

MEEC/MIEEC

RADIO FREQUENCY ELECTRONICS

Low Noise Amplifier - Part I

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1 Introduction

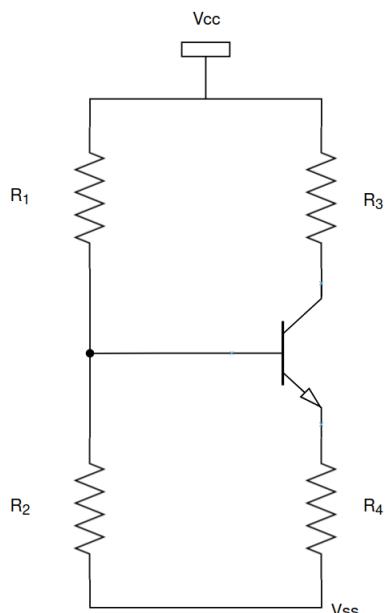
This report presents the design and analysis of a Low Noise Amplifier (LNA) designed to operate in the ISM (Industrial, Scientific and Medical) band. In modern telecom systems, LNAs play a crucial role in dealing with low amplitude signals at high frequencies with high data rates. During the development of this project, advanced RF design concepts were explored, including the use of adaptive loops for impedance, stability, gain and noise within the specified frequency range (3-6 GHz). The challenges faced, and the solutions adopted are detailed in this report.

The aim of this report is to comprehensively document the process of designing and analyzing a Low Noise Amplifier (LNA) for operation in the ISM band, with a focus on achieving critical performance specifications. The circuit will have to be designed following certain detailed specifications, starting by designing a suitable polarization network for the transistor, taking into account the effects of encapsulation.

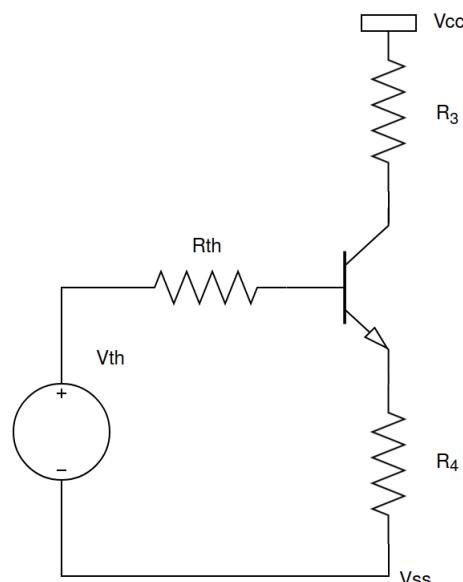
2 Design of the LNA

2.1 Transistor Bias Network

The DC bias point of a transistor directly influences its small-signal S-parameters, and hence the gain, noise figure and stability of the LNA. This makes this step crucial. Figure ?? shows the biasing circuit and its Thévenin equivalent used to simplify analysis.



(a) Transistor DC biasing circuit



(b) Bias circuit equivalent circuit

As shown in Figure 1b the Thévenin equivalent is given by the equations 1, replacing the R_1, R_2 voltage divider.

$$\begin{aligned} R_{TH} &= R_1 // R_2 \\ V_{TH} &= V_{cc} \frac{R_2}{R_1 + R_2} \end{aligned} \quad (1)$$

Using Kirchhoff voltage law, the equations 2 are derived, the first starts at V_{TH} goes through R_{TH} , V_{BE} and R_4 . The second goes from V_{CC} through R_3 , V_{CE} and R_4 .

$$\begin{cases} 0 = V_{TH} - I_b \cdot R_{TH} - V_{BE} - I_E \cdot R_4 \\ 0 = V_{CC} - R_3 \cdot I_C - V_{CE} - I_E \cdot R_4 \end{cases} \quad (2)$$

Solving the system of equations, assuming fixed values for R_2 and R_4 , originates the equations 3.

$$\begin{aligned} R_1 &= \frac{R_2 (-I_C R_4 \beta - I_C R_4 - V_{BE} \beta + V_{CC} \beta)}{I_C R_2 + I_C R_4 \beta + I_C R_4 + V_{BE} \beta} \\ R_3 &= \frac{-I_C R_4 \beta - I_C R_4 + V_{CC} \beta - V_{CE} \beta}{I_C \beta} \end{aligned} \quad (3)$$

The Table 1, shows the provided values for the biasing circuit and the fixed values for R_2 and R_4 .

Table 1: Transistor biasing parameters

Parameter	Value
R_2	1 kΩ
R_4	100 Ω
β	72.534
I_C	9 mA
V_{CC}	10 V
V_{BE}	1 V
V_{CE}	5 V

Resulting in $R_1 = 4 \text{ k}\Omega$ and $R_3 = 454 \Omega$.

2.2 S-parameters with packaging effects

With the biasing circuit designed, the next step was to simulate the S-parameters of the transistor in LTSpice. The S-parameters were taken for a frequency range of 1 GHz to 10 GHz, Figure 2 shows the S-parameters of the transistor without any matching network.

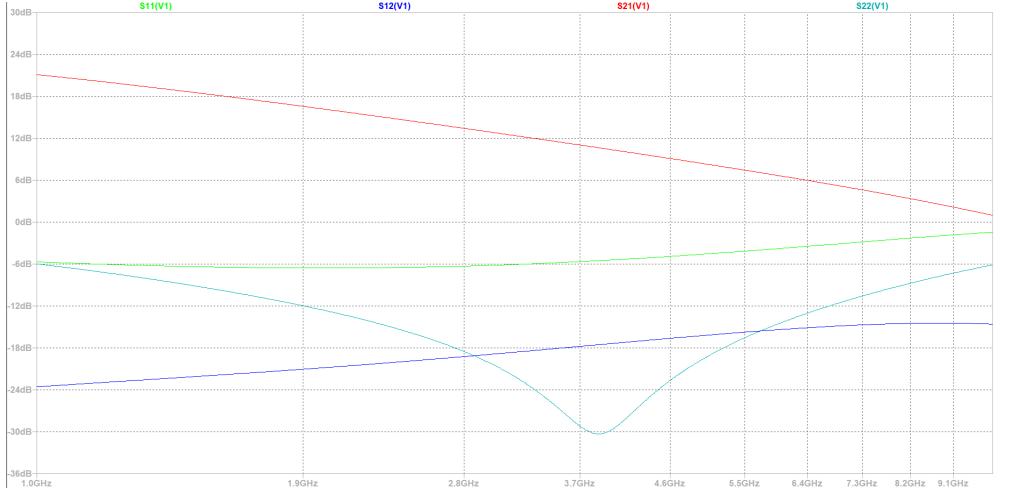


Figure 2: S-parameters of the transistor without matching network

2.3 Stability

Ensuring that the LNA remains stable is critical for reliable operation. The network is unconditionally stable for a frequency if for any source impedance value, $|\rho_{in}| < 1$ and for the load impedance $|\rho_{out}| < 1$. The stability circles can be used to determine regions for ρ_{in} and ρ_{out} where the amplifier circuit will be conditionally stable, but simpler tests can be used to determine unconditional stability.

Defining K as:

$$K = \frac{1 - |S_{11}|^2 - |S_{22}|^2 + |\Delta|^2}{2|S_{12} \cdot S_{21}|} \quad (4)$$

If:

- $K > 1$ and $|\Delta| < 1 \rightarrow$ unconditionally stable
- $K > 1$ and $|\Delta| > 1$ or $K < 1 \rightarrow$ potentially unstable or always unstable

Another criteria is the μ factor,

Defining μ as:

$$\mu = \frac{1 - |S_{11}|^2}{|S_{22} - \Delta S_{11}^*| + |S_{12} \cdot S_{21}|}$$

if $\mu > 1 \rightarrow$ unconditionally stable In addition, it can be said that larger values of μ imply greater stability.

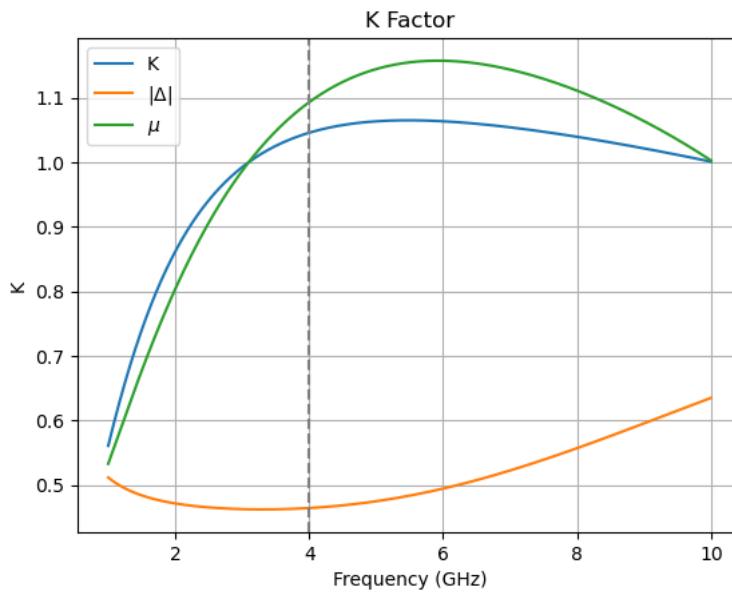


Figure 3: Stability tests

Figure 3, shows that the LNA is stable for frequencies above 3.1 GHz and above 10 GHz loses stability again.

At this stage another important figure is the Maximum Available Gain, MAG , which for the bilateral case can be expressed as the equation 5.

$$MAG = \left| \frac{S_{21}}{S_{12}} \right| \cdot [K \pm \sqrt{K^2 - 1}] \quad (5)$$

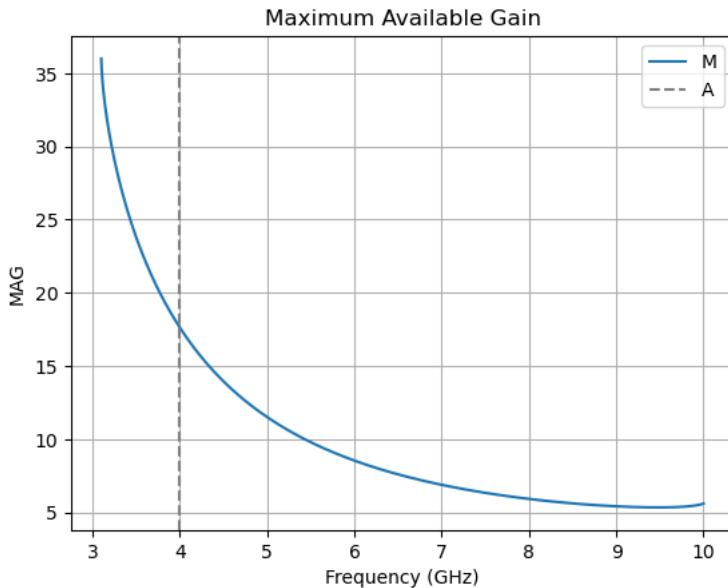


Figure 4: Maximum Available Gain

Now having the full picture of the LNA characteristics, an operating frequency can be decided. It is a compromise between stability and gain. The frequency chosen was 4 GHz.

2.4 Input and output matching networks for maximum gain

The adaptation for maximum gain is done using the line impedance transformation method. The input and output matching networks are designed to transform the input and output impedances of the transistor to the desired values, which are 50Ω in this case. In the Smith chart, the matching is done with inductors and capacitors and lines and stubs.

2.4.1 Matching with lumped elements

The matching networks are designed using the Smith chart, which allows for the visualization of the impedance transformation. The input and output impedances of the transistor are transformed to 50Ω using a combination of inductors and capacitors. The values of the components are also calculated using the equations for impedance transformation.

The matching using the Smith Chart for the input and output are shown in Figures 5 and 7, where the input and output impedances of the transistor are transformed to 50Ω using a combination of inductors and capacitors.

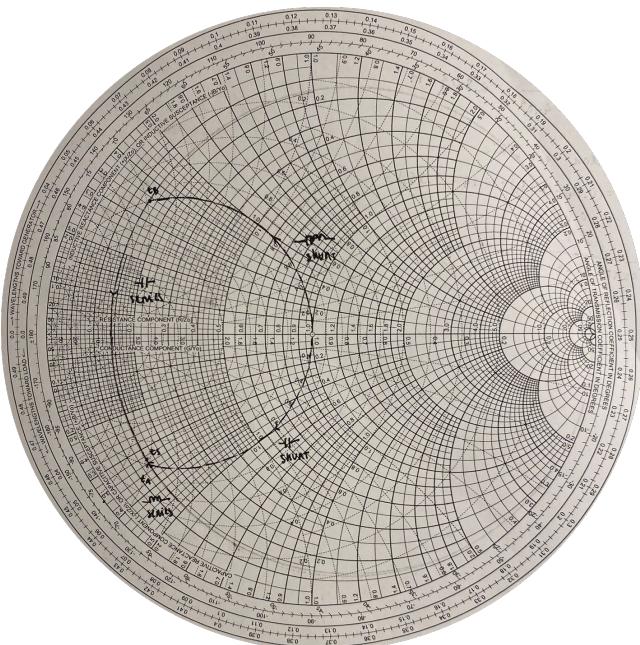


Figure 5: Smith chart for input matching with lumped elements

The adaptation mesh for the input was done with a shunt inductor and a series capacitor and the equivalent circuit is shown in Figure 6. The values of the components were also calculated using the equations for impedance transformation as a form of validation.

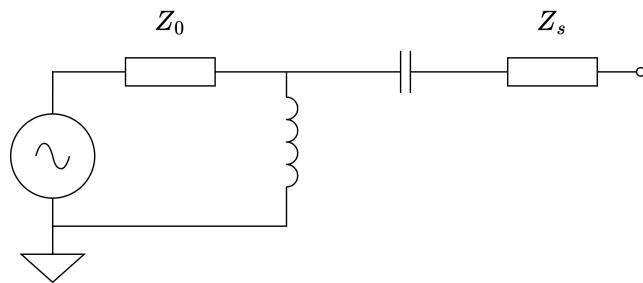


Figure 6: Matching circuit for input

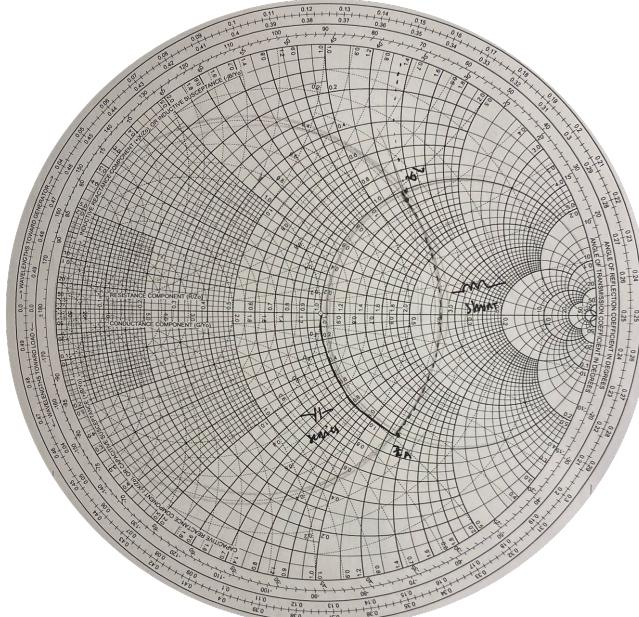


Figure 7: Smith chart for output matching with lumped elements

The adaptation mesh for the output is done with a series capacitor and a shunt inductor and the equivalent circuit is shown in Figure 8. The values of the components were also calculated using the equations for impedance transformation as a form of validation.

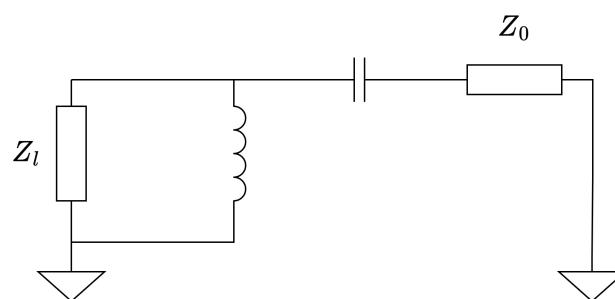


Figure 8: Matching circuit for output

The resulting circuit is shown in Figure 9, where the input and output matching networks are designed using a combination of inductors and capacitors.

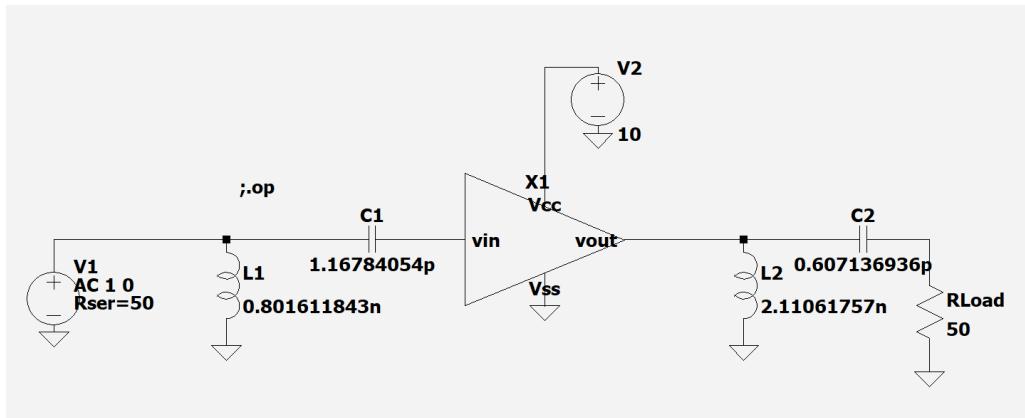


Figure 9: Matching circuit for input and output with values

2.4.2 Matching lines and stubs

The matching networks were also designed using transmission lines and stubs, this type of adaptation allows greater frequencies (more than 1 GHz) in real conditions. The input and output impedances of the transistor were transformed to 50Ω using a combination of transmission lines and stubs. The values of the components were also calculated using the equations for impedance transformation to validate the results.

The matching using the Smith Chart for the input and output are shown in Figures 10 and 11.

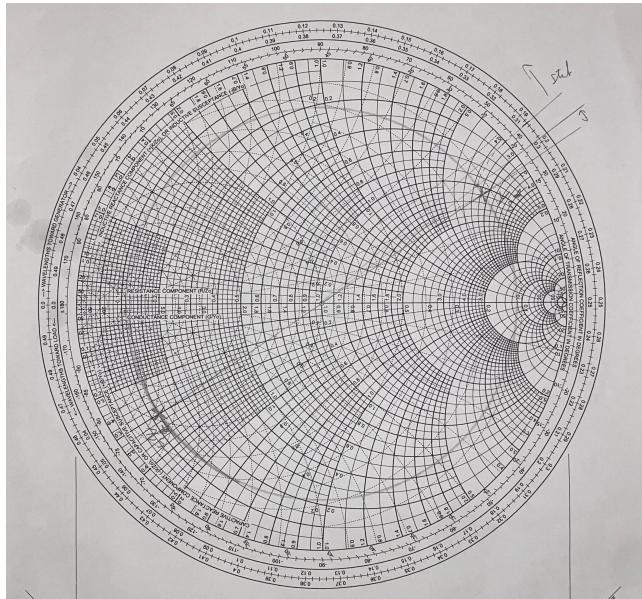


Figure 10: Smith chart for input matching with lines and stubs

The adaptation mesh for the input was done with an open circuit shunt stub and a series line.

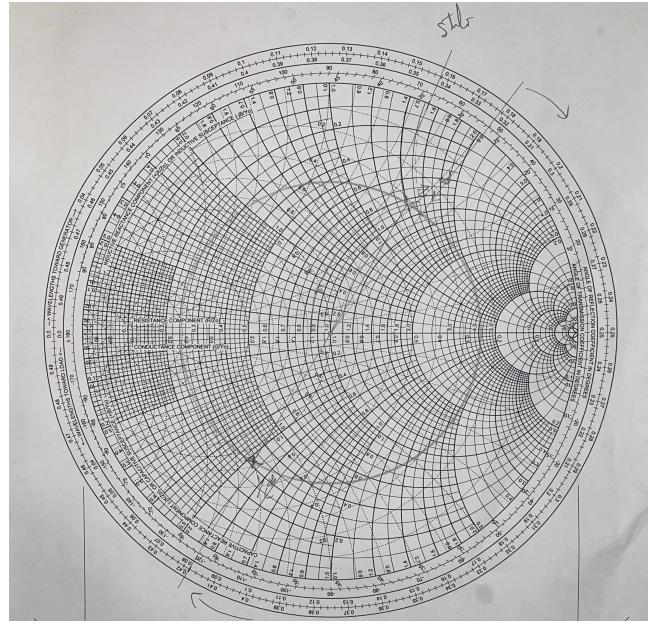


Figure 11: Matching circuit for input with lines and stubs

The adaptation mesh for the output is done with a series line and an open circuit shunt stub.

The final circuit is shown in Figure 12, where the input and output matching networks are designed using a combination of transmission lines and stubs.

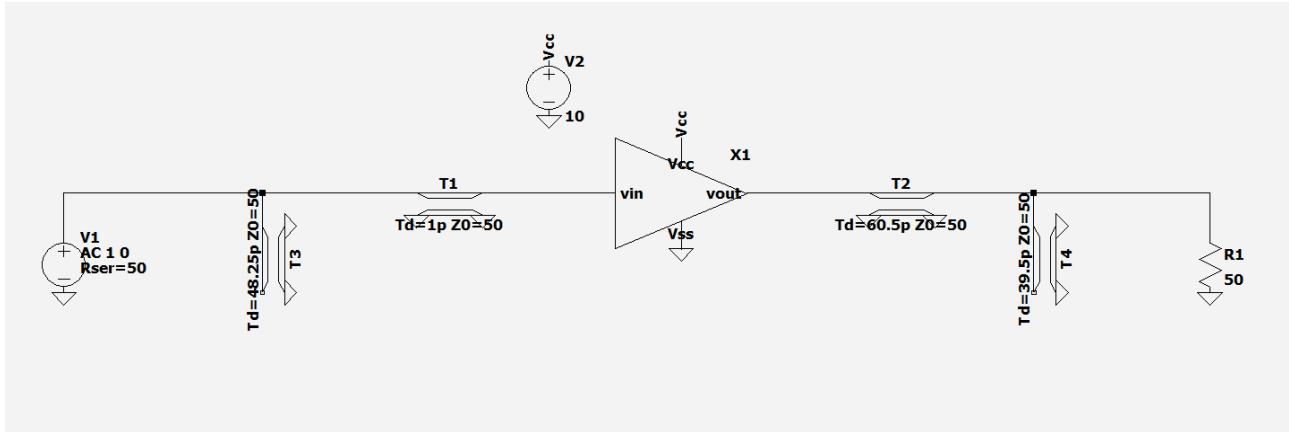


Figure 12: Matching circuit for input and output with values

3 Simulation

In this section, the simulations of the LNA and the corresponding matching networks will be presented.

3.1 Validation of the LNA design

First, using the LTSpice, the T502 transistor was added and the parasites capacitance and inductance of the package were considered, resulting in the simulated real transistor circuit in Figure 13.

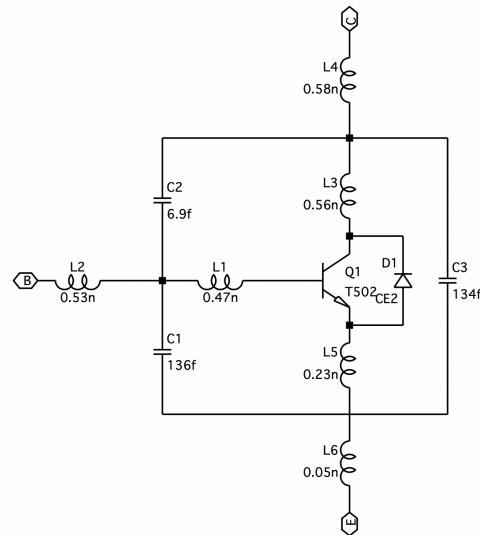


Figure 13: Transistor with package effects

After this, the biasing circuit of the transistor for the required parameters is present in Figure 14.

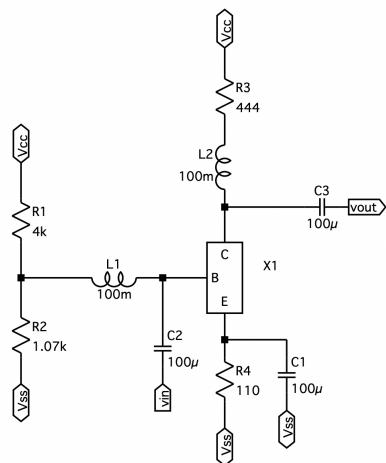


Figure 14: Biasing circuit simulated

After simulating the operation point of the previous circuit, the result for the required parameters is shown in Figure 15.

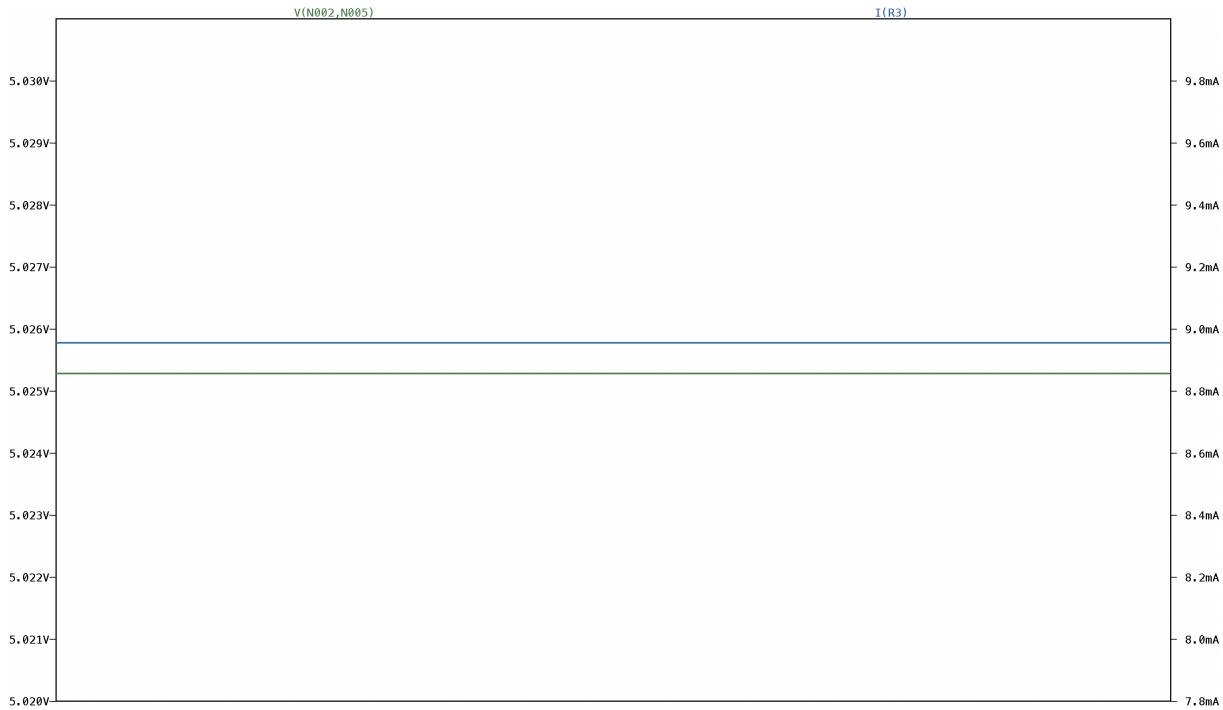


Figure 15: Result of the operation point simulation

After analyzing the previous graphic, it is possible to confirm that result parameters of the biasing circuit are within the required.

At the same time, the same circuit was implemented in Cadence, to ensure greater reliability of the results obtained. So, this circuit can be seen in Figure ??.



Figure 16: Biasing circuit simulated in Cadence

So the matching networks for the source and the load, both with an impedance of 50Ω , can be implemented.

3.2 Input and output matching networks design simulation

As mentioned before, the first step in designing a matching network in an LNA is to know the S-parameters of the amplifier circuit, so, switching to an AC analysis of the LNA circuit,

and adding both the source and the load, the simulated circuit is shown in Figure 17.

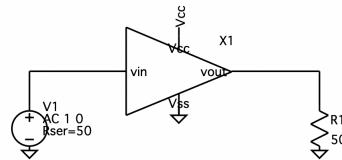


Figure 17: Circuit for the S-parameters

The resulting S-parameters can be seen in Figure 18.

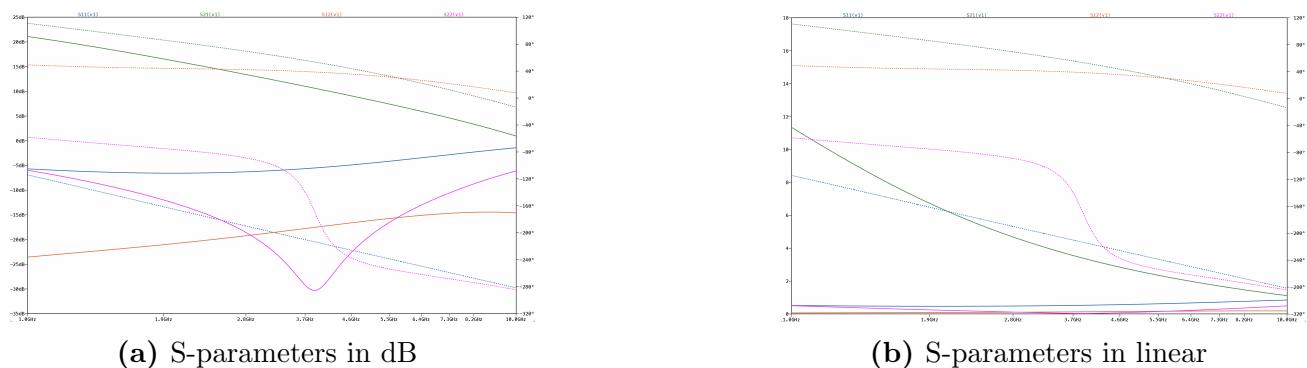


Figure 18: S-parameters of the LNA

After assuming a working frequency of 4GHz, the resulting matching networks using capacitors and inductors is exhibit in Figure 19.

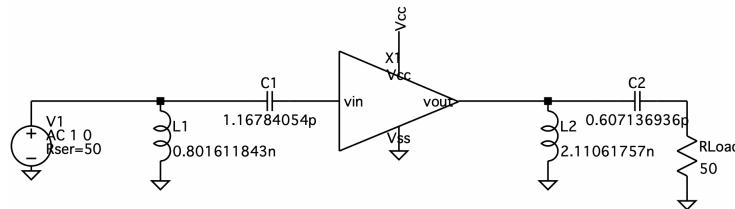


Figure 19: Matching networks using inductors and capacitors

Using again the same AC analysis, the S-parameters of new circuit using the capacitors and inductors matching networks is displayed in Figure 20.

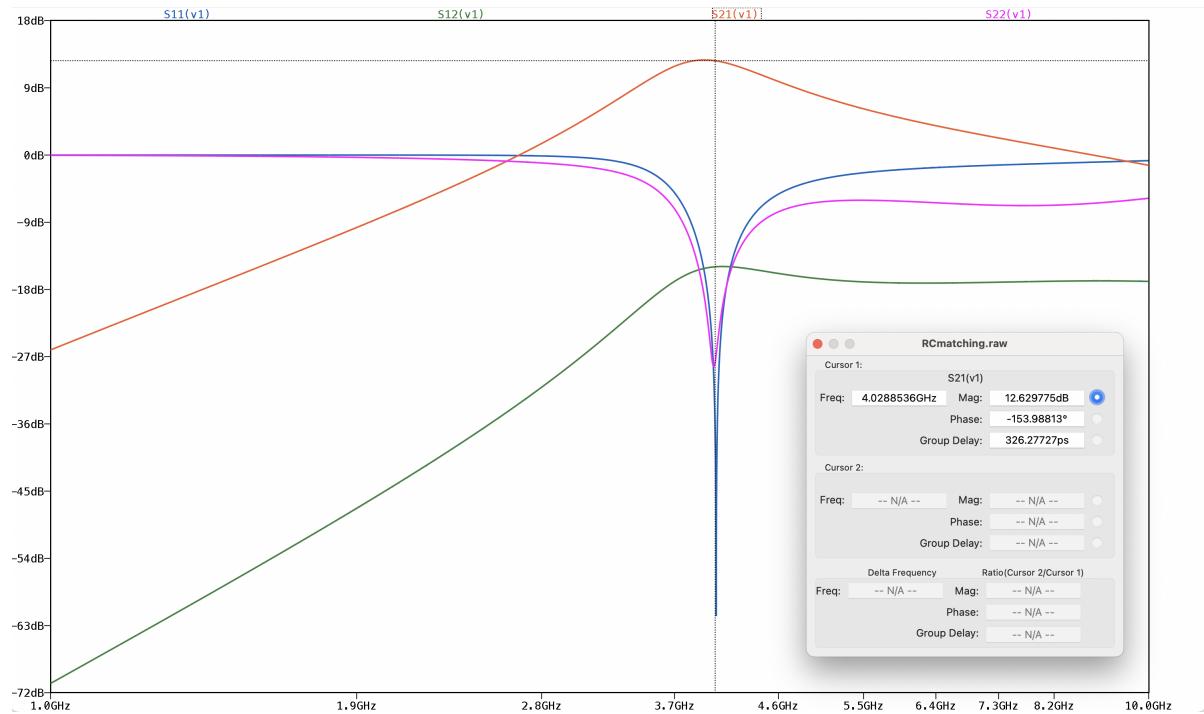


Figure 20: S-parameters for the matching networks using inductors and capacitors

After looking at the graphic above, it is possible to conclude that this matching network is working properly, since there is a sharp drop in both S_{11} and S_{22} at the desired frequency of $4GHz$ as well as a high point in the S_{21} curve.

In cadence, the circuit for the matching using inductors and capacitors is the following.

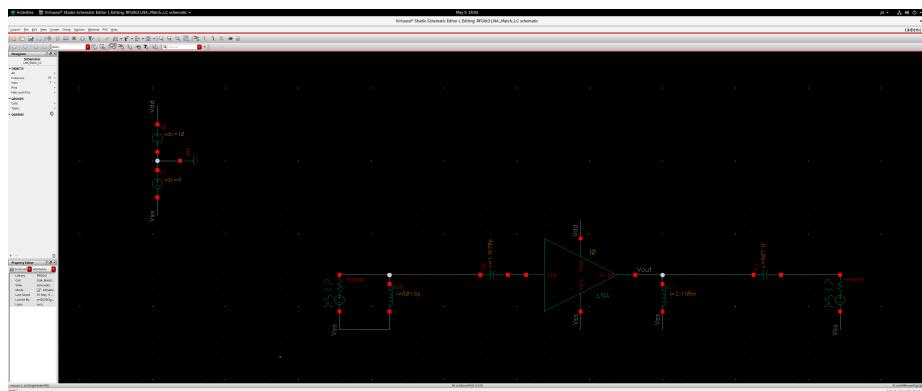


Figure 21: Matching networks using inductors and capacitors in Cadence

Simulating, the S-parameters of this circuit with the mentioned matching networks is visible in Figure 22.

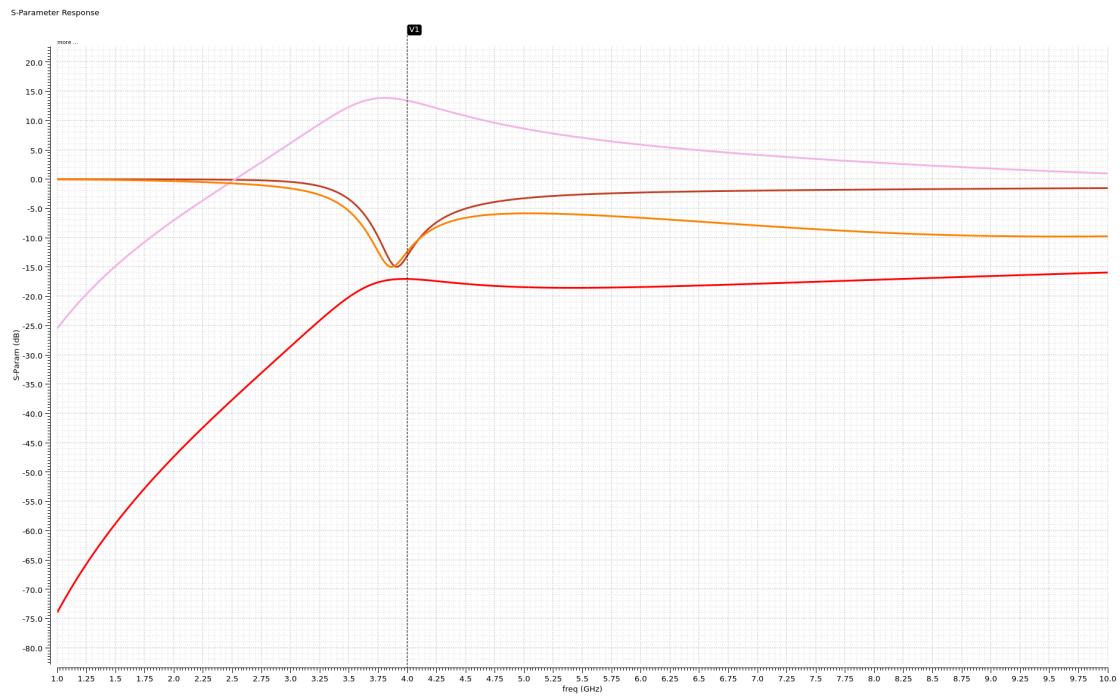


Figure 22: S-parameters for the matching networks using inductors and capacitors in Cadence

Passing to the matching networks using transmission lines and stubs, and using the same working frequency, the new LNA circuit is shown in Figure 23.

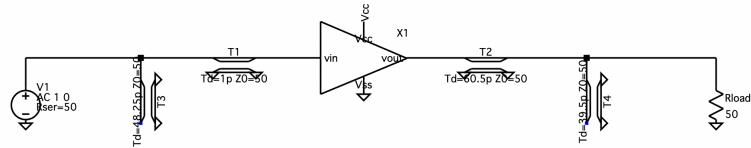


Figure 23: Matching networks using transmission lines and stubs

The S-parameters for this new matched circuit can be seen in Figure 24.

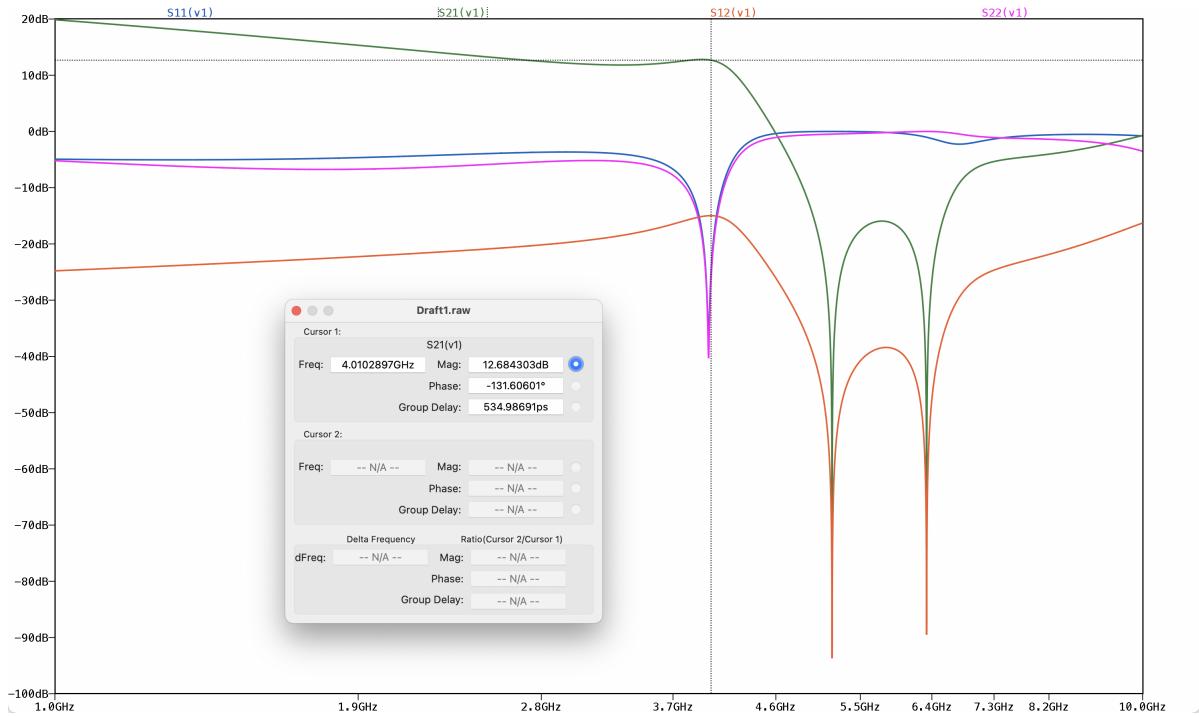


Figure 24: S-parameters for the matching networks using transmission lines and stubs

Similarly to the first matching networks, the drop in both S_{11} and S_{22} can also be seen, as well as the same approximated value of S_{21} , so, this matching network using transmission lines and stubs is correctly working.

In cadence, the circuit for the matching using transmission lines and stubs is the following.



Figure 25: Matching networks using transmission lines and stubs in Cadence

Simulating, the S-parameters of this circuit with the mentioned matching networks is visible in Figure 26.

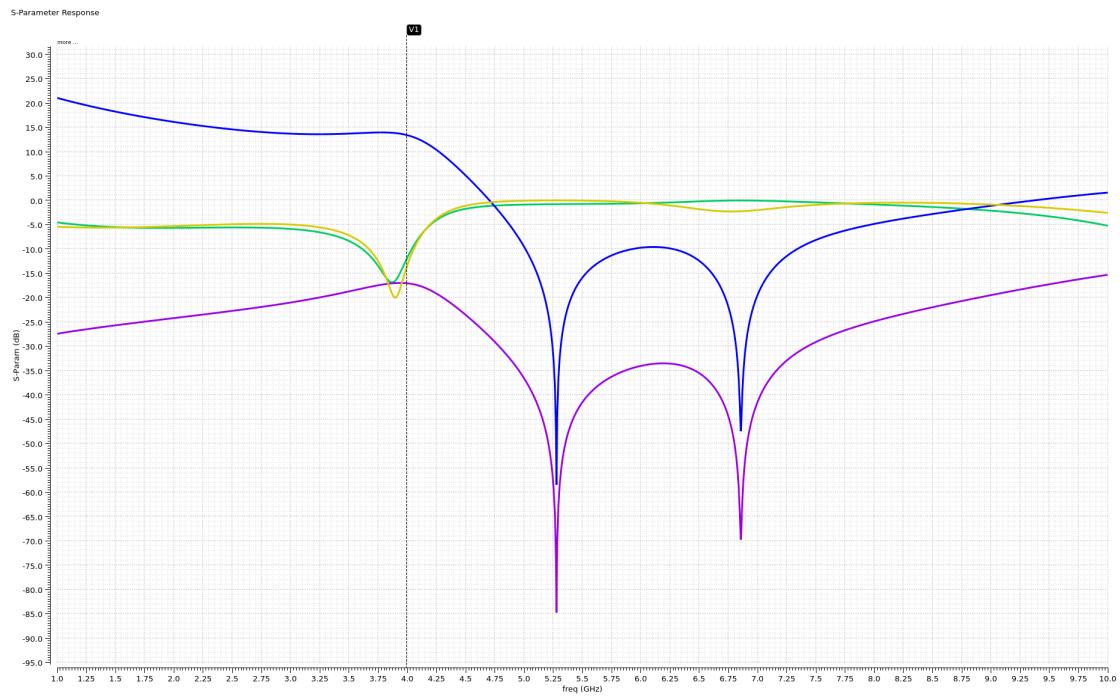


Figure 26: S-parameters for the matching networks using transmission lines and stubs in Cadence

3.3 Noise

To simulate the noise of each matching network, the Cadence was used, resulting in the graphic shown in Figure 27 for the inductors and capacitors.

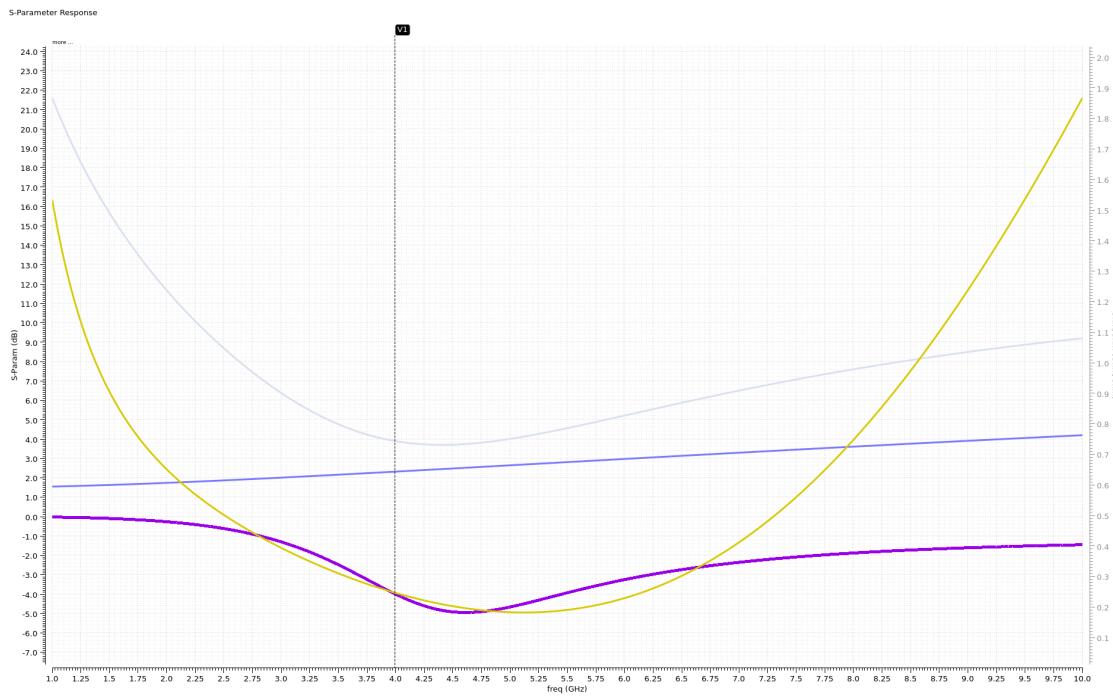


Figure 27: Noise for the matching networks using capacitors and inductors in Cadence

And for transmission lines and stubs in Figure 28.

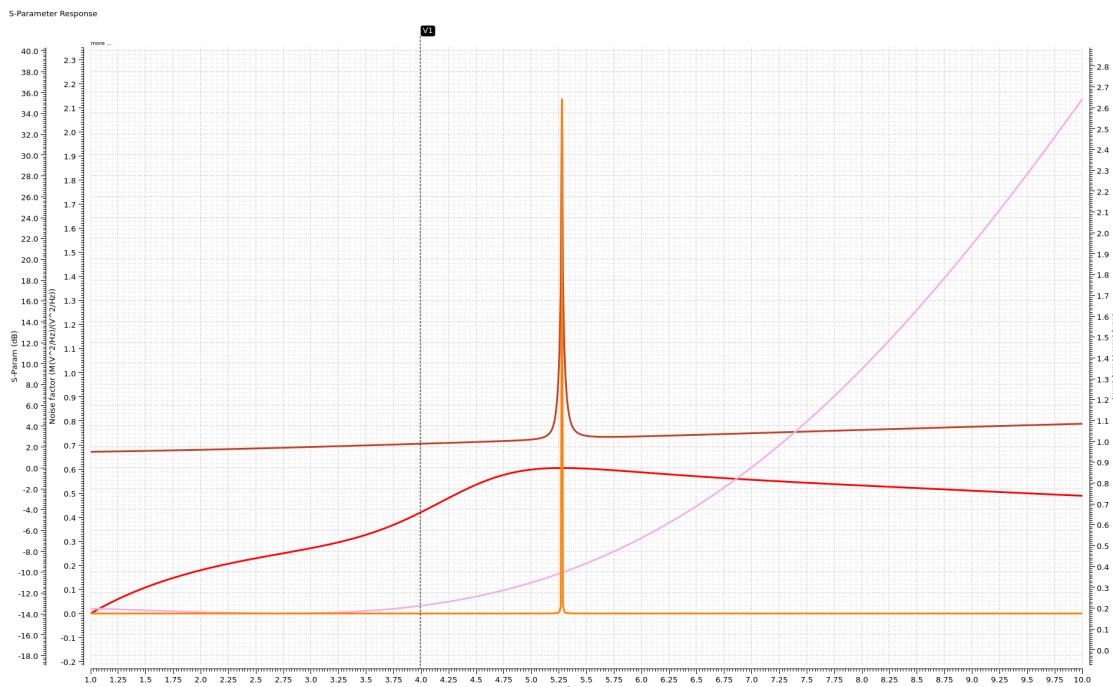


Figure 28: Noise for the matching networks using transmission lines and stubs in Cadence

4 Conclusion

The Cadence simulation were not what was expected because of an error in the initial transistor package circuit that effected the remaining project, but in LTspice, after correcting this mistake, all results were the expected for both matching networks. In second phase, the mistake will be corrected in Cadence as well.

References