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 blocks. 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:

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

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

\[
Z_{in} = \frac{g_m L_s}{C_{gs}} \quad (2)
\]

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

\[
f_0 = \frac{1}{2\pi \sqrt{(L_s + L_g)C_{gs}}} \quad (3)
\]

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 match 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 \( L_s, g_m \) and \( L_c \) 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 \( C_g \) and \( C_s \) 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 1. Common-source inductive degeneration LNA circuit.](image1)

![Figure 2. LNA scheme with the control elements \( C_g, C_s, R_{tune} \) and \( C_{tune} \).](image2)

A. Input Match Quality and Its Center Frequency Control Technique

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

\[
Z_{in} = \left[ \frac{\omega L_s}{\omega C_{gs}} \right] + \frac{\omega L_s}{\omega C_{tot}} \left[ \frac{1}{\omega^2 L_c C_{gs}} \right] + \frac{g_m L_s}{\omega C_{tot}} \left[ \frac{1}{\omega^2 L_c C_{gs}} \right] \quad (4)
\]

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

\[
\frac{1}{C_{tot}} = \frac{1}{C_g} + \frac{1}{C_{gs}} \quad (5)
\]

Equation (4) shows that the real part of the input impedance depends on \( C_g \) and not on \( C_{gs} \). 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 \( C_c \) 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):

\[
\omega_{0,1,2} = \frac{1}{\sqrt{2}} \sqrt{\left( \frac{1}{L_{C}C_{s}} + \frac{1}{L_{g}C_{s}} + \frac{1}{L_{g}C_{tot}} \right) - \Delta}
\]  
\(6\)

where
\[
\Delta = \left( L_{g} C_{tot} + L_{s} C_{tot} + L_{s} C_{s} \right)^{2} - 4 \left( L_{g} L_{s} C_{tot} \right)
\]  
\(7\)

Equation (6) indicates a lower frequency \(\omega_{0,1}\) and a higher frequency \(\omega_{0,2}\). 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 \(\omega_{0,2}\) is rejected.

The used resonance frequency is given by (8):

\[
f_{0} = \frac{1}{2\pi\sqrt{2}} \sqrt{\left( \frac{1}{L_{C}C_{s}} + \frac{1}{L_{g}C_{s}} + \frac{1}{L_{g}C_{tot}} \right) - \Delta}
\]  
\(8\)

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.

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

\[
Z_{in,0,0} = \text{Real}(Z_{in}) = \frac{g_{m} L_{s}}{1 - \omega_{0}^{2} L_{s} C_{s} C_{gs}}
\]  
\(9\)

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 \(C_{gs}\).

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 \(C_{l}\), a load inductance \(L_{l}\) in series with the load resistance \(r_{L}\), and an equivalent parasitic capacitance \(C_{p}\) of
the cascode structure constituted of the transistors M₁ and M₂. The output impedance is given by (10):

\[ Z_{out} = \text{Real}(Z_{out}) + j\text{Imag}(Z_{out}) \]  

(10)

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

\[ \text{Real}(Z_{out}) = R_{\text{tune}} + \frac{r_d}{[1 - \omega^2 C_L L_d] + \omega C_d} \]  

(11)

\[ \text{Imag}(Z_{out}) = \frac{\alpha C_{\text{tune}} (1 - \omega^2 C_L L_d - \omega t_d C_i) + \omega^2 C_d}{[1 - \omega^2 C_L L_d] + \omega C_d} - \frac{1}{\omega C_{\text{tune}}} \]  

(12)

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

\[ C_i = C_d + C_p \]  

(13)

The resonance frequency is obtained when the imaginary part is equal to zero. This results in four solutions. Then, the higher frequency resonance frequency equal to 2.45GHz does not admit two positive solutions that are expressed by (14) and two negative solutions that are discarded:

\[ \omega_{h, l, b} = \sqrt{-\frac{\beta \pm \sqrt{\delta}}{2\alpha}} \]  

(14)

where \( \alpha, \beta, \delta \) are given by (15), (16) and (17) respectively.

\[ \alpha = -C_{\text{tune}} C_i L_d^2 - (C_i L_d)^2 \]  

(15)

\[ \beta = C_{\text{tune}} (L_d - C_i t_d)^2 + 2 C_i L_d + (t_d C_i)^2 \]  

(16)

\[ \delta = \beta^2 - 4\alpha \lambda \]  

(17)

where \( \lambda \) is equal to:

\[ \lambda = -1 \]  

(18)

Equation (14) indicates a higher frequency \( \omega_{h, b} \) and a lower frequency \( \omega_{l, l} \). 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 \( \omega_{h, b} \) is rejected. The used resonance frequency is given by (19):

\[ f_r = \frac{1}{2\pi} \sqrt{-\frac{\beta + \sqrt{\delta}}{2\alpha}} \]  

(19)

The elements of the output matching network \( R_{\text{tune}}, C_{\text{tune}}, C_d, L_d \) 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 \( R_{\text{tune}} \). On the other hand, equation (12) indicates that the output impedance imaginary part depends only on the control element \( C_{\text{tune}} \). Then, the resonance frequency depends on \( C_{\text{tune}} \) and not on \( R_{\text{tune}} \). Accordingly, the control of the output match center frequency using \( C_{\text{tune}} \) has no effect on the output match quality and the output match quality control using \( R_{\text{tune}} \) 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 \( C_s, C_p, R_{\text{tune}} \) and \( C_{\text{tune}} \) are shown in Table I.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( S_{11} ) (dB)</td>
<td>19.80</td>
</tr>
<tr>
<td>( S_{11} ) (dB)</td>
<td>-56.23</td>
</tr>
<tr>
<td>Real(( Z_{in} )) (Ω)</td>
<td>50.15</td>
</tr>
<tr>
<td>( S_{22} ) (dB)</td>
<td>-53.65</td>
</tr>
<tr>
<td>Real(( Z_{out} )) (Ω)</td>
<td>49.80</td>
</tr>
<tr>
<td>NF (dB)</td>
<td>1.93</td>
</tr>
<tr>
<td>CP₁ (dBm)</td>
<td>-21.43</td>
</tr>
</tbody>
</table>

A. Controlling the Input Match Quality

The capacitance \( C_i \) 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 \( C_i \). 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 \( C_i \) tends to 1000fF. Fig. 7 shows the tuning of the real part of input impedance around 50Ω at 2.45GHz by \( C_i \).

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 \( C_i \) 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.

\[
\begin{array}{l}
\text{freq, GHz} \\
\text{dB(S(1,1))} \\
\text{m1} \\
\text{freq=2.450GHz} \\
\text{dB(S(1,1))=-55.71} \\
\text{Cs=1.005000E-12} \\
\text{2.450GHz} \\
\text{m2} \\
\text{freq=2.450GHz} \\
\text{dB(S(1,1))=-42.50} \\
\text{Cs=5.075000E-13} \\
\text{2.450GHz} \\
\text{m3} \\
\text{freq=2.450GHz} \\
\text{dB(S(1,1))=-33.11} \\
\text{Cs=2.000000E-12} \\
\end{array}
\]

Figure 6. Controlling the parameter \( S_{11} \) using \( C_g \) at 2.45GHz.

\[
\begin{array}{l}
\text{freq, GHz} \\
\text{real(Zin)} \\
\text{m4} \\
\text{freq=2.450GHz} \\
\text{real(Zin)=48.39} \\
\text{Cs=1.000000E-14} \\
\text{2.450GHz} \\
\text{m5} \\
\text{freq=2.450GHz} \\
\text{real(Zin)=52.22} \\
\text{Cs=2.000000E-12} \\
\end{array}
\]

Figure 7. Controlling the input impedance real part around 50Ω using \( C_g \) at 2.45GHz.

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.

C. Controlling the Output Match Quality

The resistance \( R_{\text{tune}} \) is swept around the nominal value 16Ω in the range [5Ω – 28Ω]. This range is chosen so that the gain attenuation \( S_{22} \) does not exceed 1dB for all the values of \( R_{\text{tune}} \) included in this range.

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

\[
\begin{array}{l}
\text{freq, GHz} \\
\text{real(Zin)} \\
\text{m4} \\
\text{freq=2.361GHz} \\
\text{real(Zin)=23.808} \\
\text{Cg=5.320000E-13} \\
\text{2.361GHz} \\
\text{m5} \\
\text{freq=2.450GHz} \\
\text{real(Zin)=52.256} \\
\text{Cg=4.255000E-13} \\
\text{2.450GHz} \\
\text{m6} \\
\text{freq=2.603GHz} \\
\text{real(Zin)=3.190000E-13} \\
\text{Cg=3.190000E-13} \\
\end{array}
\]

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

\[
\begin{array}{l}
\text{freq, GHz} \\
\text{real(Zin)} \\
\text{m4} \\
\text{freq=2.361GHz} \\
\text{real(Zin)=23.808} \\
\text{Cg=5.320000E-13} \\
\text{2.361GHz} \\
\text{m5} \\
\text{freq=2.450GHz} \\
\text{real(Zin)=52.256} \\
\text{Cg=4.255000E-13} \\
\text{2.450GHz} \\
\text{m6} \\
\text{freq=2.603GHz} \\
\text{real(Zin)=3.190000E-13} \\
\text{Cg=3.190000E-13} \\
\end{array}
\]

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

\[
\begin{array}{l}
\text{Parameters} \\
\text{Variation range} \\
S_{21} \text{ (dB)} \\
[19.63 , 19.95] \\
S_{22} \text{ (dB)} \\
[-60.97 , -49.19] \\
\text{Real (Zout) (Ω)} \\
[49.66 , 49.91] \\
\text{NF (dB)} \\
[1.93 , 1.94] \\
\text{CP}_1 \text{ (dBm)} \\
[-21.59 , -21.24] \\
\end{array}
\]

Table II: Impact of the Input Match Quality Control on the Other Parameters of the LNA at 2.45GHz

\[
\begin{array}{l}
\text{Parameters} \\
\text{Variation range} \\
S_{21} \text{ (dB)} \\
[18.81 , 19.80] \\
S_{22} \text{ (dB)} \\
[-53.77 , -31.08] \\
\text{Real (Zout) (Ω)} \\
[47.50 , 50.33] \\
\text{NF (dB)} \\
[1.67 , 2.62] \\
\text{CP}_1 \text{ (dBm)} \\
[-21.43 , -20.13] \\
\end{array}
\]

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

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-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 $R_{\text{tune}}$ tends to 16Ω. Fig. 11 shows the control of the output impedance real part using $R_{\text{tune}}$ around 50Ω at 2.45GHz.

D. Controlling the Output Match Center Frequency

The sweeping range of the capacitance $C_{\text{tune}}$ 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 $C_{\text{tune}}$ included in this range.

Fig. 12 shows the control of the output match center frequency by sweeping the capacitance $C_{\text{tune}}$. 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 $C_{\text{tune}}$, as we obtained solely one curve of real($Z_{\text{out}}$) as $C_{\text{tune}}$ is tuned between 208fF and 307fF. Thus, the control of the output match center frequency by $C_{\text{tune}}$ does not affect the output match quality.

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>
<thead>
<tr>
<th>Parameters</th>
<th>Variation range</th>
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<tr>
<td>$S_{21}$ (dB)</td>
<td>[18.82, 20.82]</td>
</tr>
<tr>
<td>$S_{11}$ (dB)</td>
<td>[-57.57, -41.56]</td>
</tr>
<tr>
<td>Real ($Z_{\text{in}}$) (Ω)</td>
<td>[49.65, 50.74]</td>
</tr>
<tr>
<td>NF (dB)</td>
<td>[1.92, 1.94]</td>
</tr>
<tr>
<td>CP$_1$ (dBm)</td>
<td>[-20.30, -22.6]</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Variation range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_{21}$ (dB)</td>
<td>[18.81, 19.80]</td>
</tr>
<tr>
<td>$S_{11}$ (dB)</td>
<td>[-56.71, -31.48]</td>
</tr>
<tr>
<td>Real ($Z_{in}$) (Ω)</td>
<td>[47.87, 50.69]</td>
</tr>
<tr>
<td>NF (dB)</td>
<td>No change [1.93, 1.93]</td>
</tr>
<tr>
<td>$CP_1$ (dBm)</td>
<td>[-21.5, -19.03]</td>
</tr>
</tbody>
</table>

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.

REFERENCES