Analysis and Design of Differential LNAs with On-Chip Transformers in 65-nm CMOS Technology

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Outline

Background

Analysis of Differential LNAs with On-Chip Transformer

- Differential Common-Source (CS) LNA
- Differential Common-Gate (CG) LNA
- Design Considerations and Comparison

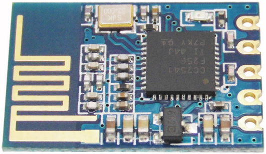
Simulation

- Schematic
- Simulated Results
- Comparison

Summary

Background

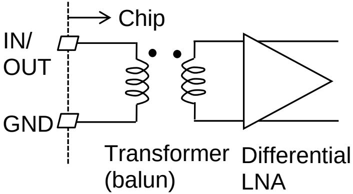
- Wearable devices with Bluetooth Low Energy (BLE) have required small-size RF modules
- Single-ended input/ output RF transceivers reduce PCB area



RF2541 BLE Module (NiceRF Wireless Technology)

Challenges: On-chip balun

- LNAs often employ differential topologies
- On-chip transformer



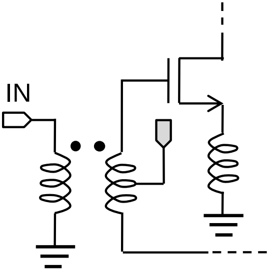
☺ provides single-to-differential conversion

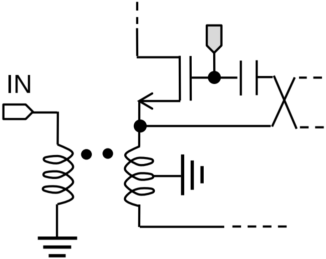
☹ greatly influences the LNA peformances: input impedance, gain, and noise figure

Objectives

Analyze influences of transformer on

- Inductively-degenerated CS LNA (widely used)
- Cross-coupled CG LNA





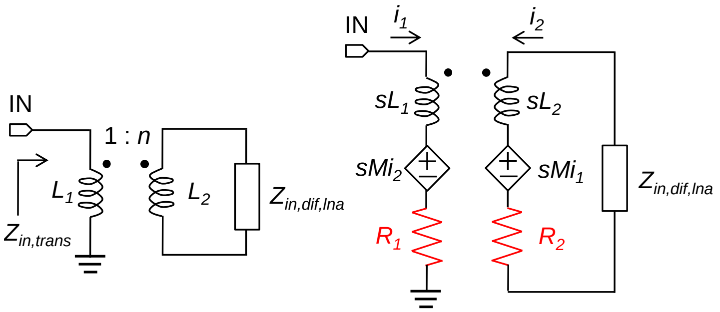
Analytical expressions

- Input impedance
- Current gain
- Noise figure

Design considerations

- Required Q and L of inductors in transformer
- Comparison of topologies

Input Impedance of Transformer Loaded with LNA

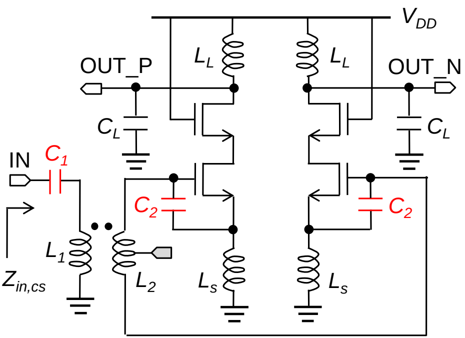


- Input impedance of differential LNA without transformer, $Z_{in,dif,lna}$
- Mutual inductance, M $(= nkL_1)$, and coupling factor, k
- Parasitic resistances ($R_i = \omega_0 L_i / Q_i$, $i = 1,\ 2$) included

$$Z_{in,trans} = R_1 + j\omega L_1 - \frac{(j\omega nkL_1)^2}{R_2 + j\omega n^2 L_1 + Z_{in,dif,lna}}$$

Input Impedance of Differential CS LNA

- Additional capacitors (C_1, C_2) resonate with inductors (L_1, L_2 and L_s) at operating frequency, ω_0



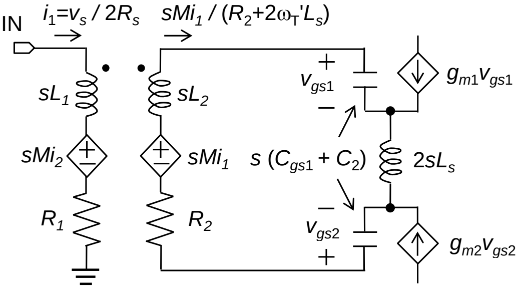
$$Z_{in,cs} = R_1 + \frac{\omega_0^2 n^2 k^2 L_1^2}{R_2 + 2\omega_T' L_s},$$

$$\omega_T' = \frac{g_m}{C_{gs} + C_2}$$

- $2\omega_T' L_s$: Real part of input impedance of differential CS LNA without transformer, conventionally set to 50 Ω.

For a larger L_1, we have to increase $2\omega_T' L_s$ accordingly to achieve input impedance matching.

Current Gain and NF of Differential CS LNA



Current gain and noise factor:

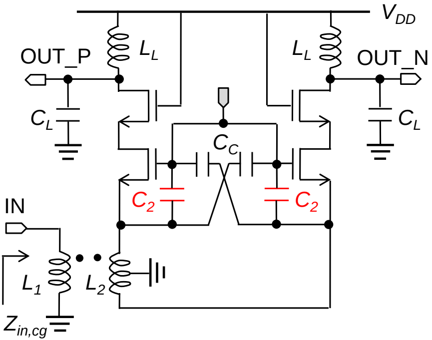
$$\alpha_{cs} = \left|\frac{g_m v_{gs1}}{v_s/2R_s}\right| = \left|\frac{g_m \cdot sM}{s(C_{gs}+C_2)(R_2+2\omega'_T L_s)}\right| = \frac{\omega'_T n k L_1}{R_2 + 2\omega'_T L_s},$$

$$F_{cs} = 1 + F_{R_1} + F_{R_2} + F_{R_{L_s}} + \frac{\gamma}{2\alpha_{cs}^2} g_m R_s + \frac{2R_s}{\alpha_{cs}^2 R_{eq,L_L}}$$

Current gain (α_{cs}) influences noise figure.

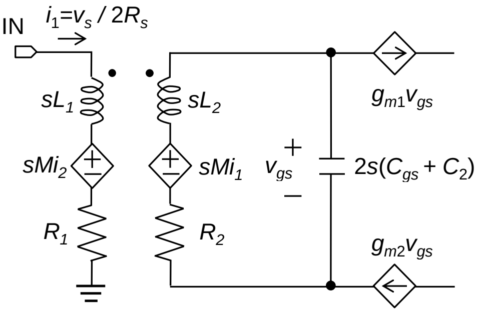
Input Impedance of Differential CG LNA

- Additional capacitors (C_2) resonate with inductors (L_1 and L_2) at ω_0
- Equivalent resistance of LC tank (L_2, C_2 and C_{gs}): $R_{eq,L_2} = Q_2^2 R_2$
- Input admittance of CG LNA without transformer: $g_m + 1/R_{eq,L_2}$



$$Z_{in,cg} \approx R_1 + \frac{k^2}{n^2\left(g_m + 1/R_{eq,L_2}\right)}, \quad \text{where } k^2 \approx 1.$$

Current Gain and NF of Differential CG LNA



Current gain and noise factor:

$$\alpha_{cg} = \left|\frac{g_m v_{gs1}}{v_s/2R_s}\right| = \left|\frac{\frac{sM}{R_2+sL_2} \cdot g_m}{\frac{1}{R_2+sL_2} + g_m + 2s(C_{gs} + C_2)}\right| \approx \frac{k g_m}{n\left(g_m + 1/R_{eq,L_2}\right)},$$

$$F_{cg} = 1 + F_{R_1} + F_{R_2} + \frac{\gamma}{2\alpha_{cg}^2} g_m R_s + \frac{2R_s}{\alpha_{cg}^2 R_{eq,L_L}}.$$

Dependence of α on transformer design parameters (L and Q) provides us useful information

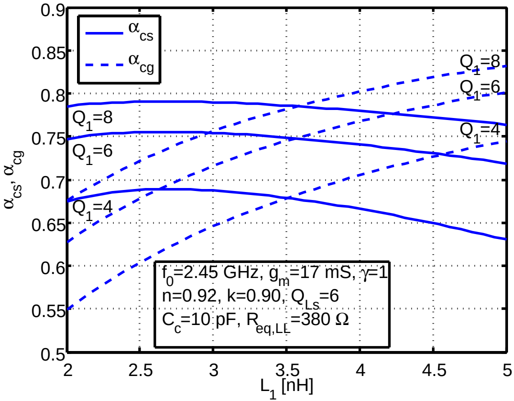
Calculated Current Gain (α_{cs} and α_{cg}) vs. L_1 and Q_1

- CS LNA

$$\alpha_{cs} = \frac{\omega'_T n k L_1}{R_2 + 2\omega'_T L_s}$$

- CG LNA

$$\alpha_{cg} = \frac{k g_m}{n\left(g_m + 1/R_{eq,L_2}\right)}$$

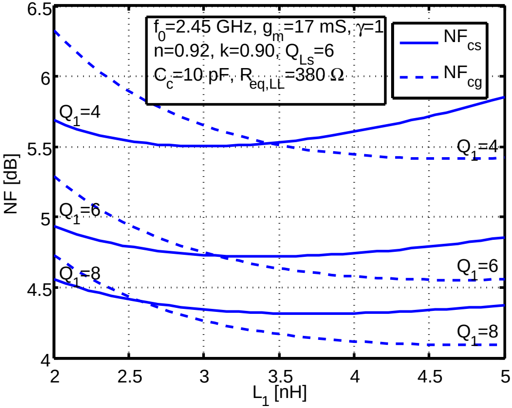


- Increasing Q_i results in higher current gains
- α_{cs} has the maximum value (around $L_1 = 2.6$ nH), while α_{cg} increases as L_1 increases
- CG LNA obtains a higher current gain for $L_1 > 3.5$ nH

Calculated NF vs. L_1 and Q_1

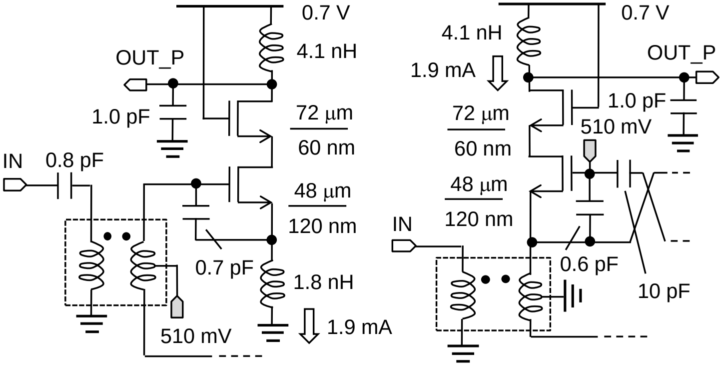
$$F_{cs} = 1 + F_{R_1} + F_{R_2} + F_{R_{Ls}} + \frac{\gamma}{2\alpha_{cs}^2} g_m R_s + \frac{2R_s}{\alpha_{cs}^2 R_{eq,L_L}},$$

$$F_{cg} = 1 + F_{R_1} + F_{R_2} + \frac{\gamma}{2\alpha_{cg}^2} g_m R_s + \frac{2R_s}{\alpha_{cg}^2 R_{eq,L_L}}.$$



- Increasing Q_i results in lower NFs
- Transformer with $Q > 6$ provides $NF < 5$ dB
- CG LNA has a lower NF than CS LNA for $L_1 > 3.5$ nH

Schematics (Half) of Differential CS and CG LNAs

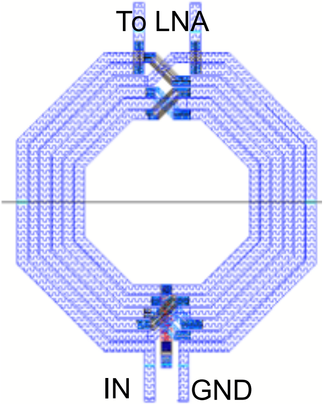


- Renesas Silicon-on-Thin-Buried Oxide (SOTB) 65-nm CMOS
- Frequency=2.45 GHz; Current consumption=3.8 mA@0.70 V

Layout of Transformer

Structure

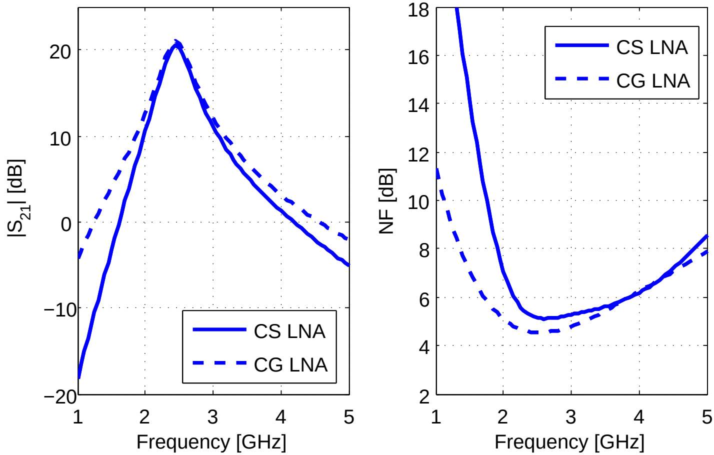
- Two inter-winding symmetric octagonal inductors
- Stacked with top three metal layers (1.7 μm in thickness)
- Outer diameter (d_{out}): 300 μm
- Metal width: 10 μm



Characteristics@2.45 GHz (Simulated with Momentum)

- $L_1 = 3.6$ nH, $L_2 = 3.1$ nH
- $Q_1 = 5.7$, $Q_2 = 5.4$
- $k = 0.91$

Simulated S_{21} and NF of CS and CG LNAs



- CG LNA achieved a slightly higher gain and a lower NF ($|S_{21}| = 20.9$ dB, $NF = 4.55$ dB) than CS LNA ($|S_{21}| = 20.4$ dB, $NF = 5.18$ dB)

Comparison between Simulations and Calculations

LNA	Transformer			Simulated*			Calculated†	
	d_{out} [μm]	L_1 [nH]	Q_1 [-]	$\|S_{11}\|$ [dB]	$\|S_{21}\|$ [dB]	NF [dB]	$\|S_{21}\|$ [dB]	NF [dB]
Spec.	-	-	-	< -10	>20	<5	>20	<5
CS	300	3.6	5.7	–27.2	20.4	5.18	21.0	4.80
	360	5.3	6.2	–25.8	20.7	5.53	20.8	4.78
CG	300	3.6	5.7	–18.8	20.9	4.55	21.0	4.68
	360	5.3	6.2	–25.9	21.0	4.42	21.6	4.57

* $f_0 = 2.45$ GHz, $V_{DD} = 0.7$ V, $I_{DD} = 3.8$ mA.
† $f_0 = 2.45$ GHz, $g_m = 17$ mS, $\gamma = 1$, $Q_{Ls} = Q_{LL} = 6$, $C_c = 10$ pF.

- Two transformers (d_{out} =300, 360 μm) are used
- Calculated NFs of CS LNAs are slightly lower than simulations, due to parasitic capacitances of transformer
- Calculations of CG LNAs agree with simulations, because these capacitances can be considered as C_{gs}

Summary

Derived analytical expressions for differential CS and CG LNAs with on-chip transformers:

- Calculations agree well with simulations, except for NF of CS LNA
- CG LNA (with $L >$3.5 nH) achieves a higher gain and lower NF than CS LNA

Presented design considerations:

- Minimum requirements for Q and L of transformer: $Q >$6 for $NF >$5 dB and $L >$3.5 nH for CG LNA

Significantly reduce the design efforts to differential LNAs with on-chip transformers.