DESIGN OF AMPLIFIERS WITH POTENTIALLY UNSTABLE TRANSISTORS

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Abstract

Paper presents overview of methods used for stabilization of high frequency and microwave transistors amplifiers using potentially unstable transistors. The S-parameter approach is used for analysis of the amplifier stability over the required bandwidth. The treatment takes in consideration the influence of the operating conditions on noise, gain and mismatch for the particular application. Because the subject is treated in the literature only briefly, the summary presented in this short paper shows to the designer methods used in practical design.

Keywords:
microwave transistor amplifier, stabilisation

Introduction

Microwave and high frequency transistors are subject to the same laws of physics as their low frequency counterparts, therefore we could start to analyze their potential as active elements in amplifiers in the same manner, but a the same time must take in consideration their different nature, needed for their operation at elevated frequencies. One basic difference between high and low frequency transistors (be it BJT or FET device), is the small geometry needed for operation at microwave frequencies. This small geometry limits the operation of microwave devices to relatively low voltages (3-10 Volts max.), and in some cases to low power as well. Generally, the smaller the geometry, the higher the transfer frequency of the device. As the gain product of such transistors is constant, like in case of low frequency devices, this results in very high potential gains at lower frequencies. Such high gain, because there is always present internal feedback in any device, results in the tendency to instability at lower frequencies. This fact is in standard analysis using scattering parameters for microwave transistors reflected by the variation of the stability factor K with frequency. The K factor is always decreasing with frequency decrease, and at certain frequency, different for each device, reaches the value of unity, indicating the boundaries of potential unstability of the transistor. Below this frequency the device is unstable, and the constant gain-bandwidth product line became meaningless, as we cannot safely realize operation of such device below such frequency. Note that some devices can became again potentially unstable at the high frequency side. In the literature are published various methods to assure stable operation of such transistors, all of them depending on reduction of the device gain and in some cases also in degradation of noise figure and output power. The most widely used methods are summed below, and their advantages or disadvantages for various applications are evaluated.

1. Methods used for stabilizing potentially unstable transistors

Obviously there are many ways how to make potentially unstable transistor stable. In the following treatment we will at first consider the stability at one frequency only, and later will discuss the methods used for the wide frequency operation (note here that the single frequency designs do have with simple two element matching networks in some cases bandwidths well over 10%!). First, and trivial solution, which will work in all cases, is to replace potentially unstable transistor with another, stable at design frequency. This simple solution can save lot of time and money during the design.

If, for one or another reason, we decide to stay with potentially unstable device, we have to decide on the method we will use for stabilizing the transistor operation. In the literature [1-3] we can find four basic engineering methods used for this purpose. The non engineering, primitive, method which will be not considered here, is the design of the amplifier without previous knowledge of scattering parameters or other methods of analysis. Even if this method in many cases works, and is based on haphazard mismatching of the device, its results are unpredictable and therefore not engineering in the full meaning of the word.

In most engineering methods employed today, we normally use two port representation of an active device. For high frequency and microwave devices we use nearly exclusively S (scattering) parameters even if other parameters, like y-parameter, were, and are still often used for the lower frequency transistors. For that reason we will limit the following analysis only to S-parameter approach, with active device represented by a two port having corresponding S-parameters, as shown in Fig.1.1.

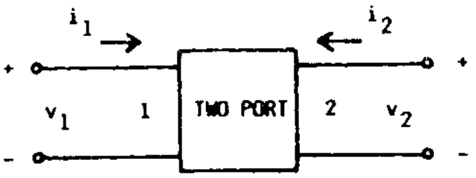

Fig.1.1
Two port network with orientation of voltages and current

1.1 Moving the reflection coefficients away from area of instability

This method requires the knowledge and application of Smith chart, which use is recommended in all cases, as it gives the designer graphical illustration and feeling what is actually happening when one or another parameter of the network is changed. At first we need to draw the instability circles in the input and output plane, or use conjugate circles [4] in one plane only. Next we plot the calculated reflection coefficients for the source and load needed to match the transistor. Obviously in case of potentially unstable transistor one or another, or both reflection coefficients will tend to terminate INSIDE the corresponding instability circle. At this moment the designer needs to decide on degree of stability required for safe operation of the device. This will be reflected in movement of the reflection coefficient vector away from the area of instability. If, for example the output reflection coefficient terminates inside the output instability circle, we can move it from this position in any direction to the inside the Smith chart by MISMATCH at the output. How far away we will move it from unstable area, will determine the degree of stability at the output. Obviously the mismatch will have its negative effect, first of which will be the decrease in gain. Next, we need to recalculate for this new output reflection coefficient, the corresponding input reflection coefficient, and verify, if this move did not position the end of the input reflection coefficient into the instability area in the input plane. If this is so, we need to return to the output plane and choose new position of the output reflection coefficient, which will keep the input reflection coefficient outside input instability area. The transistor, and resulting amplifier will be stable only if BOTH reflection coefficients will end outside corresponding instability areas. As an example we show in Fig.1.2 the Smith chart for bipolar transistor MRF571 operating at 500MHz with biasing 6V at 5mA, where it is potentially unstable, having K=0.57. The input and output instability circles include areas inside the chart, which must be avoided for stable operation. In this case we achieve this by first mismatching the output, and still keeping the gain as high as possible, by choosing the smallest output reflection coefficient (Rml) needed for match on the calculated 18.3dB constant gain circle, also constructed in the chart. Note here that the smallest Rml results in minimum VSWR, which obviously simplifies the design of the output matching circuit. The 18.3dB is fairly close to the Maximum Stable Gain, defined as MSG = |S21|/|S12| (which in our case is 18.37dB), but still provides for stable operation as can be verified by calculating and constructing the corresponding input reflection coefficient (Rms). Obviously any output reflection coefficient terminating on 18.3dB constant gain circle can be selected, but the corresponding input reflection coefficient will be elsewhere on the chart, and for stable operation must be also outside the instability area for the input. Note that in this case, as is a standard practice, we plotted input and output planes in the same chart. Obviously any other value of gain or reflection coefficient can be selected and previous method applied for this new value.

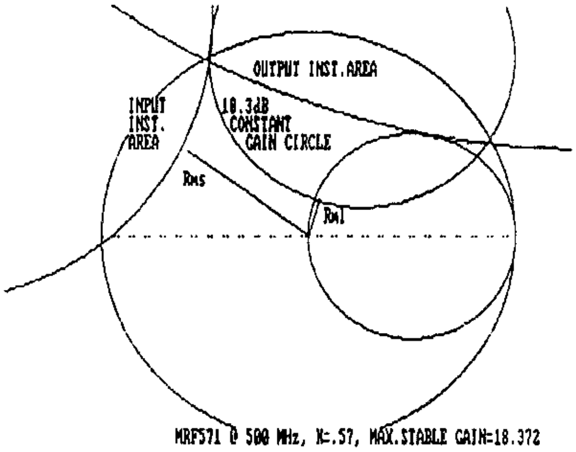

Fig.1.2

The conclusion for this method is that we knowingly MISMATCH input or output (in rare cases we use mismatch at both ends), and then perfectly match the other end of the transistor. For the renewed stability we pay with loss of gain, and in some cases by increased noise figure. But using this method we could always CONTROL this parameters and the movement of reflection coefficients by change of external matching circuits.

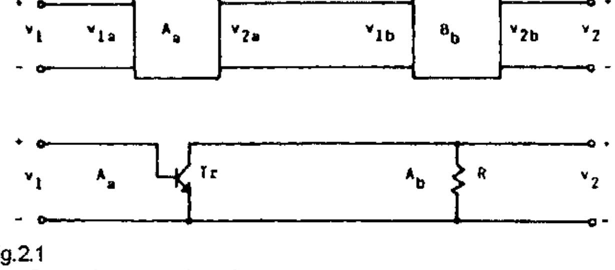

Fig.2.1
Cascode connection of two port networks

2. Adding an external loading resistance at the output

This method depends on use of external loading resistance, as shown in Fig.2.1, which changes the scattering parameters of the device to the parameters of the device and resistor combination, in such a manner that it moves the instability circles outside the Smith chart.

To obtain the overall S parameters for the combination, we have to convert both S matrices to ABCD matrices, calculate the their product and convert back to overall S matrix for transistor resistor combination. The resistor value should be such that the overall stability factor K > 1, then the transistor-resistor combination will be inherently stable and we could proceed with the design in the manner used for unconditionally stable device. Obviously even with this method we are decreasing the potential gain of the amplifier to preserve the stability. As this method requires only to add appropriately chosen resistance, it is simpler than the first method which needs the assistance of Smith chart to follow the movement of reflection coefficient away from unstable areas. As the resistance is added at the output of the transistor, it reduces only the gain, but the noise figure is influenced only minimally, which could be in many cases the desired solution. It is important to mention at this point that use of the biasing resistor for the output port can provide for the same effect if it is small enough and not separated from the high frequency path via choke or other means. It is also possible to add very small resistor in series with input or output port, but resistor in the input adversely influence the noise figure and in the output its function is equivalent to the loading resistor, so these methods are usually avoided.

3. External feedback methods

The last two methods depends on the application of negative feedback, with all its positive and negative effects. Two types of feedback are used in single stage high frequency amplifiers, shunt and series. Each case will be discussed separately.

Shunt feedback, shown in Fig.3.1, is applied by connecting an external impedance from the output to the input port of the transistor, i.e. from collector (or drain) to base (or gate). This impedance can be realized by series or parallel combination of resistance, inductance and capacitance. In some cases we exclude one or another element. Using the capacitance in the network serves also (or only) for d.c. isolation between the output and input terminals.

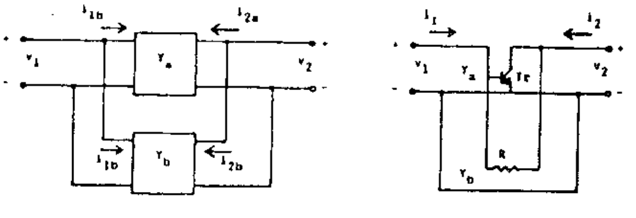

Fig.3.1
Parallel (shunt) connection of two port networks

The calculation of overall S parameters is here done by converting the original S matrices to Y matrices, adding them and again reconvert the result to overall S matrix. This type of feedback, as known from analysis for low frequency networks, reduces the gain, but also decreases the input and output impedance of the device. In case when we use feedback resistance only, the undesirable result is the increase of the noise figure by about 1 dB. The practical values of this resistance are in most cases between 300-500 ohms depending on the device. For this reason we use this type of feedback mostly in the amplifier with two stages (many MIC's use this type of circuit to stabilize gain over wide bandwidth). Because the feedback is applied over two stages the value of feedback resistor could be much larger and therefore its contribution to overall noise is much smaller (practical values results in contribution to noise figure in the range of .3db).

The amount of reduction of input impedance should be also considered very carefully, as in case of higher power microwave transistors, their impedance is already very low, resulting in requirement for very elaborate matching networks. The output impedance is usually higher, therefore we need to consider the feedback effect mainly on input impedance.

The second type of feedback used for stabilization of microwave transistors is series feedback, shown in Fig.3.2. In this case we need to convert original S matrices to Z matrices, add them and again reconvert the result to overall S matrix for the combination.

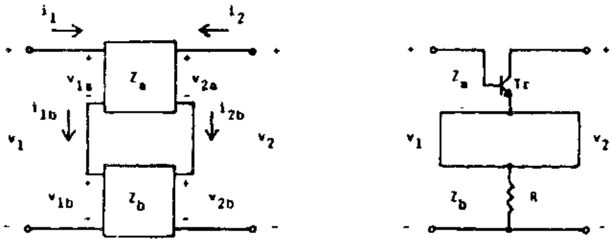

Fig.3.2
Series connection of two port networks

Series feedback is in microwave transistors realized by inserting an impedance in series with the grounded terminal of the device, i.e. introducing it in the output as well as input current path. Again, as in previous case, it introduces some reduction in gain, but also results in increase of input as well as output impedance. Because the impedance is in path of input current we avoid using large value resistors as feedback elements, because they substantially contribute to the noise figure of the network. Practical values are of order of few ohms, and like in previous case this type of feedback is to be preferably used in two stage amplifiers and MIC's. In many cases we avoid the use of resistor altogether and prefer to insert in the circuit only a small inductance, which does not greatly influence the noise figure and still provides the benefits of this type of feedback.

Depending on application we often use both types of feedback in combination, to achieve stabilization of gain over wide bandwidths as well as preserving stable input and output impedance over this range, therefore reducing the variation of standing wave ratio, good overview of all methods is in [5]. Two remaining types of feedback, series-shunt and shunt-series are mostly used in multistage amplifiers and will not be discussed here.

4. Wide band design

The standard approach in case of unconditionally stable transistors is to design for maximum gain at the highest frequency and use the frequency dependency of the matching networks to reduce gain at lower frequencies to provide constant gain over the desired bandwidth. The stability then must be also checked at the lowest frequency of the design. If this is satisfactory the design ends here. In case of potentially unstable devices we need to reduce gain at the highest frequency first by any of the previously mentioned methods and after that check if also at the lowest frequency is the device stable. If not, we need to stabilize the device first at the lowest frequency before continuing with the design. Again, as in all cases, we could use with advantage the frequency dependency of the matching networks to stabilize the amplifier. Matching networks of this type are therefore acting as an gain equalizer network. In the final check the amplifier must be stable over all the desired frequency range and outside as well, but particularly at low end where the danger of oscillations is greatest. For this type of amplifiers we first make design for one frequency only (usually the highest), using some type of matching network with wide band characteristics, and then enter the complete network into the computer program with optimizing subroutine to finish the design. In modern circuit design the computer analysis and synthesis can substantially reduce the time needed for this type of amplifiers.

5. References

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Stanislav Novak was born in Czechoslovakia 1932. He received his MSc and PhD at Slovak Technical University in Bratislava in 1959 and 1968. After 1969 he was with Portsmount Polytechnic and University of Lancaster as a Research Associate. Then he continued at University of Warwick, University of Nebraska, Bolton Institute of Technology, ITU in Geneva, University of Wyoming. Since 1989 he is a Director of Microwave Laboratory, teaching postgraduate courses in microwaves, microwave measurements and laboratory automatisation at Instituto Militar de Engenharia, Rio de Janeiro.