Analysis and Simulation of Balanced Low Noise Amplifier

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***Abstract*—We give an analysis of balanced low noise amplifier (LNA) which has good voltage standing wave ratio (VSWR) performance, higher linearity and good stability. A mathematic model of balanced LNA has been setup and an analysis of gain, noise figure (NF) and VSWR based on it is presented. According to analysis in time domain and simulation in advance deign system (ADS), the unbalance of gain, NF and VSWR will affect the performance of the balanced LNA module. It gets a zero reflection on condition that its two branches totally balanced. 10dB difference of gains causes NF increased by 1dB.**

Keywords-balanced, low noise amplifier (LNA), noise figure (NF), voltage standing wave ratio (VSWR), stability

I. INTRODUCTION

The balanced amplifier is one of the most commonly used amplifier topologies. It demonstrates a number of virtues, including good voltage standing wave ratio (VSWR), excellent bandwidth, higher linearity and good stability, making it a reliable broadband topology [1]-[3]. Stability is an important specification of low noise amplifier (LNA) in the interest frequency rang. The S-parameters of the transistor always change as temperature, especially at lower temperature. The change of S-parameters makes the VSWR worse. Self-oscillation easily occurs at bad VSWR. The balanced structure proposed by this paper gets a better performance of VSWR. It solves the self-oscillation problem at low temperature.

The topology of balanced LNA is shown in Fig. 1. It contains two low noise amplifiers and two 3dB bridges [4]. The insert loss of 3dB bridge is very small commonly, it is ignored in this analysis. The gain of balanced LNA is same to its branches and VSWR is smaller than its branches on condition that its two branches have same specifications. Balanced LNA is also more stable than single LNA. This issue gives a theory analysis of balanced LNA and does a simulation in simulation tool ADS, comparisons between traditional LNA and balanced LNA are proposed too.

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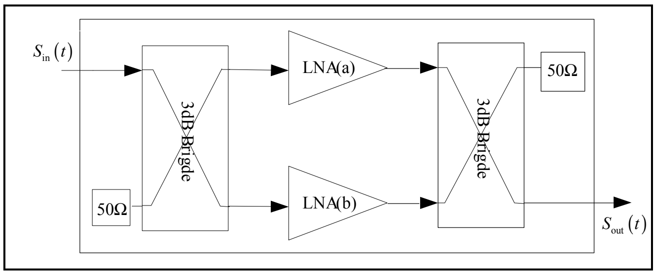

Figure 1. Topology of balanced LNA.

II. ANALYSIS OF BALANCED LNA

Analysis about balanced LNA in time domain has been done in order to find factors which affect performances of the balanced LNA module.

A. Gain

Analysis model of gain is shown in Fig. 2. The input signal is divided into two parts by 3 dB bridge. Provide that the input signal is:

$$S_{in}(t) = \sin(\omega t)$$

Thus the input signal of LNA (a) and LNA (b) at the dotted line 1 is given by:

$$S_{in}^{a}(t) = \frac{\sqrt{2}}{2}\sin(\omega t)$$

$$S_{in}^{b}(t) = \frac{\sqrt{2}}{2}\sin(\omega t + 90^\circ)$$

The output signal of LNA (a) and LNA (b) at the dotted line 2 is given by:

$$S_{out}^{a}(t) = \frac{\sqrt{2}}{2}\beta_a \sin(\omega t + \varphi_a)$$

$$S_{out}^{b}(t) = \frac{\sqrt{2}}{2}\beta_b \sin(\omega t + 90^\circ + \varphi_b)$$

Where β_a, β_b, φ_a, and φ_b are gains and phase shifts of LNA (a) and LNA (b). The output signal of balanced LNA module is given by:

$$S_{\text{out}}(t)=\frac{\sqrt{2}}{2}\cdot\frac{\sqrt{2}}{2}\beta_a\sin\left(\omega t+90^\circ+\varphi_a\right)+\frac{\sqrt{2}}{2}\cdot\frac{\sqrt{2}}{2}\beta_b\sin\left(\omega t+90^\circ+\varphi_b\right) \tag{1}$$

From (1), we can see the variable parameters β_a, β_b, φ_a, and φ_b which come from LNA (a) and LNA (b) decide the performance of balanced LNA. If $\varphi_a=\varphi_b=\varphi$, (1) can be written as:

$$S_{\text{out}}(t)=\frac{1}{2}(\beta_a+\beta_b)\sin(\omega t+90^\circ+\varphi) \tag{2}$$

From (2), we can see the gain of balanced LNA is:

$$\beta=\frac{1}{2}(\beta_a+\beta_b)=\frac{1}{2}\left(10^{\frac{G_a}{20}}+10^{\frac{G_b}{20}}\right) \tag{3}$$

Where G_a and G_b are power gains of LNA (a) and LNA (b). So that the power gain of balanced LNA is:

$$\text{Gain}=20\log\left[\frac{1}{2}\left(10^{\frac{G_a}{20}}+10^{\frac{G_b}{20}}\right)\right] \tag{4}$$

From (4), it is easily to find that the power gain of balanced LNA falls between the values of its two branches. It gets the biggest gain on condition that $G_a=G_b$.

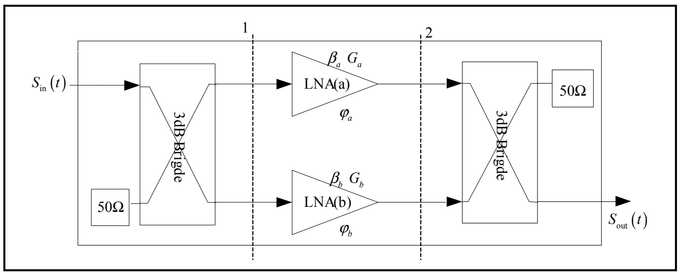

Figure 2. Model of gain analysis.

B. Noise Figure

Analysis model of NF is shown in Fig. 3. Thermal noise $N_1(t)$ and $N_2(t)$ at the input ports of the first 3dB bridge is -174dBm/Hz and uncorrelated [5]. The noise at the first 3dB bridge output ports is the same to the input ports as it is noise floor. We ignore the insert loss of 3dB bridge in this analysis. The noise is amplified by LNA (a) and LNA (b), thus the noise at the dotted line 2 is:

$$N_a'(t)=N_2(t)N_a(t)\beta_a$$

$$N_b'(t)=N_1(t)N_b(t)\beta_b$$

Where $N_a(t)$ and $N_b(t)$ are created by LNA (a) and LNA (b). Noise at input ports of the second 3dB bridge is no longer noise floor, but uncorrelated too. The 3dB bridge combines noise as well as signal. Thus signal and noise at the output port of the module is:

$$S_{\text{out}}(t)=\frac{\sqrt{2}}{2}\cdot\frac{\sqrt{2}}{2}\beta_a S_{\text{in}}(\omega t+\varphi_a)+\frac{\sqrt{2}}{2}\cdot\frac{\sqrt{2}}{2}\beta_b S_{\text{in}}(\omega t+\varphi_b)$$

$$N_{\text{out}}(t)=\frac{\sqrt{2}}{2}N_2(t)N_a(t)\beta_a+\frac{\sqrt{2}}{2}N_1(t)N_b(t)\beta_b$$

According to the definition of NF, the NF of LNA (a), LNA (b) and balanced LNA module are:

$$\text{NF}_a=10\log\left(\frac{\dfrac{\frac{1}{2}S_{\text{in}}^2(t)}{N_2^2(t)}}{\dfrac{\frac{1}{2}S_{\text{in}}^2(t+\varphi_a)\beta_a^2}{N_2^2(t)N_a^2(t)\beta_a^2}}\right) \tag{5}$$

$$\text{NF}_b=10\log\left(\frac{\dfrac{\frac{1}{2}S_{\text{in}}^2(t)}{N_1^2(t)}}{\dfrac{\frac{1}{2}S_{\text{in}}^2(t+\varphi_b)\beta_b^2}{N_1^2(t)N_b^2(t)\beta_b^2}}\right) \tag{6}$$

$$\text{NF}=10\log\left(\frac{2\left[N_a(t)\beta_a+N_b(t)\beta_b\right]^2}{(\beta_a+\beta_b)^2}\right) \tag{7}$$

When $\beta_a=\beta_b=\beta$, (5), (6), (7) can be written as:

$$\text{NF}_a=10\log N_a^2(t)$$

$$\text{NF}_b=10\log N_b^2(t)$$

$$\text{NF}=10\log\left(\frac{\left[N_a(t)+N_b(t)\right]^2}{2}\right) \tag{8}$$

In (8), $N_a(t)$ and $N_b(t)$ is uncorrelated [5]. Therefore (8) can be written as:

$$\mathrm{NF}=10\log\left(\frac{N_a^2(t)+N_b^2(t)}{2}\right)=10\log\left(\frac{10^{\frac{\mathrm{NF}_a}{10}}+10^{\frac{\mathrm{NF}_b}{10}}}{2}\right) \quad (9)$$

From (18) we can see that the value of NF of balanced LNA falls between the values of NF of its two branches. It gets the best noise performance when its two branches have same specifications.

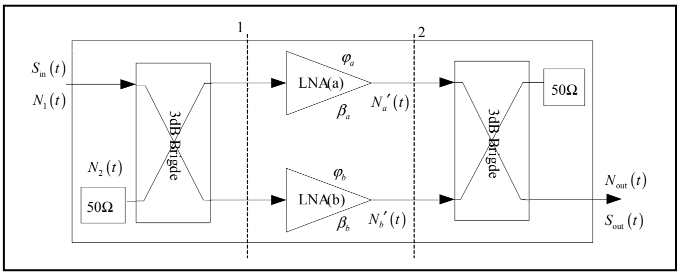

Figure 3. Model of noise figure analysis.

C. VSWR

VSWR is another important specification in amplifier design [6]. Analysis model of VSWR is shown in Fig. 4. Suppose that the reflection coefficient of LNA (a) and LNA (b) is Γ_a and Γ_b. Thus the reflection signals of LNA (a) and LNA (b) are:

$$S_{\mathrm{reflex}}^{a}(t)=\frac{\sqrt{2}}{2}S_{\mathrm{in}}(\omega t+\theta_a)\Gamma_a$$
$$S_{\mathrm{reflex}}^{b}(t)=\frac{\sqrt{2}}{2}S_{\mathrm{in}}\left(\omega t+90^\circ+\theta_b\right)\Gamma_b$$

Where θ_a and θ_b stand for phase shifts of reflection signal. The first 3dB bridge combines the reflection signal. So that, the reflection signal of balanced LNA module is:

$$\begin{aligned}S_{\mathrm{reflex}}(t)=&\frac{\sqrt{2}}{2}S_{\mathrm{in}}(\omega t+\theta_a)\Gamma_a\\&+\frac{\sqrt{2}}{2}S_{\mathrm{in}}\left(\omega t+90^\circ+\theta_b+90^\circ\right)\Gamma_b\end{aligned} \quad (10)$$

If $\theta_a=\theta_b=\theta$, (10) can be written as:

$$S_{\mathrm{reflex}}(t)=\frac{\sqrt{2}}{2}S_{\mathrm{in}}(\omega t+\theta)(\Gamma_a-\Gamma_b) \quad (11)$$

Equation (11) shows the VSWR of balanced LNA is always smaller than its branches. It gets the smallest value when the two branches have same specifications.

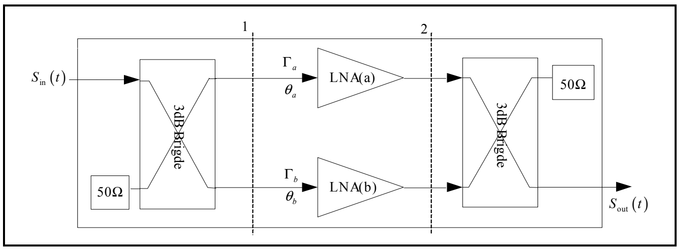

Figure 4. Model of VSWR analysis.

III. SIMULATION RESULTS

It is easily to find factors which affect the performance of balanced LNA according to simulation. Different simulations have been done in simulation tool ADS.

Provide that the two branches of balanced LNA are totally balanced, the simulation results are shown in TableⅠ. The parameters of single LNA are: S11=-10dB, S12=-20dB, S21=20dB, S22=-20dB, NF=0.6dB. It is easily to find that the simulation result coincide with analysis above.

TABLE I. SIMULATION RESULTS OF TOTALLY BALANCED BRANCHES

Freq	dB(S11)	dB(S12)	dB(S21)	dB(S22)	NF (dB)
810MHz	-35.624	-20.000	20.000	-45.624	0.611
820MHz	-35.624	-20.000	20.000	-45.624	0.611
830MHz	-35.624	-20.000	20.000	-45.624	0.611
840MHz	-35.624	-20.000	20.000	-45.624	0.611

Provide that the two branches of balanced LNA have same specifications except gains, simulation results are shown in TableⅡ. Gain of LAN (a) is smaller than LNA (b) by 10dB. The parameters of LNA (b) are: S11=-10dB, S12=-20dB, S21=20dB, S22=-20dB, NF=0.6dB. The gain of balanced LNA is 16.366dB which coincides to (4). From TableⅡ we can see, 10dB difference of gain causes NF increased by 1dB. Uncertainty of gains makes NF worse [7]. Unbalanced gain does not affect balanced LNA module's VSWR.

TABLE II. SIMULATION RESULTS OF UNBALANCED GAINS

Freq	dB(S11)	dB(S12)	dB(S21)	dB(S22)	NF (dB)
810MHz	-35.624	-20.000	16.366	-45.624	1.657
820MHz	-35.624	-20.000	16.366	-45.624	1.657
830MHz	-35.624	-20.000	16.366	-45.624	1.657
840MHz	-35.624	-20.000	16.366	-45.624	1.657

Provide that the branches of balanced LNA have same specifications except NF, simulation results is shown in Table Ⅲ. The NF of LAN (a) is 0.6dB and NF of LNA (b) is 1.0dB. The NF of balanced LNA is 0.815dB, which coincides to the (18).

TABLE III. SIMULATION RESULTS OF UNBALANCED NOISE FIGURE

Freq	dB(S11)	dB(S12)	dB(S21)	dB(S22)	NF (dB)
810MHz	-35.624	-20.000	20.000	-45.624	0.815
820MHz	-35.624	-20.000	20.000	-45.624	0.815
830MHz	-35.624	-20.000	20.000	-45.624	0.815
840MHz	-35.624	-20.000	20.000	-45.624	0.815

Provide that the branches of balanced LNA have same specifications except VSWR. Provide that S_{11} of LAN (a) is -10dB and S_{11} of LNA (b) is -15dB, simulation results is shown in TableⅣ. Comparing to TableⅠ, unbalanced VSWR just effects the VSWR of balanced LNA module and makes it worse.

TABLE IV. SIMULATION RESULTS OF UNBALANCED VSWR

Freq	dB(S11)	dB(S12)	dB(S21)	dB(S22)	NF (dB)
810MHz	-23.060	-20.000	20.000	-45.624	0.611
820MHz	-23.060	-20.000	20.000	-45.624	0.611
830MHz	-23.060	-20.000	20.000	-45.624	0.611
840MHz	-23.060	-20.000	20.000	-45.624	0.611

From the simulation data, it is easily to find that the VSWR of balanced LNA is better than other LNA structures [8]-[10], making it the most stable topology. This is the biggest virtue of balanced LNA. But the NF of balanced LNA is easily influenced by other factors, such as gain difference between its branches.

IV. CONCLUSIONS

Balanced LNA offers a number of benefits comparing to single LNA structure. Keeping its two branches totally balanced is the key item to get best performance. The gain of balanced LNA depends on the gains of its branches. The NF of balanced LNA module depends on NF and also the gain of its branches. The VSWR of balanced LNA just depends on VSWR of its branches. Simulation results in ADS coincide to theory analysis. In balanced LNA design, the most important thing is to make the difference of the two branches as small as possible.

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