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Research Article

PERFORMANCE ENHANCEMENT OF LNA USING SERIES FEEDBACK

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ABSTRACT

In this paper, a small-signal microwave transistor with the series inductive feedback application subject to the required noise figure (F_{req}) and output mismatching ($VSWR_{out}$) is analyzed at the chosen bias condition (V_{DS}, I_{DS}). Performance measure functions like Noise Measure (*M*), Mismatch Loss (*ML*), and Figure of Merit (*FOM*) are used to choose the beneficial feedback value for the design of Low Noise Amplifier (*LNA*). Once the optimum feedback value is selected, then the LNA application of a series inductive feedback applied transistor subject to the required noise figure and output mismatching is simulated with the input and the output matching circuit at the chosen frequency.
Keywords: LNA, feedback, noise measure, gain, VSWR.

1. INTRODUCTION

Low Noise Amplifier (*LNA*) is the most important part of the microwave receiver design because its performance is directly related to the receiver system performance. Challenge of a LNA design is to get a maximum gain and minimum noise figure subject to the good mismatching at input and output ports. LNA design strategy depends on either using optimization method [1], [2] and [3] or calculation of the highly nonlinear small signal performance equations [4] and [5] for an operation condition respect to the source (Z_S) and the load (Z_L) terminations.

In [4], [5], analytical formulation of the gain $G_{Tmin}(f) \leq G_T(f) \leq G_{Tmax}(f)$ in terms of the noise figure $F_{req} \geq F_{min}$ and input voltage standing wave ratio $VSWR_{inreq} \geq 1$ for an unconditionally/conditionally stable microwave transistor has developed with the source and load terminations $\{Z_S(f), Z_L(f)\}$ in the z- and S-domain, respectively.

In [6], performance characterization of a microwave transistor has been analytically performed for the maximum gain subject to the required noise that result in the compatible $(F_{req} \geq F_{min}, VSWR_{out}=1, G_{Tmax})$ triplets and together with their terminations $\{Z_S, Z_L=Z^*_{out}(Z_S)\}$.

In [7], [8] the compatible $(F_{req} \geq F_{min}, VSWR_{inreq} \geq 1, VSWR_{outreq} \geq 1, G_{Tmin} \leq G_T \leq G_{Tmax})$ quadrates are determined with their (Z_S, Z_L) terminations solving the nonlinear performance equations of a

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microwave transistor analytically and numerically subject to the trade-off relations between gain, noise and mismatch losses at the input and output ports respectively.

In the literature, a number of works have been published on LNA designs with feedback. In [9], a graphical design method for the single-stage or two-stage cascade low-noise amplifiers with the given feedback is presented in the load plane. In [10], a feedback method is assessed to ease the noise/gain trade-off at the LNA's input and described the mathematical basis for tradeoffs among noise figure, gain and return loss of an LNA, with the implementation by a design tool and the design is verified with measurement. In [11], an LNA design technique and computer design method that a low noise match can be maintained while simultaneously matching for low *VSWR* in LNA is given. In [12], [13] it is stated that, feedback improves the amplifier's stability, it modifies the device's noise parameters, it helps to get a slightly lower active device noise figure and a lower sensitivity to source impedance changes, because of the noise resistance R_n decrease. In [14], [15] the optimum series feedback is determined for the noise and gain trade-off using the Noise Measure (M) [16]. The changes of the noise figure in the case of either parallel or series feedback are worked out in [17]. In [18], series and parallel feedback are analyzed in order to get simultaneously optimum noise and good input/output standing-wave ratio. The formulas for the noise parameters and noise figure of amplifiers with parallel feedback and lossy input and output matching circuits are derived in [19]. [20], addresses the noise in broad band microwave amplifiers with parallel feedback and formulas for the equivalent noise parameters and noise figure of such amplifiers are presented. In [21], LNA design techniques using constant input and output mismatch circles are investigated with the help of a series feedback in the S-parameter domain and trade-off between input and output mismatching is established.

In this work, a small-signal microwave transistor with the series inductive feedback application subject to the ($F_{req}=F_{min}$, $VSWR_{out}=1$, $G_T=G_{Tmax}$) triplet is analyzed using the performance measure equations to determine the compatible/incompatible performance triplets with their (Z_S, Z_L) terminations along the device's operation band at the chosen bias condition (V_{DS}, I_{DS}). The advantage of this work, over existing literature is that it proposes the analytical method using the performance measure functions for the form of the feedback applied LNA's design configurations as opposed to the optimization techniques commonly used in previous studies. Proposed method gives the designer an overview of possible/impossible design configurations of feedback applied LNA using the amplifier's full capacity at the chosen frequency. This work presents complete series feedback analysis of an LNA aspect of gain, minimum noise figure, input and output mismatching using the performance function. In the next section, performance measure function is given according to the feedback applied transistor. In Section 3, series inductive feedback analysis of an LNA is presented. Then, conclusion is given in Section 4.

2. PERFORMANCE EQUATIONS OF FEEDBACK APPLIED TRANSISTOR

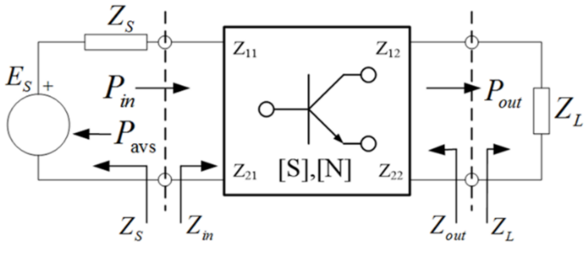
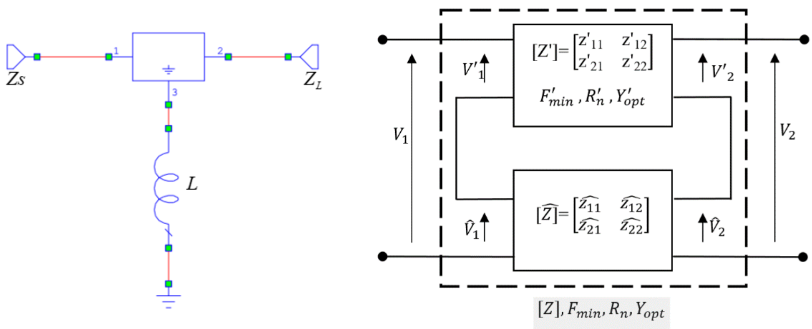


Figure 1. A small signal transistor and its port impedances.

Figure 1 shows the two-port representation of a small-signal microwave transistor with its termination and port impedances. These are valid for the feedback applied transistor whose feedback network's parameters and noise parameters can be included into the transistor's parameters using linear and noise theories [22]. Noise figure *F*, input and output *VSWRs*, gain G_T of a small-signal transistor (Figure 1) are highly nonlinear equations in the Z-parameter domain as given in [7] in details.

$$F = \frac{(S/N)_i}{(S/N)_o} = F\{Z_S\} = F_{\min} + \frac{R_n}{|Z_{opt}|^2}\frac{|Z_S - Z_{opt}|^2}{R_S} \tag{1}$$

In Eq. (1) F_{min}, R_n, Z_{opt}, $Z_s=R_s+jX_s$ show minimum noise figure, equivalent noise resistance, optimum source impedance, source impedance respectively. As can be seen from Eq.(1), noise figure (*F*) of the transistor depends on only the input termination Z_S. If the input termination $Z_S=R_S+jX_S$ is selected Z_{opt}, noise figure *F* is equal to minimum noise figure F_{min}.



(a) (b)

Figure 2. (a) Generalized Series Feedback, (b) Simulation Model of Series Inductive Feedback

In Figure 2a, the " ^ " quantities relates to the feedback network and " ' " quantities to the main network. Also in Figure 2a, Y'_{opt} shows optimum source admittance of main network. In this work, a small-signal microwave transistor with the series inductive feedback is characterized as a linear two-port in terms of the signal and noise parameters of the device and feedback [22]. Feedback applied network Z-parameters are formed from main network's Z-parameters and feedback network's Z-parameters like in Eq.(2).

$$[Z] = [Z'] + [\hat{Z}] \tag{2}$$

Feedback applied network noise parameters (F, Y_c, G_u and R_n) can be calculated using the equations given in [22]. Gain, input VSWR and output VSWR of feedback applied network can be calculated analytically in terms of feedback applied network Z-parameter.

Some performance measure equation like Noise Measure, Mismatch Loss and Figure of Merit are used to select the useful feedback value within the operation domain *(V_{DS}, I_{DS}, f)*. Noise Measure (*M*), given in Eq.(3), is one of the performance measure function of an LNA [16]. An LNA which has a maximum gain, *G*, and minimum noise figure, *F*, has a minimum noise measure value *M*. So, minimum noise measure valued LNA is preferable.

$$M = \frac{F-1}{1-\frac{1}{G}} \tag{3}$$

Mismatch Loss (*ML)*, given in Eq.(4), is constituted using input port reflection coefficient (Γ_{in}) and optimum noise figure reflection coefficient (Γ_{om}) [15]. Mismatch Loss indicates how close the input impedance is to optimum source impedance. Minimum mismatch loss valued LNA design is efficient.

$$ML = \frac{\left|1-\Gamma_{om}\Gamma_{in}\right|^2}{\left(1-\left|\Gamma_{om}\right|^2\right)\left(1-\left|\Gamma_{in}\right|^2\right)} \tag{4}$$

Figure of Merit (*FOM)*, given in Eq.(5), is constituted from the multiplication of the noise measure value and the mismatch loss [15]. Since for the LNA design with a minimum noise measure value and a minimum mismatch loss value is preferable, minimum Figure of Merit valued LNA design shows the performance of the LNA subject to the input mismatching, noise and gain.

$$FOM = M \cdot ML \tag{5}$$

Feedback applied transistor stability conditions can be calculated using feedback applied network S-parameters or Z-parameters. In the S-parameter domain the necessary and sufficient conditions for unconditional stability are $K>1$ and $B1>0$ given in Eq.(6) and Eq.(8).

$$K = \frac{1-\left|S_{11}\right|^2-\left|S_{22}\right|^2+\left|\Delta\right|^2}{2\left|S_{21}S_{12}\right|} \tag{6}$$

$$\Delta = S_{11}S_{22} - S_{21}S_{12} \tag{7}$$

$$B1 = 1+\left|S_{11}\right|^2-\left|S_{22}\right|^2-\left|\Delta\right|^2 \tag{8}$$

Unconditional stability conditions in terms of the Z-parameters are given in [7] and Eq. (9).

$r_{11}>0$, $r_{22}>0$ and $Q > |z|$ (9)

where,

$r_{ij}=Re[z_{ij}]$, $z=z_{12}z_{21}=r+jx$ and $Q=2r_{11}r_{22}-r$ (10)

Conditional stability conditions in terms of the Z-parameters are given in [7] and Eq. (11).

$$r_{11} > 0\,,\, r_{22} > 0\,,\;\; 0 < (Q/|z|) < 1 \tag{11}$$

3. SERIES INDUCTIVE FEEDBACK ANALYSIS OF LNA WITH SIMULATION

In this section, FHX13LG, super low-noise high gain high electron mobility transistor is used to analyze the feedback effects of series inductive feedback. For the analysis, required noise figure is selected as the minimum noise figure value of feedback applied transistor ($F_{req}=F_{min}$) for the design requirement and output mismatching is selected to perfect match case ($VSWR_{out}=1$) for maximize the gain. For the circuit analysis, series inductive feedback configuration given in Figure 2b is constructed in the simulation program. For the feedback, inductance value is selected 0 nH (without feedback case), 0.2 nH, 0.4 nH, 0.6 nH, 0.8 nH, 1 nH, 2 nH and 5 nH separately.

Before the simulation stage, source and load terminations must be calculated analytically subject to the $F_{req}=F_{min}$ and $VSWR_{out}=1$. Then, S- (or Z-parameters) parameters of transistor, noise parameters of transistor and feedback value are allocated set to the circuit simulator for the input parameters. Source termination ($Z_s=R_s+jX_s$) is selected subject to the required noise figure. For our case $F_{req}=F_{min}$ *dB*, so source impedance is selected to optimum source impedance value ($Z_s=Z_{sopt}$). Feedback applied transistor's optimum source impedance can be found as follows:

$$Z_{opt}=1/Y_{opt}\ ;\ Y_{opt}=G_{opt}+jB_{opt}=\sqrt{G_c{}^2+\frac{G_u}{R_n}}-jB_c\ ;\ Y_c=G_c+jB_c\ ;\ Z_S=Z_{opt}\Big|_{F_{req}=F_{\min}} \tag{12}$$

Y_c (correlation admittance), G_u (equivalent noise conductance) and R_n (noise resistance) parameters of feedback applied transistor are calculated using the equations which are found in [22]. Load termination ($Z_L=R_L+jX_L$) is selected conjugate matching value ($VSWR_{out}=1$) of feedback applied network output impedance for the maximum power delivery to the load. Once source impedance is calculated then output impedance can be calculated using Eq.(13)

$$Z_L=Z_{out}^*\ ;\ Z_{out}=R_{out}+jX_{out}=z_{22}-\frac{z_{12}.z_{21}}{z_{11}+Z_S} \tag{13}$$

In the simulation; gain, input *VSWR*, output *VSWR* and stability parameters are calculated separately for each of feedback value for given source and load terminations. In Table 1, transistor FHX13LG with several series inductive feedback design configurations at 2 GHz are presented.

Table 1. Design configuration of FHX13LG with several series inductive feedback value at 2 GHz.

Feedback Value [nH]	$VSWR_{in}$	$VSWR_{out}$	G_T [dB]	R_L [Ohm]	X_L [Ohm]	R_S [Ohm]	X_S [Ohm]
0	106.59	1	17.88	28.61	13.88	16.18	192.06
0.2	11.69	1	**17.92**	28.76	37.71	16.43	189.64
0.4	5.73	1	**17.95**	29.05	61.54	16.69	187.23
0.6	3.60	1	**17.95**	29.48	85.37	16.94	184.81
0.8	2.52	1	**17.93**	30.04	109.20	17.18	182.40
1	**1.89**	1	**17.89**	30.74	133.03	17.43	179.98
2	**1.95**	1	17.48	36.16	252.23	18.60	167.91
5	43.66	1	15.35	69.41	610.62	21.74	131.68

According to Table 1, when there is no feedback (L=0 nH), input port behaves nearly short circuit ($VSWR_{in}$=106.59). The input port mismatching value gradually gets better with increasing feedback value until 5 nH. Especially, input mismatching value is preferable ($VSWR_{in}\leq 2$) when the series inductive feedback values are 1 nH and 2 nH. Also, the gain value can be increased with the application of feedback, like that the gain value without feedback case is nearly 17.88 dB and the gain value slightly increases to 17.95 dB with the application of 0.6 nH series inductive feedback. In Figure 3, 0 nH to 5 nH series inductive feedback applied transistor's $VSWR_{in}$-G_T variations subject to $V_{out}=1$ and $F_{req}=F_{min}$ *dB* are presented.

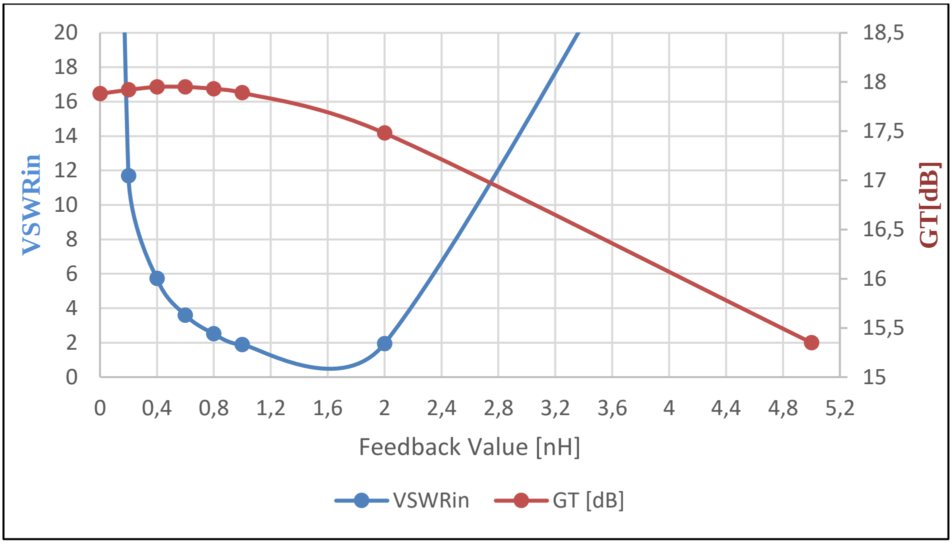


Figure 3. Gain and $VSWR_{in}$ variations for the transistor with the series inductive feedback 0nH≤L≤5nH subject to $V_{out}=1$ and $F_{req}=F_{min}$ *dB.*

Besides this, noise measure, mismatch value and figure of merit can be used to choose the correct feedback value. In Table 2, noise measure values, mismatch values and figure of merit values of feedback applied transistor are given according to the feedback values.

Table 2. Performance measure values of FHX13LG with several series inductive feedback at 2 GHz.

Feedback Value [nH]	$F_{req}=F_{min}$ [dB]	Noise Measure	Mismatch Loss	Figure Of Merit
0	0.33	0.080	101.524	8.148
0.2	0.33	0.080	31.856	2.556
0.4	0.33	0.080	27.840	2.234
0.6	0.33	0.080	24.075	1.932
0.8	0.33	0.080	19.801	1.589
1	0.33	0.080	15.704	**1.260**
2	**0.329**	0.080	**5.433**	**0.435**
5	**0.327**	0.081	24.878	2.004

According to Table 2, minimum noise figure value is slightly decreased with the application of feedback. Minimum noise figure value is decreased to 0.327 dB with the application of 5 nH series inductive feedback comparing to the without feedback case. Noise Measure value is nearly same for each of series inductive feedback values. Mismatch Loss value is getting better with the increasing feedback value until 2 nH. Mismatch value has a minimum value (nearly 5.4) with the application of 2 nH series inductive feedback. Besides this, Figure of Merit, which has multiplication of Noise Measure and Mismatch Loss, has a minimum value when the application of 2 nH series inductive feedback. Also, a feedback value between 1 nH and 2 nH is preferable for the application of series inductive feedback for the LNA design since minimum Figure of

Merit value is obtained between these ranges. In Figure 4, 0 nH to 5 nH series inductive feedback applied transistor's F_{min}, Mismatch Loss, Figure of Merit variations are presented.

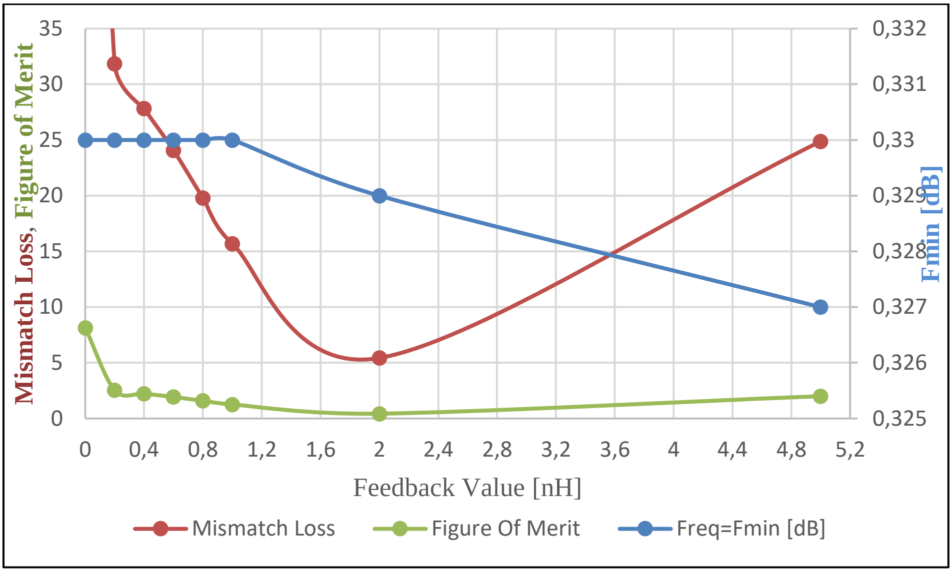


Figure 4. F_{min}, Mismatch Loss, Figure of Merit variations for the transistor with the series inductive feedback 0nH≤L≤5nH.

Another performance analysis of feedback applied transistor is performed according to the stability condition. In Table 3; *K*, *B1* and *Q*/|*z*| stability performance values are presented.

Table 3. Stability performance values of FHX13LG with several series inductive feedback at 2 GHz.

Feedback Value [nH]	K	B1	R_{11}	R_{22}	*Q*/|*z*|
0	0.22	1.85	0.683	1.78	0.222
0.2	0.6	1.6	0.683	1.78	0.606
0.4	0.85	1.35	0.683	1.78	0.859
0.6	0.96	1.1	0.683	1.78	0.965
0.8	0.99	0.86	0.683	1.78	0.999
1	**1.005**	**0.62**	**0.683**	**1.78**	**1.004**
2	0.97	-0.34	0.683	1.78	0.974
5	0.93	-1.39	0.683	1.78	0.933

According to Table 3, the transistor is conditionally stable without feedback case since K<1 and $Q/|z|<1$. In this case, if 1 nH series inductive feedback applied to the transistor stability changes to unconditional case because unconditionally stability criteria $K>1$, $B1>0$, $R_{11}>0$, $R_{22}>0$ and $Q/|z|>1$ are satisfied for the application of 1 nH series inductive feedback.

According to the Table 1, 2 and 3; the feedback value is selected to 1 nH, then input matching network and output matching network is designed according to the load and source terminations which are given in Table 1. Figure 5 shows, schematic of LNA including input and output matching circuit and biasing circuit of feedback applied transistor. Transistor is biased at (2V, 10mA). Figure 6 shows, printed circuit layout of LNA design. After including matching and biasing circuit to the design, gain value is founded nearly 17.8 dB at 2 GHz.

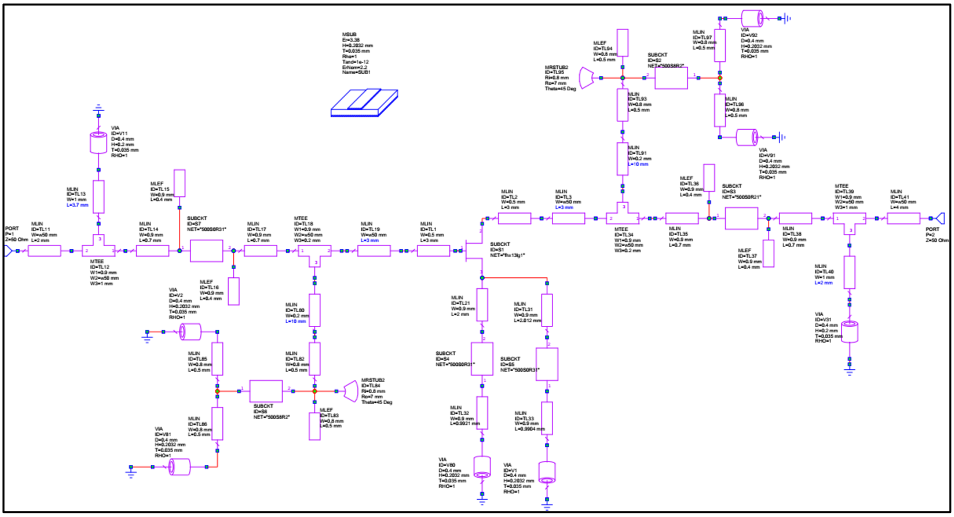


Figure 5. 1 nH series inductive feedback applied LNA schematic with input and output matching and biasing circuits at 2 GHz.

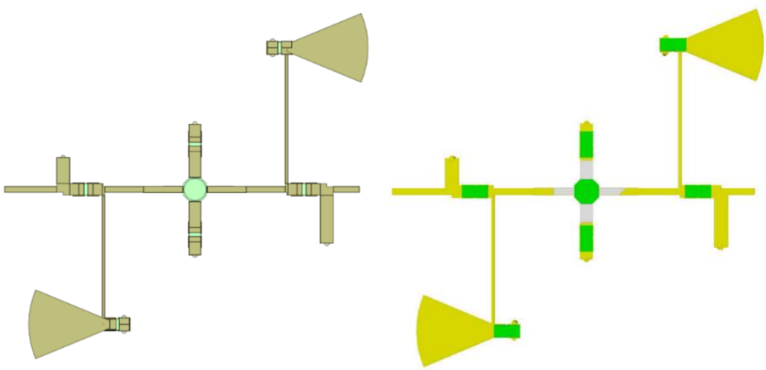


Figure 6. 1 nH series inductive feedback applied LNA layout at 2 GHz.

Figure 7 shows, gain-frequency variations of proposed 1nH series inductive feedback applied LNA circuit. According to Figure 7, 3 dB frequency bandwidth is nearly 0.3 GHz (1.8 GHz-2.1 GHz) subject to the $VSWR_{in} \leq 2$.

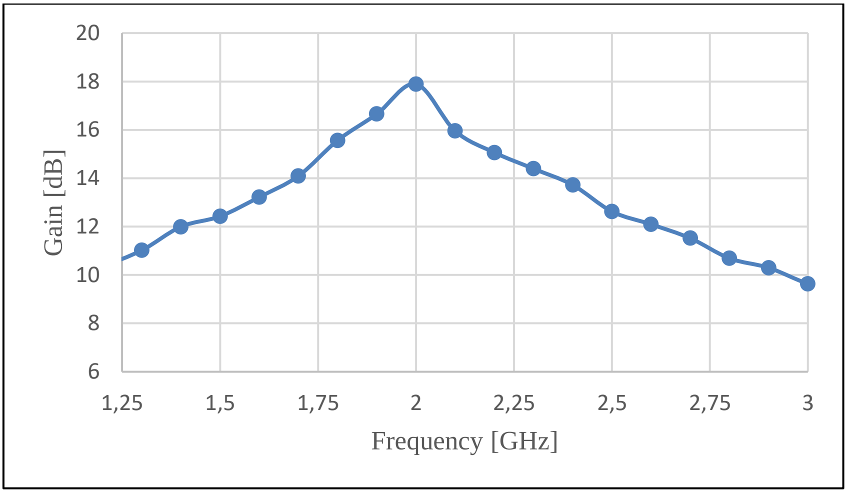


Figure 7. Gain-frequency variations of 1nH series inductive feedback applied LNA.

4. CONCLUSION

In this work, a small-signal microwave transistor with the series inductive feedback application subject to the ($F_{req}=F_{min}$, $VSWR_{out}=1$, $G_T=G_{Tmax}$) triplet is analyzed at the chosen bias condition (V_{DS}, I_{DS}). Performance measure functions like Noise Measure, Mismatch Loss, and Figure of Merit are used to choose the beneficial feedback value for the design of feedback applied LNA. In this work, it is shown that, design of the LNA subject to the $F_{req}=F_{min}$ and $VSWR_{out}=1$ at the chosen frequency without feedback case may not be possible because of the high mismatching at the input port. However, an LNA can be designed at the chosen frequency through the use of beneficial series inductive feedback. Application of series inductive feedback not only improves the input mismatching but also increases gain, changes the stability conditional case to unconditional case and reduces the minimum noise figure.

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