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Computation of Constant Gain and NF Circles for 60 GHz Ultra-low noise Amplifiers

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Abstract

Wireless communication is a constantly evolving and forging domain. The action of the RF input module is critical in the radio frequency signal communication link. This paper discusses the design of a RF high frequency transistor amplifier for unlicensed 60 GHz applications. The Transistor used for analysis is a FET amplifier, operated at 60GHz with 10 mA at 6.0 V. The simulation of the amplifier is made with the Open Source Scilab 6.0.1 console software. The MESFET is biased such that Sll = 0.9<30°, S12 = 0.21<-60°, S21= 2.51<-80°, and S22 = 0.21<-15o. It is found that the transistor is unconditionally stable and hence unilateral approximation can be employed. With these assumptions, the maximum value of source gain of the amplifier is found to be at 7.212 dB and the various constant source gain circles and noise figure circles are computed. The transistor has the following noise parameters: Fmin = 3 dB, Rn = 4 Ω, and Γopt = 0.485<155°. The amplifier is designed to have an input and output impedance of 50 ohms which is considered as the reference impedance.

Keywords: Millimetre wave, amplifier, FET, gain, transistor, Scilab

1. Introduction

High Frequency communication designs are developed to meet the present and future requirements of users who are growing exponentially every year. The bandwidth requirement

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and wireless applications are anticipated to continue into the future [1-5]. To meet these demands and assure a good QoS to the users, new wireless communication standards and generations have been launched. The prime objective of high frequency communication technology is to increase the transmission rate (speed), thus providing better receiver links at affordable cost. To implement a successful wireless application, the output power, reliability, linear operation, and cost of the amplifier are significant [6-8]. In this simulation, a MESFET is operated at f = 60 GHz and is unilaterally biased. It is assumed that the transistor is unconditionally stable and unilateral approximation is employed.

Our manuscript is structured as below: section II presents the mathematical analysis of constant gain & NF circles, section III presents the simulation and plotting of the circles, section IV lists the results obtained and section V, gives the conclusion of the work.

2. Design of Constant Gain & NF Circles

Any transistor has to be connected with a wide range of source and load impedance values. Noise can never be avoided in a circuit [9-13]. The matching of input and output networks determine the gain and noise value of the transistor. Source gain must be matched for constant gain requirement and load must be matched to have minimum or tolerable noise requirements [14-17]. To better understand the constant gain and noise matching, Circles are plotted in Smith chart and intersecting or overlapping points are chosen as per specifications. A detailed explanation on the design of gain and noise circles is given below:

A. Constant Gain Circles

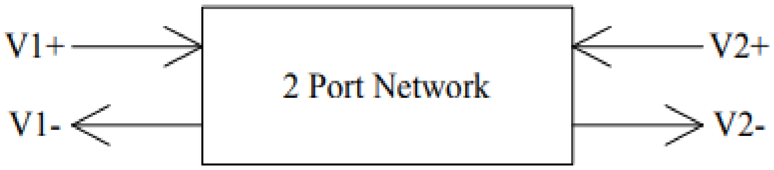

Figure 1. Illustration of a 2-port network

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$$\begin{bmatrix} V_1^- \\ V_2^+ \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \tag{1}$$

An amplifier is said to be unilateral if $S_{12} = 0$, the feedback or reverse gain is assumed to be zero. This condition can be applied to all amplifiers, mainly the operational amplifiers where there is a clear separation of the output from the input signal.

The input and output reflection coefficients are then given by:

$$\Gamma_{in} = S_{11} + \frac{S_{12}S_{21}\Gamma_{load}}{1 - S_{22}\Gamma_{load}} \tag{2}$$

$$\Gamma_{out} = S_{22} + \frac{S_{12}S_{21}\Gamma_{source}}{1 - S_{11}\Gamma_{source}} \tag{3}$$

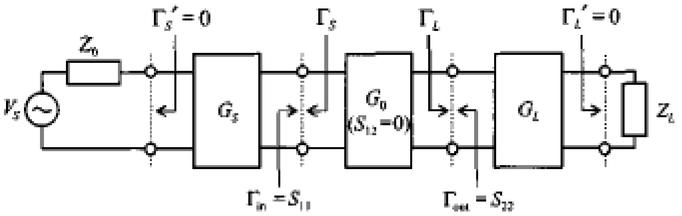

Figure 2. Block diagram of Unilateral System

Besides ensuring stability of the amplifier, the importance to attain the required gain performance is a crucial factor in the amplifier design task, If, the transistor's feedback is neglected ($S_{12} = 0$), we can apply the unilateral power gain G_{TU}.

The Unilateral power gain is given as

$$G_{TU} = \frac{1 - |\Gamma_S|^2}{|1 - S_{11}\Gamma_S|^2} \times |S_{21}|^2 \times \frac{1 - |\Gamma_L|^2}{|1 - S_{22}\Gamma_L|^2} = G_S \times G_o \times G_L \tag{4}$$

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Gs and G_L are assumed to be the gains of the source and load matching networks and Go is the insertion gain of the transistor. The network gains might be greater than unity and may seem to dominate as they do not contain any active devices. But without perfect matching a considerable power loss can occur at both the ports of the amplifier. Source and load gains considered in the design, reduce the innate losses, which is can in turn be considered as a gain. If S_{11} and S_{22} are less than one, maximal value of unilateral power gain G_{TUmax} occurs since source and load are now matched. For this special case it can be seen that

$$G_{S\max} = \frac{1}{1-|S_{11}|^2} \tag{5}$$

$$G_{L\max} = \frac{1}{1-|S_{22}|^2} \tag{6}$$

Source and Load gain values,Gs and G_L are conformed with regard to their maximum values such that

$$g_s = \frac{G_S}{G_{S\max}} \tag{7}$$

$$g_L = \frac{G_L}{G_{L\max}} \tag{8}$$

Though Eqn. (7) and (8) provide a clear insight for the gain values for the source and load matching networks, they do not provide parametric curves of constant gain.

$$g_i = \frac{1-|\Gamma_i|^2}{|1-S_{ii}\Gamma_i|^2}(1-|S_{ii}|^2) \tag{9}$$

Gain, g_i is obtained using Eqn. (9) for the reflection coefficient Γ_i. The outcome is a set of gain circles that can be drawn with center locations at

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$$C_{gi} = \frac{g_i S_{ii}^*}{1 - |S_{ii}|^2 (1 - g_i)} \tag{10}$$

And radii of size

$$r_{gi} = \frac{\sqrt{1 - g_i (1 - |S_{ii}|^2)}}{1 - |S_{ii}|^2 (1 - g_i)} \tag{11}$$

The interpretation made from the constant gain circle equations in (10) & (11) are that the maximum gain $G_{imax} = 1 /(1 - |S_{11}|^2)$ is obtained for $\Gamma_i = S_{ii}^*$, which coincides with the constant gain circles whose center points are at $C_{gi} = S_{ii}^*$ and of zero radii. All the constant gain circles will have their center points on the line connecting the origin to S_{ii}^* or the angle line of S_{ii}. This is tabulated in Table 2 values. When the gain values decreases, the center point C_{gi} starts moving towards the origin. For the case $\Gamma_i = 0$, the normalized gain becomes $g_i = 1 - |S_{ii}|^2$ and centre and radii C_{gi} and r_{gi} will then be equal $C_{gi} = r_{gi} = |S_{ii}|/(l + |S_{ii}|^2)$. The $G_i = 1$ (or 0 dB) circle passes through the origin of the Γ_i -plane.

To design an amplifier with maximum gain, the input matching network and the output matching network gains must be $G_S = 1$ and $G_L=1$, as summarized above. While designing an amplifier for maximum power gain requirement, it may lead to unstablity. If the S-parameter S_{12} has a comparatively larger magnitude then bilateral approach can be used.

B. Noise Figure Circles

In receiver end RF amplifiers, signal amplification with less noise intensification becomes a crucial constraint. Unfortunately, designing a LNA contends with factors as stability and gain. Using Smith chart circles allows us to have a visual understanding of the sway of noise and gain values and observe the possible trade-offs between gain and stability. When designing circuits with transistors, noise parameters are known either through data given by

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the fabricators or via direct measurements. The minimum noise figure F_{min} behaviour depends on both the biasing of the amplifier and its operating frequency. For an ideal noiseless amplifier, $F_{min} = 1$, with the circle center location d_{Fk} denoted by the complex number

$$d_{F_k} = \frac{\Gamma_{opt}}{1+Q_k} \tag{12}$$

And the associated radius

$$r_{F_k} = \frac{\sqrt{(1-|\Gamma_{opt}|^2)^2 Q_k + Q_k{}^2}}{1+Q_k} \tag{13}$$

3. Modeling and Simulation

The Transistor used for said design is a MESFET, operated at 60GHz with 10 mA at 6.0 V. The simulation of the amplifier is made with the Open Source Scilab 6.0.1 console software. The MESFET is biased such that $S_{ll} = 0.9<30°$, $S_{12} = 0.21<-60°$, $S_{21} = 2.51<-80°$, and $S_{22} = 0.21<-15^o$. From the Rollett K factor calculation, it is found that the transistor is unconditionally stable and so unilateral approximation is applied. With these hypothesis, maximum source gain of the amplifier is found to be at 7.212 dB and the various constant source gain circles and noise figure circles are computed. The MESFET has the parameters: $F_{min} = 3$ dB, $R_n = 4\ \Omega$, and $\Gamma_{opt} = 0.485<155°$. The amplifier has an input and output impedance of 50 ohms which is taken as the reference impedance.

4. Results And Discussion

The maximum source gain was computed to be 5.2631579or 7.212dB.

The source matching network ($Ts = S_{ll}^*$) and the amplifier provide a gain of **7.212** dB. Inorder to minimize or reduce the noise figure value for a specified gain, the source reflection

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coefficient should be chosen on a noise figure circle that is closest to the location of Γopt from the constant gain circle.

Table 1. Computation of Gain Circle parameters

G_T (dB)	**g_s**	**Centre**	**Radius**
-2	0.315	0.33-0.909i	0.85
-1	0.397	0.33-0.909i	0.71
0	0.5	0.33-0.909i	0.58
1	0.629	0.33-0.909i	0.47
2	0.792	0.33-0.909i	0.37
3	0.99	0.33-0.909i	0.28
4	1.25	0.33-0.909i	0.21
5	1.58	0.33-0.909i	0.15
6	1.99	0.33-0.909i	0.11

Table 2. Computation of Noise Figure Circle parameters

NF (dB)	**Centre**	**Radius**
4	-0.3 + 0.14i	0.63
3.8	-0.30 + 0.14i	0.54
3.6	-0.3 + 0.14i	0.46
3.4	-0.3 + 0.14i	0.37
3.2	-0.3 + 0.14i	0.27

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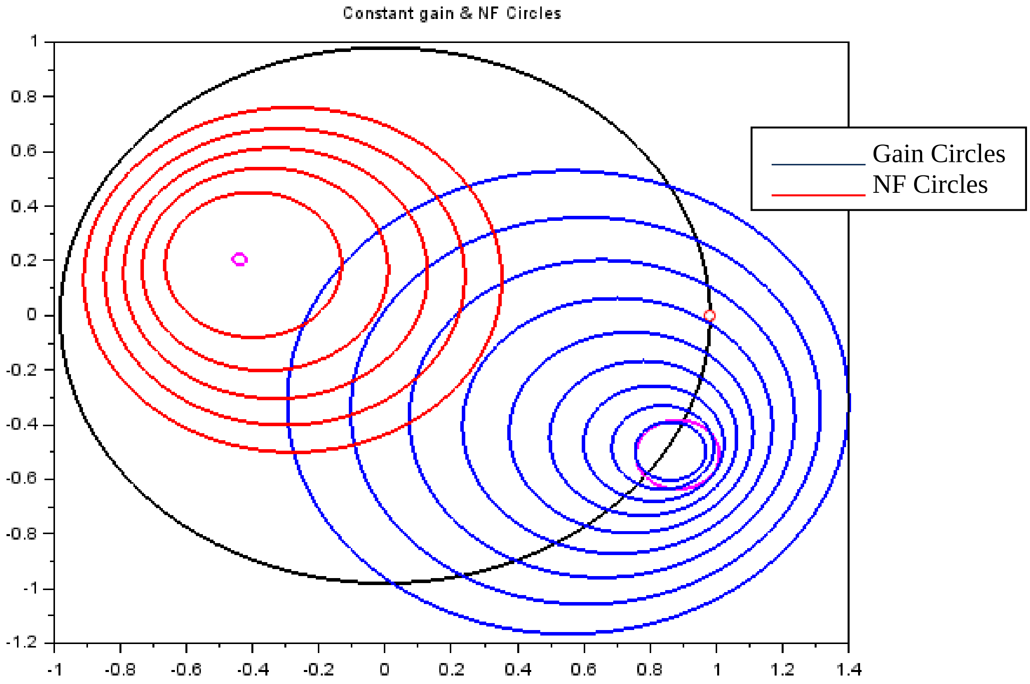

Figure 3. Constant gain & NF Circles Obtained

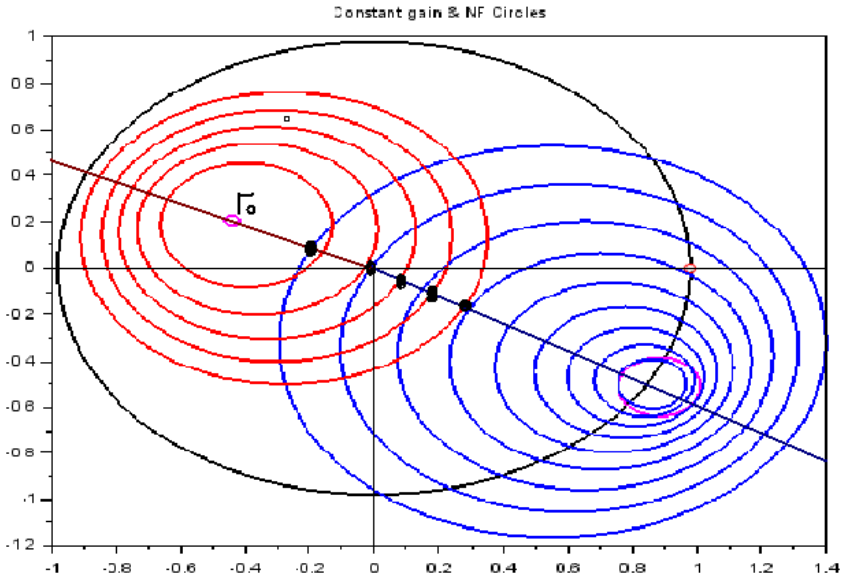

Figure 4. Values of gain and NF

5. Conclusion and Future Work

Both maximum signal gain and minimum noise gain are system design trade-offs and can never be achieved concurrently. All applications explicitly recommend a maximum tolerable noise value that the amplifier design must satisfy. This becomes essential during system integration where several amplifiers are usually cascaded. The error obtained by using the unilateral design approach can be measured by calculating the unilateral figure of merit. Starting from the operating power gain equations, constant gain circles with optimal source matching are calculated, tabulated and plotted in Smith chart. Starting with the available power gain equations, constant gain circles under optimal load matching are tabulated. The position and overlapping of the two circles gives the various possibilities for a circuit designer to choose his signal and noise levels.

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Christina Gnanamani works in the Department of Electronics and Communication Engineering at Coimbatore Institute of Technology, Coimbatore, Tamil Nadu, India. Her area of research includes Sustainable information systems, Wireless Networks, Internet of Things, Computer Networks, Mobile Communication, Software Defined Wireless communication systems, Cyber Physical Systems, Green Data Centres, Cognitive principles and techniques.

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