Differential method for measuring the maximum achievable transmission coefficient of active microwave quadripole

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Abstract. In the paper it is proposed a differential method for measuring the maximum achievable transfer coefficient of active quadripole. A new structural scheme of a measuring device and a sequence of measurements and calculations that implement the method are proposed. The differential method is intended to measure transfer coefficient of the power by an active quadripole in the microwave range at the border of its potential stability. The parameters of the active quadripole have a dimension that corresponds to the dimension of the elements of the standard W-parameters of microwave electric circuits. The results of measurements of the maximum achievable transfer coefficient of microwave bipolar transistors are presented in the paper. The advantages of the method are: 1) a small error of measurement, that is less than 5%; 2) there is no need to make individual measurements in short circuit or idling mode; 3) the small dependence of the results on the coefficient of standing wave of the loaded measuring path.

1. Introduction
Nowadays, there are a many of different methods [1, 2] and equipment’s [3, 4] for measuring the parameters of the quadripole. When measuring quadripole parameters in different modes receive different system parameters [5]. These systems are equivalent from the point of view of recalculation from one system to another, but in practice they can not be considered equivalent [6]. Thus, a generalized W-parameter system can only be conventionally considered to be working in microwave range. This is a consequence of the fact that currents and voltages are not measured directly in this range, and their relationship with power, that is usually measured in microwave range, is not always unambiguous [6]. Moreover, the provision of "short circuit" and "idle" modes necessary for measuring W-parameters is often impossible due to the probable instability in these quadripole modes of investigation. It is most expedient to consider such a system whose parameters are included in the equations describing the operation of the device [2, 6]. Therefore, various system parameters may be suitable for different applications. For example, in the range of relatively low frequency of consideration and measurement of voltage and currents [7], in the HF and microwave ranges - the signals of incident and reflected waves [8].

The difficulty of measuring the parameters of the quadripole in the microwave range is related to the potential instability of semiconductor devices, that causes their self-excitation and uncontrolled change of parameters, and leads to the impossibility of their use [9].

Thus, for each specific case, it is necessary for each particular mode to choose one or another method of measuring the parameters of the quadripole [10].
When! describing the quadripole in terms of energy properties usually are used two characteristics of
the power gain—working $K_P$ and the nominal $K_{Pn}$ coefficients of the power gain (transmission) [11].
The working factor of the power gain is equal to the ratio of the power $P_d$, which is allocated in the
real component of the immittance of the loading $W_L$, to the power $P_in$, which is supplied to the input of
the quadripole. Consider the generalized structural scheme for measuring the transmission coefficients
of the active quadripole (Fig. 1).

![Diagram](image)

**Figure 1.** A generalized scheme for measuring the transmission coefficients of an active quadripole.

If $U_1$ is an amplitude of the input voltage, then [11]

$$P_{in} = 0.5U_1^2 \text{Re} W_{in}, \quad (1)$$

where $W_{in}$ is an input immitance of the quadripole.

Power that is distinguished in loading is a

$$P_L = 0.5U_L^2 \text{Re} W_L, \quad (2)$$

where $U_L$ is a voltage amplitude on loading; $W_L$ is an immittance of the loading.

The nominal power gain is equal to the ratio of the power $P_L$ that allocated in the actual component of
the loading immittance to the nominal power of the generator $P_G$ that equal to the power given by the
generator to the agreed loading (the input immitance of the active quadripole) [11]

$$P_G = \frac{I_G^2}{8\text{Re} W_G}, \quad (3)$$

where $I_G$ is a current amplitude; $W_G$ is an immitance of the generator.

The values of $K_P$ and $K_{Pn}$ are invariant, their numerical values do not depend on the choice of the
system of parameters of the quadripole, so it can be written in generalized $W$-parameters [11]

$$K_P = \frac{P_L}{P_{in}} = \frac{|W_{21}|^2 \text{Re} W_L}{|W_{22} + W_L|^2 \text{Re} W_{in}}, \quad (4)$$

$$K_{Pn} = \frac{4|W_{21}|^2 \text{Re} W_G \text{Re} W_L}{\left|\left(W_{11} + W_G\right)\left(W_{22} + W_L\right) - W_{12}W_{21}\right|^2} = \frac{P_L}{P_G}. \quad (5)$$

From equation (4) it follows that the working coefficient of power gain $K_P$ is a function of $\text{Re} W_L$ and $\text{Im} W_L$. Differentiating the equation (5) provided
\[
\frac{\partial K_p}{\partial \text{Re} W'_L} = 0, \quad \frac{\partial K_p}{\partial \text{Im} W'_L} = 0, \quad (6)
\]
we find the values \(\text{Re} W'_L\) and \(\text{Im} W'_L\), where \(K_p\) has maximal value

\[
\text{Re} W'_L = \frac{W_{12} W_{21} (K_{S,IN}^2 - 1) / 2}{\text{Re} W_{11}}, \quad (7)
\]

\[
\text{Im} W'_L = \frac{\text{Im} (W_{12} W_{21})}{(2 \text{Re} W_{11})} - \text{Im} W_{22}. \quad (8)
\]

Substituting equations (7) and (8) in (4), we obtain an expression for the maximum power gain coefficient

\[
K_{pm} = \frac{|W_{21}|}{|W_{12}|} \frac{K_{S,IN}^2 - 1}{K_{S,IN}}. \quad (9)
\]

As can be seen from (9), \(K_{pm}\) can be implemented with \(K_{S,IN} \geq 1\). Hence it follows that the maximum achievable coefficient of steady-state amplification (at \(K_{S,IN} = 1\)) is equal to

\[
K_{mS} = \frac{W_{21}}{W_{12}}. \quad (10)
\]

2. Raising of the task

The maximum achievable coefficient of stable amplification (transmission) at the boundary of the stability of the quadripole \(K_{mS}\) characterizes its potential enhancement capabilities, determines the values of the nominal transmission coefficient \(K_{pn} [11]\) and the coefficient of non-reciprocity [12] \(K_N = K_{2mS}\) in the stability region.

A known method for determining this coefficient is based on the results of measuring the conductivity parameters of the direct \(Y_{21}\) and the reverse \(Y_{12}\) transmission of the quadripole [13]

\[
K_{mS} = \frac{Y_{21}}{Y_{12}}. \quad (11)
\]

Another method is based on the measurement of the powers \(P_1\) and \(P_2\) of the signal, which are allocated to the real component of the loading conductivity under the condition of constant power of the generator signal and the equality of the generator resistance and loading resistance [14]

\[
K_{mS} = \left(\frac{P_1}{P_2}\right)^{1/2}. \quad (12)
\]

The disadvantage of the first method is its low accuracy in the range of high frequencies, due to the large error of measurement of the \(Y\)-parameters of transistors. For example, when using a L2-8 device at a frequency of 60 MHz, this error is 20%.
A common disadvantage of known methods is the possibility of uncontrolled excitations of an experimental model when quadripole parameters are measuring due to the presence of feedback and amplification properties \((Y_{21} \neq 0, Y_{12} \neq 0)\). All this adds additional errors to the measurement result. Most clearly this is evident in measurements in the frequency range, where the stock of stability \(K_{S,in} < 1\) [15]. Therefore, the task is to increase the accuracy of determining the parameters of potentially unstable quadripole and to ensure the stability of the operation of the measuring unit.

3. Realization of the method
To solve the problem it is suggested to use a measuring device, the structural scheme of it is given in Fig. 2. [16]. It is known that if you connect an impedance \(Z\) between the common bus of the quadripole and the common bus of the measuring device, the \(Y\)-parameters (\(W\)-parameters in the general case) of the newly-received quadripole will take the form [17]

\[
Y_{12} = \frac{(y_{12} - Z \Delta y)}{(1 + Z \sum y)},
\]

\[
Y_{21} = \frac{(y_{21} - Z \Delta y)}{(1 + Z \sum y)},
\]

where

\[
\Delta y = y_{11}y_{22} - y_{12}y_{21},
\]

\[
\sum y = y_{11} + y_{12} + y_{21} + y_{22}.
\]

We will select such an impedance \(Z\), that will compensate for some of the parameters. Let \(Z_1\) be equal

\[
Z_1 = \frac{y_{21}}{\Delta y}.
\]

Then, substituting (14) into equation (13), we get that \(Y_{21} = 0\). It corresponds to the zero value of the coefficient of direct transmission of the quadripole power.

In the case of a change the impedance \(Z\) to the value

\[
Z_2 = \frac{y_{12}}{\Delta y}
\]

conductivity \(Y_{12} = 0\). It corresponds to the zero value of the reverse coefficient of the newly formed quadripole by power [16].

Let us take the relation (14) to (15) and, comparing it with (11), we get:

\[
\left| \frac{Z_1}{Z_2} \right| = \frac{y_{12}}{y_{21}} = K_{mS}.
\]

From the equation it is obvious that by measuring the ratio of the values of impedances \(Z_1\) and \(Z_2\) in the scheme of the general output of the quadripole, that ensure the neutralization, respectively, of the coefficients of the reverse and direct transmission of the measuring scheme, it is possible to determine the maximum achievable coefficient of the \(K_{mS}\) transmission at the limit of the stability of the quadripole \(K_{S,in} = 1\).
Based on the above equations, the advantage of the proposed method for determining the maximum achievable gain (transmission) of $K_{ns}$ is evident. There is no transfer of signal power during measurement through the investigated quadripole from the generator to the indicator ($Y_{12} = 0$, $Y_{21} = 0$), that does not lead to self-excitation of the measuring device as a result of the influence of the internal feedback of the quadripole, that provides the stability of the measuring device (the theoretical value of the invariant coefficient of the stability $K_s \rightarrow 0$), that increases the accuracy of the measurement due to the impossibility of uncontrolled self-excitation. In addition, the measurement result does not depend on the immittance of the generator and the loading, that excludes the component of the methodical error of measurement of $K_{ns}$ due to non-fulfillment of the condition $Z_G = Z_L = \text{const}$, that is presented in known measurement methods [14].

Realization of the method is possible by using a measuring device, the structural scheme of which is shown in Fig. 2.

![Figure 2. Structural scheme of the measuring device of determination $K_{ns}$.](image)

As a calibrated impedance $Z$, a scheme consisting of a matching transformer of type E1-46 taken from the X5-12 device loaded on electrically controlled resistance, assembled by the circuit of the "inductive transistor" [18] is used. In the experiment, the indicator and generator of the panoramic meter of the complex transfer coefficients P4-11 are used. The measurement process is based on the equation (16). With the help of switches $K_1$ and $K_2$, the measuring device (Fig. 2) is set to the power transmission measurement mode in the forward direction. Then adjust the impedance $Z$ to the value $Z_1$ and fix it value, that corresponds to the zero value of the transmission coefficient ($Y_{21} = 0$) in the forward direction. In this case, the system consisting of the investigated quadripole and $Z$ resistance does not transmit power to the loading. It is fixed by the zero value of the PI readings.

The measurement process is repeated, with the difference that the zero value of the power transfer coefficient is set to the reverse direction ($Y_{12} = 0$). In this case, the value of the impedance $Z_2$ is fixed. Measurement and determination by this method $K_{ns}$, allows eliminating from the measuring process the errors inherent in measuring methods using short-circuit or idle modes and coordinated loadings, to make measurements of the characteristics of semiconductor devices based on the results of indirect measurements in the microwave range. This method can be used to determine the maximum achievable transmission coefficient at the limit of the stability of any active quadripole that can be described by the system of $W$-parameters.
4. Experimental testing

Experimental testing were carried out using a device, the structural scheme of which is shown in Fig 2. Indicator and generator of panoramic measurement of complex transmission coefficients P4-11 were used.

In Fig. 3 the results of experimental testing of $K_{mS}$ bipolar transistors are presented. From Fig. 3 it is evident that the nature of the change in the maximum achievable transmission coefficient $K_{mS}$, depending on the frequency, is the same for all transistors and has a spread within 10%.

![Figure 3. Frequency dependence of the $K_{mS}$.](image)

Also, the determination of the $K_{mS1}$ quadripole coefficient generated by the transistor KT-3115 ($f_m = 2$ GHz, $I_E = 5$mA, $U_{CB} = 5$V) with different schemes of its inclusion was carried out. The same coefficient of $K_{mS2}$ was determined in the manner described in [14].

In order to compare the measurement errors, the results were used to calculate the nominal gain coefficient of the quadripole [13].

$$K_{N.2.1p} = K_{mS} \left( K_{S.IN} - \sqrt{K_{S.IN}^2 - 1} \right).$$

The value of $K_{S.IN}$ was determined by the immittance method [19]. The obtained values of $K_{N.2.1p}$ were compared with the experimental values of $K_{N.2.21p}$ and the error was estimated

$$\delta = \left( \frac{K_{N.2.1p} - K_{N.2.21p}}{K_{N.2.1s}} \right) \times 100\%.$$

The results of the research showed that due to the known method, the measurement error is reduced by 6.1% and the stability of the measuring device in all modes, including the mode of negative reserve of stability.

The developed method allows us to carry out experimental studies of the frequency dependence of $K_{mS}$ on the boundary of stability of the quadripole formed by the bipolar (KT-3115) and field-effect (3P321) transistors, included according to the scheme with a general emitter and a general source. At the same time, the internal invariant coefficient of stability of the transistor was controlled. Studies
have shown that, with increasing frequency in the range of 0.1-1.0 GHz for both field and bipolar transistors, a change of the $K_{mn}$ with a slope (1.5…2) dB/GHz is observed. The nature of the reduction of $K_{mn}$ does not depend on the supply of firmness of transistor.

5. Conclusions
As a result of the carried out researches the developed technique allows to increase the accuracy of measurement of the parameters of the quadripole, ensures the stability of the experimental installation and measurement – parameters of any quadripole. The proposed method is most effective in the microwave range, where so far the problem of measuring the $S$-parameters of a potentially unstable quadripoles is not solved.

The parameters of the quadripole 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 SWR of the measuring path, as measured by the $S$-parameters.

For it measurement, it is not necessary to use the modes SC and IM or to make measurement in the coordinated measuring path, which also increases the accuracy of the measurement and provides stability in the measurement of potentially unstable quadripoles with $K_S > 0$.

6. References

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