathrm{Re}W_l}{\left|\left(W_{11}+W_{oscill.}\right)\left(W_{22}+W_l\right)-W_{22}W_{21}\right|^2}. \tag{12}$$

When the condition $W_g = W_l$ is fulfilled, dividing the expression (811) into (912), we find

$$\frac{K_{\mathrm{w}.l1}}{K_{\mathrm{w}.l2}} = \left|\frac{W_{21}}{W_{12}}\right|^2 = K_{mS}^2 , \tag{13}$$

where K_{mS} is a maximum coefficient of stable amplification (transmission) of the quadripole power.

Using the obtained expression (1013) and previously defined parameters of the quadripole (710), we find:

$$|W_{21}| = \sqrt{K_{mS}\sqrt{\mathrm{Re}^2\left(W_{12}W_{21}\right)+\mathrm{Im}^2\left(W_{12}W_{21}\right)}} = \sqrt{K_{mS}\left|W_{12}W_{21}\right|} , \tag{14}$$

$$|W_{12}| = \sqrt{\frac{\sqrt{\mathrm{Re}^2\left(W_{12}W_{21}\right)+\mathrm{Im}^2\left(W_{12}W_{21}\right)}}{K_{mS}}} = \sqrt{\frac{\left|W_{12}W_{21}\right|}{K_{mS}}} . \tag{15}$$

From the above expressions (10), (14), (15) it is evident that in order to determine the system of W-parameters of the quadripole (1), convenient for finding the main parameters of the quadripole, it is necessary to determine a number of the following parameters[9] is:

$$W_{in.A},\ W_{out.A},\ W_{in.B},\ W_{out.B},\ K_{mS},\ W'_{in.A},\ W'_{in.B}. \tag{16}$$

We call this system a nonstandard extreme system of quadripole parameters, eliminating most of the disadvantages inherent in measuring the elements of the classical standard systems of the S- and W-parameters of the quadripole, the feature of which is the application of measuring non-fixed load (resistance or conductivity).

3. EXPERIMENTAL RESEARCH

In this work, an experimental equipment for the measurement of W-parameters of microwave quadripole was developed. The block diagram of the experimental equipment is shown on Fig. 2[11,24].

The measuring installation includes: measuring generator *MG*; solenoid valve *V*; reflectometer *R*; tee *T*; phase rotator *P*; investigated quadripole *IQ*, fixed in a special holder; two short-circuiting pistons *P1* and *P2*. The reflectometer *R* is used to determine the module of the reflectance coefficient *G* or the standing wave (ρ) in the measuring path. The piston *P1* is intended to compensate for the reactive component of the input (or output) immitance of the investigated quadripole, which is transformed into the plane of the *T* tee. The piston *P2* implements the required reactive load of the quadripole $\mathrm{Im}W_l$ (or $\mathrm{Im}W_g$). Phase rotator *P* reduces the electric length ℓ_2 of the measuring path from the investigated quadripole *IQ* to the *T* axis.

To eliminate the ambiguity of measurements, the characteristic immitance of the measuring path is chosen more than the minimum value of the actual component of the immitance $\mathrm{Re}W_{in.B}$ (or $\mathrm{Re}W_{in.B}$), that is measured. In this case, the reflection coefficient module *G* from the quadripole terminal is uniquely dependent on the immitance $\mathrm{Re}W_{in}$ ($\mathrm{Re}W_{out}$) (Fig. 3).

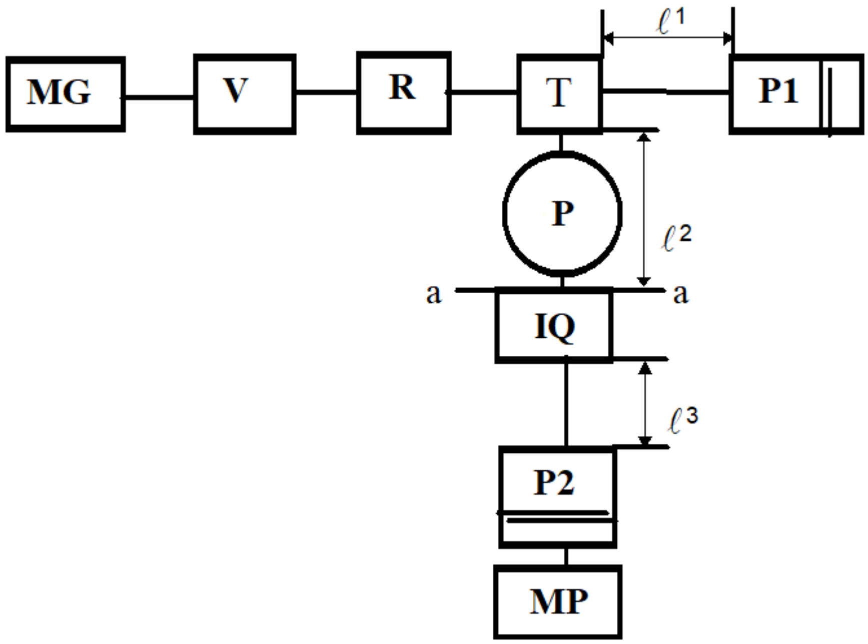

Figure 2. The block diagram of the experimental equipment to measure the non-standard system of parameters of microwave quadripole.

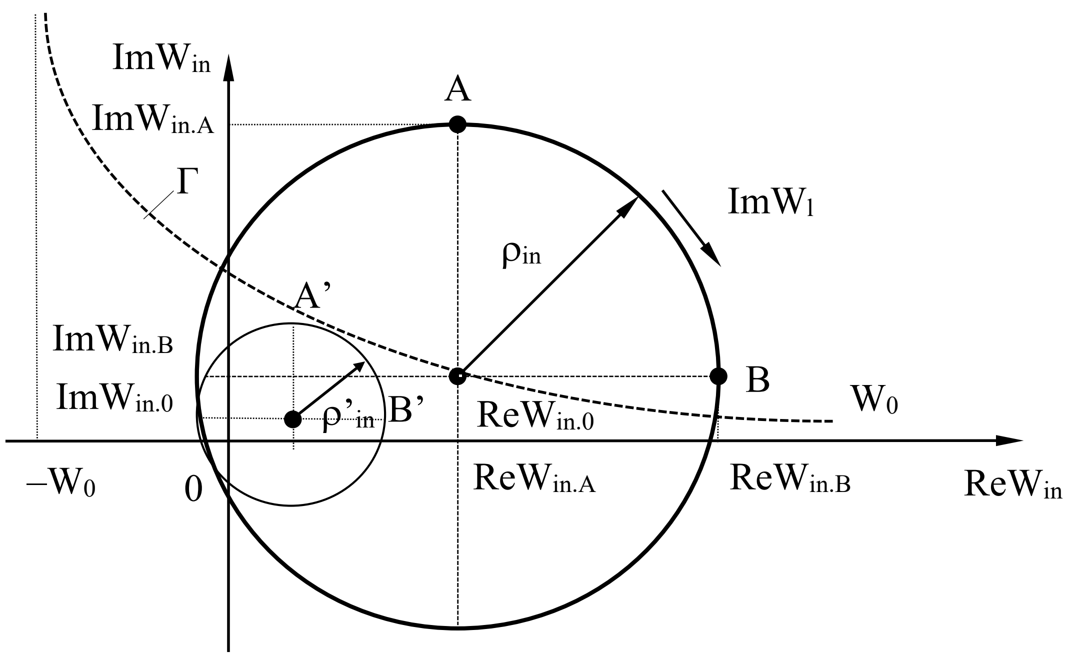

Figure 3. Comprehensive dependency plane Win= f(ImWl).

When calibrating the installation, the measurement of the measuring line in the plane A-A is shorted (Fig. 2). The length ℓ_1 of the piston *P1* is set to less than or more than a quarter of the wavelength in the measuring path. In this case, the ImW_{p1} reactive immittance implemented by the piston *P1* shunt the transmission line, providing $G<1$. By changing the phase shift produced by the phase shifter *P*, they obtain in the path of the coefficient of standing wave $G = 1$, which indicates the connection of the piston *P1* to the measuring path at a distance ℓ_2, the multiple half wavelength in the path $\ell_{02}=n\lambda/2$, which allows the measurement to pass the input (output) immitance of the quadripole in the plane of the piston *P1*. When measuring at a fixed frequency, the preliminary installation of the piston *P1* at a distance ℓ_{02} from the plane of measurement A-A can be pre-installed, which allows to exclude the phase rotator P from the measuring circuit and refuse the calibration process[12,13].

To measure the required values, replace in the installation (Fig. 2) the piston with a power meter with an input impedance equal to W_0 and set the piston P_1 at a distance $\ell_1=\lambda/4$, which eliminates its influence. We measure power P_1. Then we turn the investigated quadripole on 180° and measure the power P_2. Based on these measurements we find the last extreme parameter K_{mS} is [14,15]:

$$K_{mS} = \sqrt{\frac{P_1}{P_2}} \,. \tag{17}$$

In the course of the experiment, the results of the dependence of the extreme parameters on the frequency for bipolar and field transistors were obtained. Table 1 shows the experimental results of the dependencies of the extreme parameters of the field transistor КП391. Practical application of research results in work[13] to measure humidity[16,17,18].

Table 1. The results of experimental research.

Parameters	**Frequency**				
×10^{-2} (Om^{-1})	**1 GHz**	**0.8 GHz**	**0.6 GHz**	**0.4 GHz**	**0.3 GHz**
$ReY_{in.A}$	0.233	0.195	0.1	0.035	0.15
$ImY_{in.A}$	7.54	4.82	3.2	1.98	1.365
$ReY_{in.B}$	4.01	2.61	1.7	1.09	0.84
$ImY_{in.B}$	8.77	2.41	1.6	0.99	0.675
$ReY_{out.A}$	0.5	0.83	0.88	1.8	0.06
$ImY_{out.A}$	0.02	0.03	0.01	0.05	0.006
$ReY_{out.B}$	8.59	11.14	15.03	20.65	0.336
$ImY_{out.B}$	-8.07	-10.28	-14.4	-18.8	-0.27
K_{mS}	5.123	6.735	9.36	12.76	18.46

4. CONCLUSION

As a result of the conducted researches the method of determination of an extreme non-standard parameter system[5] has been developed, which allows to improve the accuracy of the measurement of the parameters of the quadripole. In developing this technique, three ideas were used:

1) the method of "floating loads"[10];
2) the method of differential measurements;
3) neutralization method.

Using the first two ideas allows for arbitrary (floating) loads to determine with high precision in the microwave range a system of non-standard parameters of a quadripole, sufficient for the calculation of most linear electronic devices.

The application of the neutralization method in conjunction with the method of "floating loads" ensures the stability of the experimental installation and measurement of the complete system of *W*-parameters of any quadripole.

According to the research materials given in this article, we can make the following conclusions:

1) The proposed methods are most effective in the microwave range, where so far the problem of measuring the *S*-parameters of a potentially unstable quadripole.

2) Mean-square errors were analyzed and their analytical expressions were obtained for each method. The analysis of these expressions showed a direct dependence of the methodological error on the error of measurement of incoming immitances.

3) The elements of the proposed non-standard extreme system of quadripole parameters have a dimension that corresponds to the dimensions of the elements of the standard *W*-parameters, but their measurements are carried out in the microwave range with an error of less than 5%, and to a lesser extent, depends on the KSVN of the measuring path, as measured by *S*-parameters.

4) To measure them there is no need to use the modes SC and IM or to make measurements in a coherent measuring path, which also increases the accuracy of the measurement and provides stability in the measurement of potentially unstable quadripole with $Ks > 0$.

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