Frequency analysis of RF circuits:
S parameters

1 Objectives

- Study of microstrip lines in order to understand the notions of characteristic impedance, effective relative permittivity and losses.
- Extract the characteristics (characteristic impedance, effective relative permittivity, attenuation constant, matching level) of transmission lines from S-parameters curves.
- Analysis of circuits based on stubs by using the S parameters.

2 Principles of vector network analysis

2.1 Overview of the Network Analyser

The harmonic behavior of radio frequency circuits is measured by means of the S-parameters which characterize the relative powers on each of the ports of the quadrupole (Figure 1). The vector network analyser is a system that makes it possible to obtain the S-parameters of linear quadrupoles and consequently to know their harmonic response. This device allows obtaining the magnitude and the phase of these parameters, unlike a scalar analyser which only gives the magnitude. In Figure 1, a_1, a_2, b_1 et b_2 represent waves (they are proportional to the square root of the power):

- a_1 et a_2 correspond to incoming waves (root of the injected power) on each port 1 and 2, respectively;
- b_1 et b_2 correspond to the outgoing waves (root of the outgoing power) on each port 1 and 2, respectively.

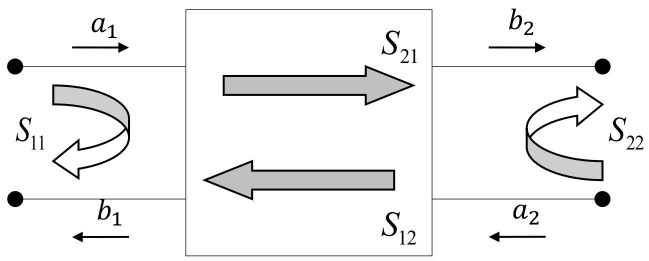


Figure 1. S parameters in a quadrupole.

Let us consider a wave a_1 injected on port 1:

- a part of this injected wave a_1 is transmitted through the quadrupole: this transmitted wave is called b_2. This wave b_2 is then transmitted towards the load :
  - if $a_2 = 0$, it means that all this wave b_2 is absorbed by the load and the quadrupole is matched on port 2.
  - if $a_2 \neq 0$, it means a part of this wave b_2 is reflected at the interface between the quadrupole and the load: the quadrupole is not matched on port 2.
- a part of this injected wave a_1 is reflected towards port 1 of the quadrupole: this reflected wave is called b_1.

The S parameters correspond to the reflection and transmission coefficients:

$S_{11} = \left[\frac{b_1}{a_1}\right]_{a_2=0}$	Reflection coefficient at port 1, port 2 being matched.	$S_{12} = \left[\frac{b_1}{a_2}\right]_{a_1=0}$	Transmission coefficient from port 2 to port 1, port 1 being matched.
$S_{21} = \left[\frac{b_2}{a_1}\right]_{a_2=0}$	Transmission coefficient from port 1 to port 2, port 2 being matched.	$S_{22} = \left[\frac{b_2}{a_2}\right]_{a_1=0}$	Reflection coefficient at port 2, port 1 being matched.

Figure 2 illustrates the interest of parameters *S*. When port 1 of a quadrupole is excited with an incident power P_{inc} (for example 1 Watt, to generalize), this power is partly transmitted to port 2. The part of transmitted power depends on the matching on port 1 (i.e. the reflection coefficient S_{11}). In the case of a lossless quadrupole, a part of the power is transmitted at the output of the quadrupole (on port 2), and another part is reflected back to the power source. **The transmitted part of the power corresponds to $|S_{21}|^2$ and the reflected part to $|S_{11}|^2$.**

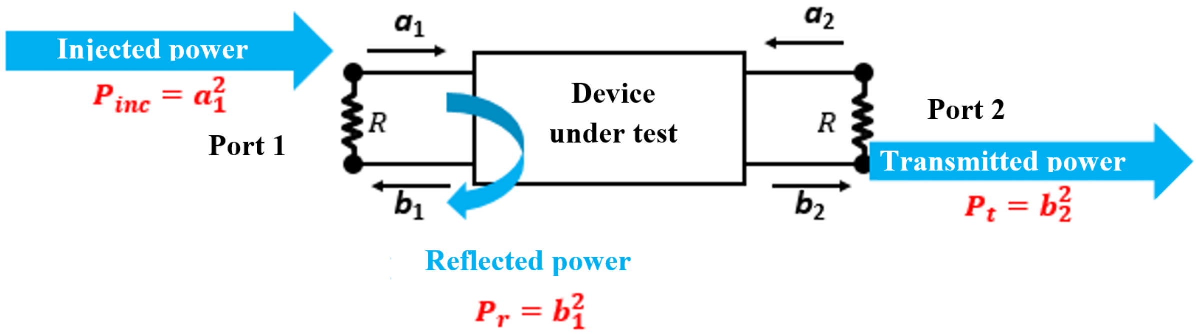


Figure 2. Power distribution in the case of excitation of port 1.

The measurement system used to perform frequency analysis of RF circuits is called a Vector Network Analyser (VNA). This device is used to measure S-parameters. Figure 3 shows a schematic diagram of a VNA.

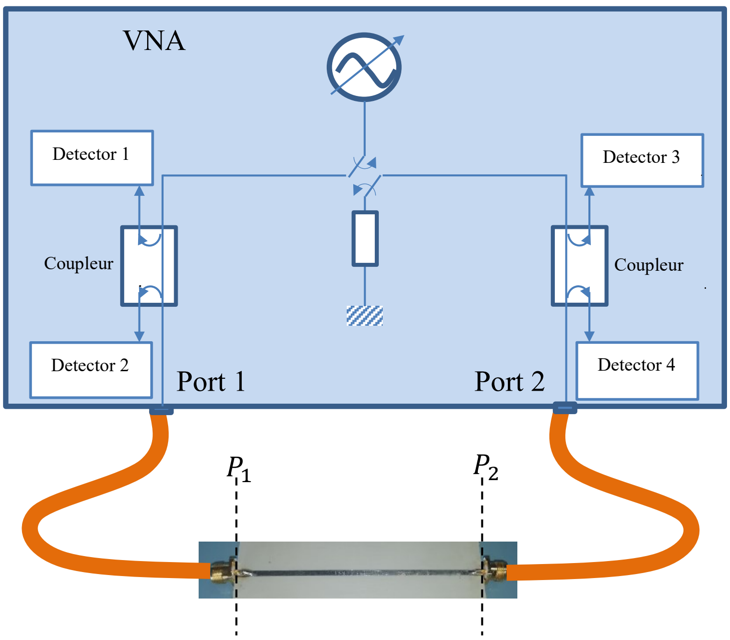


Figure 3. schematic diagram of a VNA.

A sinusoidal voltage source of variable frequency is used to generate a wave. This wave is first generated on port 1 (wave a_1) of the device under test (DUT). A coupler between the source and the output of the VNA allows a very small part of the signal from the source to be diverted to a detector (e.g.: $k_{dB} = -40\ dB$, i.e. 0.01% of the power is diverted to the detector 1). Thus, a small portion a_1' of the wave a_1 is measured. In the same way, this coupler allows obtaining a small portion b_1' of the wave b_1 diverted by the coupler: b_1' being measured by detector 2. Hence, it makes it possible to determine the parameter S_{11}: $S_{11} = {b_1'}/{a_1'}$. Similarly, in transmission, a small portion b_2' of the b_2 wave is measured using the coupler 4 present on port 2 of the VNA. This allows obtaining the parameter S_{21}: $S_{21} = {b_2'}/{a_1'}$.

The VNAs used in this labwork allow the measurement of circuits between a few MHz and several GHz. This kind of equipment allows an accuracy better than a tenth of a dB and a tenth of a degree.

2.2 VNA calibration

To take the imperfections of the vector network analyser into account, a calibration procedure is necessary. This calibration must be carried out at each new measurement campaign in order to consider the measurement configuration (connectors, coaxial cables, frequency band) as well as external environmental variations (temperature, in particular). **Measuring without calibration of this type of equipment gives incorrect RF measurement results, so calibration is essential**.
Calibration consists of measuring "standard" circuits called calibration devices. These measurements are then used to deduce an error model of the VNA, which is considered to obtain an accurate measurement of the device under test (DUT). Only "systematic errors" can be corrected, i.e. errors that are reproducible over time. Errors due to noise or possible thermal drift cannot be corrected.
The most commonly used error model has 12 error terms, including variations in source level with frequency, imperfect couplers, internal loads and the switch that alternately feed port 1 and port 2.

In the context of these practical exercises, the calibration that will be implemented will be the "Open-Short-Load-Thru" calibration (OSLT). This calibration consists of :

1. measuring at the two reference planes P_1 and P_2:
   - the reflection coefficients (S_{11} and S_{22}) successively in 3 different configurations:
     - in the presence of an open circuit (OC) connected to the output of each of the two coaxial cables
     - in the presence of a short circuit (SC) connected to the output of each of the two coaxial cables
     - then in the presence of a matched load ($Z_0 = 50\ \Omega$) connected to the output of each of the two coaxial cables.
   - the reflection coefficients (S_{11} and S_{22}) and the transmission coefficients (S_{21} and S_{12}) by placing a direct link (called "Thru") between the two coaxial cables.
2. Once the above measurements have been carried out, the measuring system (VNA) determines the parameters of the error model, which will be then automatically taken into account during subsequent measurements.

Thus, once this calibration has been carried out, the device is then calibrated between the two reference planes P_1 and P_2, for a reference impedance $Z_0 = 50\ \Omega$.

2.3 *Handling and calibration precautions*

/!\ The vector network analyser is a very expensive equipment and microwave measurements require particular care to be reproducible. In the laboratory, precautions must be taken, which can be summarized as follows:

- never unscrew a female connector as this leads to premature wear of the connectors (have the teacher explain, and only unscrew the male connectors without the female part turning),
- always keep the same measurement conditions (cable position, connector tightening)
  - do not twisting the cables and do not bend the radius too small.

Be careful, the devices under test to be measured are also very fragile, as the substrate used is easily breakable, so it must be handled with the greatest care

All measurements will be carried out in the frequency bend [2 MHz; 4 GHz]

3 Computer Aided Design (CAD)

Computer Aided Design (CAD) plays a major role today in all scientific fields, especially in the design of complex circuits and systems. In electronics, one example is the SPICE software, designed at the University of Berkeley in the early 1970s. Since then, many software tools dedicated to the analysis, modeling and design of RF circuits have been developed. These tools make it possible to consider the propagation phenomena existing at these frequencies.

3.1 *Modeling*

Modeling consists in determining an equivalent electrical or mathematical model of the device under study based on physical parameters: dimensions, characteristics of dielectrics, semiconductors, conductors. The **electrical model** is presented in the form of an electrical circuit in which the basic elements of the circuits are found: propagation lines, inductances, capacitances, resistances, diodes, transistors, current and voltage sources. The **mathematical model** consists, in the general case, of a distribution matrix, allowing linking the input and output quantities of the device under test. It is then possible to extract an electrical model.
In RF, modeling is based on the resolution of Maxwell's equations. Since space is made up of three dimensions, the modeling of propagation phenomena requires, in all rigour, a 3D modeling. In practice, for example in the case of planar transmission lines (Tlines) for which only two possible directions of propagation can be considered, it is possible to restrict the study domain to two dimensions. Hence, depending on the kind of circuits to be modeled, two-dimensional (2D) and three-dimensional (3D) modeling softwares can be chosen. In a general manner, 2D software is much faster than its 3D counterpart for solving 2D problems.

3.2 *Simulation on a CAD software*

The simulation consists of exciting the mathematical or electrical models obtained after modeling, and determining the waves generated by the circuit under study. There are different kinds of simulation tools:

- CAD based on electromagnetic modeling based on the dimensions, electrical and magnetic characteristics of the materials.
- CAD based on models already defined in libraries.

3.2.1 Getting started with the software ADS

The objective of this part is to study in simulations the circuits measured with the VNA during this labwork.

Run the software ADS "Advanced Design System".

- In your personal network space Z://, create a new project called TP_M1_CAD.
- Create a schematic by clicking on the symbol showing devices (resistor, capacitor).
  If a design assistance box appears, click on Cancel. Then, a schematic window appears.

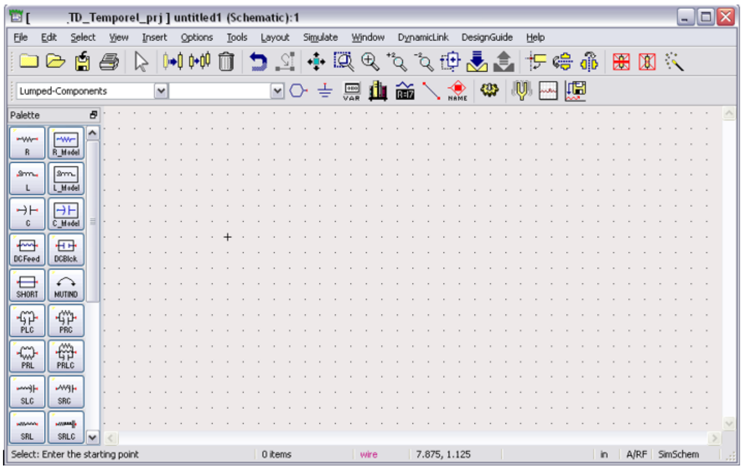


Figure 4 : fenêtre de schéma (schematic)

The devices you will simulate are present in the left-hand side drop-down menu.

- To consider microstrip transmission line, select in the library TLines-Microstrip:
  - **MLIN**: this block corresponds to the model of the microstrip line.
    You will consider for this first part a line length L=100mm and a strip width W=1.8mm. To do this, double click on the MLIN block and indicate these values.
  - **MSUB**: this block allows defining the considered substrate.
    By double-clicking on MSUB block, indicate the characterists of the substrate and metallizations (as indicated at the beginning of section **Erreur ! Source du renvoi introuvable.**).
- To feed the circuit, add 2 terminals from the library Simulation-S_Param:
  - **TERMG**: it corresponds to the source/receiver considered to feed and "measure" the du menu.
- To define the setup for the analysis, add from the library Simulation-S_Param:
  S-PARAMETERS: in this simulation box, you will define the start and stop frequency and the frequency step between two simulation points.
  By double-clicking on this block, indicate Start: 0 GHz / Stop: 4 GHz / Step: 0.01 GHz.

An example of schematic is shown in Figure 5.

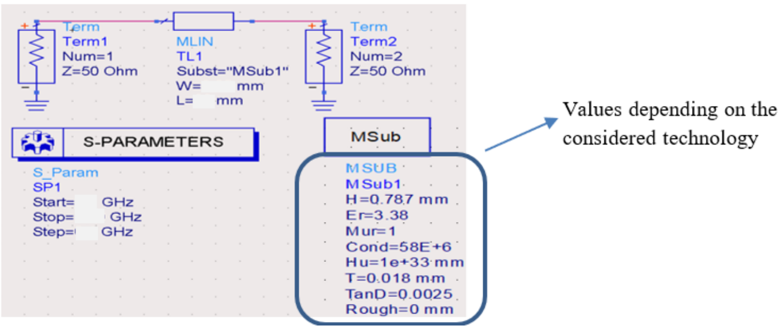


Figure 5. Example of schematic for the simulation of a microstrip line.

Then to run the simulation, you will have to click on the icon « Simulate » of the menu bar (the button looks like a gearbox).

- Once the simulation is performed, the software ADS creates a post-process window allowing plot the expected S-parameters.
  - To do this, select « Rectangular Plot » and place the block on the window.
  - Then select S(1,1) and S(2,1) with CTRL button and " »Add» " and "dB".

3.2.2 Linecalc tool

In ADS software, an analytical tool called LineCalc allows quickly calculating values of Z_c, ε_{reff}, and $\alpha_{dB/m}$ for a given transmission line (see Figure 6).
Example of microstrip study in LineClac.

- Run the LineCalc tool: Menu Tools>Linecalc
- Consider the microstrip line model: in the top left part, select as component type : MLIN.
- Indicate the characteristics of the PCB (substrate and metallizations) in the left part of the window (as indicated at the beginning of section **Erreur ! Source du renvoi introuvable.**).
- Indicate the working frequency (for example 1 GHz).
- Indicate the width W and length L of the microstrip line.
- Click on “Analyse” in order to obtain
  - the characteristic impedance of the Tline Z_c (indicated K_Eff in LineCalc)
  - the effective relative permittivity ε_{reff} (indicated K_Eff in LineCalc)

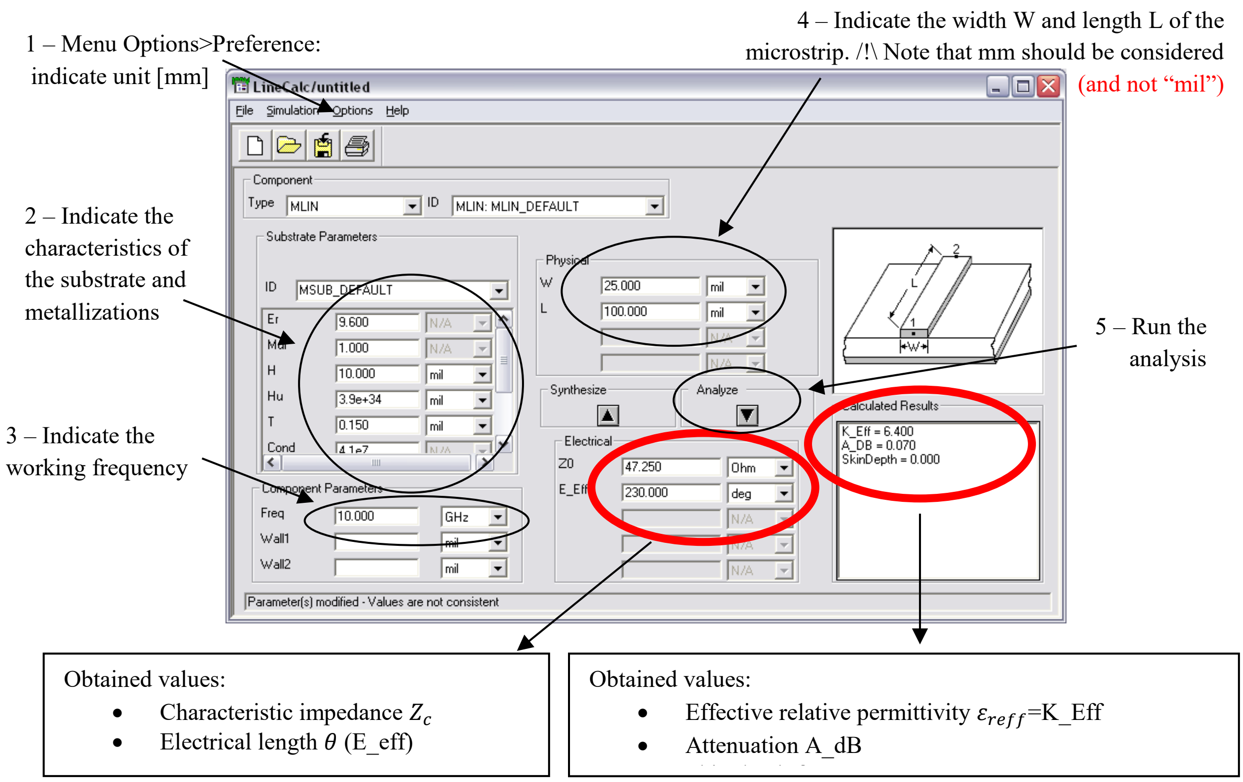


Figure 6. Linecalc Tool.

4 Preliminary study (to be carried out before the labwork session)

4.1 *Characteristics of a microstrip transmission line*

- Draw a cross-section of a microstrip line, and recall (on the cross-section) the electrical and geometrical parameters defining this type of tranmission line.
- Give the meaning of the effective relative permittivity ε_{reff}.
- Explain qualitatively how the characteristic impedance of a microstrip line varies as a function of ε_r, substrate thickness and strip width.

4.2 *Lossless circuit*

When considering a **lossless circuit**, the **power balance** is:

$$|S_{11}|^2 + |S_{21}|^2 = 1$$

- where $|S_{11}|^2$ corresponds to the part of power reflected on port 1, and $|S_{21}|^2$ corresponds to the part of power transmitted from port 1 to port 2.

- The values of $|S_{11}|$ and $|S_{21}|$ can be obtained from the values of $|S_{11}|_{dB}$ and $|S_{21}|_{dB}$ using the following formulae:

$$|S_{11}| = 10^{\frac{|S_{11}|_{dB}}{20}} \qquad \text{et} \qquad |S_{21}| = 10^{\frac{|S_{11}|_{dB}}{20}}$$

When considering a **circuit with losses**, the **power balance** is:

$$|S_{11}|^2 + |S_{21}|^2 + \frac{P_{diss}}{P_{inc}} = 1$$

- The part of dissipated power is then obtained by:

$$\frac{P_{diss}}{P_{inc}} = 1 - (|S_{11}|^2 + |S_{21}|^2)$$

- Let us consider a microstrip line. The magnitudes of S parameters were calculated at 5 GHz :

$$|S_{11}|_{dB} = -13dB \text{ and } |S_{21}| = -2{,}5dB$$

- Indicate if the microstrip line is well-matched. To determine this, calculate the part of power reflected on port 1, $|S_{11}|^2$. *Usually a device can be considered as well-matched if less than 1% of the power is reflected at its input.*
- Perform a power balance at 5 GHz, and calculate the part of dissipated power $\frac{P_{diss}}{P_{inc}}$. Is this microstrip line a lossless transmission line?

4.3 *Study of a transmission line: frequency behavior*

Consider a Tline (with a characteristic impedance Z_c, and an electrical length $\theta = \beta \cdot l$, l being the physical length of the transmission line). This Tline is inserted between both ports 1 et 2 of a VNA. The input and output impedances of the VNA being equal to $Z_0 = 50\ \Omega$, as show in in Figure 7.

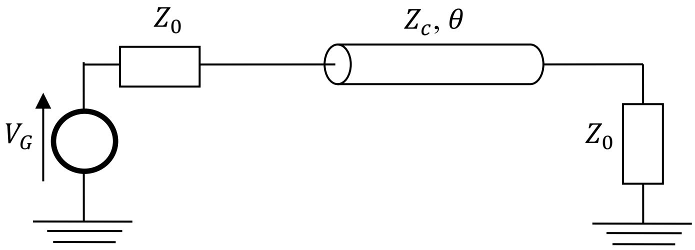


Figure 7. Electrical schematic of a transmission line inserted between both ports of a VNA.

Let us remind the ABCD matrix of a lossless transmission line:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} \cos(\theta) & j \cdot Z_c \cdot \sin(\theta) \\ j \cdot \dfrac{\sin(\theta)}{Z_c} & \cos(\theta) \end{bmatrix}$$

By considering the above ABCD matrix, we remind that it is possible to determine the S parameters of the of this lossless transmission line as:

$$S_{11} = \frac{A + \frac{B}{Z_0} - C \cdot Z_0 - D}{A + \frac{B}{Z_0} + C \cdot Z_0 + D}$$

$$S_{21} = \frac{2}{A + \frac{B}{Z_0} + C \cdot Z_0 + D}$$

where Z_0 is the impedance of the ports 1 and 2 of the VNA.

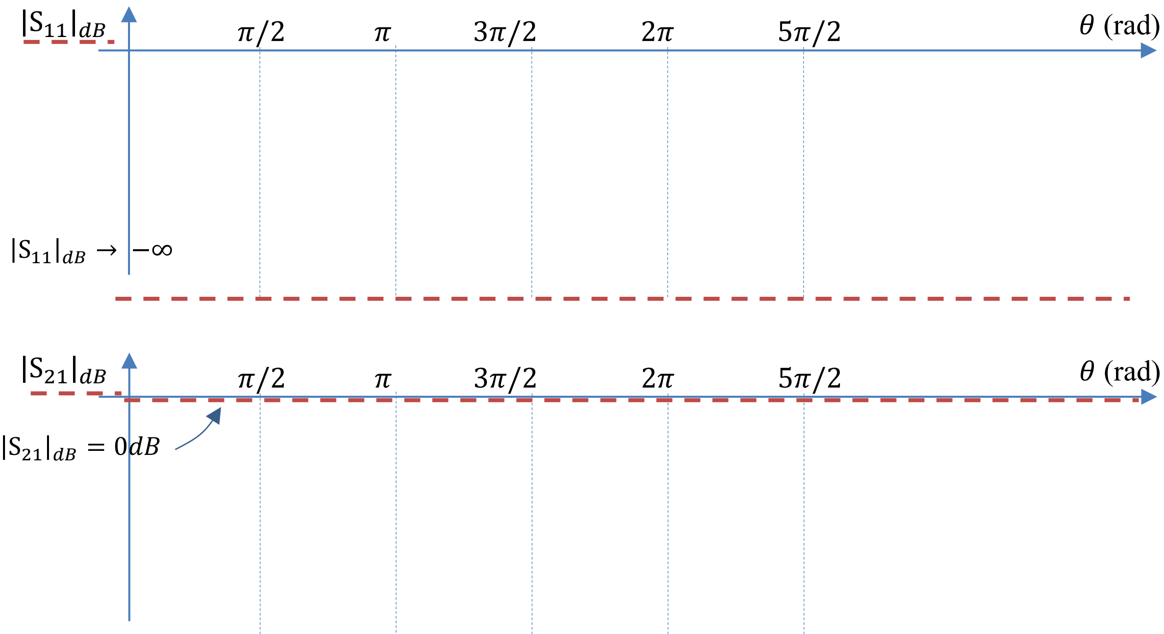
- Based on the above formulae, demonstrate that the reflection coefficient S_{11} at the input (port 1) of the Tline as a function of θ, Z_c and Z_0:

$$S_{11} = \frac{j \cdot tan(\theta) \cdot (Z_c^2 - Z_0^2)}{2Z_cZ_0 + j \cdot tan(\theta) \cdot (Z_c^2 + Z_0^2)} \qquad (*)$$

4.3.1 Matched transmission line: $Z_0 = Z_c$

Consider that the characteristic impedance Z_c of the Tline equals the impedance of the load Z_0.

- By using equation (*), show that the magnitude of the reflection coefficient $|S_{11}|$ is null, thus leading to $|S_{11}|_{dB} = -\infty\ dB$.
- Deduce that, if the Tline is a lossless Tline, then $|S_{21}|_{dB} = 0\ dB$.
- The behavior of $|S_{11}|_{dB}$ and $|S_{21}|_{dB}$ are shown versus the electrical length θ when $Z_c = Z_0 = 50\Omega$. Show that representing the behavior of these S parameters versus θ is equivalent to represent this behavior versus frequency ω. For this, remind the formula linking the electrical length θ and the frequency ω.



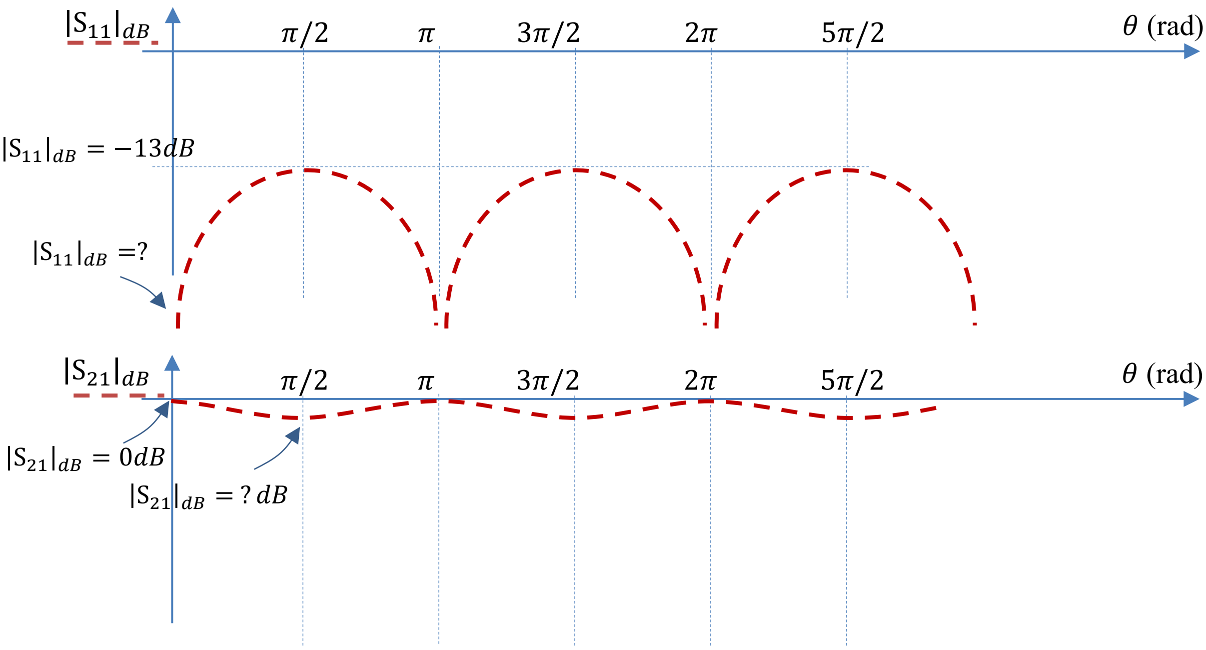
4.3.2 Unmatched transmission line: $Z_0 \neq Z_c$

Consider now that the characteristic impedance Z_c of the Tline is different from the impedance of the load Z_0.

- By considering equation (*) for $Z_0 \neq Z_c$
  - when $\theta = 0, \pi, 2\pi$ ... :
    - calculate the value of the magnitude of the reflection coefficient $|S_{11}|$
    - for a lossless Tline, deduce the values of $|S_{11}|_{dB}$ and $|S_{21}|_{dB}$.
  - when $\theta = \frac{\pi}{2}, \frac{3\pi}{2}, \frac{5\pi}{2}$ ... :
    - show that the magnitude of the reflection coefficient:

$$|S_{11}| = \frac{Z_c^2 - Z_0^2}{Z_c^2 + Z_0^2}$$

    - based on this last formula of $|S_{11}|$, demonstrate that for these particular values of $\theta = \frac{\pi}{2}, \frac{3\pi}{2}, \frac{5\pi}{2}$ ..., the value of the characteristic impedance Z_c can be deduced by using one of both below formulae:
      - $Z_c = Z_0\sqrt{\frac{1-|S_{11}|}{1+|S_{11}|}}$ if $Z_c < Z_0$ (**)
      - $Z_c = Z_0\sqrt{\frac{1+|S_{11}|}{1-|S_{11}|}}$ if $Z_c > Z_0$ (***)
- Example: consider a <u>lossless Tline</u> with a characteristic impedance Z_c to be determined (in the case $Z_c > Z_0$). The frequency behavior of this Tline is qualitatively represented below for $|S_{11}|_{dB}$ and $|S_{21}|_{dB}$.
  - Check that the proposed behaviors correspond to theory. In particular are the positions of the maxima and minima of $|S_{11}|_{dB}$ and $|S_{21}|_{dB}$ correctly placed?
  - By considering that $|S_{11}|_{dB} = -13\ dB$ for $\theta = \frac{\pi}{2}, \frac{3\pi}{2}, \frac{5\pi}{2}$, calculate the value of the characteristic impedance Z_c of the Tline.
  - These plots show that, when a Tline is not matched, a maximal mismatch is obtained for $\theta = \frac{\pi}{2}, \frac{3\pi}{2}, \frac{5\pi}{2}$ ..., corresponding to a maximum of $|S_{11}|_{dB}$, thus leading to a minimum of $|S_{21}|_{dB}$. Hence for these particular values of θ (corresponding to particular values of the frequency ω), the part of transmitted power $|S_{21}|^2$ is minimal. Calculate this part of transmitted power $|S_{21}|^2$ for $\theta = \frac{\pi}{2}$.



- Show that by measuring the frequency band Δf between the two first minimums of $|S_{11}|$, that is for $0 < \theta < \pi$, it is possible to obtain the effective relative permittivity ε_{reff} of the Tline. To do this, demonstrate that:

$$\varepsilon_{reff} = \left(\frac{c_0}{2 \cdot \Delta f \cdot l}\right)^2$$

4.4 Open circuit stub

A stub is a transmission line connected placed in parallel with the main transmission line at a given point. Figure 8 illustrates an example of open-circuited stub (of characteristic impedance Z_{s1} and electrical length θ_{s1}) placed in the middle of a transmission line (of characteristic impedance $Z_c = 50\ \Omega$ and electrical length $2 \cdot \theta_c$).

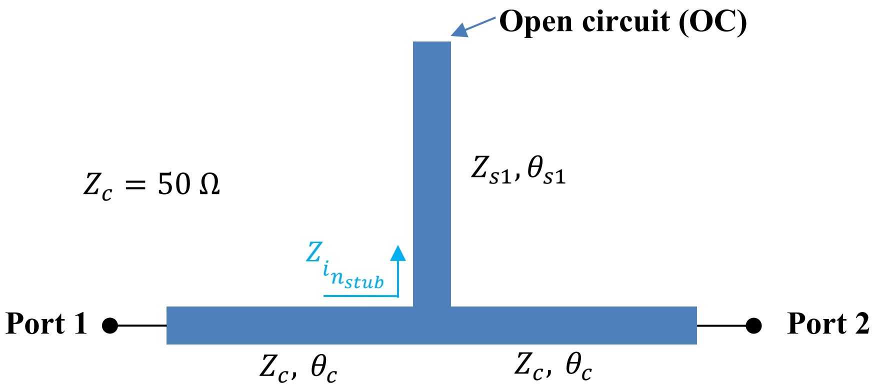


Figure 8. Open-circuited stub load on a transmission line.

In order to study the effects induced by the stub on the main transmission line, we can first calculate the input impedance $Z_{in_{stub}}$ of the stub as seen from the junction point looking towards the stub. To do this, only consider the stub loaded by the open circuit (OC), as shown in Figure 9.

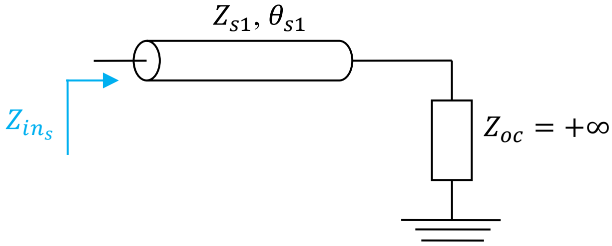


Figure 9. Equivalent electrical schematic of the stub loaded by the open circuit (OC).

- Using the ABCD matrix of a lossless transmission line, demonstrate that the input impedance $Z_{in_{stub}}$ of the stub is:

$$Z_{in_{stub}} = Z_{s1}\frac{Z_{oc} + jZ_{s1}\tan(\theta_{s1})}{Z_{s1} + jZ_{oc}\tan(\theta_{s1})} = \frac{Z_{s1}}{j \cdot \tan(\theta_{s1})}$$

- After simplification, show that this equation can be simplified as:

$$Z_{in_{stub}} = \frac{Z_{s1}}{j \cdot \tan(\theta_{s1})}$$

  - Give the values of θ_{s1} for which $Z_{in_{stub}}$ is null.
    - *For this particular case, the stub is equivalent to a short circuit at its input, as illustrated in* Figure 10. *Hence, if a signal is coming from Port 1, it cannot be transmitted to Port 2, due to the short circuit created by*

the stub at its input ($Z_{in_{stub}} = 0$). Indeed, due to this short circuit, the reflection is total.
→ $|S_{11}| = 1$ and $|S_{21}| = 0$ (corresponding to $|S_{11}|_{dB} = 0dB$ and $|S_{21}|_{dB} = -\infty$)

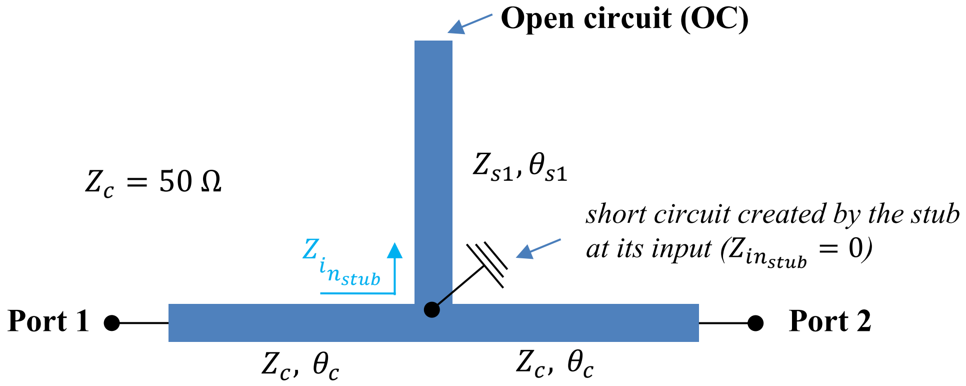


Figure 10. Equivalent circuit when $Z_{in_{stub}} = 0$.

- Give the values of θ_{s1} for which $Z_{in_{stub}}$ is infinite.
  - *For this particular case, the stub is equivalent to an open circuit at its input ($Z_{in_{stub}} = +\infty$), as illustrated in* Figure 11. *Hence, for this particular values of θ_{s1} "the stub is seen as if it was disconnected from the main transmission line". Hence, if a signal is coming from Port 1, it is totally transmitted to Port 2, without effect of the stub on its propagation. Indeed, due to this short circuit, the reflection is total.*
    → $|S_{11}| = 0$ and $|S_{21}| = 1$ (corresponding to $|S_{11}|_{dB} = -\infty$ and $|S_{21}|_{dB} = 0dB$)

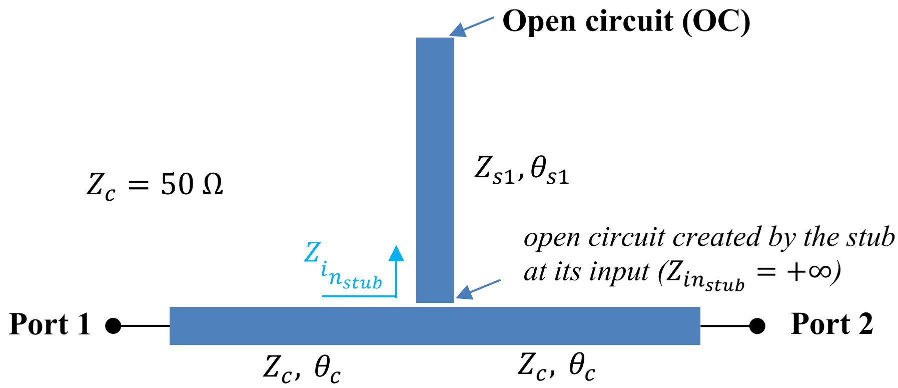
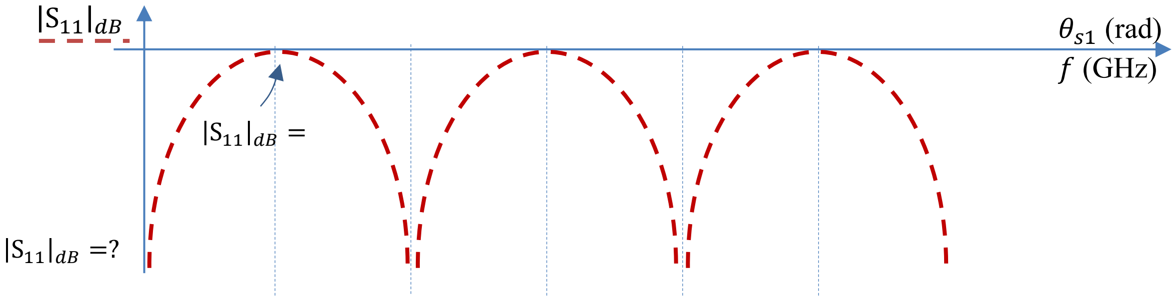
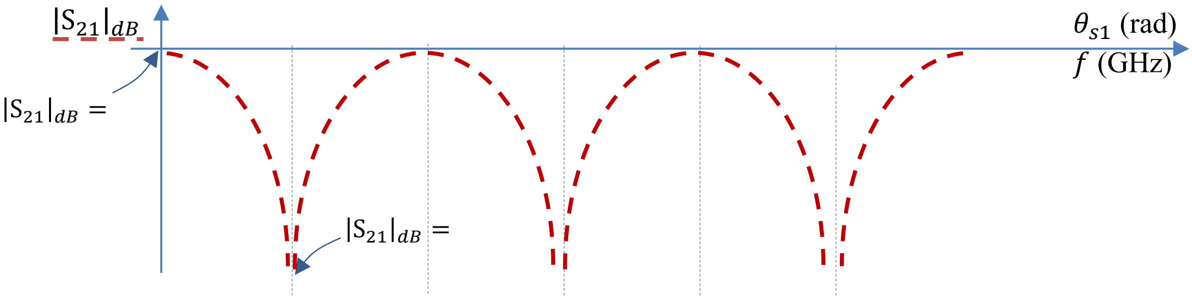


Figure 11. Equivalent circuit when $Z_{in_{stub}} = +\infty$.

- The shape of the magnitude of the S parameters $|S_{11}|_{dB}$ and $|S_{21}|_{dB}$ are sketched as a function of θ_{s1}. Indicate on these plots the values (min and max) of $|S_{11}|_{dB}$ and $|S_{21}|_{dB}$, and the corresponding values of θ_{s1} on the x-axis.





- Let us remind that $\theta_{s1} = \beta \cdot l_{s1} = \frac{\omega}{v_\varphi} \cdot l_{s1}$. Hence by considering a physical length of the stub $l_{s1} = 46\ mm$, and an effective relative permittivity $\varepsilon_{reff} = 2.9$, indicate the corresponding values between θ_{s1} and the frequencies ω and f. Then report these values on the two above plots.

θ_{s1}	0	$\pi/2$	π	$3\pi/2$	2π	$5\pi/2$
ω (rad/s)						
f (GHz)						

*

* *

Experimental part

5 Study of microstrip lines: simulations and measurements

5.1 General presentation of the fabricated microstrip lines

A photograph of three manufactured microstrip lines studied in this labwork is presented in Figure 12.

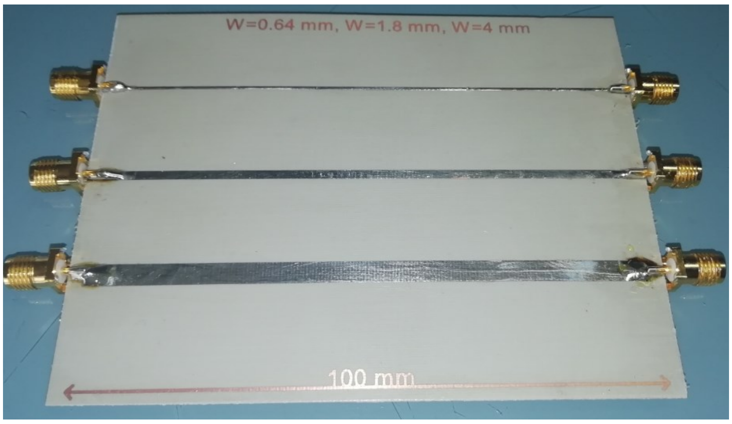


Figure 12. Manufactured microstrip lines.

These microstrip lines were fabricated on the NELCO substrate whose characteristics are:

- Substrate thickness: h = 787 µm
- Substrate permittivity: 3.38
- Loss tangent: tan(δ) = 0.0025
- Copper thickness: 18 µm
- Copper conductivity: $58 \cdot 10^6$S/m

These characteristics should be considered for all Tlines and circuits simulated and measured in this labwork.

The transmission lines lengths and width are given below.

Tline1 ($Z_{c1} > 50\ \Omega$)	$W = 0.64$ mm	$l = 10$ cm
Tline2 ($Z_{c2} \sim 50\ \Omega$)	$W = 1.8$ mm	$l = 10.6$ cm
Tline3 ($Z_{c1} < 50\ \Omega$)	$W = 4.0$ mm	$l = 10$ cm

5.2 Simulations of Microstrip lines with ADS

5.2.1 Schematic

With ADS, you will have to simulate these three microstrip lines between 0 and 4 GHz, **as detailed in section 3.2.1**. Once the simulation is performed, the software ADS creates a post-process window allowing plot the expected S-parameters.

- In the proposed PCB technology, the characteristic impedance of Tline2 is close to 50 Ω, as it will be demonstrated latter. Explain why Tline1 will have a characteristic impedance higher than 50 Ω, and Tline3 will have a characteristic impedance lower than 50 Ω.

For each microstrip line Tline1, Tline2 and Tline3:

- Plot the magnitudes $|S_{11}|_{dB}$, $|S_{21}|_{dB}$, $|S_{22}|_{dB}$ and $|S_{12}|_{dB}$ as a function of frequency (between 0 and 4 GHz)
  - Explain why $|S_{22}|_{dB}$ and $|S_{11}|_{dB}$ are identical
  - Explain why $|S_{12}|_{dB}$ and $|S_{21}|_{dB}$ are identical

- Note the frequencies for which $|S_{11}|_{dB}$ is minimal (theoretically $|S_{11}|_{dB} \to -\infty$).
  - Note the corresponding values of $|S_{21}|_{dB}$ for these frequencies.
  - Explain why, at these particular frequencies, it is possible to directly extract the attenuation per unit length $\alpha_{dB/m}$ from $|S_{21}|_{dB}$. Deduce, at these particular frequencies, these values of $\alpha_{dB/m}$.

  Example of Table:

f (GHz)	$\lvert S_{21}\rvert_{dB}$	$\alpha_{dB/m}$
…	…	…
…	…	…
…	…	…

- Extract the characteristic impedance of the microstrip :
  - Note the matching level (in dB), that is the value of $|S_{11}|_{dB}$ in the worst case. To do this, you will consider the first maximum of $|S_{11}|_{dB}$ located below 1 GHz.
  - Deduce the value of the characteristic impedance of the considered microstrip line by using on of the formulae (**) or (***).
- Extract the effective relative permittivity ε_{reff} of the microstrip line
  - Measure the frequency band Δf in between the two first minimums of $|S_{11}|$.
  - Based on the preliminary results obtained in section 4, deduce the value of ε_{reff}

- In your labwork report:
  - Plot, on the same Figure for the three different Tlines, the simulated attenuation per unit length $\alpha_{dB/m}$ as a function of frequency f. How does $\alpha_{dB/m}$ varies when frequency increases? Explain why.
  - Plot the evolving of the characteristic impedance Z_c as a function of the width W of the microstrip lines. Explain this behavior.
  - Plot the evolving of the effective relative permittivity ε_{reff} as a function of the width W of the microstrip lines. Explain this behavior.

5.2.2 Linecalc

In ADS software, an analytical tool called LineCalc allows quickly calculating approximated values of Z_c, ε_{reff}, and $\alpha_{dB/m}$ for a given transmission line. **<u>The method allowing using Line Calc is detailed in section 3.2.2</u>**.

For each microstrip line Tline1, Tline2 and Tline3:

- calculate with LineCalc:
  - the characteristic impedance Z_c

- the effective relative permittivity ε_{reff}
- the attenuation per unit length $\alpha_{dB/m}$ (to do that, in LineCalc, consider a line length of 1 meter).

- In your labwork report:
  - Plot, on the same Figure for the three different Tlines, the calculated attenuation per unit length $\alpha_{dB/m}$ as a function of frequency f. Is it consistent with simulations?
  - Plot the evolving of the characteristic impedance Z_c as a function of the width W of the microstrip lines. Is it consistent with simulations?
  - Plot the evolving of the effective relative permittivity ε_{reff} as a function of the width W of the microstrip lines. Is it consistent with ADS schematic simulations?

5.3 Measurements of microstrip lines

Before than using the VNA, carefully review and consider section 2.3 about Handling and calibration precautions.

The VNA has been calibrated (OSTL calibration) before being used. Check that "CAL" is displayed on the screen (calibration done and active). Remember the purpose of the instrument calibration step.

All measurements will be carried out in the frequency bend [2 MHz; 4 GHz]

Consider the manufactured microstrip lines presented in Figure 12.

For each microstrip line Tline1, Tline2 and Tline3, on the VNA:

- Plot the magnitudes $|S_{11}|_{dB}$ and $|S_{21}|_{dB}$ versus frequency. Insert these results in your report
  - Compare these experimental results with the simulated ones and explain the possible differences.
- In a similar way to the study carried out in simulations, note the frequencies for which $|S_{11}|_{dB}$ is minimal (theoretically $|S_{11}|_{dB} \to -\infty$).
  - Note the corresponding values of $|S_{21}|_{dB}$ for these frequencies.
  - Deduce, at these particular frequencies, these values of $\alpha_{dB/m}$.
- Extract the characteristic impedance of the microstrip:
  - Note the matching level (in dB), that is the value of $|S_{11}|_{dB}$ in the worst case below 1 GHz.
  - Deduce the value of the characteristic impedance of the considered microstrip line.
- Extract the effective relative permittivity ε_{reff} of the microstrip line:
  - Measure the frequency band Δf in between the two first minimums of $|S_{11}|$.
  - Deduce the value of ε_{reff}

- In your labwork report:
  - Plot, on the same Figure for the three different Tlines, the simulated attenuation per unit length $\alpha_{dB/m}$ as a function of frequency f. Compare these results to the simulations.
  - Plot the evolving of the characteristic impedance Z_c as a function of the width W of the microstrip lines. Compare these results to the simulations.
  - Plot the evolving of the effective relative permittivity ε_{reff} as a function of the width W of the microstrip lines. Compare these results to the simulations.
  - Are these results consistent with ADS and with LineClac?

6 Study of open-circuited stubs: simulations and measurements

A photograph of the manufactured microstrip lines loaded by open-circuited stubs is presented in Figure 13. The considered characteristic impedance of the Tlines and stubs is 50 Ω.

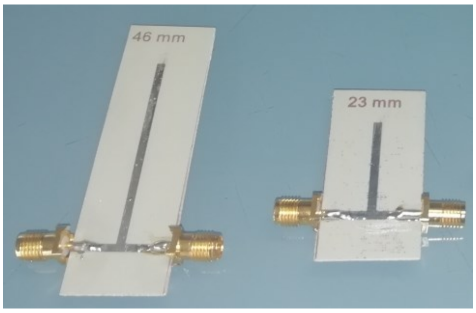


Figure 13. Maquettes de lignes chargées par des simples ou doubles stubs d'impédance caractéristique $Z_c = 50\ \Omega$.

6.1 Simulations

Run the simulation for the stub having a line length of 23 mm:

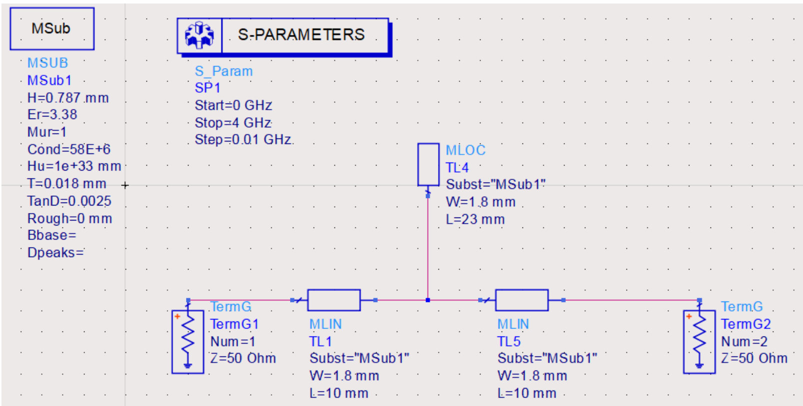


Figure 14. Schematic for the simulation of the circuit constituted of a microstrip line loaded by open-circuited stub having a length of 23 mm.

- Plot the magnitudes $|S_{11}|_{dB}$ and $|S_{21}|_{dB}$ versus frequency.
  - Note in a table the values (min and max) of the transmission coefficient $|S_{21}|_{dB}$, and the corresponding frequencies $f_{max1}, f_{min1}, f_{max2}, f_{min2}\cdots$
  - Based on the preliminary results (section 4.4), explain the behavior of $|S_{21}|_{dB}$.
  - What is the electrical length of the stub for the first frequency whose $|S_{21}|_{dB}$ is minimal f_{min1}? Check this corresponding electrical length with LineCalc.

Run the simulation for the circuit stub having a line length of 46 mm and answer the same last questions for this circuit.

6.2 Measurements

With the VNA, measure both circuits with stubs of 23 mm and 46 mm, respectively.

- Plot the magnitudes $|S_{11}|_{dB}$ and $|S_{21}|_{dB}$ versus frequency.
  - Compare these results with the simulated ones and explain the possible differences.