

# Construction of models of microwave transistors when changing the probing signal in the frequency and power range

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**Abstract.** It is shown that to model a transistor in the form of S-parameters in the large signal mode, it is necessary to present the model as two S-matrices that describe the transistor at two phase differences between the incident and reflected waves equal to 0 and 90 degrees. The problem of matching a transistor with a load is reduced to solving a nonlinear equation with respect to a previously unknown phase difference, after which the load impedance is selected from the complex-conjugate matching condition.

## 1 Introduction

Measurement of S-parameters in the mode of transistor matching with the signal source and load is often performed using coaxial impedance tuners and contact devices to install the device in a strip line with a low impedance [1,2]. To build models of high-power transistors in the frequency range, this approach is time-consuming. At the same time, a library of models high-power microwave transistors in space different power modes DC current, frequency and power input can be created using schematic nonlinear model and design automation tools, and means of microwave measurements with vector network analyzer and signal amplifier of the necessary power, as is done in the well-known concept of X-parameters [3]. S-parameters in the large signal mode depend on the load impedance, but if the model is obtained under the condition of matching the input and output circuits of the transistor at the appropriate frequency, this dependence becomes less significant for the design of amplifiers and accounting for its influence is simplified.

## 2 Representation of S-parameters of microwave transistors in the frequency range in the nonlinear mode

Consider models of high-power microwave transistors in nonlinear mode, in particular, models in the form of S-parameters. To extract the model parameters from the results of measurements of the transmission coefficient and the reflection coefficient using a single generator, a snap-in with simple matching devices [4-6] and a spatially remote variable load in the form of one or two segments of a long line is used.

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On the basis of processing the results of numerical simulation of transistors and comparison with the results of full-scale experiment it was found that in the nonlinear mode to describe the elements  $S_{12}$  and  $S_{22}$  of the  $S$ -matrix in the large signal mode requires two complex coefficients for each element, which are designated as  $S_{12r}$ ,  $S_{12i}$ ,  $S_{22r}$ ,  $S_{22i}$ .

Let the incident wave  $a_1$  from the input side of the transistor, considered as a four-port, at some frequency has a phase equal to zero, then the first coefficient in the composition of the elements  $S_{12}$  and  $S_{22}$  of the matrix describes the impact of the incident wave component  $a_2$  from the output side with phase  $0^\circ$  with respect to the wave  $a_1$  (i.e.  $Re(a_2)$ ), and the second coefficient - the impact of the wave component  $a_2$  with phase  $90^\circ$  ( $Im(a_2)$ ). For the incident wave  $a_1$  at the input without limiting the generality of consideration,  $Im(a_1) = 0$  can be taken.

Thus, the relationship between the incident  $a_1$ ,  $a_2$  and the reflected complex waves  $b_1$ ,  $b_2$  can be represented as follows

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11}(|a_1|) & S_{12r}(|a_1|) & S_{12i}(|a_1|) \\ S_{21}(|a_1|) & S_{22r}(|a_1|) & S_{22i}(|a_1|) \end{bmatrix} \begin{bmatrix} a_1 \\ Re(a_2) \\ Im(a_2) \end{bmatrix}. \quad (1)$$

where all coefficients of the extended  $S$ -matrix are complex numbers. Another representation variant (1) is written as two matrices

$$\begin{bmatrix} b_{1r} \\ b_{2r} \end{bmatrix} = \begin{bmatrix} S_{11}(|a_1|) & S_{12r}(|a_1|) \\ S_{21}(|a_1|) & S_{22r}(|a_1|) \end{bmatrix} \begin{bmatrix} a_1 \\ a_{2r} \end{bmatrix}, \quad (2)$$

$$\begin{bmatrix} b_{1i} \\ b_{2i} \end{bmatrix} = \begin{bmatrix} S_{11}(|a_1|) & S_{12i}(|a_1|) \\ S_{21}(|a_1|) & S_{22i}(|a_1|) \end{bmatrix} \begin{bmatrix} a_1 \\ a_{2i} \end{bmatrix},$$

where  $b_1 = b_{1r} + b_{1i}$ ;  $b_2 = b_{2r} + b_{2i}$ ;  $a_{2r} = Re(a_2)$ ;  $a_{2i} = Im(a_2)$  with complex coefficients  $S_{11}$ ,  $S_{21}$ ,  $S_{12r}$ ,  $S_{12i}$ ,  $S_{22r}$ ,  $S_{22i}$ .

Storing the transistor model (2) in the nonlinear mode requires two  $S$ -matrices. In the linear mode, these matrices become the same and the model goes into the traditional  $S$ -parameters. The model can be transferred to automated modeling programs in the form of two s2p-files of a typical structure.

Separation of the influence of the real and imaginary parts of the complex wave  $a_2$  incident from the output makes it possible to describe more precisely the nonlinear modes of transistor amplifiers, up to the limiting mode [7].

### **3 S-parameters in the design of matching circuits of transistor amplifiers**

Consider the problem of matching the transistor in the nonlinear mode in accordance with the model (2) and determine at what values of the load impedance at the input the maximum power will be obtained.

We will assume  $Im(a_1) = 0$ , the value  $S_{12}$  to be negligible and for simplicity we will assume  $S_{12}=0$ ;

Then the transistor on the output side can be considered as a source of current with value

$$I = |a_1| * S_{21}/\rho,$$

where  $\rho$  - wave resistance of the line.

The output impedance of the transistor, defined through the  $S$ -parameters, will be

$$Z22(\varphi) = (1 + S22r * \cos(\varphi) + S22i * \sin(\varphi)) / (1 - S22r * \cos(\varphi) - S22i * \sin(\varphi)), \quad (3)$$

where

$$\cos(\varphi) = \operatorname{Re}(a2) / |a2|, \quad \sin(\varphi) = \operatorname{Im}(a2) / |a2|,$$

$\varphi$  - the angle between vectors  $a1$  and  $a2$  on the complex plane.

It is easy to show that in the case of representation of the model in the form of two matrices (2), the maximum output power in the load  $Z2$  will be obtained under the condition of a complex conjugate matching of the load with the output impedance of the transistor  $Z22(\varphi)$

$$Z2 = \operatorname{conj}(Z22(\varphi)). \quad (4)$$

On the other hand, the angle  $\varphi$  and resistance  $Z22(\varphi)$  and  $Z2$  must satisfy the condition

$$a2 = a1 * S21 * \Gamma2,$$

where in the pairing mode

$$\Gamma2(\varphi) = (\operatorname{conj}(Z22(\varphi)) - \rho) / (\operatorname{conj}(Z22(\varphi)) + \rho). \quad (5)$$

Solving together a system of equations (3), (4), (5), which can be reduced to one equation (6) with an unknown quantity  $\varphi$

$$\cos(\varphi) * S21 * \Gamma2(\varphi) = \operatorname{Re}(S21 * \Gamma2(\varphi)), \quad (6)$$

find a corner  $\varphi$ , which for model (2) in the form of two matrices is met the maximum output power of the transistor and running the balance of the incident and reflected waves. In small signal mode matrix elements

$$S12r = S12i,$$

$$S22r = S22i$$

and they do not depend on the angle  $\varphi$ .

## 4 Conclusion

Library of models high-power microwave transistors depending on the different power modes DC current, frequency and power input, it is possible to create on the basis of the experiment by measurements of S-parameters in the nonlinear mode. The spatially remote variable load method is used to simplify measurements using only one input oscillator.

To restore the S-parameters using a single signal generator, at least two measurements at different load values are needed. It is shown that in the nonlinear mode, the S-parameters obtained by changing the real part of the load impedance and by changing its imaginary part are markedly different. In the linear mode (small signal mode), the S-parameters, which are found when changing both the real and imaginary parts of the impedance of the remote load, have the same values.

The resulting model can be used to design the output stages of transistor amplifiers by means of linear analysis and optimization of electrical circuits. The problem of choosing the optimal load that provides the maximum output power is reduced to solving a nonlinear equation with respect to the phase difference angle between the input and output incident waves, after determining which it is possible to obtain the load impedance from the complex-conjugate matching condition.

## References

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