A Power-Efficient Noise Canceling Technique Using Signal-Suppression Feed-forward for Wideband LNAs

Daiki Oki, Satoru Kawauchi, Li CongBing, Masataka Kamiyama (Gunma Univ.)
Seiichi Banba, Toru Dan, Nobuo Takahashi, Koji Sakata (Sanyo Semiconductor Co., Ltd.)
Haruo Kobayashi, Nobukazu Takai (Gunma Univ.)

Abstract This paper presents a power-efficient noise-canceling technique based on the feed-forward amplifiers, considering a fundamental tradeoff between noise figure (NF) and power consumption in the design of wide-band amplifiers. By suppressing the input signal of the noise cancellation amplifier, the nonlinear effect on the amplifier can be reduced, as well as the power consumption can be smaller. Furthermore, as a lower gain of the noise-canceling sub-amplifier can be achieved simultaneously, further reduction of the power consumption becomes possible. The verification of the proposed technique is conducted with Spectre simulation using 90nm CMOS process.

Keyword Noise-canceling, Feed-forward, Low-noise amplifier (LNA), Wide band

1. Introduction

Wide-band amplifiers suffer from an essential tradeoff between input impedance matching and noise figure (NF). Generally, wide-band low-noise amplifier (LNA) achieves a better noise figure when the value of g_m increases. However, by conducting common input impedance matching, it is difficult to adjust g_m to an expected value. The corresponding solution is introduced in [1], which consists of a main amplifier (M_i and R_f) for input impedance matching as well as signal amplification and a noise-canceling sub-amplifier for low noise figure (Fig. 1). In this solution, channel thermal noise generated in matching and signal amplification device M_i is fed back by resistance R_f, and canceled by noise cancellation amplifier $A_{v,c}$. By means of this, the tradeoff between the input impedance matching and the noise figure is broken, and a wide-band LNA with low noise figure becomes possible. Furthermore, the distortion generated in M_i can be canceled simultaneously in a similar way. Though having these advantages, this solution has a drawback that the power consumption of the noise-canceling amplifier $A_{v,c}$ tends to be comparatively large.

In this paper, a signal-suppression technique, which applies the signal-null technique [2][3], is proposed to suppress the power consumption of the noise-canceling amplifier. By exploiting an inverting amplifier where the output is the inverse of the input, the small-signal input of the noise-canceling amplifier $A_{v,c}$ can be suppressed. And for $A_{v,c}$, the tradeoff between the power consumption and the nonlinearity can be mitigated. Compared with the existing solution, this proposal reduces the power consumption of the noise-canceling amplifier, while inherits the existing advantages such as breaking the tradeoff between input impedance matching and noise figure, canceling distortion.

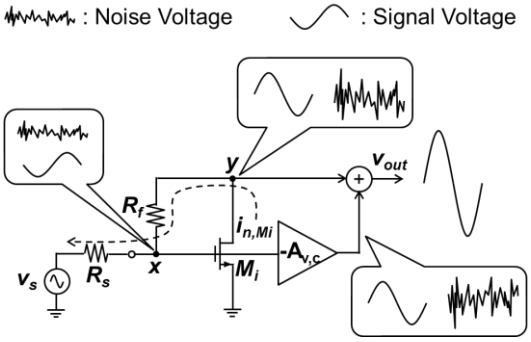


Fig.1. Conventional noise-canceling LNA.

This paper is organized as follows. Section 2 reviews the existing noise-canceling technique. Section 3 describes the detailed principle of the proposed technique. Section 4 shows the simulation results. Finally, Section 5 provides conclusions.

2. Conventional Noise-Canceling Technique

In this section, the conventional wide-band LNA noise-canceling technique is reviewed, which is illustrated in Fig. 1. Low noise figure is achieved by canceling the channel thermal noise generated in matching device M_i. The channel thermal noise travels in the direction y $\rightarrow$ R_f $\rightarrow$ x $\rightarrow$ R_s to the ground (when considering only the noise, v_s=0). By circuit inspection, the noise voltage at nodes x and y are given by

$$\begin{aligned} v_{n,x,Mi} &= R_s i_{n,Mi} \\ v_{n,y,Mi} &= (R_s + R_f) i_{n,Mi} \end{aligned} \quad (1)$$

Noise cancellation is achieved by adding the voltage $v_{n,y,Mi}$ at node y to the output of the inverting amplifier $A_{v,c}$, which is a scaled negative replica of the voltage $v_{n,x,Mi}$ at node x. Output noise voltage $v_{out,n,Mi}$ is equal to

$$\begin{aligned} v_{out,n,Mi} &= v_{y,n,Mi} - A_{v,c}v_{x,n,Mi} \\ &= \left(R_f + R_S - A_{v,c}R_S\right)i_{n,Mi} \end{aligned} \tag{2}$$

When $v_{out,n,Mi}$=0, the goal of output noise cancellation is reached. In this case, the gain of the noise-canceling amplifier is denoted as $A_{v,c,cancel}$, which is equal to

$$A_{v,c,cancel} = 1 + \frac{R_f}{R_S} \tag{3}$$

The input impedance is Z_{in}=1/g_{Mi}. Correspondingly, the input impedance matching condition is g_{Mi}=1/R_s. So when the input impedance matching condition and the noise cancellation requirement are satisfied at the matching device M_i and the noise-canceling amplifier $A_{v,c}$ respectively, low noise figure can be realized. Equation (4) expresses the voltage gain, where the input impedance is Z_{in}=1/g_{Mi} and the noise-canceling amplifier gain is $A_{v,c,cancel}$.

$$\begin{aligned} \mathrm{A_v} &= \frac{v_{out}}{v_x} = 1 - g_{Mi}R_f - A_{v,c,cancel} \\ &= -g_{Mi}R_f - \frac{R_f}{R_S} = -\frac{2R_f}{R_S} \end{aligned} \tag{4}$$

Furthermore, the distortion generated in M_i could be cancelled simultaneously with almost the same principle.

The drawback of this existing circuit is that its power consumption tends to be comparatively large due to the matching device M_i and the noise-canceling amplifier $A_{v,c}$.

3. Proposed Technique

The block diagram of the proposed circuit is illustrated in Fig. 2. It consists of main amplifiers M_i, R_{f1}, R_{f2}, as well as noise-canceling amplifier $A_{v,c}$, which provides noise cancellation for M_i. Node a, which is between the feedback resistors R_{f1} and R_{f2}, is selected as the input point for the noise-canceling amplifier $A_{v,c}$.

By suppressing the small-signal input of $A_{v,c}$, the nonlinear components generated in the noise-canceling amplifier can be reduced, and low power consumption becomes possible. Following the channel noise current in M_i, it is easy to obtain the connection between the noise voltage $v_{n,a,Mi}$ at node a and the noise voltage $v_{n,x,Mi}$ at node x (i.e. the input noise voltage of the existing noise-canceling circuit) is: $v_{n,a,Mi} > v_{n,x,Mi}$. Compared with the existing circuit, the proposed one realizes a lower power consumption by breaking the tradeoff between the impedance matching and the noise figure, and simultaneously providing low-gain characteristics to the noise-canceling amplifier $A_{v,c}$, as it always enlarges the input noise voltage. The noise of R_{f1} passes through $A_{v,c}$ without amplification, which is the same as the conventional circuit. However, the noise of R_{f2} is amplified by $A_{v,c}$, therefore the corresponding noise cancellation condition is different from M_i.

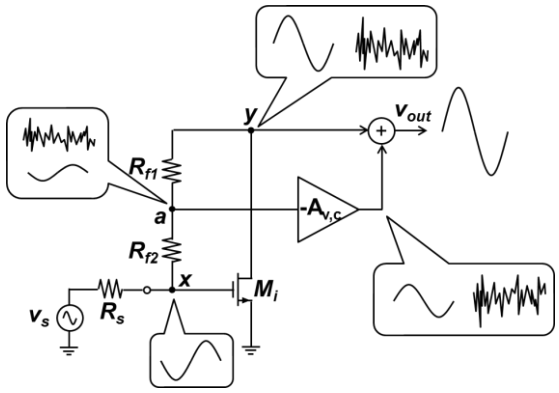


Fig.2. Proposed noise-canceling LNA.

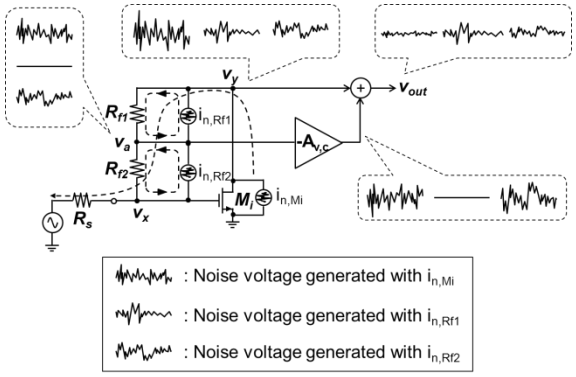


Fig.3. Noise analysis model of the proposed noise-canceling LNA.

(i) Noise Cancellation Principle

In Fig.3, the noise of M_i, R_{f1} and R_{f2} are modeled as current sources. To understand the principle of noise cancellation, the small-signal voltage and the noise voltage at each node have been analyzed in detail.

Firstly, consider the noise voltage. Noise current $i_{n,Mi}$ travels from matching device to the ground by way of feedback resisters R_{f1}, R_{f2}, R_s (the noise voltage of V_s is equal to 0). Noise current $i_{n,Rf1}$ and $i_{n,Rf2}$ pass through the feedback resisters R_{f1} and R_{f2} respectively, and then circulate back.

The noise voltages $v_{n,a,Mi}$ and $v_{n,y,Mi}$, which are generated at node a and node y respectively, are given as follows:

$$v_{n,a,Mi} = (R_s + R_{f2})i_{n,Mi} - R_{f2}i_{n,Rf2} \tag{5}$$

$$v_{n,y,Mi} = (R_s + R_{f1} + R_{f2})i_{n,Mi} - R_{f1}i_{n,Rf1} - R_{f2}i_{n,Rf1}$$

The output noise voltage $v_{n,out}$ is

$$v_{n,out} = v_{n,y,Mi} - A_{v.c}v_{n,a,Mi} \quad (6)$$

The equivalent output noise $|v_{n,out}|^2$ can be achieved based on equations (5) and (6).

$$|v_{n,out}|^2 = 4kTB\left\{|R_S + R_{f1} + R_{f2} - A_{v,c}|^2\gamma g_{Mi} + R_{f1} + |1 - A_{v,c}|^2 R_{f2}\right\}$$

γ is the excess noise factor for the short-channel device. When $|v_{n,out}|^2$ takes the minimum value, the corresponding gain of the noise-canceling amplifier $A_{v,c}$ is expressed as $A_{v,cancel}$:

$$A_{v,cancel} = \frac{(R_S + R_{f1} + R_{f2})(R_S + R_{f2})\gamma g_{Mi} + R_{f2}}{(R_S + R_{f2})^2\gamma g_{Mi} + R_{f2}}$$

The above equation is regarded as the noise cancellation condition.

Secondly, consider the small-signal voltage. v_y/v_x represents the transfer function from node x to node y, i.e. the voltage gain of the main amplifier. And v_a/v_x expresses the transfer function from node x to node a.

$$A_{v,core} = \frac{v_y}{v_x} = 1 - (R_{f1} + R_{f2})g_{Mi} \qquad \frac{v_a}{v_x} = 1 - R_{f2}g_{Mi} \quad (7)$$

v_y and v_x have opposite signs when $R_{f2}g_{Mi}<1<(R_{f1}+R_{f2})g_{Mi}$. In equation (3), the noise voltages at node a and node y have the same sign, while the small-signal voltage has an opposite one. This provides a possibility for noise cancellation. When the noise cancellation condition $A_{v,c}$ $=A_{v,cancel}$ is satisfied, the small-signal voltage gain A_v is equal to

$$A_v = 1 - (R_{f1} + R_{f2})g_{mi} - A_{v,c}(1 - R_{f2}g_{Mi}) \quad (8)$$

$$= 1 - (R_{f1} + R_{f2})g_{Mi} - \frac{(R_S + R_{f1} + R_{f2})(R_S + R_{f2})\gamma g_{Mi} + R_{f2}}{(R_S + R_{f2})^2\gamma g_{Mi} + R_{f2}}(1 - R_{f2}g_{Mi})$$

Thirdly, consider the input impedance matching. The input impedance is $Z_{in}=1/g_{Mi}$, and the corresponding input impedance matching condition is $Z_{in}=1/g_{Mi}=R_s$. According to equation (4), $A_{v,c}$ affects the noise figurer, and g_{Mi} influences the input impedance matching. By adjusting these two parameters, the tradeoff between the noise figure and the input impedance matching can be dissolved.

Figure.4 shows the circuit diagram when the noise-canceling amplifier $A_{v,c}$ is implemented with CMOS inverters.

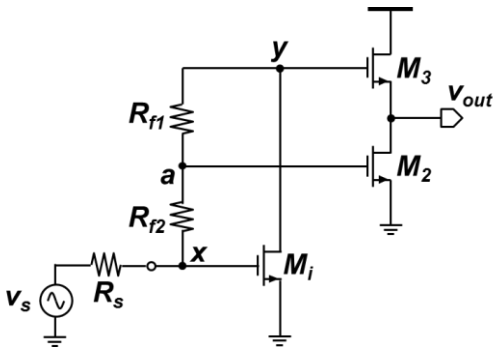


Fig.4. Circuit diagram of the proposed LNA.

From the view of node y, a source follower circuit, which consists of *M3* and *M2* (equivalent to a constant current source), takes the voltage at node y as input, and outputs V_{out} with voltage shift of *M3* gate-source voltage. From the view of node a, a source follower circuit, which consists of *M2* and load $1/g_{M3}$, accepts the voltage at node a as input, as outputs a g_{M2}/g_{M3} scaled replica, i.e. $A_{v,c}$ $=g_{M2}/g_{M3}$. The overall voltage gain and the noise cancellation condition are

$$A_V = 1 - g_{Mi}(R_{f1} + R_{f2}) - \frac{g_{M2}}{g_{M3}}(1 - R_{f2}g_{Mi}) \quad (9)$$

$$A_{v,ccancel} = \frac{g_{M2}}{g_{M3}} = \frac{(R_S + R_{f1} + R_{f2})(R_S + R_{f2})\gamma g_{Mi} + R_{f2}}{(R_S + R_{f2})^2\gamma g_{Mi} + R_{f2}}$$

The noise figure *F* of the LNA in Figure 3-2 is equal to

$$F = 1 + F_{Mi} + F_{Rf1} + F_{Rf2} + F_{M2+M3}$$

F_{Mi}, F_{Rf1}, F_{Rf2}, F_{M2+M3} represent the noise generated in each component, and they can be written as

$$F_{Mi} = \left|\left(R_S + R_{f1} + R_{f2} - \frac{A_{v,c}(R_S + R_{f2})}{A_{v,core}}\right)\right|^2 \frac{\gamma g_{Mi}}{R_S}$$

$$F_{Rf1} = \left|\frac{1+g_{Mi}R_S}{A_{v,core}}\right|^2 \frac{R_{f1}}{R_S}$$

$$F_{Rf2} = \left|\frac{(1 + g_{Mi}R_S)(1 - A_{v,c})}{A_{v,core}}\right|^2 \frac{R_{f2}}{R_S} \quad (10)$$

$$F_{(M2+M3)} = \left|\frac{1 + g_{Mi}R_S}{g_{M3}A_{v,core}}\right|^2 \frac{\gamma(g_{M2} + g_{M3})}{R_S}$$

When the input impedance matching condition is satisfied and R_{f1}=350Ω, R_{f2}=20Ω, the noise figures of each component are shown in Fig.5, with $A_{v,c}$ on the X-axis. When the value of R_{f2} varies from 0Ω to 50Ω, the corresponding noise figures of each component are

illustrated in Fig.6.

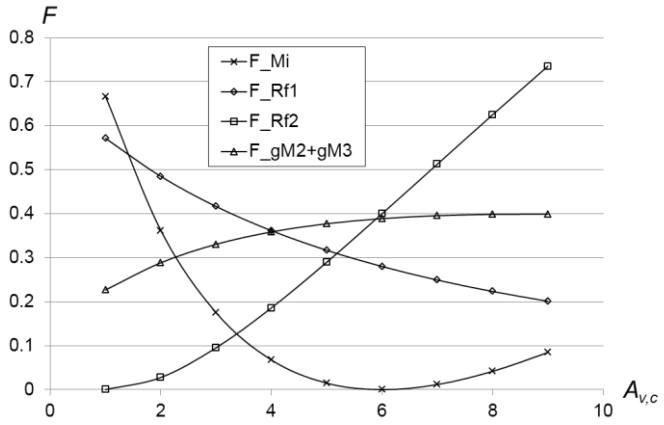


Fig.5. Noise figures of each component when $A_{v,c}$ varies (R_{f1}=350Ω, R_{f2}=20Ω)

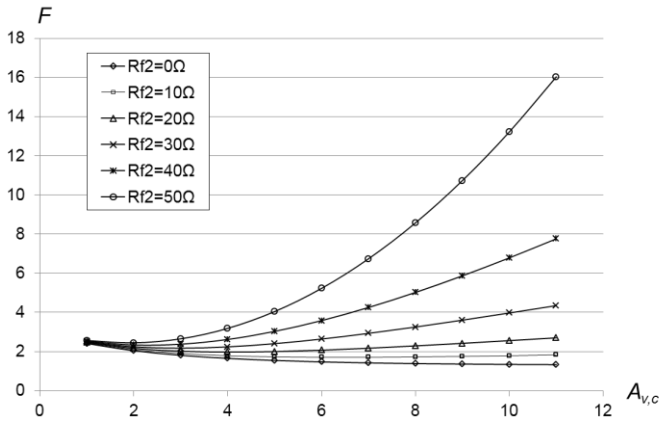


Fig.6. Noise figures of each component when $A_{v,c}$ varies (R_{f2} varies from 0Ω to 50Ω)

(ii) Distortion Cancellation

The distortion cancellation can be conducted on the same principle of the noise cancellation. The remained nonlinear component at node a is amplified by noise canceller $A_{v,c}$, and added to the one at node y.

The generated current in matching device M_i can be written as $i_{Mi}=g_m v_{gs}$+iNL, and correspondingly, the voltages at node a and y are

$$v_a = v_S - (R_s + R_{f2}) i_{n,Mi}(g_{Mi} + I_{NL})$$
$$vv_y = v_S - A_{v,c}(R_s + R_{f1} + R_{f2}) i_{n,Mi}(g_{Mi} + I_{NL}) \quad (11)$$

Equation (11) is similar to equation (3). The distortion cancellation can be achieved under the same condition as the noise cancellation

$A_{v,c}=A_{v,cancel}=1+R_{f1}/(R_S+R_{f2})$.

Through comparing equations (9) and (11), it is easy to understand that the optimal points of the noise cancellation and the distortion cancellation are not in alignment with each other, as the noise takes M_i, R_{f1}, and R_{f2} into consideration, while the distortion takes only M_i into account. So it is necessary to take both the performance of noise and the performance of distortion into design consideration.

(iii) Signal-Suppression Technique

In general, there exists a tradeoff between the MOS power consumption and the linearity. The connections between MOS drain current I_D and transistor g_m can be written as

$$g_m = \frac{2I_D}{V_{GS}-V_{TH}} \quad (12)$$

This equation shows that when g_m is constant, the lower the V_{GS} is, the smaller the drain current I_D will be. However, in terms of MOS, the lower the V_{GS} is, the larger the nonlinear effect will be. That is to say, there exists a tradeoff between the current consumption I_D (i.e. the power consumption) and the linearity.

The so-called signal-suppression technique is used to alleviate this tradeoff. By suppressing the small-signal input, the tradeoff between MOS power consumption and linearity can be mitigated.

In the proposed circuit, the small-signal voltage of node a can be changed to a lower value than that of node x (i.e. the input voltage of noise-cancelling amplifier $A_{v,c}$ in the existing circuit) by adjusting the value of R_{f2}. Correspondingly, the power consumption of *M2* can be reduced.

The small-signal voltage at node a can be written as

$$v_a = (1 - R_{f2} g_{Mi}) v_x \quad (13)$$

According to equation (13), when $0<R_{f2}g_{Mi}<2$, $|v_a| < |v_x|$. This is regarded as the signal-suppression condition.

The power consumption of the noise canceller is decided by the drain current of *M2*. Signal-suppression technique reduces the amplitude of the input signal of M2, therefore decreases V_g-V_t of *M2*. According to equation (12), the drain current of *M2* decreases correspondingly, which leads to a low power consumption of the noise-canceling amplifier $A_{v,c}$.

4. Simulation

The proposed circuit is verified by Spectre simulation with 90nm CMOS process. Simulation circuit diagram is illustrated in Fig. 5.

Ideal components (Analog lib) are applied for resistor

and capacitor modeling, and real components (tsmc 90) are used for MOS modeling. Inverter M_{ia} and M_{ib} constitute the matching device. C_2, R_{B2}, V_{B2}, C_3, R_{B3}, and V_{B3} constitute the bias circuit for *M2* and *M3*. i_{rs} is set as an ideal current source in order to achieve a stable g_m of M_2.

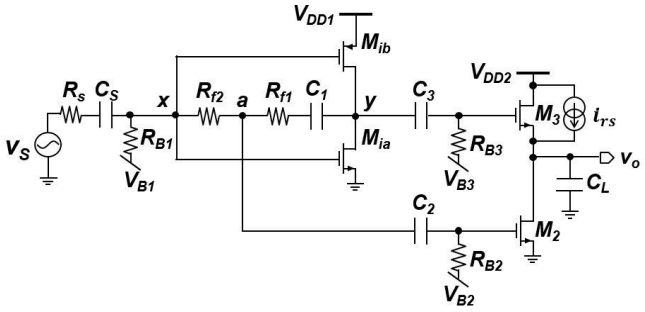


Fig.7. Simulation circuit diagram

Simulation result "$A_{v,c}$ vs. noise figure" is illustrated in Fig.7, where the frequency of the input signal is 1GHz and the value of R_{f2} varies from 0Ω to 50Ω. R_{f1}+R_{f2} is a constant value. The result shows that the noise of R_{f2} gives a great impact on the circuit's whole noise figure.

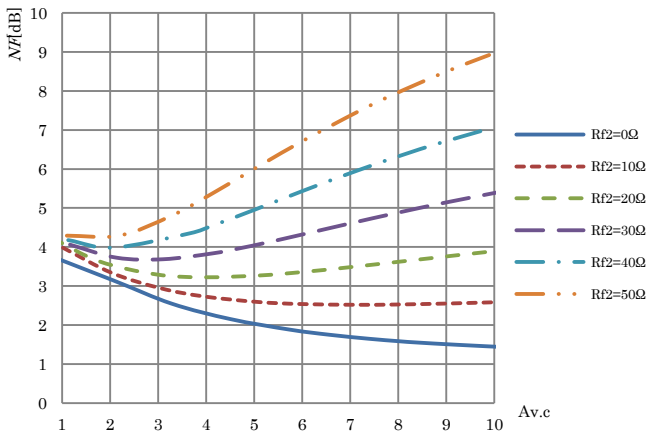


Fig.7. "$A_{v,c}$ vs. NF" when R_{f2} varies from 0Ω to 50Ω

When the value of $A_{v,c}$ satisfies the noise cancellation condition under different R_{f2} values, the corresponding "power consumption and NF" characteristics are illustrated in Fig.8.

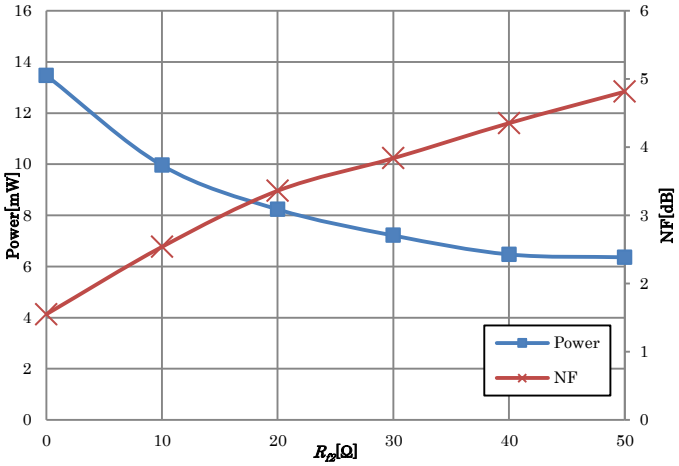
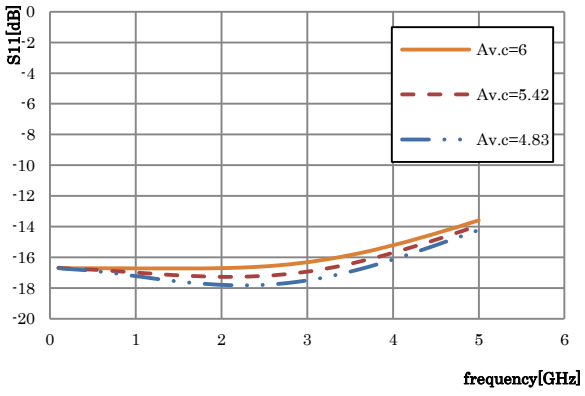
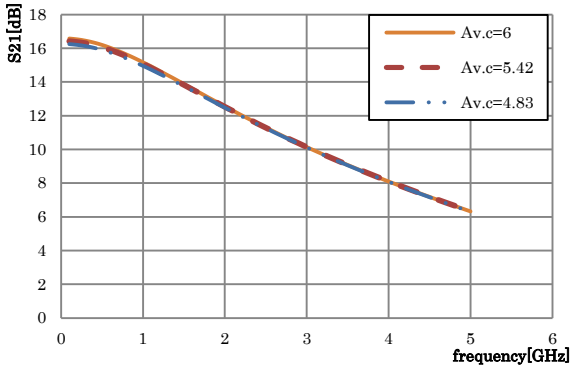


Fig.8. "Power consumption and NF" when R_{f2} varies

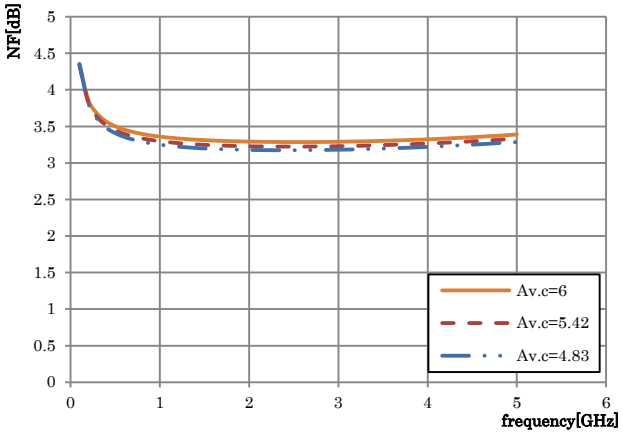
When R_{f1}=350Ω, R_{f2}=20Ω, as well as the noise cancellation condition and the distortion condition are satisfied separately, the corresponding power consumption and frequency characteristics are compared. When R_{f2}=20Ω, the noise cancellation condition is $A_{v,c}$=6, and the distortion condition is $A_{v,c}$=4.83. When these two conditions are satisfied separately, the corresponding power consumption is 8.23mW and 9.88mW. And when these two conditions are satisfied simultaneously, e.g. $A_{v,c}$=5.42, the frequency characteristics are illustrated in Fig.9.



(a)S11



(b)S21



(c)*NF*

Fig.9. Comparison of frequency characteristics.

The two tones at 849 and 851MHz are used as input signal frequency, and the power of the third-order intermodulation distortion (IMD3) at 847MHz are observed at the output in the simulation. The input third-order intercept point (IIP3) is -1.99dBm under noise cancellation condition, and -1.53dBm under distortion cancellation condition.

Table.1 shows the results when R_{f1}＝350Ω, R_{f2}=50Ω, as well as $A_{v,c}$ satisfies the noise cancellation condition and the distortion cancellation condition separately or simultaneously.

Table.1. Simulation results when R_{f2}=20Ω

$A_{v,c}$	4.83	5.42	6.00
Bandwidth	100-4600 MHz	100-4500 MHz	100-4000 MHz
S11(1GHz)	-17.22dB	-16.99dB	-16.72dB
S21(1GHz)	14.96dB	15.08dB	15.17dB
NF(1GHz)	3.25dB	3.298dB	3.36dB
IIP3(847MHz)	-1.99dBm	-1.58dBm	-1.53dBm
Power Consumption	8.23mW	9.05mW	9.87mW

5. Conclusion

In order to mitigate the tradeoff between the noise figure and the power consumption in wide-band LNA design, a novel scheme is proposed. This scheme employs the noise-cancelling technique, which is based on feed-forward amplifier, and the signal-suppression technique, which is capable of reducing the power consumption of the noise-cancelling amplifier.

In case of the noise-canceling amplifier $A_{v,c}$, the simulation results shows that there is almost no tradeoff between the noise figure and the linearity. However, a compromise exists between the *NF* and the power consumption, which provides a lot of flexibility in the design of wide-band LNA.

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