Novel Control Techniques of Input-Match and Output-Match for an Inductively Degenerated Low Noise Amplifier

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***Abstract*—This paper presents two novel techniques to control the input match and the output match for 2.45 GHz CMOS inductively degenerated Low Noise Amplifier (LNA). These control techniques allow the compensation of all deviation of these parameters caused by the undesirable factors such as Process-Temperature-Voltage (PVT) variations, parasitic elements, etc. These techniques are studied theoretically and through simulation to be validated. Moreover, we investigated the effects of the parameters tuning in the other LNA performances and we showed that these effects are not important. The simulation results present a control of the input match S11 between -33.12dB and -56.23dB. The input match center frequency can be controlled between 2.361GHz and 2.603GHz. The tuning of the output match S22 can be made between -17.98dB and -53.65dB. The center frequency of the output match can be controlled between 2.336GHz and 2.540GHz. Also, we proved that the control of the input match quality and its center frequency are independent. The same result was shown for the output match quality and its center frequency.**

***Index Terms*—low noise amplifier, control, input match, output match, resonance frequency**

I. INTRODUCTION

In recent years, a lot of research has been focused on the challenge of Radio Frequency Integrated Circuits (RFIC) regarding their integration level to achieve low cost and low power consumption circuits. In the future, the CMOS technologies (lower than 90 nm) will integrate on-chip complex analog / RF /digital circuits [1]. However, this complicates the Systems-On-Chip (SOC) and their test becomes difficult and expensive. Moreover, the test equipments are very expensive for SOCs, especially, when they are complicated. In addition, each performance test needs a different stimulus and test configuration. Therefore, the per-chip test time becomes long and needs an expensive automatic test equipment (ATE). For example, the tests for the noise figure and the third-order intercept point need significantly different tests setups [2]. Moreover, the chip manufacturers are facing a new challenge in precisely predicting the variation devices, process skew, and mismatch [3]. Therefore, the product becomes costly. On the other hand, the chip test is very necessary after the circuit manufacture as well as during the RF device operation. This is because the RF circuits are exposed to many adverse factors, such as; transistor corner variation (ff, tt, ss), bond wire inductance variation, on-chip capacitance and inductance variation (min, typ, max), temperature variation [3], [4], power supply variation, parasitic elements and process variations, leading to the degradation of the circuit performances. Therefore, the RF device operates badly. These process variations become an important problem with technology scaling. Especially, for the RF circuits that operate at GHz frequencies, such variations can considerably change the circuit performance [5].

In the radio frequency reception chain, the Low Noise Amplifier (LNA) is considered as one of the most critical RF blocs. It might also be exposed to these undesirable factors that affect the LNA parameters (Gain, input match, output match, noise figure and linearity). In this paper, we proposed tow novel techniques to control some critical performances of an inductively degenerated [6], [7] LNA, such as the input match quality and its center frequency and the output match quality and its center frequency. These control techniques are exploited to compensate all operation frequency deviations and to better the quality of the input and the output matches when they are degraded. These techniques might be very useful in the self calibration system of the input and output match of the LNA, as well.

The effectiveness of these techniques are demonstrated theoretically and by simulations for an LNA operated at the center frequency of 2.45GHz in the 2.4GHz-2.485GHz frequency band.

The remainder of this paper is organised as follows. In section 2, we present the related works and we forward a theoretical study of our techniques. In section 3, we validated them through simulation. Finally, section 4 is devoted to draw some conclusions.

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II. Input Match and Output Match Control

We are basically used to the topology of the common-source inductive degeneration LNA. The scheme of this LNA is shown in Fig .1.

As has been proven in [6], the input impedance can be written as follows:

$$Z_{in} = j\left[\omega(L_s + L_g) - \frac{1}{\omega C_{gs}}\right] + \frac{g_m L_s}{C_{gs}} \qquad (1)$$

At the resonance frequency, the input impedance becomes equal to its real part as shown in (2):

$$Z_{in} = \frac{g_m L_s}{C_{gs}} \qquad (2)$$

The expression of the resonance frequency f_0 is obtained when the imaginary part is equal to zero; it is given by:

$$f_0 = \frac{1}{2\pi\sqrt{(L_s + L_g)C_{gs}}} \qquad (3)$$

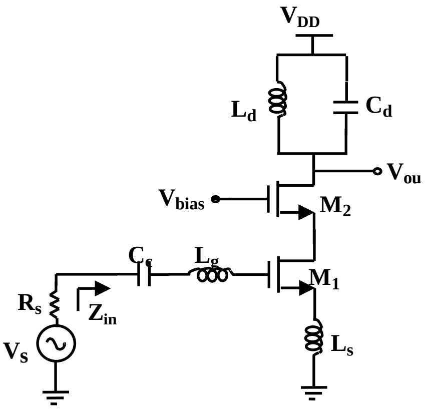


Figure 1. Common-source inductive degeneration LNA circuit.

Equation (2) shows that the input match quality can be tuned when C_{gs}, L_s, or g_m is varied. On the other hand, equation (3) shows that the resonance frequency control can be made when we adjust C_{gs}, L_g or L_s. In Ref. [8], the authors proposed a control approach of the input match by adjusting the inductance L_g. The major issue of this technique is the complication in the variable inductance implementation. As an alternative for this method, we can tune the input mach quality by means of the transconductance g_m. However, g_m can alter the gain, linearity and noise figure of the LNA. Then, the elements L_g, g_m and L_s cannot be used to tune the input match quality and the resonance frequency.

Concerning the output matching, in Ref. [9], the authors proposed an approach to control the output match S_{22} for an inductively degenerated LNA, consisting of tuning the load capacitance placed between the drain of the transistor M_2 and the ground. In this work, the impact of the control is investigated only on the gain and the input match.

In this paper, however, we propose two novel techniques:

The first technique permits to control the input match quality and its center frequency. Our main idea was to introduce two variable capacitors C_s and C_g that are used to independently tune both the quality of the input match and its center frequency respectively as shown in Fig. 2.

The second technique allows to control the output match quality and its center frequency. The idea was to introduce a variable resistance R_{tune} and a variable capacitance C_{tune} located in series between the cascode transistor drain M_2 and the load impedance R_L to control the output match quality and its center frequency respectively as shown in Fig. 2.

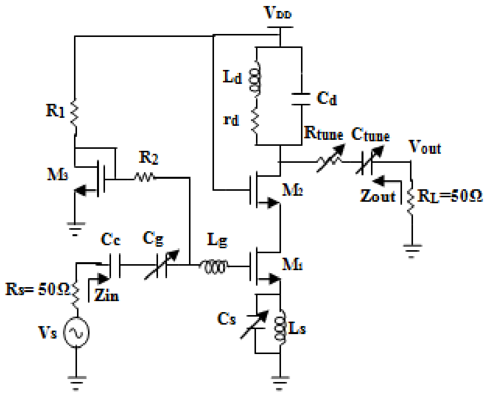


Figure 2. LNA scheme with the control elements C_s, C_g, R_{tune} and C_{tune}.

A. *Input Match Quality and Its Center Frequency Control Technique*

From Fig. 2, the expression of the input impedance is given by (4):

$$Z_{in} = j\left(\omega L_g + \frac{\omega L_s}{1-\omega^2 L_s C_s} - \frac{1}{\omega C_{tot}}\right) + \frac{g_m L_s}{(1-\omega^2 L_s C_s)C_{gs}} \qquad (4)$$

where C_{tot} is the equivalent capacitance of the association in series of C_g and C_{gs}, it is expressed by:

$$\frac{1}{C_{tot}} = \frac{1}{C_g} + \frac{1}{C_{gs}} \qquad (5)$$

Equation (4) shows that the real part of the input impedance depends on C_s and not on C_g. Then, when we tune the input match center frequency by sweeping C_g, the input match quality is not influenced. The technique proposed in Ref. [10] uses a variable capacitance C_d in parallel with C_{gs} to control the input match center frequency and a variable capacitance C_s in parallel with the inductance L_s to tune the input match quality. Nevertheless, the input match quality can be affected when C_d varies.

To obtain the resonance frequency expression, we take the input impedance imaginary part equal to zero. We find four solutions; two negative solutions that are discarded and two positive solutions that are given by (6):

$$\omega_{0,l,h} = \frac{1}{\sqrt{2}}\sqrt{\left(\frac{1}{L_s C_s} + \frac{1}{L_g C_s} + \frac{1}{L_g C_{tot}}\right) \pm \frac{\sqrt{\Delta}}{L_g L_s C_s C_{tot}}} \qquad (6)$$

where

$$\Delta = \left(L_g\, C_{tot} + L_s\, C_{tot} + L_s\, C_s\right)^2 - 4\left(L_g L_s C_s C_{tot}\right) \qquad (7)$$

Equation (6) indicates a lower frequency $\omega_{0,l}$ and a higher frequency $\omega_{0,h}$. The system of equations formed by the input impedance real part equal to 50Ω and the higher resonance frequency equal to 2.45GHz does not admit solutions. Thus, the higher frequency $\omega_{0,h}$ is rejected. The used resonance frequency is given by (8):

$$f_0 = \frac{1}{2\pi\sqrt{2}}\sqrt{\left(\frac{1}{L_s C_s} + \frac{1}{L_g C_s} + \frac{1}{L_g C_{tot}}\right) - \frac{\sqrt{\Delta}}{L_g L_s C_s C_{tot}}} \qquad (8)$$

The elements C_{tot}, C_s, L_g and L_s are sized to provide 2.45GHz center frequency associated with 2.4 – 2.485GHz band and an input match equal to 50Ω.

Fig. 3 shows the curves of the resonance frequency f_0 versus the two capacitances C_{tot} and C_s. It is clear that the resonance frequency depends greatly on C_{tot} and very faintly on C_s. Thus, C_{tot} is a fine mean to control the input match center frequency. Furthermore, the control of the input match quality by C_s does not affect the center frequency of the input match.

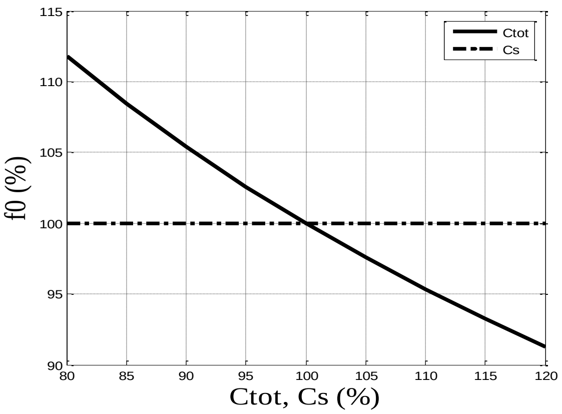
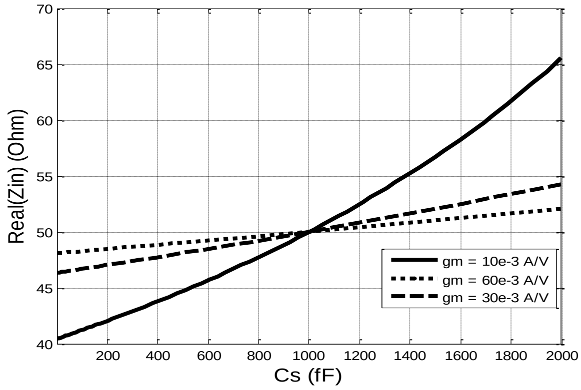


Figure 3. The plots of the resonance frequency f_0 versus the two capacitances C_{tot} and C_s.

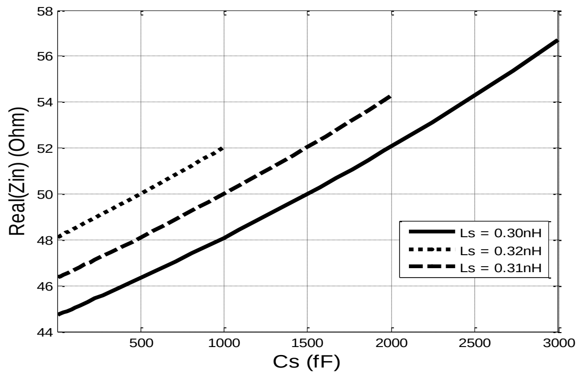
At the resonance frequency, the input impedance is equal to the real part and it is expressed by:

$$Z_{in,\omega 0} = \mathrm{Real}(Z_{in}) = \frac{g_m\, L_s}{\left(1 - \omega_0^2\, L_s C_s\right) C_{gs}} \qquad (9)$$

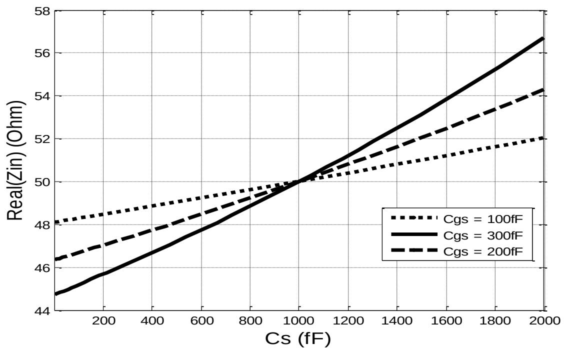
Equation (9) indicates that the input impedance depends on g_m, L_s, C_{gs}. Fig. 4(a), Fig. 4(b) and Fig. 4(c) present respectively the curves of the input impedance real part versus C_s for different values of g_m, L_s and C_{gs}.



(a)



(b)



(c)

Figure 4. Input impedance Curves versus the capacitance C_s (C_s start from 10fF):

(a) for different values of g_m. (b) for different values of L_s. (c) for different values of C_{gs}.

Fig. 4(a), Fig. 4(b) and Fig. 4(c) indicate that the control range of the input match quality using C_s depends on g_m, L_s and C_{gs} respectively. This range becomes wider if L_s decreases, g_m lessens or C_{gs} increases.

B. Output Match Quality and Its Center Frequency Control Technique

The scheme of the output matching network of the LNA is presented in the Fig. 5. The LNA output impedance Z_{out} is composed of the control elements R_{tune} and C_{tune}, a load capacitance C_d, a load inductance L_d in series with the load resistance r_d, and an equivalent parasitic capacitance C_p of the cascode structure constituted of the transistors M_1 and M_2. The output impedance is given by (10):

$$Z_{out} = Real(Z_{out}) + jImag(Z_{out}) \tag{10}$$

where the $Real(Z_{out})$ and the $Imag(Z_{out})$ are respectively the real and imaginary part, given by (11) and (12) respectively.

$$Real(Z_{out}) = R_{tune} + \frac{r_d}{\left(1-\omega^2 C_t L_d\right)^2 + \left(\omega r_d C_t\right)^2} \tag{11}$$

$$Imag(Z_{out}) = \frac{\omega L_d \left(1-\omega^2 C_t L_d\right) - \omega r_d{}^2 C_t}{\left(1-\omega^2 C_t L_d\right)^2 + \left(\omega r_d C_t\right)^2} - \frac{1}{\omega C_{tune}} \tag{12}$$

where C_t is the equivalent capacitance of the association in parallel of C_d and C_p. It is given by (13):

$$C_t = C_d + C_p \tag{13}$$

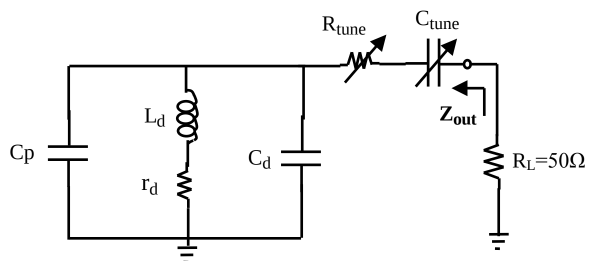


Figure 5. Output matching network Schematic.

The resonance frequency is obtained when the imaginary part is equal to zero. This results in four solutions; two positive solutions that are expressed by (14) and two negative solutions that are discarded:

$$\omega_{r,l,h} = \sqrt{\frac{-\beta \pm \sqrt{\delta}}{2\alpha}} \tag{14}$$

where α, β, δ are given by (15), (16) and (17) respectively.

$$\alpha = -C_{tune} C_t L_d{}^2 - \left(C_t L_d\right)^2 \tag{15}$$

$$\beta = C_{tune}\left(L_d - C_t\, r_d{}^2\right) + 2C_t L_d + \left(r_d C_t\right)^2 \tag{16}$$

$$\delta = \beta^2 - 4\alpha\lambda \tag{17}$$

where λ is equal to:

$$\lambda = -1 \tag{18}$$

Equation (14) indicates a higher frequency $\omega_{r,h}$ and a lower frequency $\omega_{r,l}$. The system of equations formed by the output impedance real part equal to 50Ω and the higher resonance frequency equal to 2.45GHz does not admit solutions. Then, the higher frequency $\omega_{r,h}$ is rejected. The used resonance frequency is given by (19):

$$f_r = \frac{1}{2\pi}\sqrt{\frac{-\beta + \sqrt{\delta}}{2\alpha}} \tag{19}$$

The elements of the output matching network R_{tune}, C_{tune}, C_d, L_d and r_d are sized to have an output match 50Ω at 2.45GHz operation frequency.

Equation (11) shows that the output impedance real part depends only on the control element R_{tune}. On the other hand, equation (12) indicates that the output impedance imaginary part depends only on the control element C_{tune}. Then, the resonance frequency depends on C_{tune} and not on R_{tune}. Accordingly, the control of the output match center frequency using C_{tune} has no effect on the output match quality and the output match quality control using R_{tune} doesn't affect the center frequency of the output match. Then, the tunings of the output match quality and its center frequency are performed separately.

III. Techniques Validation

In this part, we validated the proposed control techniques through simulation. We sized the LNA taking into account the control elements. The nominal values of these elements are determined in order to ensure an input and output match of 50Ω at 2.45GHz operation frequency. The LNA simulation is performed using 0.35µm CMOS technology. The circuit parameters at 2.45 GHz using nominal values of C_s, C_g, R_{tune} and C_{tune} are shown in Table I.

TABLE I. LNA Parameters at 2.45GHz

Parameters	Value
S_{21} (dB)	19.80
S_{11} (dB)	-56.23
Real(Zin) (Ω)	50.15
S_{22} (dB)	-53.65
Real (Zout) (Ω)	49.80
NF (dB)	1.93
CP_1 (dBm)	-21.43

A. Controlling the Input Match Quality

The capacitance C_s is swept around the nominal value 1000fF in the range of [10fF – 2000fF].

Fig. 6 shows the control of the input match S_{11} at 2.45GHz operation frequency by C_s. This control can be achieved between -33.12dB and -56.23dB. Then, for an input match quality alteration due to the undesirable factors, S_{11} can be calibrated until 23.11dB approximately. Also, it can be seen that the input match S_{11} reaches the lowest value at 2.45GHz when C_s tends to 1000fF. Fig. 7 shows the tuning of the real part of input impedance around 50Ω at 2.45GHz by C_s.

On the other hand, the study of the impact of the input match quality control on the other LNA parameters is necessary. Table II shows that the sweeping of C_s to tune the input match quality has no significant impact on the other parameters of the LNA: the gain, output match, noise figure and linearity.

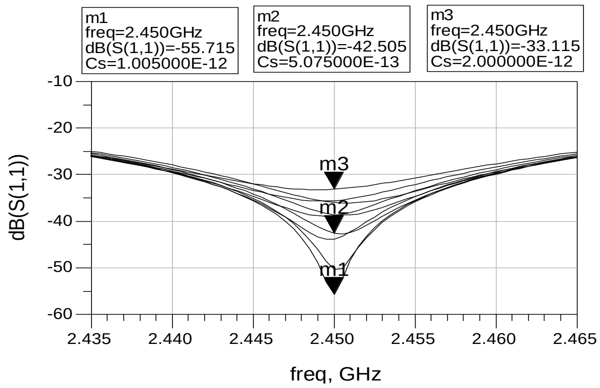


Figure 6. Controlling the parameter S_{11} using C_s at 2.45GHz.

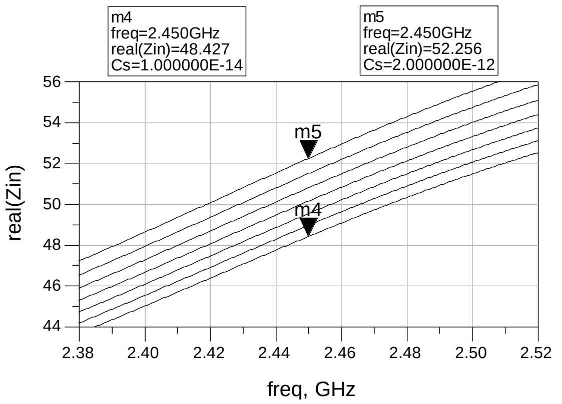


Figure 7. Controlling the input impedance real partaround 50Ω using C_s at 2.45GHz.

TABLE II. Impact of the Input Match Quality Control on the Other Parameters of the LNA at 2.45GHz

Parameters	Variation range
S_{21} (dB)	[19.63 , 19.95]
S_{22} (dB)	[-60.97 , -49.19]
Real (Zout) (Ω)	[49.66 , 49.91]
NF (dB)	[1.93 , 1.94]
CP_1 (dBm)	[-21.59 , -21.24]

B. Controlling the Input Match Center Frequency

The capacitance C_g is swept around the nominal value 425.16fF in the range of [319fF–532fF]. The latter is chosen so that the gain attenuation S_{21} does not exceed 1dB for all the values of C_g included in this range.

Fig. 8 shows the control of the input match center frequency by varying the capacitance C_g. This center frequency can be controlled between 2.361GHz and 2.603GHz. Thus, we obtain a tuning band of approximately 242MHz. Accordingly, for a shift of the input match center frequency caused by the undesirable factors, we can calibrate this center frequency up to about 242MHz.

From Fig. 9, it can be seen that the input match center frequency control by C_g has no impact on the input match quality.

On the other hand, Table III shows that the center frequency control by sweeping the capacitance C_g has no significant effect on the other LNA parameters.

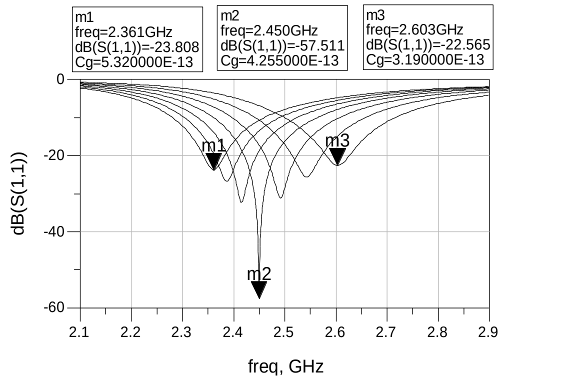


Figure 8. Controlling the S_{11} center frequency by means of C_g.

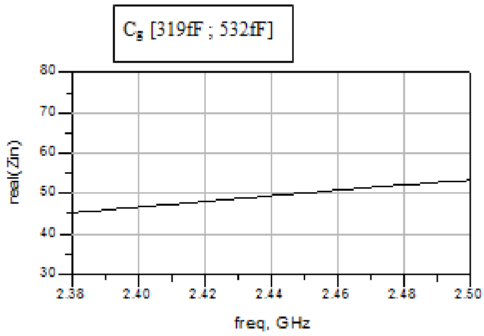


Figure 9. Not influence of C_g variation on the input match quality (C_g is swept between 319fF and 532fF)

TABLE III. Effect of the Input Match Center Frequency Control on the Other Parameters of the LNA at 2.45GHz

Parameters	Variation range
S_{21} (dB)	[18.81, 19.80]
S_{22} (dB)	[-53.77, -31.08]
Real (Zout) (Ω)	[47.50, 50.33]
NF (dB)	[1.67, 2.62]
CP_1 (dBm)	[-21.43 , -20.13]

C. Controlling the Output Match Quality

The resistance R_{tune} is swept around the nominal value 16Ω in the range [5Ω – 28Ω]. This range is chosen so that the gain attenuation S_{21} does not exceed 1dB for all the values of R_{tune} included in this range.

Fig. 10 shows the control of the output match S_{22} at 2.45GHz using R_{tune}. This control can be made between

-17.98dB and -53.65dB. Thus, for an output match quality variation due to the undesirable factors, S_{22} can be calibrated until 35.67dB roughly. Also, it can be seen that the output match S_{22} achieves the lowest value at 2.45GHz when R_{tune} tends to 16Ω. Fig. 11 shows the control of the output impedance real part using R_{tune} around 50Ω at 2.45GHz.

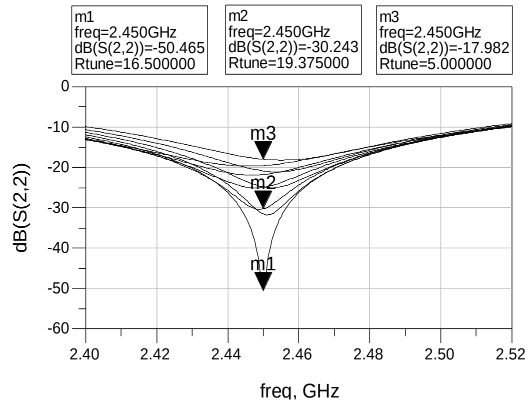


Figure 10. Controlling the parameter S_{22} using R_{tune} at 2.45GHz.

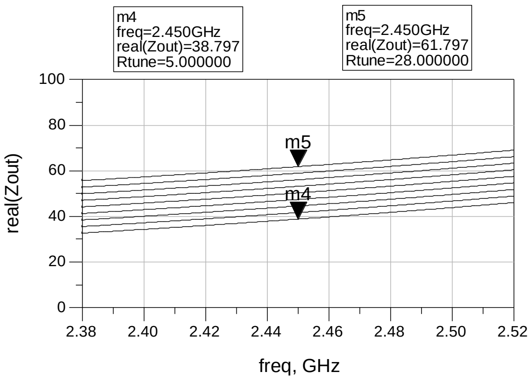


Figure 11. Controlling the output impedance real part using R_{tune} at 2.45GHz.

We have also studied the impact of the output match quality control on the other LNA parameters at 2.45GHz. This study is summarized in Table IV and shows that the output match quality control has no significant impact on the other LNA parameters at 2.45GHz.

TABLE IV. IMPACT OF THE OUTPUT MATCH QUALITY CONTROL ON THE OTHER LNA PARAMETERS AT 2.45GHZ

Parameters	Variation range
S_{21} (dB)	[18.82 , 20.82]
S_{11} (dB)	[-57.57 , -41.56]
Real (Zin) (Ω)	[49.65 , 50.74]
NF (dB)	[1.92 , 1.94]
CP_1 (dBm)	[-20.30 , -22.6]

D. Controlling the Output Match Center Frequency

The sweeping range of the capacitance C_{tune} about the nominal value 247.8fF is [208fF – 307fF]. This range is chosen so that the gain attenuation S_{21} does not exceed 1dB for all the values of C_{tune} included in this range.

Fig. 12 shows the control of the output match center frequency by sweeping the capacitance C_{tune}. This center frequency can be controlled between 2.336GHz and 2.540GHz. Hence, we obtain a control band of approximately 204MHz. Consequently, for a deviation of the output match center frequency caused by the undesirable factors, we can calibrate this center frequency until about 204MHz.

From Fig. 13, it can be seen that the output impedance real part is independent from C_{tune}, as we obtained solely one curve of real(Z_{out}) as C_{tune} is tuned between 208fF and 307fF. Thus, the control of the output match center frequency by C_{tune} does not affect the output match quality.

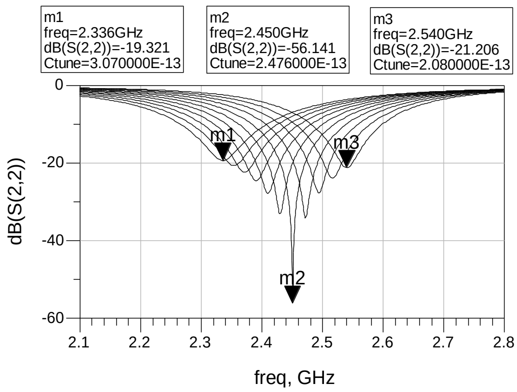


Figure 12. Controlling the S22 center frequency by means of Ctune.

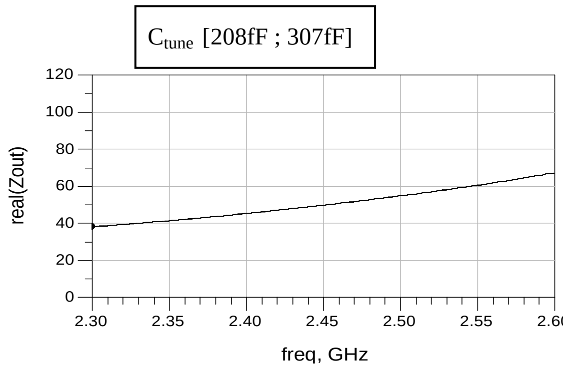


Figure 13. No influence of C_{tune} variation on the output match quality(C_{tune} is swept between 208fF and 307fF)

We have studied the impact of the output match center frequency control on the other LNA parameters at 2.45GHz. This impact is shown in Table V. We can conclude that the output match center frequency control has no important impact on the other LNA parameters at 2.45GHz.

TABLE V. IMPACT OF THE OUTPUT MATCH CENTER FREQUENCY CONTROL ON THE OTHER PARAMETERS OF THE LNA AT 2.45GHZ

Parameters	Variation range
S_{21} (dB)	[18.81, 19.80]
S_{11} (dB)	[-56.71, -31.48]
Real (Zin) (Ω)	[47.87, 50.69]
NF (dB)	No change [1.93, 1.93]
CP_1 (dBm)	[-21.5, -19.03]

IV. CONCLUSION AND FUTURE WORKS

This paper presented two techniques to control the input match and the output match of an inductively degenerated LNA. The simulation results show a control of the input match S_{11} between -33.12dB and -56.23dB. The input match center frequency can be controlled between 2.361GHz and 2.603GHz. The control of the output match S_{22} can be achieved between -17.98dB and -53.65dB. The center frequency of the output match can be controlled between 2.336GHz and 2.540GHz. We also demonstrated that the controls of these performances are made in an independent way. Besides, these controls have no significant effects on the other LNA parameters at 2.45GHz. Therefore, the methodology of the control shows the advantage of this proposed controllable circuit.

These techniques are validated theoretically and through simulation using ideal tuning elements. As future works, we propose the implementation of these control elements. However, the implemented control elements contain parasitic elements that might affect the LNA performances. For this reason, we will use these techniques to compensate the LNA parameters shifts caused by these parasitic elements.

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