Study of dual-band concurrent LNA equipping mutual inductive notch filter matching circuit

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Abstract In this paper, small-area dual-band concurrent LNA with small gain deviation and low NF at a wide frequency range has been studied. Proposed LNA incorporates mutual inductive notch filter matching circuit on the input/output sides to improve gain deviation and NF, to reduce circuit area, and to expand operating frequency range. The measured gain at the desired frequencies. Furthermore, the area is 0.47 mm². This LNA was designed by using TSMC-180 nm CMOS process.

Keywords: LNA, dual-band, small area, small gain deviation, low NF, wide frequency range

Classification: Integrated circuits (memory, logic, analog, RF, sensor)

1. Introduction

Recently, as applications on the mobile phone evolve, the demand for improvement of data rate is increasing. In order to improve the data rate, it is necessary to expand the bandwidth, and to do so, the carrier frequency must be high. However, it is not possible to communicate long distances at high carrier frequencies, and it is unsuitable for mobile phones. Therefore, carrier aggregation (CA) technology launched at 4G is used to expand bandwidth even if the sub 6 GHz band. However, current individual single-band receivers cannot receive multi-band and many receivers are required, so the circuit area and the power consumption are increased. In the future, if we increase the number of receivers to meet the demand for further data rate improvement, as a result, it will be difficult to implement them on mobile phones.

Therefore, a new receiver for multi-band processing with one receiver is required. In this work, a dual-band concurrent low noise amplifier (LNA) has been studied.

As multi-band LNA, a circuit that obtains narrowband matching only at the target frequencies [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30] and a circuit that obtains wideband matching [31, 32, 33, 34, 35] can be considered. However, in the case of wideband matching, signals other than the desired wave are also input and amplified, which is disadvantageous in linearity. Therefore, in this paper, we will examine to use the narrowband matching circuit.

In recent years, a dual-band concurrent LNA has been studied by many parties [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30], but almost all research faces the problem that is gain deviation and/or noise figure (NF) degradation. For example, gain and NF of 2.26/4.76 GHz dual-band concurrent LNA using mutual induction circuit designed by [1] were 18/10 dB and 5.4/6.3 dB, and that of 2.44/5.25 GHz dual-band concurrent LNA using notch filter circuit designed by [2] were 19.7/14.4 dB and 3/3.75 dB. Furthermore, since the operating frequency ratio of previous works was about double [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24] thus, this paper aims to make the operating frequency ratio more versatile by tripling that. In this work, we studied the 1.5/4.5 GHz LNA to improve gain deviation and NF, and to reduce the circuit area, especially focused on both matching circuits.

2. Circuit design

2.1 Input matching circuit

Figure 1 shows the inductive source degeneration (ISD) circuit on the input side regardless of the number of matching frequencies and is used as a common single-band LNA. At the matching frequency, Cgs, the input impedance (Zin) of the LNA is shown Eq. (1). and the gain of the input matching circuit ([Qi] = [vgs/vin]) at a state of the ideal input matching is expressed in Eq. (2), where gmn, Cgs are transconductance and gate-to-source capacitance of M1, Ls is source inductance, and Rs is source resistance.

\[ Z_{in} = \frac{g_m L_S}{C_{gs}} + j \left( X + \omega_0 L_S - \frac{1}{\omega_0 C_{gs}} \right) = R_s + j0 \] (1)

![Fig. 1 Inductive source degeneration circuit.](image-url)
If no matter what circuit is used for the X part in Fig. 1, the \( Q_{in} \) at a state of the ideal input matching is always \( 1/2R_{g}L_{gs}C_{gs} \) from Eq. (2), because the reactance of equipped circuit at a state of the ideal input matching is always 0.

In this paper, a mutual inductive notch filter matching circuit as an application of the ISD circuit to obtain dual-band matching was considered. Figure 2 shows the mutual inductive notch filter input matching circuit. This circuit consists of the series inductor \( (L_{gs}) \), parallel inductor \( (L_{gp}) \), and parallel capacitor \( (C_{gp}) \), where \( k_{in} \) is the coupling coefficient between \( L_{gs} \) and \( L_{gp} \). The input impedance \( (Z_{kin}) \) of this circuit is shown in Eq. (3), and the operating frequency \( (f_{op}) \) of this circuit is shown in Eq. (4) which obtained from \( \text{Im}(Z_{kin}) = 0 \) in Eq. (3). Where, \( L_{in} = L_{gs} + L_{S} + M_{in} \) and \( M_{in} = L_{gp} + M_{in} \). The coupling inductance of \( L_{gs} \) and \( L_{gp} \) \( (M_{in} = k_{in}\sqrt{L_{gs}L_{gp}}) \). It can be seen that dual-band matching is obtained from Eq. (4).

\[
Z_{kin} = \frac{g_{m}L_{S}}{C_{gs}} + j \left( \omega L_{in} - \frac{1}{\omega C_{gs}} + \frac{\omega L_{gp}}{1 - \omega^2L_{gp}C_{gp}} \right)
\]

\[
f_{op} = \sqrt{\left( \frac{L_{in} + C_{gs}^2 + 1}{L_{in} + C_{gs}^2 + 1} \right)^2 - \frac{4L_{in}C_{gs}}{8n^2L_{in}C_{gp}}}
\]

Furthermore, Eq. (5) of noise is obtained from Fig. 3.

\[
F = 1 + \frac{R_{Lgs}}{R_S} + \left\{ \frac{1}{1-\omega^2L_{gp}C_{gp}} \right\}^2 \frac{R_{Lgp}}{R_S} + \frac{R_{g}}{R_S} + \frac{j\omega C_{gs} \left( R_S + \frac{g_{m}L_{S}}{C_{gs}} \right)}{g_{m}} \left( \frac{7}{8} \right) \frac{S_{in}}{S_{g}}
\]

If \( L_{gp} = 6.5 \text{ nH}, L_{gs} = 6.0 \text{ nH}, L_{S} = 82 \text{ pF}, C_{gp} = 848 \text{ fF}, C_{S} = 225 \text{ fF}, g_{m} = 84.2 \text{ mS}, \) and \( k_{in} = 0.29 \) substitute into Eq. (5), the input matching is realized and Fig. 4 is obtained. Where \( Q = 8 \) and each of parasitic resistances set to \( \omega_{k} L/8 \). Compared to the mutual induction matching circuit in [1], this circuit has two coupled inductors connected, and the influence of the additional parasitic resistance of the inductor on the secondary side cannot be seen, so making it does not degrade noise.

Figure 5 shows the simulated results of the change in operating frequency due to the change in the coupling coefficient between \( L_{gs} \) and \( L_{gp} \). The coupling coefficient, \( k = 0 \), shows a normal notch filter type matching circuit as shown in [6] and \( k > 0 \) shows the two inductors are coupled. Red and blue lines show realizing input matching on the high- and low-frequency side. Since the operating frequency can be expanded by increasing the coupling coefficient, it can be seen that the proposed circuit of this paper is highly versatile. The operating frequency range of the previous circuit [6] was doubled. On the other hand, it is expected that if the coupling coefficient is 0.4/0.9, that will be triple/decuple.

### 2.2 Output matching circuit

It was found that the conventional dual-band LNA with a large gain deviation adopted a circuit on both input and output with \( -1 \)st order characteristics with respect to frequency. Therefore, either the input or output circuit must be a circuit that is suitable for the application.
with characteristics of 1st order with respect to frequency. However, as mentioned in Chapter 2.1, the input side is always $1/2R_s\omega_0C_{gs}$ at a state of the ideal input matching obtained, so it is necessary to change output side.

Figure 6 shows the mutual inductive notch filter output matching circuit. This circuit consists of the series inductor ($L_{ds}$), parallel inductor ($L_{dp}$), series capacitor ($C_{ds}$), and parallel capacitor ($C_{dp}$) where $k_{out}$ is the coupling coefficient between $L_{ds}$ and $L_{dp}$ ($M_{out} = k_{out}\sqrt{L_{ds}L_{dp}}$), $R_{L_{ds}}$ is parasitic resistance of $L_{ds}$, and $R_L$ is the load resistance.

The transimpedance gain of this circuit ($jQ_{out}/jQ_{in} = g_mR_L/R_{L_{ds}} + R_L\sqrt{(R_{L_{ds}})^2 + \omega_0(L_{ds} + M_{out})})^2$) is shown in Eq. (6) and shows that the gain of this circuit has a characteristic of 1st order with respect to frequency. The total gain of LNA is shown in Eq. (7) from Eqs. (2), (6) and illustrated in Fig. 7. If this circuit is adopted, as a result, gain deviation will be improved.

$$[Q_{out}] = \frac{R_L}{R_{L_{ds}} + R_L}\sqrt{(R_{L_{ds}})^2 + \omega_0(L_{ds} + M_{out})}$$

$$|G| = \frac{R_{in}\cdot q_m}{Q_{out}}$$

$$= \frac{R_{L_{ds}} + R_L}{2R_S\omega_0C_{gs}}\sqrt{(R_{L_{ds}})^2 + \omega_0(L_{ds} + M_{out})}^2$$

2.3 Whole circuit

The proposed LNA that has the mutual inductive notch filter matching circuit for input and output is shown in Fig. 8. In this circuit, the gain stage is a cascode connection amplifier for the isolation between input and output and for the suppression mirror capacitance, and the bias circuit consists of the current mirror circuit.

3. Simulation and measurement results

Design, fabrication, and evaluation were done by using the TSMC-180nm CMOS process. The design was performed on Cadence’s Virtuoso, circuit analysis was performed using Cadence’s Specter-RF, and electromagnetic field analysis was performed using Cadence’s EMX. The on-wafer probe station was used for measurement, and HP (Keysight) 8510C network analyzer was used for S-parameter measurement, and Keysight’s N9010A spectrum analyzer and 8673G, 8648D signal generators were used for NF and linearity measurement.

Figure 9 shows the simulation results of S-parameters and NF. The simulated $S_{11}$, $S_{22}$, $S_{21}$, and NF of the proposed LNA were $-10.4$, $-12.0$, $19.4$, and $2.91$ dB at 1.5 GHz, and $-11.7$, $-24.1$, $16.6$, and $2.69$ dB at 4.5 GHz, respectively. As a result, the gain deviation is 2.8 dB.

Figure 10 shows the measurement results of S-parameters and NF. The measured $S_{11}$, $S_{22}$, $S_{21}$, and NF of the proposed LNA were $-14.2$, $-10.0$, $10.9$, and $2.64$ dB at 1.5 GHz, and $-10.9$, $-16.5$, $10.3$, and $2.99$ dB at 4.38 GHz, respectively. As a result, the gain deviation is only 0.6 dB. We believe that the 2.6% shift in both frequencies is due to changes in the coupling coefficient and the parasitic inductance and capacitance of the wiring inside the chip.

Figure 11 shows the measurement results of $P_{in} - P_{out}$ characteristics of the proposed LNA. The IP1dB of the
proposed LNA were $-15.9$ dBm at 1.54 GHz, and $-7.5$ dB at 4.38 GHz. The power consumption is 14.6 mW under 1.8 V supply voltage.

The chip microphotograph is shown in Fig. 12, and chip area was $506 \mu m \times 938 \mu m$ (0.47 mm$^2$).

4. Conclusion

In this work, we designed a small-area dual-band concurrent LNA with small gain deviation and low noise figure at a wide frequency range. The operation of dual-band concurrent reception was confirmed by adopting a mutual inductive notch filter matching circuit for both the input and output sides. The gain deviation of designed concurrent LNA was only 0.6 dB, NF of it was 2.64 dB at 1.54 GHz and 2.99 dB at 4.38 GHz, and the chip area was 0.47 mm$^2$. Furthermore, the performance of LNA of this work is compared to other results as shown in Table I, and the performance improvement methodology of this work is obtained performance including small gain deviation, low NF and small area, has the advantage.

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