ECS644U Microwave and Millimetrewave Electronics Lab 4

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December 1, 2016

Contents

1 Aim

The aim of this third lab of ECS644U is to design microwave filters. In Part A we are asked to design an equal ripple LC low pass filter, transform it to a band pass filter and simulate the two in AWR. In Part B, Richard's Transformations and Kuroda identities are aplied to derive a transmission-line-based model of Part A's LPF, the AWR Axiem solver is then utilised to design and simulate the TX-line design.

2 Method

2.1 LC Filters

In the lab sheet we are required to apply the *Insertion Loss* method. This method comprises the following steps:

1. Determine Specifications: Different filters, with different characteristic responses, are implementable. The application's requirements should determine the choice of one, or another type. In the lab sheet these are clearly stated:

    - Filter type: Various types and designs are possible, in the lab the required ones are low pass and band pass 0.5 dB equal ripple response filter.
    - Cutoff frequency ω_c: In the most general case (band pass/ band stop) cutoff frequencies are either upper (f_H) or lower (f_L) frequencies: their value corresponds to the frequency value for which the gain is at $P_{LR} = IL = 2 = -3dB$
    - Centre frequency / Bandwidth: The bandwidth is defined as difference of upper and lower cutoff frequencies $BW = f_H - f_L$ and the centre frequency is usually defined as their arithmetic mean.
    - Source impedance R_s: Impedance of the source network which the filter is connected to: in the lab sheet, 50Ω.
    - Roll-off: specifies how quickly the transition between pass-band and stop-band occurs. This transition area is defined as transition band. It is usually specified in terms of insertion loss: in the lab sheet, 20 dB @ 1.5 GHz.

2. Design prototype Low pass filter: this has normalised frequency (1GHz), impedance (1Ω) and type (LPF) and is solely composed of L and C components.

    - Order Different plots -specific to the utilised type of filter- have been created to relate the required roll-off to the required filter order. The order of the filter is imposed by the specification of an attenuation value for a certain normalised frequency (the quicker the roll-off, the higher the order). By subtracting the normalised frequency, for which an attenuation value is provided, to the normalised cutoff frequency, the x-axis on these tables is identified. Then, moving along the y-axis value which corresponds to the provided attenuation value, the required order is found at the intersection with the x-axis value. Of course, if this intersection isn't along any of the N-order curves, the closest higher order is chosen, to ensure the minimum specifications are met.
    - Component values Once the order has been defined, the the values of the components to be placed, is set. Once again, tables that relate the number of elements to their values, are available, providing admittance values for all the N_{order} components present in the filter. If the element is in series, admittance should be considered as inductance, whereas if the element is shunt, then the value should be considered as capacitance. This last consideration ensures that both inductors and capacitors can be used in whichever configuration, shunt or series.

These tables and plots derive from Power Loss Ratio equations, in which this amount is expressed in terms of the transmission coefficient Γ.

$$P_{LR} = \frac{P_{inc}}{P_{load}} = \frac{1}{1 - |\Gamma(\omega)|^2} \tag{1}$$

It is possible to express Γ as

$$|\Gamma|^2 = 1 + \frac{M(\omega^2)}{N(\omega^2)} \tag{2}$$

in which $M(\omega^2)$ and $N(\omega^2)$ are both polynomials. As previously seen, it is possible to relate the transmission coefficient to the input impedance felt from the source network;

$$P_{LR} = \frac{Z_{IN} - 1}{Z_{IN} + 1} \tag{3}$$

Hence, combining the three equations and considering the filter's type, it is possible to achieve Power Loss Ratio equations as a function of conductance and inductance of the utilised components, of normalised frequency, and of the order. As the order increases, solving these equations becomes more complex, hence the opposite procedure is generally adopted: Once plotted or tabulated the results in their general form, it is possible to carry out the inverse procedure, utilising the general results, to determine a particular case.

3. <u>Scale and transform to required filter</u> As previously said, the order of our filter simply determines the width of the transition band. Full control over cutoff frequency and input/load impedance can be achieved:

   - Impedance: multiplying input/output resistance and inductor by same R_0 value, but dividing the capacitance by it.

     $$L' = R_0 L, C' = C' R_0, R'_s = R_0, R'_L = R_0 R_L \tag{4}$$

   - Frequency: to scale a LPF to a different cutoff frequency, scaling $\omega \leftarrow \frac{\omega}{\omega_c}$. As the reactive elements are frequency dependent, their impedance value have to be evaluated again: $jX_k = j\frac{\omega}{\omega_k}L'_k, jB_k = j\frac{C_k}{\omega_k}C_k$, where jX_k, jB_k are series reactance and shunt susceptance values.
   - $LPF \rightarrow HPF$: this transformation can be done by not only scaling the frequency, but also inverting its sign. This yields inductive shunt elements and capacitive series elements.
   - $LPF \rightarrow BPF$: knowing upper and lower cutoff frequencies, it is possible to achieve such transformation by substituting

     $$\omega \leftarrow \frac{\omega_0}{\omega_2 - \omega_1}(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}) \tag{5}$$

   - $LPF \rightarrow BSF$: this is the inverse of the above BPF, hence

     $$\omega \leftarrow -\frac{\omega_0}{\omega_2 - \omega_1}(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega})^{-1} \tag{6}$$

   Where $\Delta = (\frac{\omega_0}{\omega_2 - \omega_1})^{-1}$ is the *Normalised bandwidth*. As for the first two, the latter two transformations also yield changes in the reactive components. They obviously can be evaluate mathematically, following a similar procedure as above, but, as for the purpose of the lab it is sufficient to apply the final results, these are visible in the below figure.

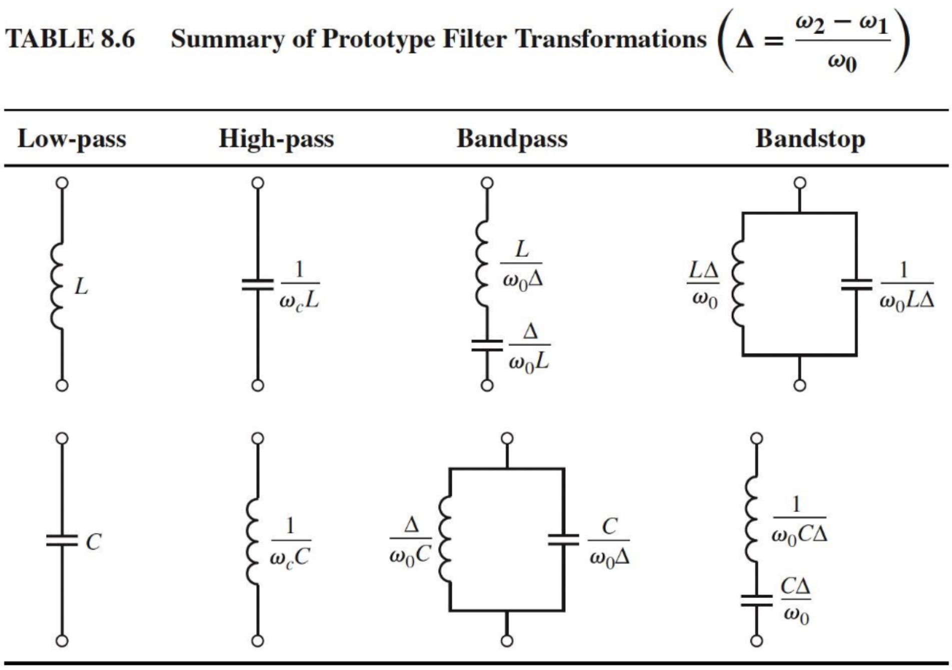

Figure 1: Summary of Prototype Filter Transformations.

2.2 AWR Simulation

In order to efficiently carry out the following simulations, it's important to set the Global Project Units as a first step. For metric, capacitance and inductance units, these will be mm, pF, nH.

2.2.1 Low Pass Filter

The logic behind the schematic utilised in AWR (Fig. 2) is presented.

- The Generator Network can be modelled, either with a voltage source, a source resistance, a volt meter and an amp meter (which will provide us the value of voltage and current felt by this network); or it can be modelled using a port, of which, characteristic impedance can be easily specified. Given the much greater simplicity to plot graphs and perform measurements utilising the port, this solution will be adopted. Hence, the port's impedance should be set to be equal to the characteristic impedance that has to be matched: 50Ω.
- The load $Z_L = 50\Omega$ could be modelled either combining resistors to match the Z_L. A better solution could be using a second Port where resistivity can be specified.
- Inductors and capacitors are placed to form a $\pi - Network$ and their values are modified to the calculated values.
- In order to achieve a graph where the transmission coefficient is clearly visible, first set the operating frequency in the Project Options as a range from 0 to 2 GHz, with steps of 0.01Hz, then add a new graph plotting the S21 parameter (transmission coefficient achieved when stimulating Port 1 and measuring the output power from Port 2). Of this complex value, the magnitude is plotted in logarithmic scale.

Below circuit schematics regarding the described procedure.

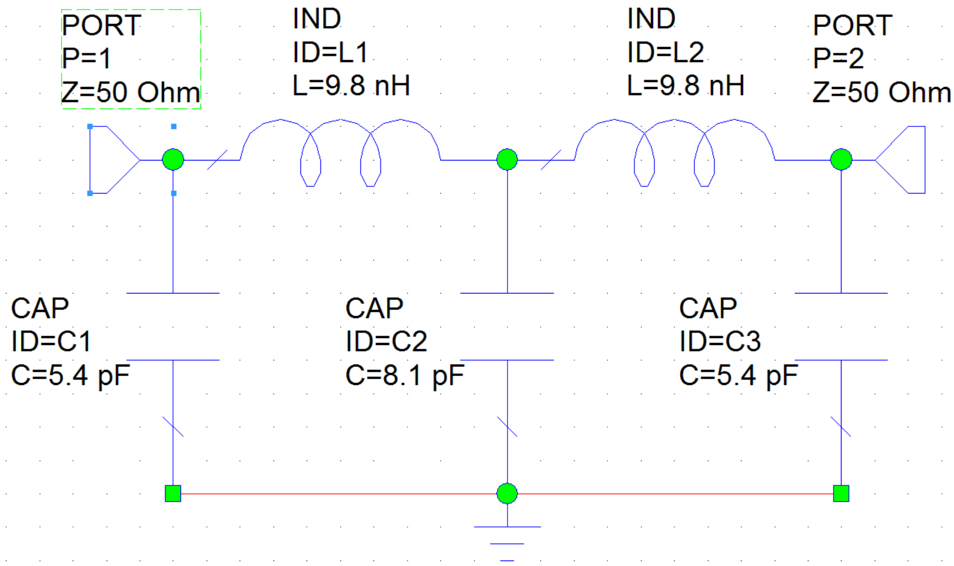

Figure 2: Circuit schematic for the LPF.

2.2.2 Band Pass Filter

The logic behind the schematic utilised in AWR (Fig. 5) is presented.

- The Generator Network can be modelled, either with a voltage source, a source resistance, a volt meter and an amp meter (which will provide us the value of voltage and current felt by this network); or it can be modelled using a port, of which, characteristic impedance can be easily specified. Given the much greater simplicity to plot graphs and perform measurements utilising the port, this solution will be adopted. Hence, the port's impedance should be set to be equal to the characteristic impedance that has to be matched: 50Ω.

- The load $Z_L = 50\Omega$ could be modelled either combining resistors to match the Z_L. A better solution could be using a second Port where resistivity can be specified.

- Inductors and capacitors are placed to form a $\pi - Network$ and their values are modified to the calculated values.

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Below circuit schematics regarding the described procedure.

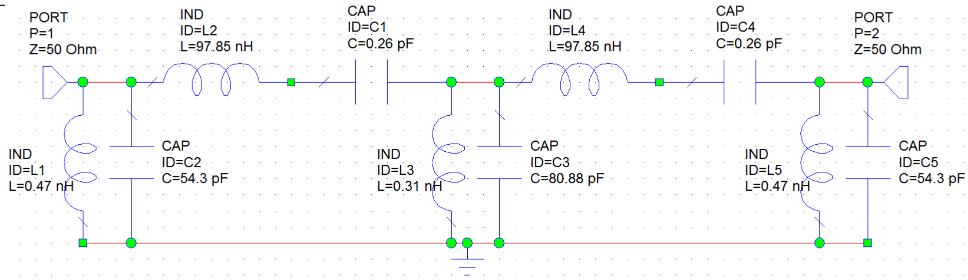

Figure 3: Circuit schematic for the BPF.

2.3 Transmission Line Filters

To convert a lumped-element filter into a transmission line filter transformations, known as Richard's and Kuroda's, need to be carried out.These transformation occur prior to renormalisation, hence re-normalising impedance and frequency will be the last step.

2.3.1 Richard's Transformation

Effectively *Richard's Transformations* equate the impedance of a transmission line to an impedance.

$$\Omega = tan(\beta l) = tan(\frac{\omega l}{v_p}) \tag{7}$$

$$jX_L = j\Omega L = jLtan(\beta l) \tag{8}$$

$$jB_C = j\Omega C = jCtan(\beta l) \tag{9}$$

If $l = \frac{\lambda}{8}$ then $tan(\beta l) = 1$. We would then have that transmission lines of length $\frac{\lambda}{8}$ and impedance of L (or C) would effectively be equivalent to a lumped element L (or C). This becomes more visible by formalising once again the input impedance equation for high frequency circuits.

$$Z_in = \frac{Z_L + jZ_0tan(\theta)}{Z_0 + jZ_Ltan(\theta)} \tag{10}$$

It becomes therefore clear that a short circuited stub of length $\frac{\lambda}{8}$ would correspond to an inductor, whereas an open circuited stub of the same length would correspond to a capacitor.

$$\lim_{Z_L \to \infty} \to Y_{in} = jB_c = j\Omega C = jY_0 \tag{11}$$

Where $Y_0 = C$

$$\lim_{Z_L \to 0} \to Z_{in} = jX_L = j\Omega L = jZ_0 \tag{12}$$

Where$Z_0 = L$
These last two equations explain why, one of the first steps performed when converting a lumped element filer into a transmission line filter is converting the admittance values for capacitive elementes read off the table into impedance, as transmission lines will be characterised by impedance, not admittance.

2.3.2 Kuroda's Identity

The difficulty to implement short circuited stubs in the manufacturing process requires us to carry out *Kuroda's Identities*. These utilise redundant transmission lines to achieve more practical microwave filter implementations. The TX lines are said to be redundant as their length is equivalent to $\frac{\lambda}{8}$ at cutoff frequency and their presence doesn't affect the filter's response (their impedance matches perfectly the characteristic impedance). In the below figure the transformations of interest are displayed.

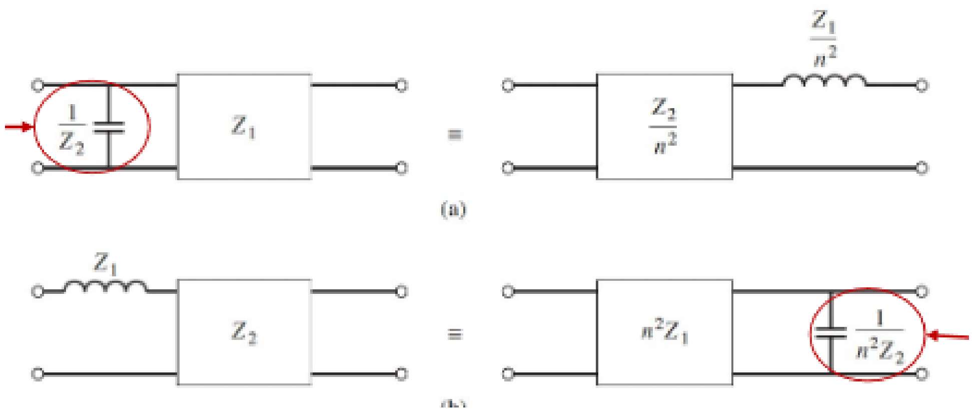

Figure 4: First and second Kuroda Identities.

It's visible how, by adding a redundant transmission line, it becomes possible to transform a short circuited stub (represented by an inductor) into an open circuited stub (represented by a capacitor). For the two configurations to be equivalent the ABCD matrices of the two configurations need to be equal. This yields the condition

$$n^2 = 1 + \frac{Z_2}{Z_1} \tag{13}$$

2.3.3 Renormalisation

- Z_0 : All impedance values should be multiplied by Z_0 for the network to match the characteristic impedance.
- f_0: The length of all stubs is modified for it to be $\frac{\lambda}{8}$ at cutoff frequency.

2.4 AWR Simulation

In order to simulate the designed 5^{th} order Low Pass stub filter using the AXIEM solver in AWR it's necessary to first create a circuit schematic of the circuit. This circuit is implemented solely with transmission line elements, hence the TXLINE tool will be vital to determine the correct physical characteristics of each transmission, given certain set electrical characteristics. Furthermore, the MSUB component will have to be present in the circuit schematic, to specify parameters of the dielectric substrate adopted in the manufacturing process. Hence, the specifications provided on the lab sheet need to be taken into consideration.

- Substrate material: this is specified to be FR-4. Given the TXLINE tool doesn't have preset values for it, a quick google search [1] can provide us with the parameters to be set in the tool and in the MSUB component.

[1] Microwave101.com, wikipedia.com

Dielectric	FR4
Dielectric constant	4.34
Loss tangent	0.018

- Conductor material: this is specified to be Copper. TXLINE has conductivity values for this material, hence no research is required.
- Substrate thickness: specified to be $h = 1.6mm$. This value will be set in MSUB and in the physical characteistics in TXLINE.
- Conductor thickness: specified to be $t = 0.015mm$. This value will be set in MSUB and in the physical characteistics in TXLINE.

We want to use TXLINE for it to return us correct length and thickness of a transmission line having specified both electrical length (set to be $\frac{\lambda}{8}$ due to previous explanations) and impedance. It is therefore important to set the correct frequency of operation and this will coincide with our cutofff frequency ($1GHz$), as this will allow to set the Electrical length to a specific quantity (measured in degrees): 45°. Below a view of the TXLINE tool. metric units within the tool should be set to mm.

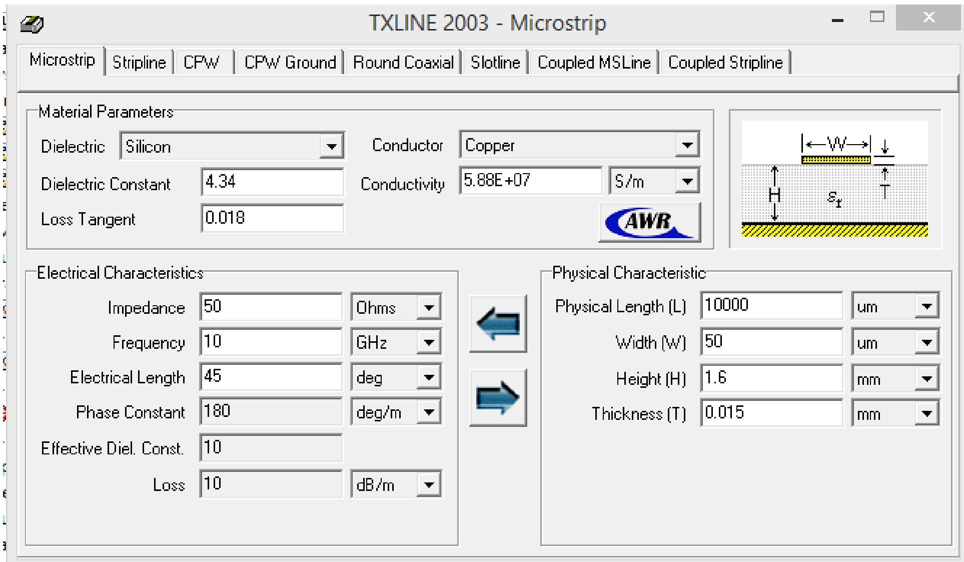

Figure 5: View of TXLINE tool.

Once designed the final 5^{th} order Low Pass stub filter - having applied all necessary Richard's Transformaions and Kuroda's Idenities - the circuit schematic should be implemented in AWR. In order to place a Open Circuit stub, the MLEF component can be used. To connect this to a MLIN (standard txline component) a MTEE junction should be adopted. In order to set correct values for each MLIN or MLEF, XLINE tool can be used. Values for MTEE instead are kept as default, as no specification was given on this. Below figures of circuit schematic, 2D view and 3D view of the created stub filter.

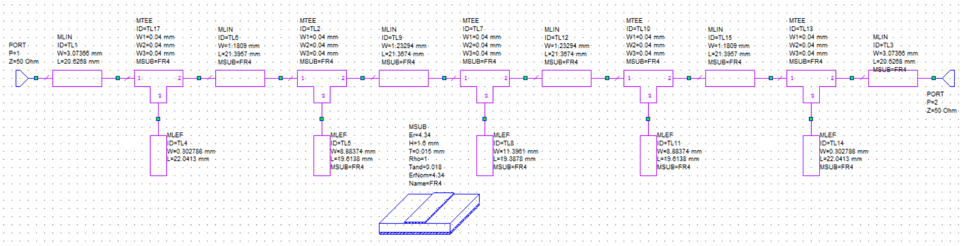

Figure 6: Circuit schematic of the 5^{th} order stub filter.

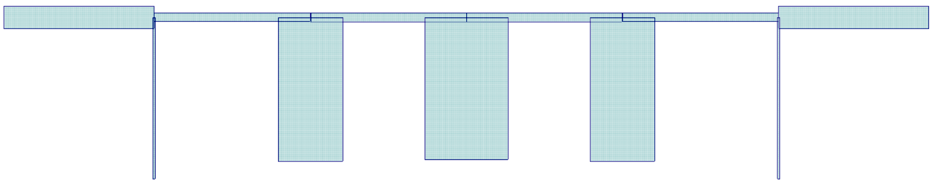

Figure 7: 2-D view of the 5^{th} order stub filter.

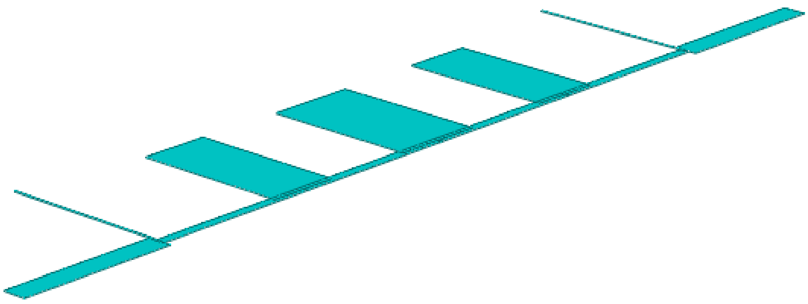

Figure 8: 3-D view of the 5^{th} order stub filter.

Once these schematics have been created, a new EM Structure has to be defined. To do so, first create a STACKUP structure within Global Definitions. This can be done by opening the Elements tab, navigating to Substrates and selecting SACKUP from the bottom window. Double clicking on this new element it is now possible to define the materials that compose the structure. Adding the FR4 dielectric and the Copper conductor, and specifying their parameters as before is the first step. Then a dielectric layer has to be added: this will be air (and we set arbirarily the thickness to be 3mm). Top, bottom and side boundaries of the structure are set from the second tab to be Approx. Open. A material called Trace1 is inserted (and set to match the characteristics of copper), in order to thn set a new EM layer of it. Figures below illustrate the process.

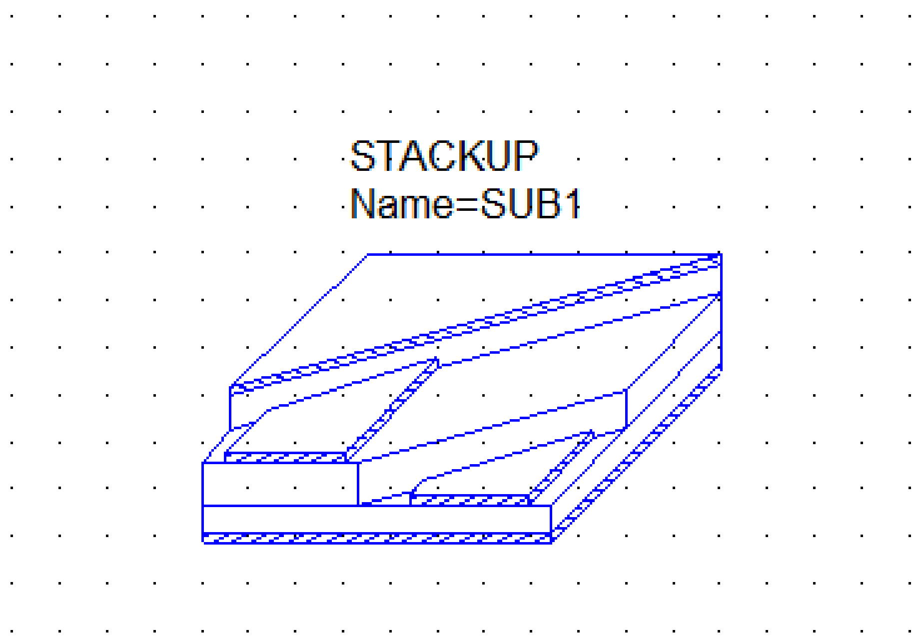

Figure 9: Stackup view from the Global Definition tab.

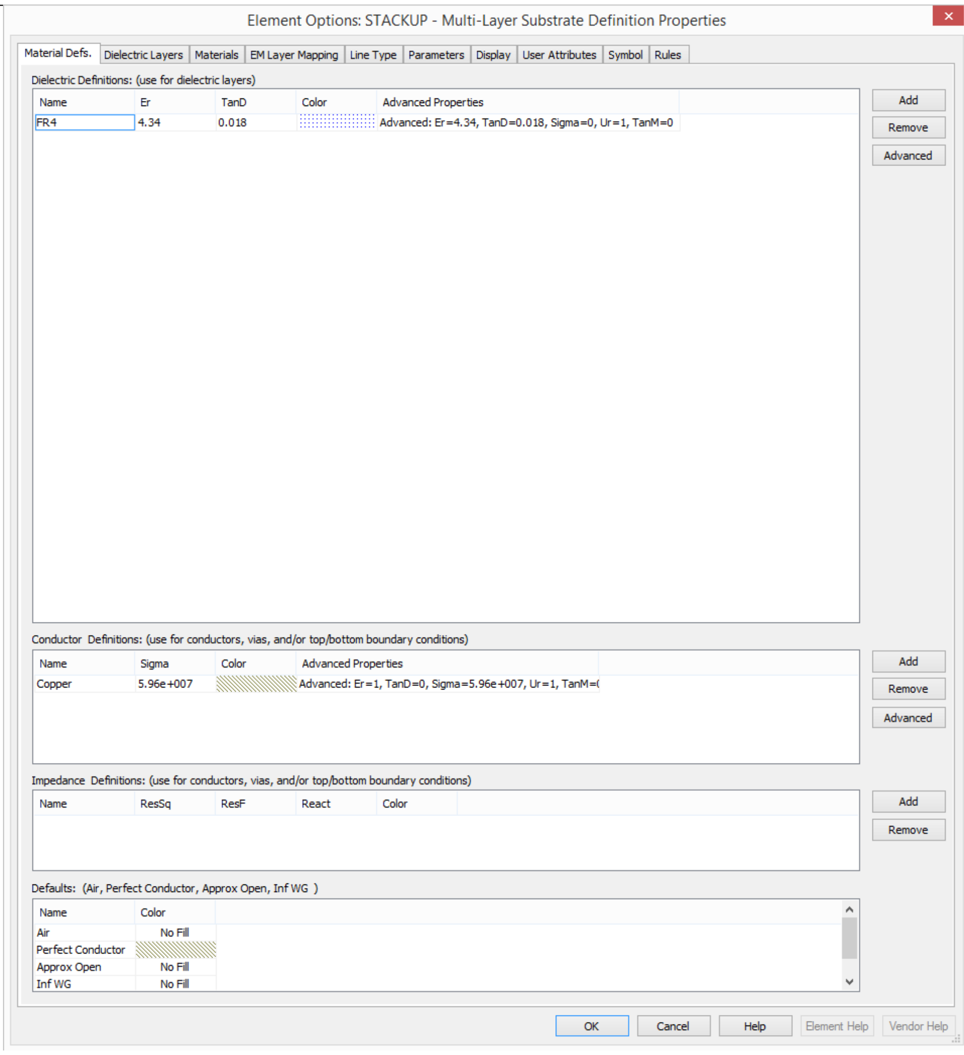

Figure 10: View of material definition properties window from Stackup view from the Global Definition tab.

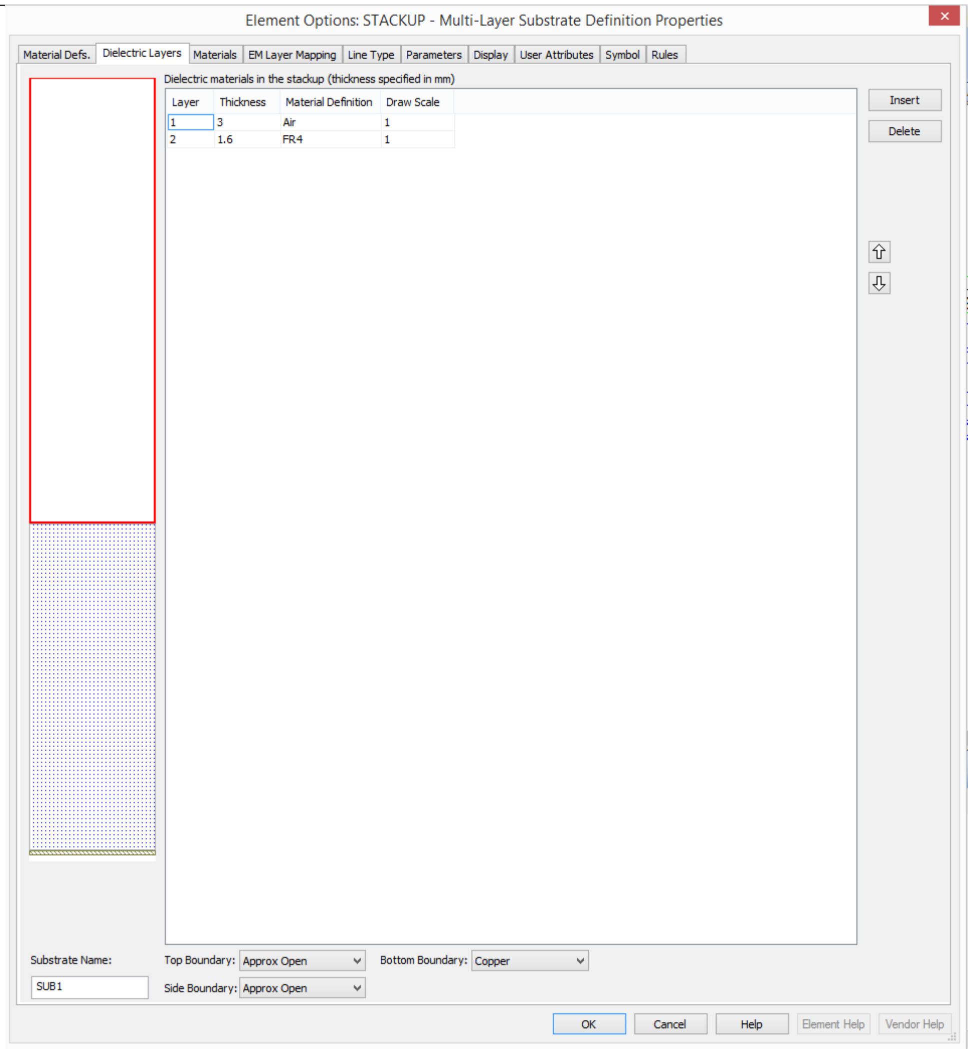

Figure 11: View of dielectric definition properties window from Stackup view from the Global Definition tab.

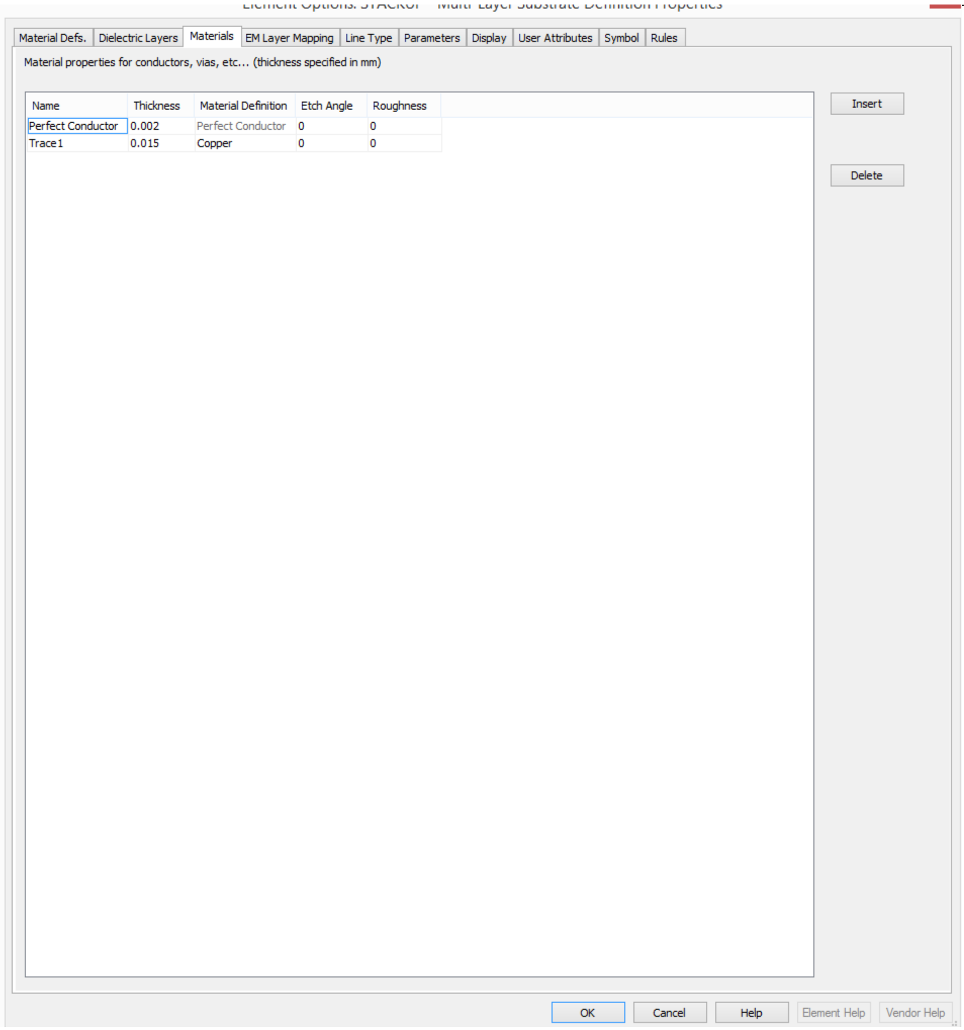

Figure 12: View of material properties window from Stackup view from the Global Definition tab.

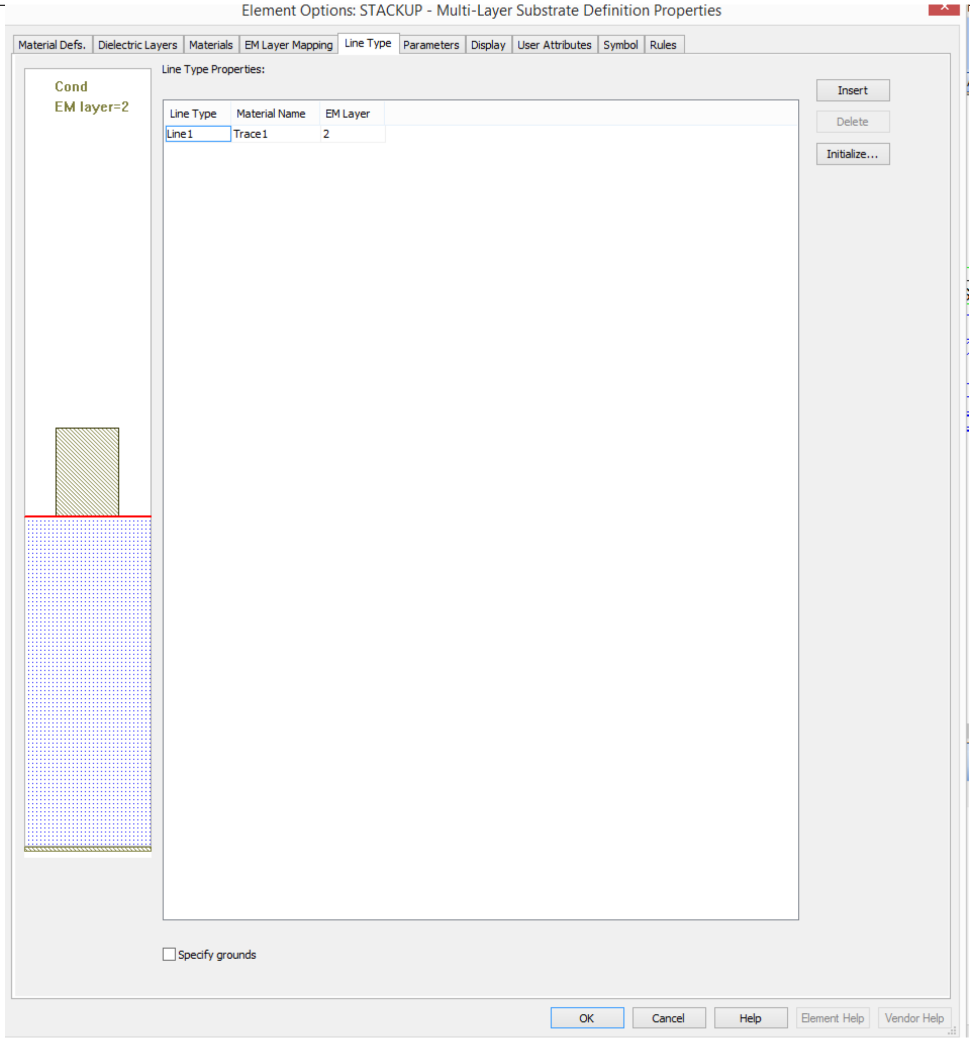

Figure 13: View of line type properties window from Stackup view from the Global Definition tab.

A new EM structure is now ready to be created. To do so, right click on EM Structures, New EM structure, select AWR AXIEM Async as the simulator and copy/paste the 2D stub network created previously. To add ports, click on the edges and select (from top tab) Edge Port. The final structure in AXIEM should look like the below figure.

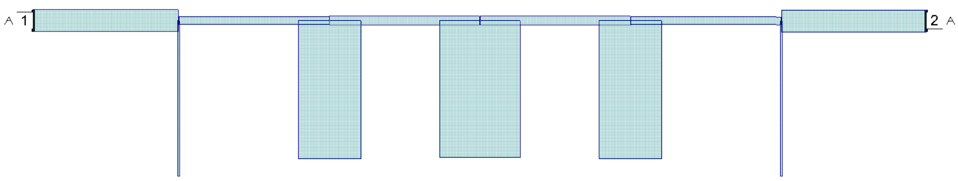

Figure 14: View of filer network within the AXIEM EM Structure.

It is now possible to create a new graph, setting the measurements to be taken from the ports on the EM Structure. In order to visualise not only the 3D structure of the stub filter, but also the microstrip line (dielectric?) on which it's going to be built upon, going back to the circuit schematic and adding a EXTRACT element, selecting all the MLINs, MTEEs and MLEFs, going to their general properties and linking them with the EXTRACT component, it's then possible (by clicking on New Extract) to create a 2D view of this schematic. Clicking on View > 3D view it is then possible to acheive the desired view. This is visible in the below figure.

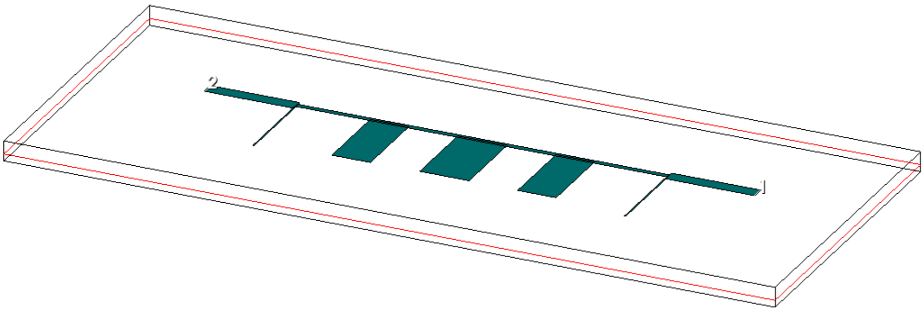

Figure 15: View of filer network within the AXIEM EM Structure and the dielectric material on which it's built.

3 Results

3.1 LC Filters

3.1.1 Low Pass Filter

In order to design the specified Low pass filter, the methodology 1 will be applied:

1. Determine specifications: The lab sheet provides us with the necessary information:
   - Filter type: Low pass 0.5 dB equal ripple response filter.
   - Cutoff frequency: ω_c: $f_C = 1GHz$
   - Source impedance: R_s: 50Ω.
   - Roll-off: 20 dB @ $f_{RL} = 1.5GHz$.
2. Design prototype Low pass filter
   - Order: To evaluate the x-axis position: $\frac{w_{RL}}{w_C} - 1 = \frac{f_{RL}}{f_C} - 1 = 0.5$ The intersection with the y-axis attenuation value is visible in the below figure. This requires a 5-Order filter.

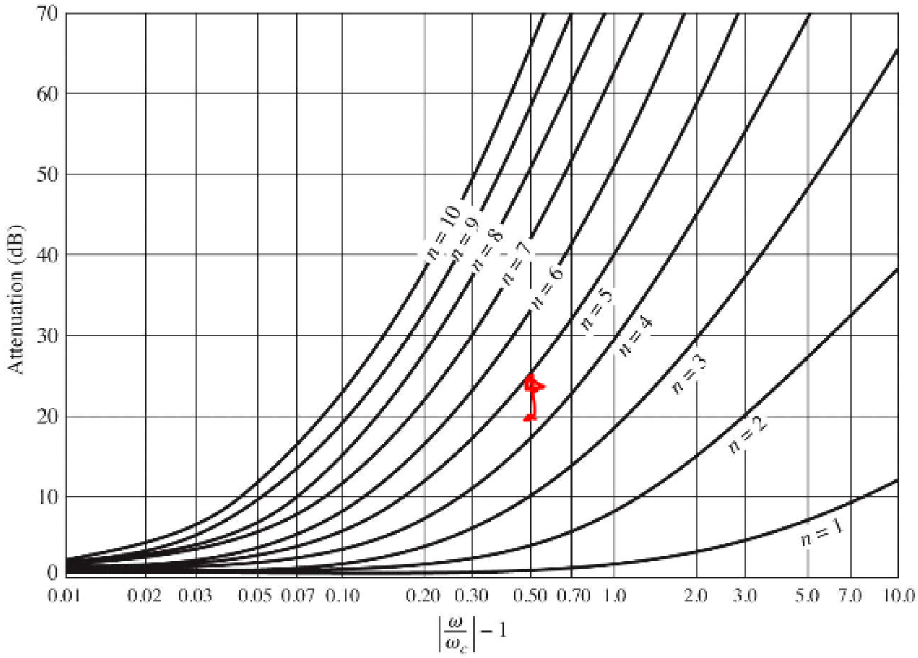

Figure 16: Attenuation vs Normalised frequency.

- Component values: Six admittance values are visible in the 0.5 dB equal ripple table, for N=5.

g_1	1.7058
g_2	1.2296
g_3	2.5408
g_4	1.2296
g_5	1.7058
g_6	1.0000

3. Scale and transform to required filter Knowing the last element is going to be the load resistor, the first 5 values, provide the admittance of the five reactive components, from the source network, to the load. Given there is no real difference whether inductors or capacitors are connected in series or in parallel, a 5-Order PI network will be implemented. In this configuration capacitors are suhunt connected, whereas inductors are connected in series. It is therefore possible to evaluate capacitance C_n and inductance L_n for the n^{th} component applying the following

$$C_n = \frac{g_n}{2\pi f_c R_s} \tag{14}$$

$$L_n = \frac{g_n R_s}{2\pi f_c} \tag{15}$$

Plugging g_n, f_c and R_s values in these equation we get

$$C_1 = C_5 = \frac{1.7058}{2\pi 10^9 50} = 3.42pF \tag{16}$$

$$C_3 = \frac{2.5408}{2\pi 10^9 50} = 8.1pF \tag{17}$$

$$L_2 = L_4 = \frac{1.2296 * 50}{2\pi 10^9} = 9.8nH \tag{18}$$

3.1.2 Band Pass Filter

In order to design the specified Band pass filter, the methodology 1 will be applied, although only the required steps -given this simply is a transformation of the LPF that has just been designed:

1. Determine specifications: The lab sheet provides us with the only necessary information that is missing:
   - Centre frequency / Bandwidth: $\omega_0 = 1GHz$, $\Delta = 100MHz$
2. Scale and transform to required filter: In order to evaluate what reactive components are necessary for the filter figure 1 can be utilised. In order to evaluate their values, the normalised bandwidth is required.

$$\Delta = (\frac{\omega_0}{\omega_2 - \omega_1})^{-1} = \frac{2\pi(f_2 - f_1)}{2\pi f - 0)} = \frac{f_2 - f_1}{f_0} = \frac{BW}{f_0} = \frac{100M}{1G} = 0.1 \tag{19}$$

Once again a PI-Network configuration is considered for the LPF, hence a shunt capacitor will be transformed into a shunt LC network and a series inductor into a series LC network. Shunt LC elements will have values

$$L'_k = \frac{\Delta R_0}{C_k \omega_0} \tag{20}$$

$$C'_k = \frac{C_k}{\Delta \omega_0 R_0} \tag{21}$$

Whereas series LC elements will have values

$$L'_k = \frac{L_k R_0}{\Delta \omega_0} \tag{22}$$

$$C'_k = \frac{\Delta}{C_k \omega_0 R_0} \tag{23}$$

Plugging Δ, R_0, ω_0 into these equations we get

$$L_1 = L_5 = \frac{\Delta R_0}{C_k \omega_0} = \frac{0.1 * 50}{2\pi * 10^9 * 1.7058} = 0.47nH \tag{24}$$

$$C_1 = C_5 = \frac{C_k}{\Delta \omega_0 R_0} = \frac{1.7058}{2\pi * 10^9 * 50} = 54.3pF \tag{25}$$

$$L_2 = L_4 = \frac{L_k R_0}{\Delta \omega_0} = \frac{1.2296 * 50}{2\pi * 10^9 * 0.1} = 97.85nH \tag{26}$$

$$C_2 = C_4 = \frac{\Delta}{C_k \omega_0 R_0} = \frac{0.1}{2\pi * 10^9 1.2296 * 50} = 0.26pF \tag{27}$$

$$L_3 = \frac{\Delta R_0}{C_k \omega_0} = \frac{0.1 * 50}{2\pi * 10^9 * 2.5408} = 0.31nH \tag{28}$$

$$C_3 = \frac{C_k}{\Delta \omega_0 R_0} = \frac{2.5408}{2\pi * 10^9 * 0.1 * 50} = 80.88pF \tag{29}$$

3.2 AWR Simulation

3.2.1 Low Pass Filter

Simulating the low pass filter network shown in figure 2 between 0 and 2 GHz the achieved results are shown below.

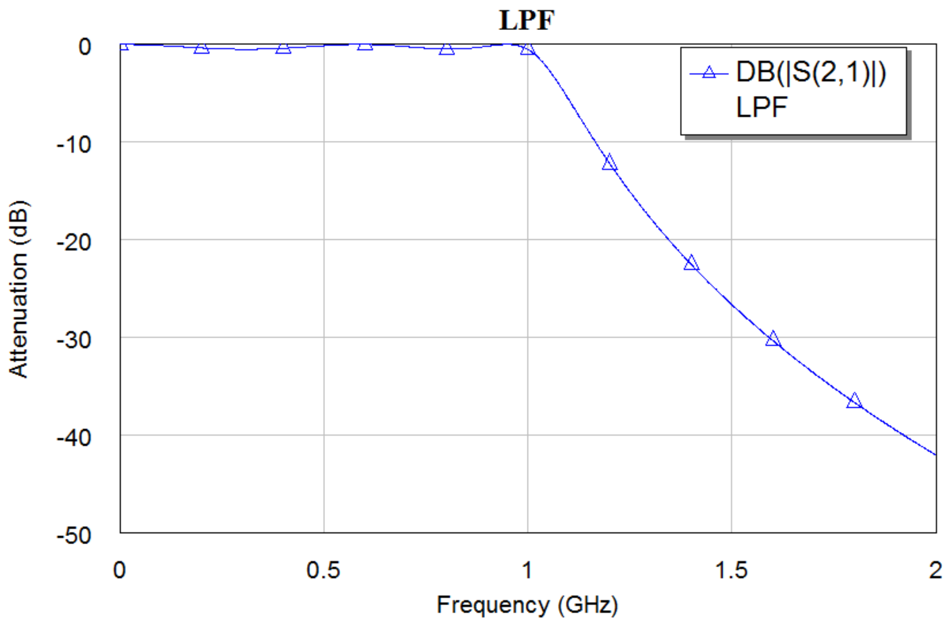

Figure 17: Magnitude frequency response for the LPF.

3.2.2 Band Pass Filter

Simulating the low pass filter network shown in figure 5between 0 and 2 GHz the achieved results are shown below.

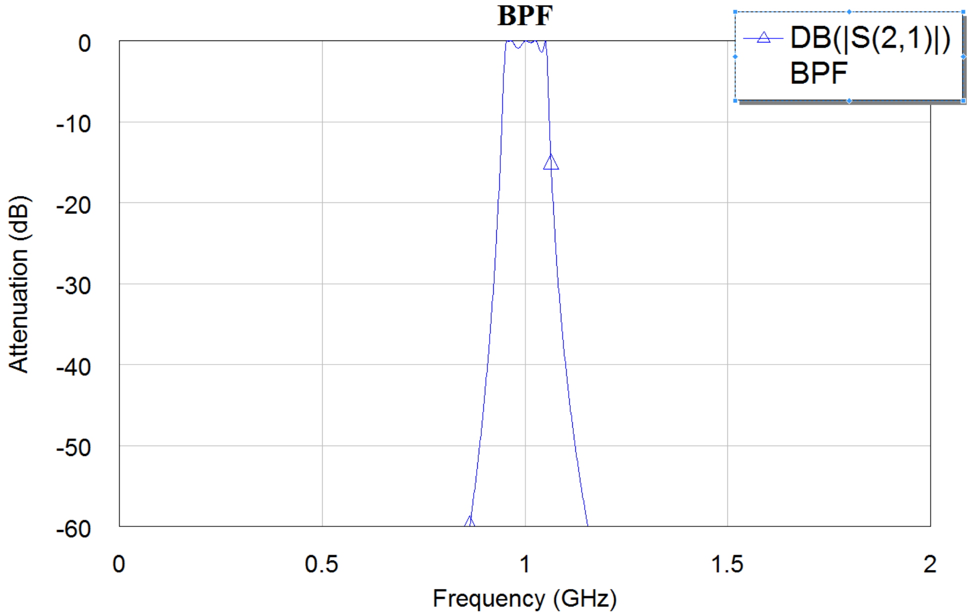

Figure 18: Magnitude frequency response for the BPF.

3.3 Transmission Line Filters

Prior to applying the transformations, admittance values read off the lumped element table (for capacitive components only), need to be converted into impedances, for equation 12 to be applied. As a π configuration is applied, and N = 5, these values result being:
$Y_1 = Y_5 = 1.7058 \rightarrow Z_1 = Z_5 = \frac{1}{1.7058} = 0.5862$
$Z_2 = Z_4 = 1.2296$
$Y_3 = 2.5408 \rightarrow Z_3 = \frac{1}{2.5408} = 0.3936$

Applying these transformations the resulting circuit becomes as shown in the below figure

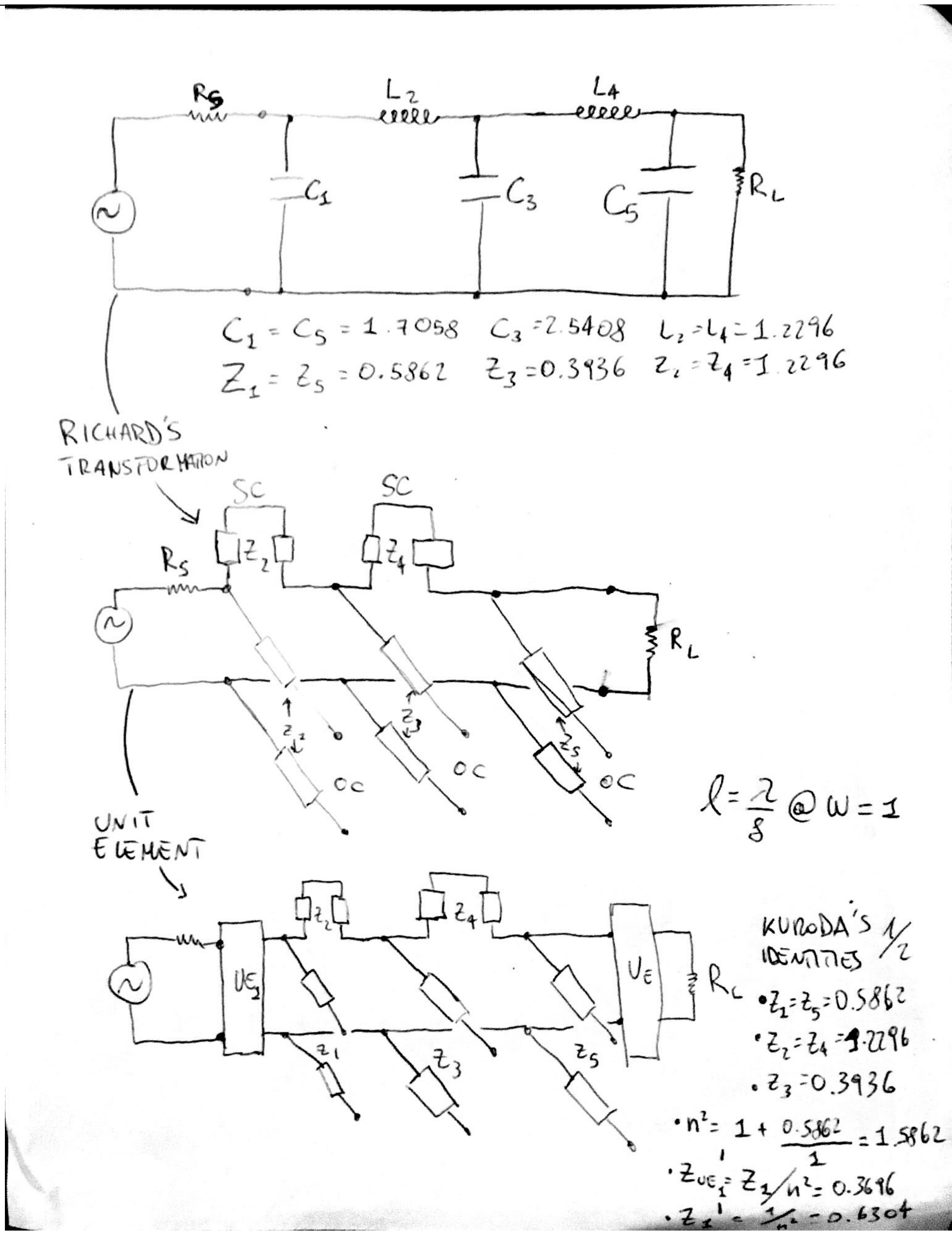

Figure 19: Richard's transformation for the LPF.

Imposing the length of all transmission lines equate to to $l = \frac{\lambda}{8}$ and adding unit elements in order to prepare Kuroda's identities the resultant circuit is the third circuit visible in the above image. Remembering that

$$Z_1 = Z_5 = 0.5862 \tag{30}$$

$$Z_2 = Z_4 = 1.2296 \tag{31}$$

$$Z_3 = 0.3936 \tag{32}$$

It is possible to compute the equation defined above 13 ie the Kuroda's identity

$$n^2 = 1 + \frac{0.5862}{1} = 1.5862 \tag{33}$$

which yields

$$Z_{UE} = \frac{Z_1}{n^2} = 0.3696 \tag{34}$$

$$Z_1 = \frac{1}{n^2} = 0.6304 \tag{35}$$

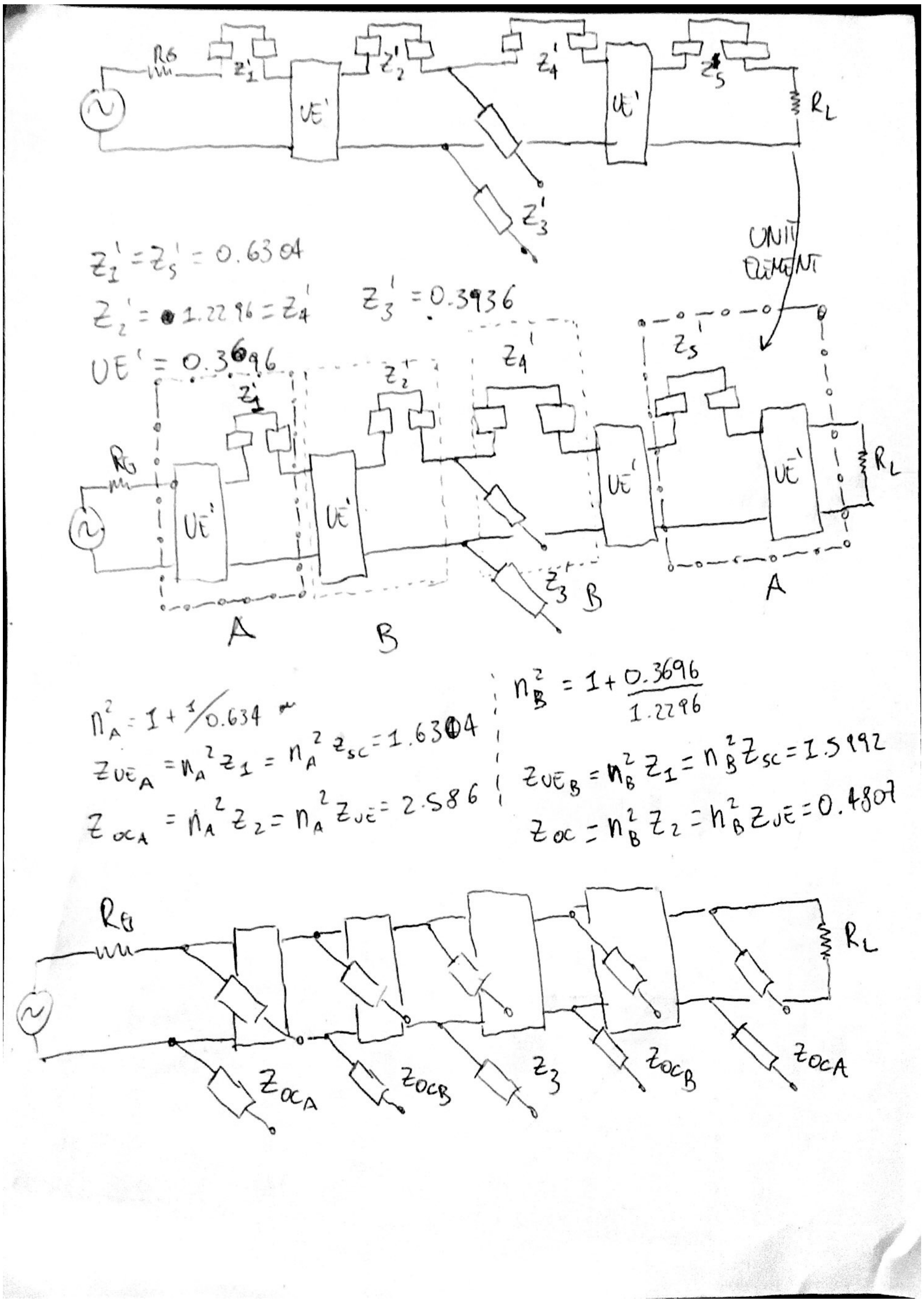

Figure 20: Kuroda's Identities for the LPF.

Now the Richard's transformation should be applied again (as our aim is to arrive to a shunt-only configuration). This is visible in the below figure second circuit schematic in the above figure. Applying once again Kuroda's identities it is possible to arrive to the third circuit diagram present in the above figure. The equations, visible between second and third schematic are presented below and derive from equation 13.

$$n_a^2 = 1 + \frac{1}{0.6304} = 2.5773 \tag{36}$$

which yields

$$Z_{UEa} = Z_1 * n^2 = Z_{sc} * n_a^2 = 1.6304 \tag{37}$$

$$Z_{OCa} = Z_2 * n^2 = Z_{UE} * n_a^2 = 2.586 \tag{38}$$

$$n_b^2 = 1 + \frac{0.3696}{1.2296} = 1.3005 \tag{39}$$

which yields

$$Z_{UEb} = Z_1 * n^2 = Z_{sc} * n_b^2 = 1.5992 \tag{40}$$

$$Z_{OCb} = n^2 * Z_2 = Z_{UE} * n_b^2 = 0.4807 \tag{41}$$

It is then necessary to re-normalise impedance values to match the requirements. This is achieved as follows:

$$Z_S = R_S * Z_0 = 50\Omega \tag{42}$$

$$Z_{1F} = Z_{5F} = Z_{OCa} * Z_0 = 129.3\Omega \tag{43}$$

$$Z_{2F} = Z_{4F} = Z_{OCb} * Z_0 = 24\Omega \tag{44}$$

$$Z_{3F} = Z_3' * Z_0 = 19.7\Omega \tag{45}$$

A poorly hand drawn figure of the resulting structure is visible below

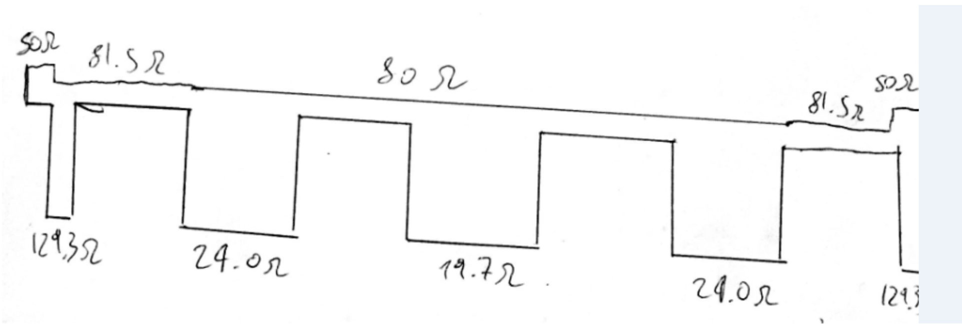

Figure 21: Hand drawn view of the LPF.

3.4 AWR Simulations

After having designed the filter in AWR as seen above and generated it's EM Structure, it's possible to simulate it and plot the measured transmission coefficient (S_{12}). This is visible in the below figure.

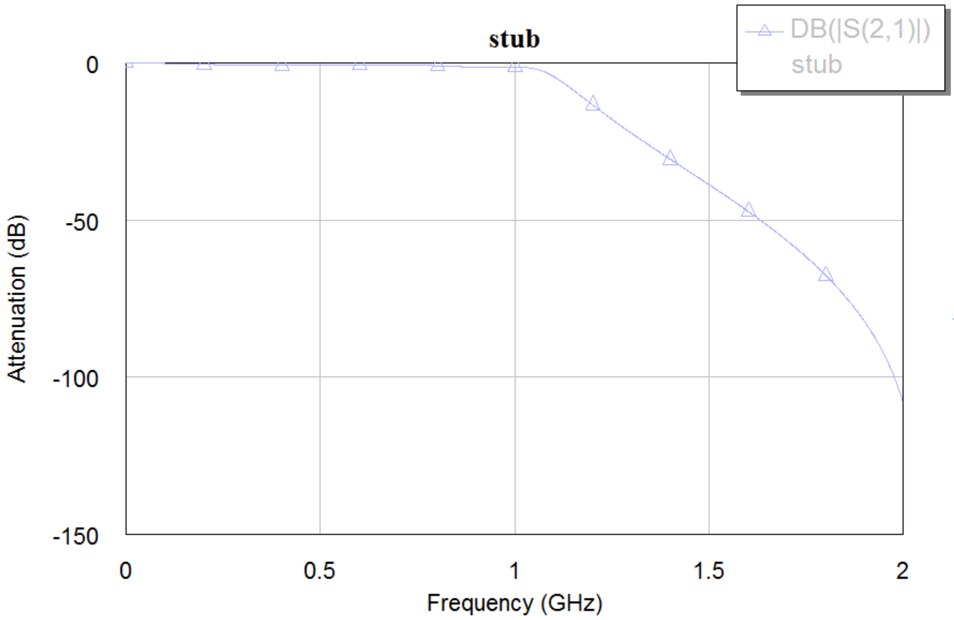

Figure 22: Magnitude response of transmission coefficient.

4 Discussion

For both of the lumped element filters, in the band pass 5 peaks and 4 sinks are visible. This shouldn't be of any surprise given it's required to design a 0.5 dB EQUAL RIPPLE type filter of 5th order.

4.1 Low Pass Filter - lumped elements

The transmission coefficient plotted in AWR proves the correctness of the design carried out. It's possible to see that N ripples of max 0.5 dB occur within the passband. Furthermore, having designed a 5^{th} order filter we see that at 1.5 GHz the attenuation is actually greater than the requirement (-20 dB). This is because from the table 16 we saw the intersection between the normalised frequency and the required attenuation fell between two curves. As designs always should be resilient to the worst case scenario, we impose a steeper transition band.

4.2 Band Pass Filter - lumped elements

Applying the required transformations it was possible to convert the brick wall low pass filter prototype into a band pass filter. Again, given our prototype was a 0.5 dB equal ripple filter, we expect 0.5 dB ripples in the passband and an transition band of steepness determined by the bandwidth required. It's likely I performed slight calculation errors, as it's visible in the graph the ripples of the produced filter are not homogeneous as they should be (as in the LPF case). Furthermore, what confirms the fact calculations errors mus have been performed is the fact that the slope of the transition band is way steeper than it should be, not providing the required bandwidth. Going back to check the calculations I can see errors for:

$$C_1 = C_5 = \frac{C_k}{\Delta\omega_0 R_0} = \frac{1.7058}{2\pi * 10^9 * 50} = 5.43pf \neq 54.3pF \tag{46}$$

Although other errors might be present, time constraints don't allow me to review all calculations and perform new simulation, unfortunately.

4.3 Low Pass Filter - stub

As visible from the produced graph the design respects the requirements. The smallest stub in use has width of 0.3 mm. In case of manufacturing difficulties, these stubs should be removed as they would have little effect on the produced circuit.

5 Resources

1. David M. Pozar *MICROWAVE ENGINEERING* Chapters 8
2. Microwaves101.com *FR4 dielectric properties*
3. Design a stub filter