УДК 681.514
DOI: 10.22213/2413-1172-2021-3-53-60

Bandwidth Analysis of a Broadband Amplifier with Two-Stage Matching System Using the Smith Chart

A.A. Sherstneva, PhD in Engineering, Associate Professor, Novosibirsk State University of Economics and Management, Novosibirsk, Russia

This paper describes a novel trace structure for the analysis and design of two-stage Broadband Frequency Low Noise Amplifiers based on standard Smith chart procedures and program algorithm realization. The method allows to put the transistor's S-parameters and details of the source and load networks and to interactively explore the effects of these quantities on design variables such as gain, noise figure and stability. It also facilitates the design of two-element matching networks to transform the source and load impedances to optimum values to achieve the desired gain and noise performance.

The extended Smith chart concept is proposed to enable the advanced graphical interpretation of devices containing complex properties. This methodology is based on the Smith chart concept, and makes it easy to deal with devices containing signal sources, nonlinearity, very high Q factors and negative resistances.

The concept of explaining the use of the Smith chart in combination with using modern tools as MATLAB scripts is exemplified in graphical forms. Phyton-based program contains the algorithm for parameters calculation. It explains the procedure that must be used to solve the two-stage impedance-matching problem.

The point of this proposal is using of Smith chart plane for the graphical processing for its application to oscillator analysis. To demonstrate the effective usage of this methodology an interpretation and analysis of the oscillator, especially in terms of gain, noise and stability, are provided.

The practical relevance concludes results of multistage design using impedance matching LC networks for the intersection level. The values of the parameters of the integrated microcircuit confirm the possibility of using the calculation methodology considered in the paper.

The proposed solution is validated with extensive RF measurements at 3.5 GHz and is benchmarked against several frequency ranges for noise, stability and gain values. The methodology shown in the paper can be used in the development and design of modern microwave amplifiers, as well as for research and analysis of the efficiency of existing devices.

Keywords: microwave, Smith chart, broadband amplifier, design, multistage, intersectio.

Introduction

Amplifying devices are one of the most important components of radio-electronic equipment and largely determine its quality indicators.The development of an amplifying device is a solution to a complex of circuitry and design issues. The design of the amplifier, its manufacturability, stability over time and with changing operating conditions largely depends on how rationally the circuit is chosen and the operating mode of its elements is correctly calculated. Since the requirements for radio devices are usually contradictory, the developer is looking for the best option that best meets all the requirements.

Particular requirements are usually specified in addition to the terms of reference. Actually, the synthesis problem, and this is precisely the problem of developing high-frequency amplifiers, presupposes the presence of several alternative options, of which, taking into account the requirements of the technical specification, the most preferable is reasonably selected.

Scattering parameters are very useful set over the frequency range. A set is characterized in terms of traveling waves and totally defined two-port network’s behavior at microwave frequencies. The S parameters are quite simply to use in analysis, and flow graph theory is directly appreciable.

One of the techniques that permit to analyze and show transmission waves and reflection waves is a signal flow graph. Creation this graph is convenient approach to obtain relations between the variables using Mason's rule. Such technique allows to derive few expressions for power gains and voltage gains of complex microwave amplifiers.

For developing a signal flow graph variable should be considered as a node of construction, reflection coefficients and S parameters are designated as branches. Moreover, input branches dependent variable nodes and output from the opposite side, independent. Therefore, incident waves mean independent variable nodes and reflected mean dependent nodes. And sum of the input branches is defined as a node.

The main effectiveness of using signal flow graph analysis is in calculation of the input and output reflection coefficients. Overall, these graphs allow calculating power and voltage gain [1-4].

Some special cases assume such tasks as maximum power gain and minimum value of noise figure in the same time. Obviously, that is not easy derivable purpose. For solving this, Smith chart is one of the most suitable methods to develop power gain circle. Compromise between noise figure and gain performance would be founded through reflection coefficients and aimed to be solved in this article. Trade-offs that results from noise considerations, stability and gain are also considered in this article.

The article aimed to design low noise amplifier (LNA) with broadband frequency range from 1 to 3.5 GHz. Gain should be as constant as possible. Gain balance is equal $G_T = \pm 1$ dB. Noise figure corresponds to 2.5 dB. Such characteristics as gain flatness, stability at highest level and minimum possible noise are under consideration for design process.

Applying circuit analysis allows to change primary issues mixing few parameters and find out appropriate response. Another opportunity is in the lack of information redundancy. It is not necessary to make reanalyze of full schematic and it is possible to concentrate on every small elements or problem part. A field analysis using Maxwell's equations can't response for these issues and is also sophisticated task.

Nowadays computer aided design packages permit to resolve the biggest part of radio frequency analysis problems. Such programs simulate RF design. The article presents network analysis results and its application.

Problem Statement

The analysis of transmission lines and matching circuits problems are quite complicated tasks in analytical form. It is presented as a plot of all passive impedances in a reflection coefficient chart and restrict by unit radius. An accuracy of Smith chart is enough for the great majority of different practical design problems for microwave transistor amplifier [5-7].

Matching circuits providing balance of performance are obtained by using the normalized impedance and admittance Smith chart. It can be used to provide frequency dependence of scattering parameters likewise noise characteristic of amplifier.

Microstrip lines are applied as passive circuit elements and even more as a medium where complete microwave amplifier is implemented. The interconnections feature of the microstrip line is unsurpassed. Chip of transistors are connected to the strip conductors of the microstrip line. A practical circuit construction technique using microstrips is presented in this article.

The article focuses on complete strategy for the design of RF amplifiers. Overall, a linear power amplifier can be designed on the same basic matching principles used for small signal designs. However, power matched output isn't appearing to be conjugate matched. Sometimes, the design of a power amplifier becomes analogous to the design of a low noise amplifier, where to achieve the best possible noise performance, its input must be represented with a reflection coefficient that will differ significantly from the conjugate match of input resistance.In the case of linear PA, the device has to be presented with output power matching to extract the maximum power from the device in question. The key requirement represents a major design problem in the development of such amplifiers.The article shows that using simple capacitive harmonic matching with load impedance tuned to somewhat reactive can give very satisfactory results without the use of narrow band resonators.

Smith Chart and Matching

Smith chart is a plot of complex reflection overlaid with an impedance and/or admittance grid referenced to 1-ohm characteristic impedance. It contains almost all possible real or imaginary impedances within one circle. All imaginary impedances from - infinity to + infinity is represented, but only positive real impedances appear on the «classic» Smith chart. For thesteadystate AC term [8-12]:

$$Z = R + jX,$$

where Z - impedance, R - resistance, X - reactance.

For inductor:

$$X = j\omega L.$$

For capacitor:

$$X = \frac{1}{j\omega C},$$

where radian frequency ω is equal to $2\pi f$.

Basically, Z is equal to complex quantity with resistance as a real part and reactance as an imaginary part. These terms represent «opposition» quantities and are a natural fit for series-connected circuits where impedances add together. However, many circuits have elements connected in parallel or «shunt» that are a natural fit for the «acceptance» quantity of admittance (Y) and its constituent quantities of conductance (G) and susceptance (B):

$$Y = G + jB,$$

$B = j\omega C$ for a capacitor;

$B = \frac{1}{j\omega L}$ for an inductor.

Admittances add together for shunt-connected circuits. Additionally,

$$Y = \frac{1}{Z} = \frac{1}{R + jX}.$$

Normalization

The general configuration of an arbitrary two-port networkis shown inthe figure 1.

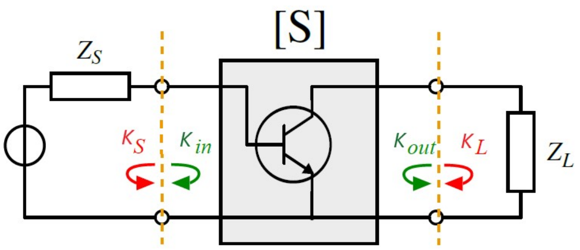

Fig. 1. A basic schematic

Moving along a uniform transmission line doesn't change the magnitude of the reflection coefficient or its radial distance plotted on the Smith chart. Reflection coefficient K is, by definition, normalized to transmission line Z_0 (characteristic impedance) [13-17]. To derive expressions of powergain in terms of S parameters, reflection coefficientsfrom source and load sides are:

$$K_L = \frac{Z_L - Z_0}{Z_L + Z_0}, \quad (1)$$

$$K_S = \frac{Z_S - Z_0}{Z_S + Z_0}. \quad (2)$$

Likewise, the impedance (admittance) values indicated on the grid lines are normalized to the characteristic impedance (admittance) of the transmission line to which the reflection coefficient is normalized.

The main function of the Smith chart is to convert reflection coefficients to normalized impedances or admittance and opposite operation. It is also useful to visualize the input and output matching. The Smith chart includes all possible impedances which can be imaginary or real, inside the circle. Mainly, in the Smith chart positive real impedances occur.

The matching network will be done at the input and at the output. To maximize the power dissipated by a load matching network provide a transformation of impedance to a desired value ensuring corresponds impedance is appropriate to amplifier [18-20].

For the figure 1 reflection coefficients K_{in} and K_{out} are defined as:

$$K_{in} = S_{11} + \frac{S_{12}S_{21}K_L}{1 - S_{22}K_L}, \quad (3)$$

$$K_{out} = S_{22} + \frac{S_{12}S_{21}K_S}{1 - S_{11}K_S}. \quad (4)$$

The transducer power gain is defined as the ration of the power delivered to the load and the power available from the source. In accordance with (3), (4) separate effective gain factors such as G_S for the input matching network, G_0 for the transistor and G_L for the output matching network are defined as follows:

$$G_S = \frac{1 - |K_S|^2}{|1 - K_{in}K_S|^2},$$

$$G_0 = |S_{21}|^2,$$

$$G_L = \frac{1 - |K_L|^2}{|1 - K_{out}K_L|^2}.$$

The maximum gain can be realized when these sections ensure a conjugate match between the amplifier source or load impedance and the transistor. Except stability and gain, one more important design consideration is noise figure. The equations for constant noise figure of a two-port amplifier can be expressed as:

$$F = F_{\min} + \frac{R_N}{G_S}|Y_S - Y_{opt}|,$$

where Y_S means source admittance presented to transistor, Y_{opt} - optimum source admittance that results in minimum noise figure.

$F_{\min}$ - minimum noise figure of transistor, attained when $Y_S = Y_{opt}$; R_N - equivalent noise resistance of transistor; G_S - real part of source admittance.

Instead of admittance Y_S and Y_{opt}, reflection coefficients K_S and K_{opt} are used:

$$Y_S = \frac{1}{z_n}\frac{1 - K_S}{1 + K_S}, \quad (5)$$

$$Y_{opt} = \frac{1}{z_0}\frac{1 - K_{opt}}{1 + K_{opt}}. \quad (6)$$

$F_{\min}$, K_{opt}, R_N are called noise parameters. Their values are given by the manufacturer or measured. Finally, in accordance with (5) and (6), the noise parameter N is defined as:

$$N = \frac{F - F_{\min}}{4R_N / Z_0} \left|1 + K_{opt}\right|^2 . \quad (7)$$

Experimental Results

For practical solution some special case in transmission theory is useful for impedance transformation. First case we have when $l = \frac{\lambda}{4}$ using $\beta l = \frac{\pi}{2}$, $Z_{in} = \frac{Z_0^2}{Z_l}$. Impedance Z_l at the end is transformed into new impedance $\frac{Z_0^2}{Z_l}$ at the input. This works for a length of exactly $\frac{\lambda}{4}$. Hence, the transformation is strongly frequency dependent. The bandwidth widen of the transformation is cascading by several of this $\frac{\lambda}{4}$ - transformers. For case with line length $l = \frac{\lambda}{2}$, $Z_{in} = Z_l$, $\beta = \pi$.

This means, that inserting a line of half a wave length does now change the impedance of the load. No matter if the load is matched or not. This is also valid for one frequency only.

The open and short line impedances can vary with the length of the lines. Using L-C equivalent circuits presented in the article [A. Sherstneva, Intersection realization for multistage RF amplifier design, IEEE International Multiconference on Industrial Engineering and Modern Technologies, Vladivostok, 2020] makes modelingline impedance.The description of two-port networks in terms of S parameters permits the use of signal flow graph in the analysis of microwave transistor amplifier. Next part of methodology consists in conjugate matching networks. During algorithm implementation a software program was developed for reflection coefficients K_S and K_L estimation [A. Sherstneva. Program for parameters calculation of a low-noise broadband microwave amplifier, Reg. No. 2021619080,03.06.2021]. Design of amplifier was made by using software “AWR Design Environment”. According to program results,

$$K_s \text{ equals } 0.24\angle -104°$$

In accordance withprogram optimization algorithm:

$$K_S = 0.0581 - 0.2329,$$

$$K_{out} = 0.1981 - 0.1369,$$

$$K_L = 0.1981 + 0.1369,$$

$$K_L = 0.2408\angle 34.645^{\circ}.$$

Moreover, the algorithm contains the use of Smith Chart to define the lengths from source and load parts.

Then, computer aided design package “TXline” permit to replace microstrip lines structure.Particular values of elements are calculated [A. Sherstneva, Program for parameters calculation of a low-noise broadband microwave amplifier, Reg. No. 2021619080,03.06.2021] and may vary for different elements. For purpose of article schematic makes sense and its structure is presented.

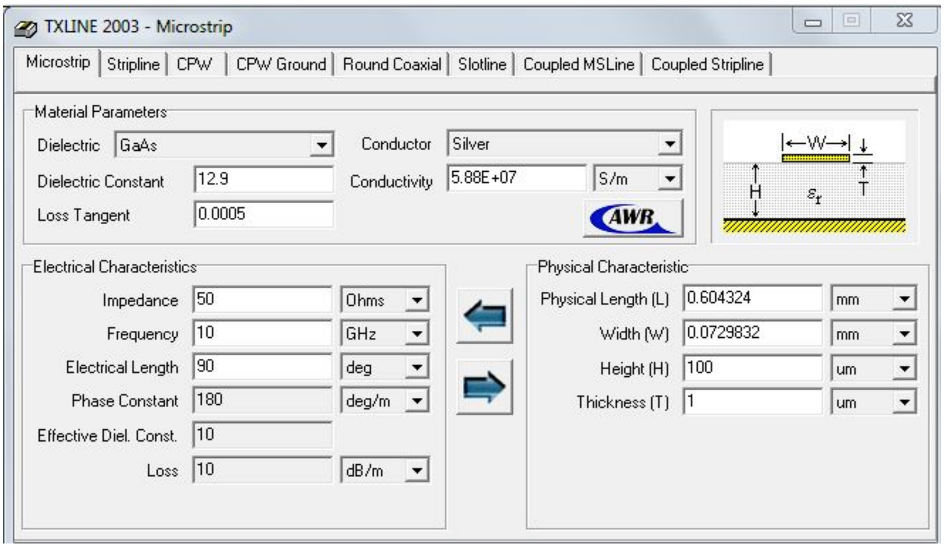

Fig. 2. “TXline” tool

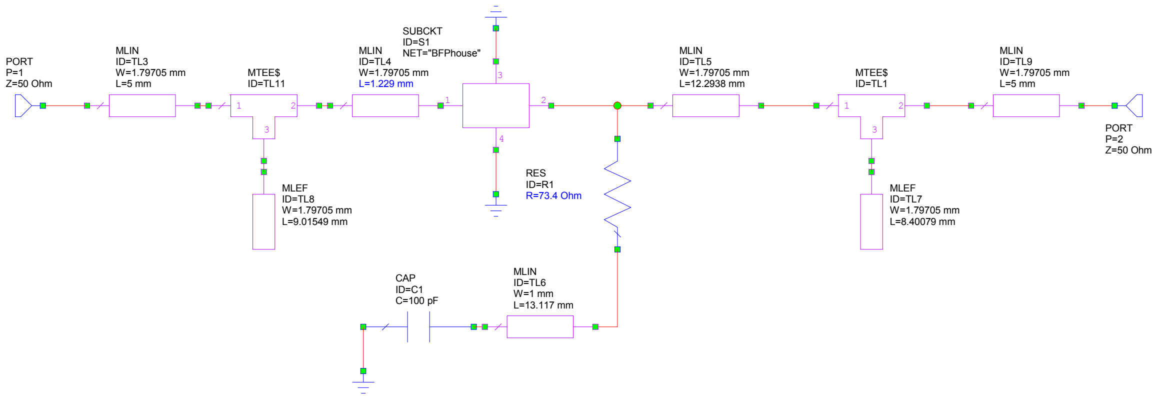

Fig. 3. Microstrip lines schematic for LNA

Discussion of Results

The stability of network is the main factor shows that transistor doesn't have oscillations at frequency range. For this reason, the resistor is used to make the transistor unconditionally stable. The resistor will be connected to the output port of the amplifier as a shunt. Stability circle of amplifier can be seen from the Smith chart by simulating.

The gain value is equal 14 dB and is fairly flat from 1 GHz to 3.5GHz. In this range of frequencies, the distinction is no more than ±1 dB that is quite desirable.

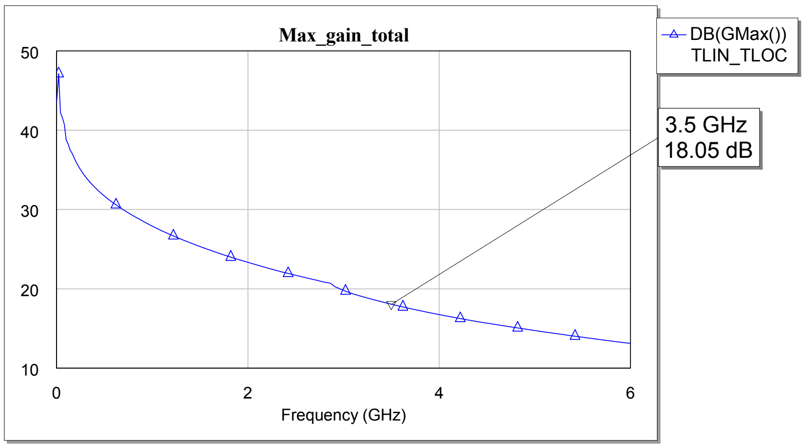

Fig. 4. Gain value for LNA

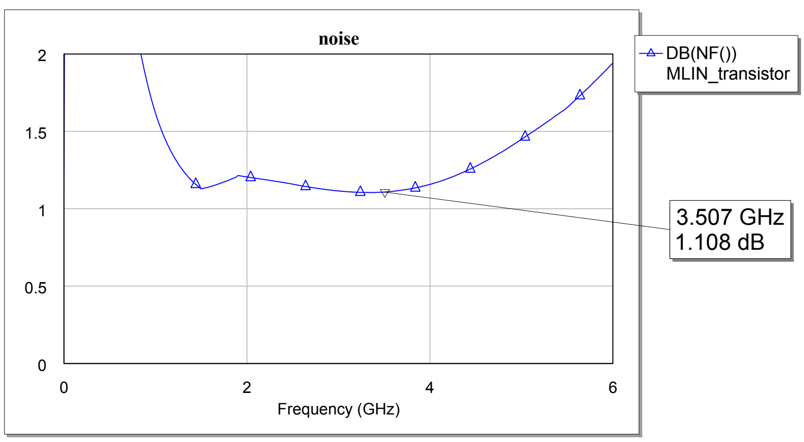

Fig. 5. Noise value for LNA

To provide a flat gain response negative feedback is extremely useful. As a disadvantage negative feedback decrease the noise figure and reduce the maximum power gain available from a transistor.

Bias tee is presented as an ideal capacitor that allows AC through but blocks the DC bias and an ideal inductor that blocks AC but allows DC. Basically, bias tees are developed using capacitor and inductor. In practice a few components have parasitic elements.

Due to bias tees are operated for a range of signal frequencies, reactance is designed with minimal impact at the lowest frequency.

Calculation of the values of the resistors using Data Sheet for transistor «DC Characteristics»:

$$I_C = 20 \text{ mA},$$

$$VCE = 3 \text{ V},$$

$$VCC = 5 \text{ V},$$

$$\beta = 110,$$

$$VBE = 0{,}8 \text{ V(const)},$$

$$R_4 = \frac{V_{CC} - V_{CE}}{I_C},$$

$$R_4 = \frac{5 \text{ V} - 3 \text{ V}}{20 \text{ mA}} = 0{,}1 \text{ k}\Omega = 100\ \Omega,$$

$$\beta = \frac{I_C}{I_B},$$

Means,

$$I_B = \frac{I_C}{\beta} = \frac{20 \text{ mA}}{110} = 0{,}18 \text{ mA}.$$

$$V_X = 1{,}5 \text{ V},$$

$$I_X = 5 \text{ mA}.$$

Then,

$$R_3 = \frac{V_X - V_{BE}}{I_B} = \frac{1{,}5 \text{ V} - 0{,}8 \text{ V}}{0{,}18 \text{ mA}} = 3{,}88 \text{ k}\Omega = 3888\ \Omega,$$

$$R_1 = \frac{V_X}{I_X} = \frac{1{,}5 \text{ V}}{5 \text{ mA}} = 0{,}3 \text{ k}\Omega = 300\ \Omega,$$

$$R_2 = \frac{V_{CC} - V_X}{I_X + I_B} = \frac{5 \text{ V} - 1{,}5 \text{ V}}{5 \text{ mA} + 0{,}18 \text{ mA}} = 0{,}7 \text{ k}\Omega = 675\ \Omega.$$

Bias tee layout for low noise amplifier design is listed below.

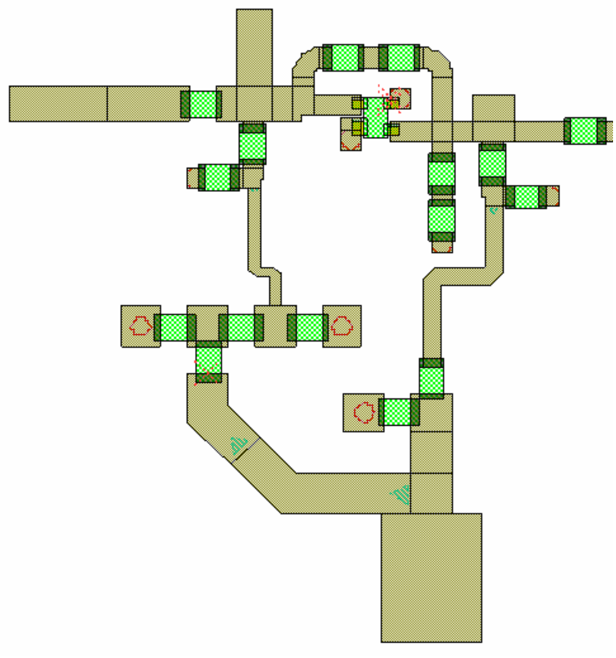

Fig. 6. Bias tee layout for LNA

Over a large frequency range of bias tees, the inductor has to be large at the lowest frequency, that allows a stray capacitance and self-resonant frequency as a result. At a high enough frequency, the stray capacitance presents a low-impedance shunt path for the signal, and the bias tee becomes ineffective. Practical wide-band bias tees are designed in circuit topologies that avoid the shunt path. Instead of one inductor, there should be a series string of inductors. Additionally, resistors and capacitors to prevent resonances are constructed to the schematic.

Conclusion

The use of well-known techniques implemented in the form of software based on the generated algorithm allows simulating the design algorithm to obtain the necessary characteristics of the device being developed. Software simulation of the circuit allows improving the efficiency of the analysis and evaluating the properties of the circuit. The results obtained during hardware implementation make it possible to assert that approbation of the technique was carried out successfully and the required characteristics were provided.

There have to be a balance between some characteristics such as flat gain, noise figure and stability. Getting a perfect match is also necessary part of design because matching networks provide a transformation of impedance to expected value for maximization the power dissipated by load.

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Анализ полосы пропускания широковещательного усилителя с двухступенчатой системой согласования

А. А. Шерстнева, кандидат технических наук, доцент, Новосибирский государственный университет экономики и управления, Новосибирск, Россия

Предложен программный метод проектирования двухкаскадных широкополосных малошумящих усилителей. Новизна метода проектирования заключается в применении расширенной диаграммы Смита в сочетании с такими современными инструментами, как сценарии Matlab, программное обеспечение AWR Design Environment. В статье в графическом виде даны необходимые пояснения их совместного использования. Для анализа предлагаемого метода проектирования составлена программа на базе Phyton, которая содержит алгоритм расчета параметров. В результате анализа выявлено, что предлагаемый метод позволяет в интерактивном режиме исследовать влияние входных параметров на предмет шума, стабильности и значений усиления.

В целом предлагаемый метод облегчает проектирование согласующих цепей для преобразования импеданса источника и нагрузки до оптимальных величин с целью достижения желаемых характеристик усиления и шума. Программное моделирование схемы позволяет улучшить эффективность проводимого анализа и оценить свойства исследуемой схемы. Результаты, полученные в ходе реализации устройства на плате, позволяют утверждать, что апробация методики выполнена успешно и требуемые характеристики были обеспечены.

Предлагаемое решение подтверждено радиочастотными измерениями на частоте 3,5 ГГц и протестировано в нескольких частотных диапазонах на предмет шума, стабильности и значений усиления. Представленная в статье методика может быть использована при разработке и проектировании современных СВЧ-усилителей, а также для исследования и анализа эффективности существующих устройств.

Ключевые слова: СВЧ-диапазон, диаграмма Смита, усилитель широковещательный, проектирование, многокаскадный, скрещивание.

Получено 28.05.2021

For Citation

Sherstneva A.A. Bandwidth Analysis of a Broadband Amplifier with Two-Stage Matching System Using the Smith Chart. *Vestnik IzhGTU imeni M.T. Kalashnikova*, 2021, vol. 24, no. 3, pp. 53-60. DOI: 10.22213/2413-1172-2021-3-53-60.