A CMOS dual-feedback reconfigurable low noise amplifier with improved stability and reduced noise

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Abstract: This paper presents a multiband reconfigurable low noise amplifier (LNA) based on dual-feedback common-gate (CG) configuration. The input impedance of the LNA is tuned synchronously with output load due to the reflection of load impedance to input by the proposed source-follower positive feedback method. This method also improves the stability of the LNA, which is an issue in conventional positive feedback methods. In addition, both the source-follower positive feedback and the negative feedback by capacitor cross-coupling help to reduce noise figure. Fabricated in TSMC 0.18\,\mu m CMOS process, measurement results show the LNA is reconfigurable from 1.833 GHz to 2.47 GHz, with S11 automatically centered with S21. It achieves a power gain from 15 to 17.4 dB, 1.62 dB minimum NF, and −4.4 dBm maximum IIP3. 10.5 mA current is consumed from 1.8 V supply.

Keywords: LNA, reconfigurable, multiband, feedback, noise reduction

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1 Introduction

With increased amount of frequency bands integrated in smart phones, the transceivers face a big challenge in terms of complexity and cost. In existing commercial applications, almost every frequency band has its own dedicated RF path for the best performance. With evolution from 4G to 5G, this will significantly increase the RF front-end complexity.

Cognitive or reconfigurable radio [1, 2, 3] is a promising solution with a high level of hardware sharing. Within this architecture, a wideband low noise amplifier (LNA) [4, 5] can be utilized to cover all needed frequency bands. This method benefits from the lowest complexity and concurrent reception of more than one signal band. But it suffers from serious out-of-band interferences. A reconfigurable one [1, 2, 3, 6, 7] with frequency selectivity in both input and output is able to receive only the desired frequency band, thus improve the immunity of the receiver from out-of-band interferers.
In the design of reconfigurable LNAs, the inductively degenerated common source (CS) configuration is difficult to tune its narrowband input matching network, and the added tunable components induce extra noise [6, 7]. Moreover, keeping both input matching and output tank centered on the desired frequency in all conditions over PVT is challenging. Common gate (CG) topology has been investigated as reconfigurable LNA in [1, 2, 3]. In [2], an inverse-amplifier based positive feedback path is added between output and input of CG-LNA to achieve a tunable narrow-band input matching, but this method has unstability issues. In addition, to make performance of CG-topology based reconfigurable LNA comparable to that of multiple parallel narrow-band CS-LNA, the noise figure needs to be reduced. Positive-negative feedback was introduced in [8] to improve the gain and noise performance of CG-LNA, but the design in that paper has no frequency selectivity.

To address the issues mentioned above, this paper presents a multiband reconfigurable LNA based on dual-feedback CG configuration. Besides easy configurability, the LNA has improved stability and reduced noise. The outline of the paper is as follows. In section 2, the analysis and design of the presented LNA is described, including input impedance, gain, noise, stability, linearity and configurability. In section 3, detailed characterization results of the prototype chip are shown, followed by a conclusion in section 4.

2 The proposed dual-feedback reconfigurable LNA

CG-LNA features superior bandwidth, linearity, stability, but suffers from low gain and poor noise performance compared to the CS-LNA. Although it is generally used as a wideband LNA, it can also be used to develop a narrowband one with wideband configurability. The proposed LNA is shown in Fig. 1, consisting of cross-coupled capacitors (C₁, C₂) and NMOS transistors (M₅, M₆) in a differential

![Fig. 1. Complete circuit of the proposed dual-feedback reconfigurable LNA.](image-url)
CG configuration. An off-chip balun transforms the input single-ended signal into differential signals and provides DC ground for the LNA. The differential signals then flow to the sources of input transistors ($M_1$, $M_2$), and are also cross-coupled to the gates of the opposite input transistors through capacitors, which results in a shunt-series negative feedback. The outputs of the LNA are coupled to the sources of the input transistors through $M_3$ and $M_6$, creating a shunt-shunt positive feedback loop. A tunable LC tank with binary weighted capacitor array acts as the load. For measurement purpose, a differential source-follower buffer is designed on chip, with broadband output matching.

Before exploring the detailed characteristics of the presented LNA, it is helpful to review the properties of CG-LNA and its various feedback configurations, as shown in Fig. 2. Here $A_{NEG}$ is defined as the voltage gain of the gate voltage over the source voltage of the CG transistor, and $A_{POS}$ is defined as the current gain of the current from the positive feedback branch over the current going into the source of the CG transistor. In conventional CG-LNA in Fig. 2(a), the transconductance ($g_m$) is limited to $1/R_S$ by the input matching condition, resulting in a poor noise figure. A capacitor-cross-coupled (CCC) negative feedback configuration [9], shown in Fig. 2(b), uses $g_m$ boosting which reduces noise figure and power consumption by a factor of two. However, due to the passive $g_m$ boosting, the transconductance still has limited design range. In contrast, positive feedback topology [2] in Fig. 2(c), alleviates the restriction of low $g_m$. Since the input impedance is $1/[(1 - A_{POS})g_m]$ and $A_{POS}$ can be designed from 0 to 1, thus $g_m$ can be arbitrarily set for input impedance matching. Positive-negative feedback, in Fig. 2(d), was introduced in [8] to further improve the gain and noise performance of CG-LNA.

The feedback configurations decouple the noise figure from the input matching, resulting in a lower noise figure without impacting input matching. Moreover, the positive feedback correlates the input impedance with output load.

Fig. 2. Conventional CG-LNA and its different feedback configurations.

2.1 Input matching and gain
As for the presented reconfigurable CG-LNA in Fig. 1, the single ended model is shown in Fig. 3(a). The input impedance is derived as
\[ Z_{in}(\omega) = \frac{1}{2g_{m1} + g_{m2}} + \frac{g_{m2}}{Z_{L}(\omega)} Z_{L}(\omega), \]  

where \( g_{m1} \) and \( g_{m2} \) are the transconductances of \( M_1 \) and \( M_2 \) in Fig. 3(a), respectively, and \( Z_{L}(\omega) \) is the LNA load impedance. The input impedance is a function of \( Z_{L}(\omega) \), and it is increased by the positive feedback. In (1), if \( g_{m2} \) is 0, meaning no positive feedback, the input impedance is \( 1/(2g_{m1}) \), which is the same as that of CCC-LNA [9]. With the load being a tunable LC tank as shown in Fig. 1, the input impedance also becomes tunable, due to the partial reflection of the load impedance to the input, provided by the source-follower positive feedback. At the load resonant frequency, the input impedance is purely resistive, and can be matched to the source resistance. Under input matching condition, the transconductance of input transistor is

\[ g_{m1} = \frac{1 + g_{m2}[Z_{L}(\omega_0) - R_S]}{2R_S} = \frac{1 + g_{m2}(R_L - R_S)}{2R_S}, \]

where \( R_L \) is the tank parallel resistance at resonant frequency \( \omega_0 \), and \( R_S \) is source impedance. By properly selecting \( g_{m2} \) and \( R_L \) values, the transconductance of the input transistor is no longer restricted as in conventional CG-LNA, and can be any arbitrary value. In input matching condition, the effective transconductance gain (defined as \( G_m = i_{out}/v_s \)) of the LNA is

\[ G_m = \frac{1}{2R_S}. \]

### 2.2 Noise figure

Referring to Fig. 3(a), the noise figure of the LNA is computed. For simplicity, only the three main noise sources, i.e., the thermal noise of the two transistors \( (M_1 \) and \( M_2 \)) and the noise of the load are considered. At the resonant frequency, the noise factors contributed from \( M_1, M_2 \) and the load, are expressed as follows:
where $\gamma$ is the MOS transistor thermal noise coefficient, $\alpha$ is defined as the ratio of $g_m$ to the zero-bias drain conductance $g_{d0}$. The total noise factor is expressed as

$$F = 1 + \left[ \frac{1}{(2g_{m1} + g_{m2})R_S} \right] \left[ \frac{2\gamma}{\alpha} (g_{m1} + g_{m2})R_S + \left[ 1 + \frac{1 + g_{m2}R_L}{(2g_{m1} + g_{m2})R_S} \right] \frac{2R_S}{R_L} \right].$$

(7)

Under input matching condition, the noise factor is

$$F_{\text{match}} = 1 + \frac{g_{m1} + g_{m2}}{(2g_{m1} + g_{m2})^2R_S} \frac{\gamma}{\alpha} + \frac{4R_S}{R_L}.$$  

(8)

Fig. 4 shows the plots of the noise figure in equation (8) and input transistor’s transconductance ($g_{m1}$) in equation (2) vs. feedback transistor’s transconductance ($g_{m2}$). Here, $\alpha = 1$, $\gamma = 2/3$, $R_S = 50 \Omega$, and $R_L = 1000 \Omega$ (output impedance measured from simulation of the presented LNA) are used. With $g_{m2}$ increases, the noise figure decreases significantly and a sub-1 dB NF can be obtained which is comparable to the NF of an inductor-degenerated CS-LNA. $g_{m1}$ increases linearly with $g_{m2}$, meaning the power consumption also increases. Therefore, there is a tradeoff between NF and power consumption. In this design, $g_{m2} = 3 \text{ mS}$ is selected.

### 2.3 Stability

Even though the CG-type LNA itself is very stable, stability needs to be carefully considered since positive feedback exists in the presented topology. As shown in equation (1), the input impedance is always larger than zero, no matter how transconductance of positive-feedback transistor changes. It means that the LNA
is stable with the proposed source-follower positive feedback topology. As for the conventional inverse-amplifier based positive feedback LNA [8], shown in Fig. 3(b), the input impedance is

$$Z_{in} = \frac{1}{2g_{m1}(1 - \frac{g_{m2}}{g_{m1}}R_L)}.$$  \hspace{1cm} (9)

Fig. 5 shows the input impedance vs. the transconductance ratio ($g_{m2}/g_{m1}$) of the positive feedback transistor over input transistor. With the $g_{m2}/g_{m1}$ increases, meaning more positive feedback, the input impedance increases monotonously and always larger than zero in the source-follower positive feedback LNA. However, in inverse-amplifier based positive feedback LNA, the input impedance becomes smaller than zero, when $g_{m2}/g_{m1}$ above some value, resulting in un-stability. So, the proposed positive feedback method shows improved stability compared to the conventional inverse-amplifier based positive feedback.

![Input impedance vs. transconductance ratio](image)

**Fig. 5.** Input impedance vs. the transconductance ratio of positive feedback transistor over input transistor.

### 2.4 Linearity

The LNA distortion mainly comes from two elements: the input transistor M1 and the additional positive-feedback path provided by M2. Because of a large gate-source voltage swing across M2, the transistor M2 needs to be properly biased. Simulation is done to investigate the effect of overdrive voltage of M2 on LNA IIP3, as shown in Fig. 6.

### 2.5 Reconfigurability

As mentioned in 2.1, the input impedance is a function of $Z_L(\omega)$, thus the input matching of the LNA can be reconfigured for each RF band by simply changing the resonant frequency of the load network. A 4-bit binary-weighted switched MIM capacitor array as shown in Fig. 1 is used as tunable capacitor in LC tank for load tuning. To reduce loss of tunable capacitor, a large resistor is added at the gate of the MOS switch in this design to isolate the signal leakage to the gate bias path. The
The resistors at the source, drain, and body of the NMOS switch [15] are not used in this work. When output voltage swing of LNA is large and the NMOS switch is off, the body-source or body-drain diode will be forward biased. It will reduce the IIP3 of the LNA. A frequency selective input matching is obtained as shown in Fig. 7. The proposed LNA has $S_{11}$ automatically centered with $S_{21}$, which is in synch with the LC tank resonant frequency. The minimum noise figure of the circuit also tracks the load impedance change accordingly.

Fig. 6. Simulated IIP3 vs. overdrive voltage of $M_2$.

Fig. 7. Schematic-level simulated reconfigurability of the LNA.
Table I gives a summary of main characteristics of the proposed LNA and comparison with other feedback LNAs.

|                  | CCC Negative Feedback [9] | Inverse-amplifier Positive Feedback [2] | Inverse-amplifier Positive-Negative Feedback [8] | This work |
|------------------|----------------------------|----------------------------------------|-----------------------------------------------|-----------|
| $Z_{in}$         | $\frac{1}{g_m(1 + A_{neg})}$ | $\frac{1}{g_m(1 - A_{pos})}$           | $\frac{1}{g_m(1 + A_{neg})(1 - A_{pos})}$    | $1 + \frac{g_m R_L}{2g_m + g_m}$ |
| $g_m@$ input matching | $\frac{1}{2R_S}$          | $\frac{2}{R_S}$                        | $\frac{1}{R_S}$                              | $1 + \frac{g_m R_L - R_S}{2R_S}$ |
| $A_v@$ input matching | $\frac{R_L}{2R_S}$        | $\frac{R_L}{R_S}$                      | $\frac{R_L}{R_S}$                            | $\frac{R_L}{2R_S}$ |
| $NF@$ input matching | $1 + \frac{\gamma}{2\alpha} + \frac{4R_S}{R_L}$ | $1 + \frac{\gamma}{2\alpha} + \frac{g_m R_L \gamma}{\alpha}$ | $1 + \frac{\gamma}{4\alpha} + \frac{g_m R_L \gamma}{\alpha}$ | $1 + \frac{g_m R_L + g_m R_L \gamma}{4R_S + \gamma R_L}$ |
| With unstability issue? | no                         | yes                                    | yes                                           | no        |

$A_{neg} = 1$, $A_{pos} = 0.5$ are assumed.

3 Experiment results

The LNA prototype is fabricated in TSMC 0.18 µm CMOS with ESD protections on all pins and assembled in chip-on-board with external baluns for testing. The chip dimensions of the LNA are 0.68 × 0.9 mm$^2$ including the pads and buffers. The circuit consumes 10.5 mA from a 1.8 V supply. S-parameters are measured in different configuration states. Four control bits are used to control the capacitor array of LNA’s LC tank to set LNA to work in different center frequencies. Fig. 8 shows S-parameters in different configurability states, with the center frequency tunable from 1.833 GHz to 2.47 GHz. A narrow-band input matching is achieved and the S11 is automatically centered with S21. The peak gain in all states varies from 15 dB to 17.4 dB, while the S11 at the center frequencies of all states is smaller than −10 dB. The S22 and S12 are smaller than −10 dB and −43 dB, respectively for all configuration states in the tuned bandwidth. Noise figures in all configurability states are measured and the 0.8 dB insertion loss of the input balun is de-embedded. Here, for clear display, only 7 states are shown in Fig. 9. The minimum noise figures in different states range from 1.62 to 2.05 dB. Fig. 10 shows the IIP3 ranges from −6.7 to −4.4 dBm for all states. Chip micrograph is shown in Fig. 11. Finally, the measured results of this work are summarized and compared with previously published works in Table II.
Fig. 8. Measured S-parameters in different configurability states.
Fig. 9. Measured noise figures in 7 configurability states.

Fig. 10. Measured IIP3 at different center frequencies.

Fig. 11. Chip micrograph.
4 Conclusions

This paper has presented a multiband reconfigurable LNA based on dual-feedback CG configuration. With the proposed source-follower positive feedback method, input impedance can be tuned synchronously with output load thanks to the reflection of load impedance to input. This method has the benefit of improved stability, which is an issue in conventional inverse-amplifier based positive feedback method. In addition, by the help of both the source-follower positive feedback and the negative feedback of capacitor cross-coupling, the fixed relationship between input impedance and transconductance in conventional CG-LNA is decoupled, resulting in a reduced noise figure. Fabricated in TSMC 0.18 µm CMOS process, measurement results show the LNA is reconfigurable from 1.833 GHz to 2.47 GHz, with S11 automatically centered with S21. The peak gain in all configurability states ranges from 15 to 17.4 dB. 1.62 dB minimum NF is achieved which verifies the benefits of the dual-feedback method. Maximum IIP3 is −4.4 dBm. 10.5 mA current is consumed from 1.8 V supply. In summary, the proposed LNA has achieved easy configurability, improved stability and shows superior noise performance compared to the published works.

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