Semester S1

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Foundations of electromagnetic wave propagation

Practical Work PW5

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From specifications to filter

I INTRODUCTION

In this practical workshop, we will study the synthesis of a filter, from the specifications to the final object.

This time, the filter creation will also include the dimensioning of the resonator and an alternative (and more up to date) way to specify metrics for the filter will also be introduced.

The specifications to fulfill are as follows:

Central frequency (f_o)	6 GHz
Bandwidth (BW)	0.1 GHz
Unloaded quality factor (Qo)	3000
Rejection	-40 dB @ fc ± 0.6 GHz
Return loss	20 dB
Connectivity	WR159

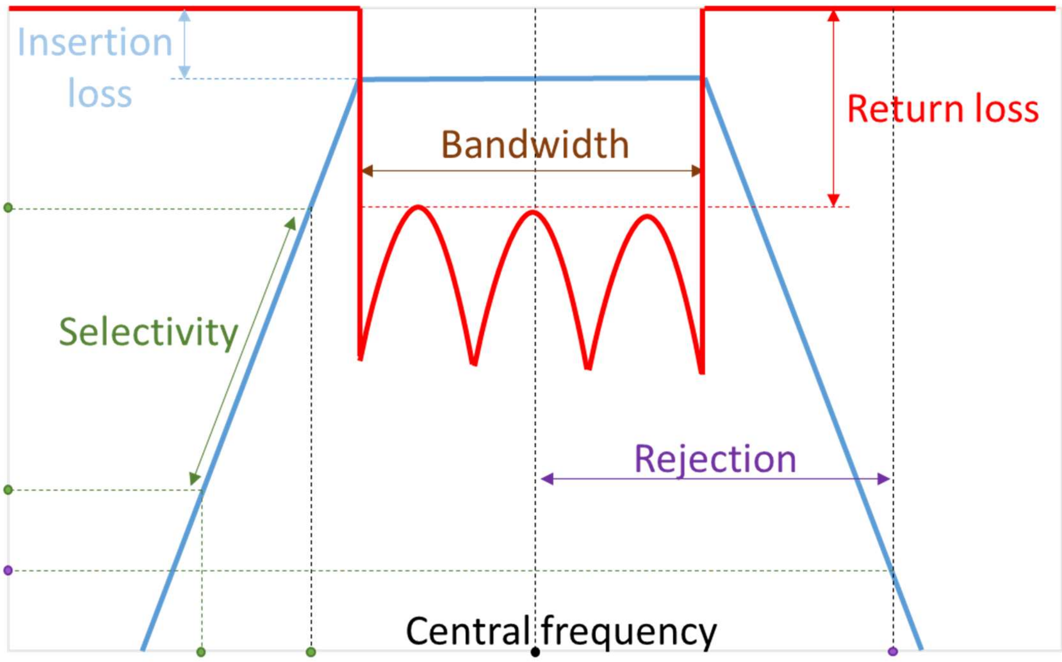


Figure 1: specifications.

The insertion losses depend of the unloaded quality factor, the relative bandwidth and the number of poles.

II ANALYTICAL SYNTHESIS

- Go to http://farquaad.xlim.fr/synth1.php

- Enter the parameters above and find the appropriate number of poles to satisfy the required selectivity.

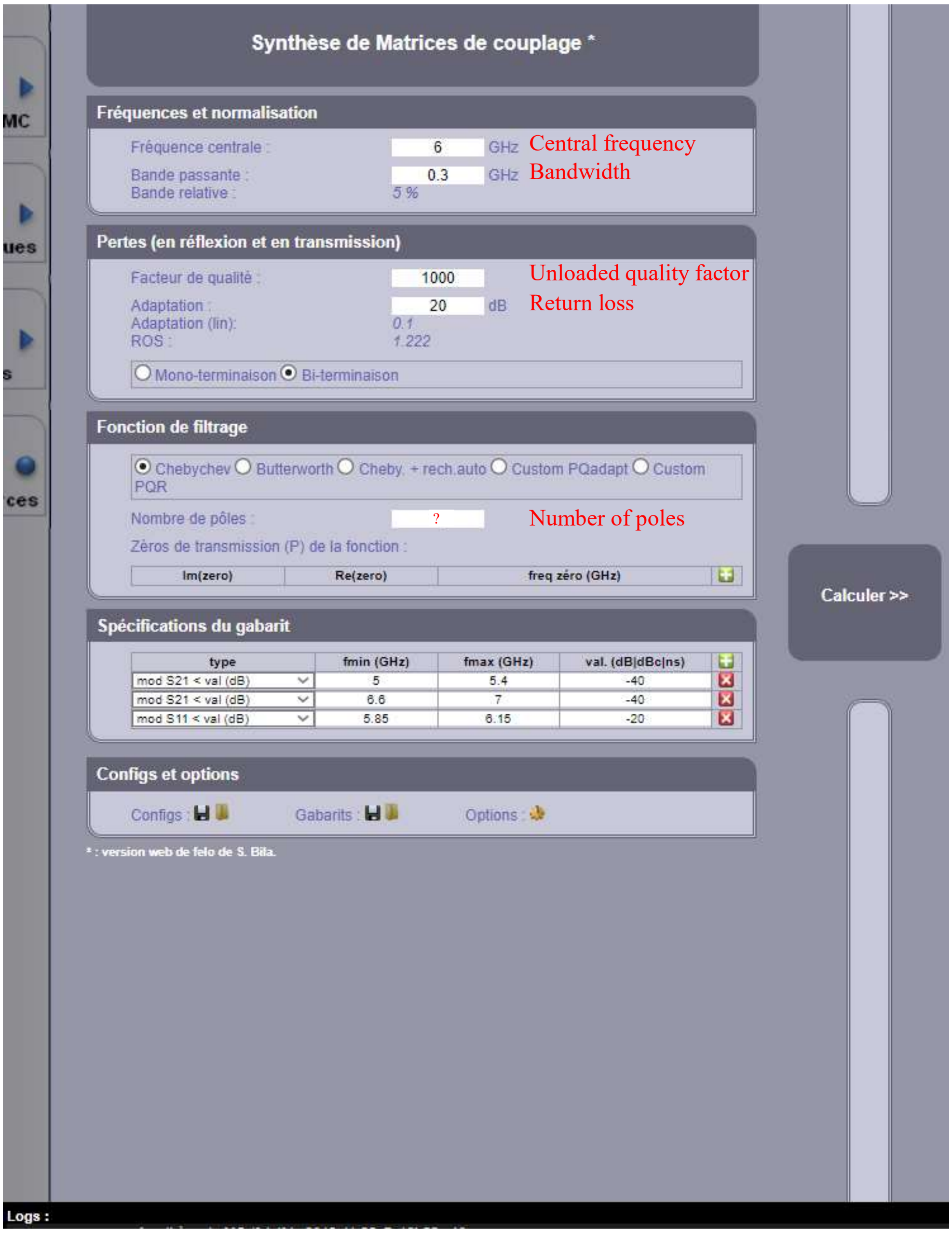


Figure 2: Felo webpage.

- Get the coupling matrix (m) you have obtained and save it to your hard-drive in your HFSS folder:

  Click on ![icon] in the log section

  Go to the last entry and right click on the **_fleche.mc* file

  Then click on **Enregistrer la cible du lien sous** (= save as) and save it to your HFSS folder.

This coupling matrix represents the relationships (couplings) between the resonators of a filter, they will be detailed in the next parts of the PW. This matrix determines the final "shape" of the filter: changing one coefficient and the filter response will be different.

The matrix is normalized in frequency, which means that, for a given shape, the coupling matrix will remain the same whatever the frequency and the bandwidth we want.

III RESONATORS

The next step is to dimension coarsely the resonators

- Go to http://achille.xlim.fr
- Click on the link *Fréquences de résonance et Qo d'une cavité rectangulaire* in the section Résonateurs

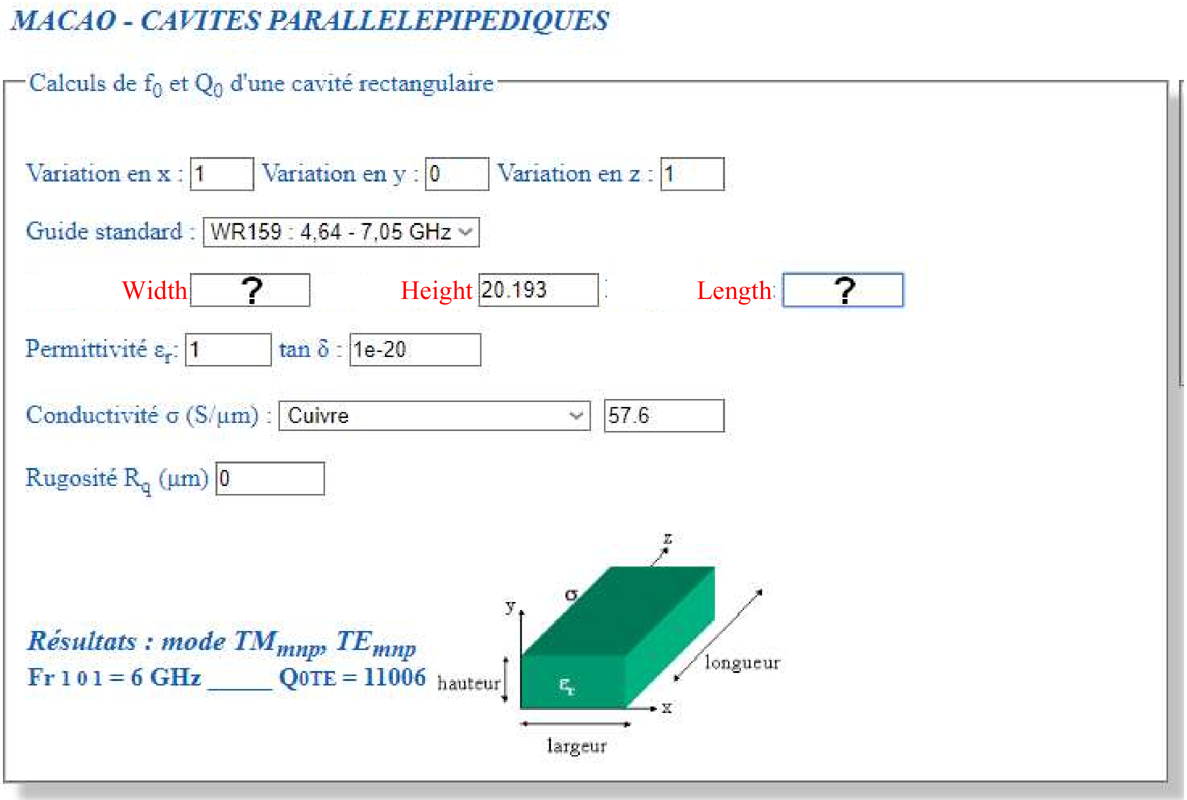


Figure 3: Achille webpage.

- Choose **Guide Standard**: WR159
- For the filter, we will use the fundamental (i.e. TE_{101}). Play with the fields **largeur** (Width) and **longueur** (Length), keeping these values identical, and try to set the Fr101 close to 6 GHz.

Now we move to HFSS.

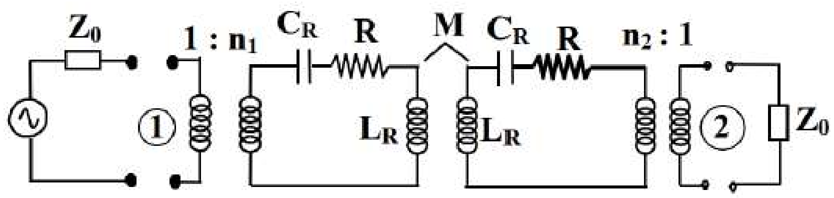
- Launch HFSS, create a new project and call it “PW5_HFSS_filter”.
- Create a new design and name it “Res”.
- Set the **Solution Type** (**HFSS**, **Solution Type**) to **Eigenmode**.
  This allow HFSS to calculate the natural resonant frequencies of a structure, i.e. the different modes that can exist for this structure.
- Draw a box with the dimensions you found in part II.
- Create a new setup:
  Minimum frequency: 2 GHz (no modes under this frequency can be find)
  Number of mode: 5 (= how many modes to find)
  Maximum number of passes: 5
  Maximum Delta Frequency Per Pass: 1
- Launch the analysis
  - ➢ Go to Solution data and analyse the results
  - ➢ What are the other mode given?
- Draw the E-field (isovalues and vector)
  - ➢ Comments on it

To change from a field to another, right click on **Field Overlays** in **Project Manager**, **Edit Sources** and then change the **Scaling Factor** (0 or 1 for each source).

IV RESONATOR COUPLING

IV.1 RESONATOR TO RESONATOR COUPLING: THEORY

As seen in the PW2, two coupled resonators can be modeled by an equivalent electrical model with localized elements:



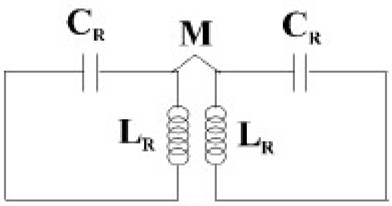
L_R, C_R and R characterize the resonator. The resonator frequency is:

$$f_0 = \frac{1}{2\pi\sqrt{L_R C_R}} \tag{1}$$

Where:

- R is representative for the resonator losses. We will have two cases
  - R= 0: no loss calculation
  - $R = \frac{L\omega_0}{Q_0}$ with Q_0 the unloaded quality factor of the resonator.
- The inter-resonator coupling is characterized by the mutual inductance M.
- The coupling of the resonator with the access lines depends on parameters n_1 and n_2 of the perfect transformers.

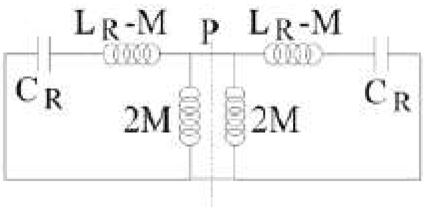
Therefore, when one want to express the coupling between two resonators, the following model can be used:



The coupling coefficient is given by:

$$k = \frac{M}{\sqrt{L_R L_R}} = \frac{M}{L_R} \tag{2}$$

This coefficient can also be calculated by replacing the set-up above by the one beyond, where P represents a symmetry plane:



Based on that, two resonance frequencies, corresponding to the odd and even modes, can be defined:

- If P is an open circuit, frequency of the odd mode is written:

$$f_{co} = \frac{1}{2\pi\sqrt{(L_R + M)C_R}} = \frac{1}{2\pi L_R^2\sqrt{(1+k)C_R}} \tag{3}$$

- If P is an short circuit, frequency of the even mode is written:

$$f_{cc} = \frac{1}{2\pi\sqrt{(L_R - M)C_R}} = \frac{1}{2\pi L_R^2\sqrt{(1-k)C_R}} \tag{4}$$

It results in a coupling k given by the following equation:

$$k = \frac{f_{cc}^2 - f_{co}^2}{f_{cc}^2 + f_{co}^2} = \frac{M}{L_R} \quad (5)$$

k is also often called the un-normalized coupling, by opposition to the couplings in the coupling matrix (m) which are normalized in frequency.

If we consider that resonators *i* and *j* are coupled together, there is a direct relationship between k_{ij} and m_{ij} ($i \neq j,\ i \neq 0,\ j \neq 0,\ i \neq n$ *and* $j \neq n$):

$$k_{ij} = m_{ij} . \frac{BW}{fo} \quad (6)$$

Where:

- fo is the central frequency of the filter
- BW is the bandwidth of the filter

Therefore, if we want to design the analytical filter we calculated in part II, we just need to find the value k that fulfill the equation above. In addition, we also know how to calculate k from the even and odd modes of a circuit. The last thing to do is to get the even and odd modes from two coupled cavities: this can be simply done with HFSS and eigen simulations of 2 coupled resonators!

IV.2 RESONATOR TO RESONATOR COUPLING: DRAWING

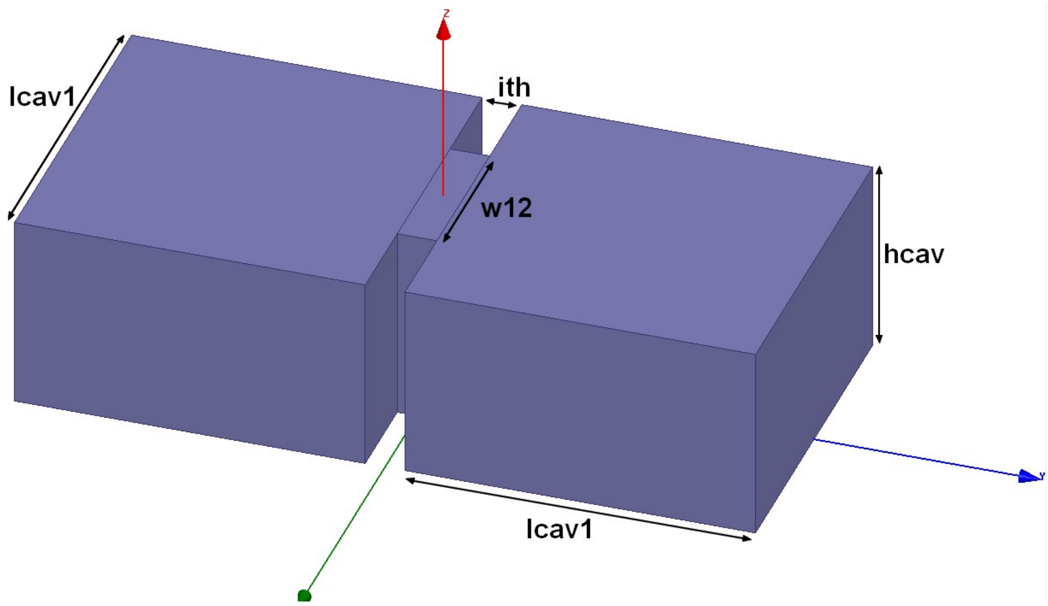


Figure 4: 2 coupled resonators.

- Create a new design, on which we will create two resonators and an iris. Name it "res_res_coupling"
- For the first resonator, draw a box for which:

Origin	-lcav1/2	-ith/2	0
Size	lcav1	-lcav1	hcav

- Duplicate with symmetry toward xOz plane to obtain the second resonator
- For the iris between first and second resonator, draw a bow for which:

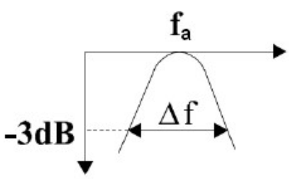
Origin	-w12/2	-ith/2	0
Size	w12	ith	hcav

Lcav1	35.33 mm	**ith**	4 mm
hcav	20.193 mm	**w12**	*Vary from 8 to 24 mm*

- As in the first part, do the eigen calculations for this structure, considering we want to obtain the two first modes.
- Plot the two first modes.
  - ➢ What do you observe?
- Calculate k.
- Make a table of k for different values of w12.
  - ➢ What are the values of w12 to realize the couplings m12 and m23 (index of first row is 0)?

IV.3 ACCESS COUPLING: THEORY

The calculation of the input/output coupling has also been studied in the PW2. As a reminder, for a resonator equally coupled on both sides, its input/output couplings are obtained with the following calculations:



f_a is the resonance frequency of the resonator once coupled on each side. f_a is slightly different from f_o due to a loading effect due to the couplings

Δ_f is the 3 dB bandwidth.

Then, the loaded Quality factor can be expressed as:

$$Q_L = \frac{f_a}{\Delta f} \tag{7}$$

With $$\frac{1}{Q_L} = \frac{1}{Q_{e1}} + \frac{1}{Q_{e2}} + \frac{1}{Q_o} \tag{8}$$

We are looking for Qe, considering that:

$$Q_e = \frac{f_o}{BW\,.m_{ij}^2} \tag{9}$$

This formula links the coupling matrix to the external quality factor, itself linked to the physical structure.

IV.4 Access coupling: drawing

For the calculation of the external quality factor, no losses will be involved for the resonator (so $Q_o \rightarrow \infty$ which leads to $\frac{1}{Q_o} \rightarrow 0$) and the structure will be symmetric (so $Q_{e1} = Q_{e2}$), which implies that $Q_l = 2.Q_e$

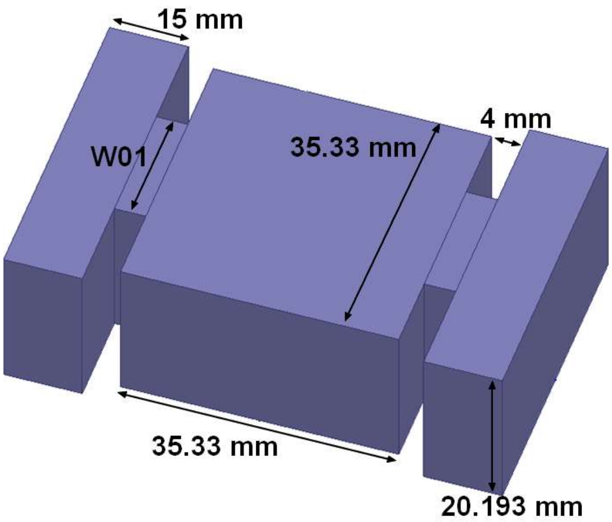


Figure 5: resonator coupled on both accesses.

- Create a new design and name it “input_output_coupling”
- Create a box and center it along X- and Y-axes. Dimensions:

  X: 35.33 mm Y: 35.33 mm Z: 20.193 mm
- Create two irises (one on each side of the resonators). Dimensions:

  X: w01 (*20 to 25 mm)* Y: 4 mm Z: 20.193 mm
- Create two other boxes that will represent the accesses. Dimensions:

  X: 40.39 mm Y: 15 mm Z: 20.193 mm

The dimensions of these boxes along X-axis correspond to the standard dimensions of a WR159 waveguide.

- Simulations are in driven modal, so set the **Solution Type** to driven modal.
- Add two ports.
- Create **Setup** with a **Solution Frequency** of 6 GHz and a **Frequency sweep** from 4.9 to 7 GHz, with a frequency step of 0.001 GHz (**fast**).
- Launch the simulation.
- For each value of the width of the iris, calculate the corresponding m_{ij} and find the appropriate width to satisfy the value of m_{01}.

V FILTER DESIGN

- Thanks to the previous studies, determine all the dimensions of the filter.
- Create the design (help yourself using symmetry and variables).
- Simulate the filter using setup and frequency sweep parameters used in part IV.
  - ➢ Comment your results.