Design of a sharp response low-pass filter
Through comparison of microwave design software

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Preface

I really would like to say thank you to my supervisor Efrain Zenteno because of his help in the manufacturing part and the tips he gave me to carry out this thesis.

I am also really thankful to my examiner José Chilo because he gave me the opportunity of coming here to study and do this thesis and also because he accepted to evaluate this work.

And latest but not the least I say thanks to my family who has been supporting me during this whole year here in Gävle and because without them this could not be possible.
Abstract

The aim of this thesis is to do a research about three microwave design software packages and evaluate them with the purpose of getting the sharpest filter as possible and also know which one is more efficient in this task. In order to achieve this purpose we designed, simulated and tried to manufacture the same low-pass filter (using microstrip lines) in different software. This way we are able to compare features as the S-parameters of the filters, the possibilities they give us, how easy to use they are, how long takes us to run a simulation, how much deviation they have in the simulations and how much deviation we get in the measurements of the manufactured filters.

The filter has to be a low-pass filter with the cut off frequency at 1.8 GHz and a minimum attenuation of -26dB at 4.6 GHz.

The next step will be design of the 3 filters with the 3 different software. Once we have done the designs we are ready to do simulations and manufacture them in order to evaluate which one of them is more accurate and give us the best response.

To do the measurements we used a Vector Network Analyzer, in order to get the S-parameters, and a Vector Signal Generator and a Signal Analyzer in order to check the response of the filters with real signals.

Finally, as a conclusion, evaluating all the results we got we can say that ADS is the software package that has more positive points and therefore the best suited to our needs.
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1 Introduction

1.1 Background

Nowadays filters are present in a wide variety of devices, and as we know, at microwave frequencies, lumped elements, as capacitors and inductors, are too difficult to implement. In addition, the distance between the components of the filter has to be taken into account. To solve this problem we chose to implement filters in microstrip technology. In addition, this kind of technology is cheap, easy to manufacture and we can integrate different circuits easily [1].

Low-pass filters are commonly used to filter harmonics and spurious signals and in microstrip designing when we increase the sections we have a sharper response [2]. But what we are going to do is find out which of the software give us a the sharpest response for the same number of sections.

Microwave software packages have an important role in the microwave industry nowadays, since they give us some advantages as:

- Help us to reduce the cost of production.
- Less costly process when we want to change features in our design.
- Let us save some time in the process of achieving the results we are required
- They give us a close-to-optimal result.

For these reasons we have considered that is interesting to do a review of these three software packages we had available. They are called Advanced Design System (ADS) from Agilent, High Frequency Structural Simulator (HFSS) from Ansoft and Microwave Office from AWR. Although we can find many more software with similar characteristics to these ones.

1.2 Thesis objective

The aim of this thesis is to evaluate some of the characteristics of the three software packages focusing our results in the development of a filter made in microstrip technology. To achieve our aim we decided to design, simulate and manufacture one filter with the three different software packages (the same filter but different software).
1.3 Procedure

First of all we designed the filter made with lumped elements and we simulated it in order to know which of the software give us the possibility of designing with lumped elements and to know if we designed correctly our filter.

With the values of the capacitors and inductors we can calculate the shape of our microstrip filter and implement it in the software. This way we are able to check:

- The facilities they give us to design as it could be a tool to calculate strip sizes.
- How quick and easy is to design in the environment.
- If they are intuitive or we need a guide in order to use them.

Once we have the design of the microstrip filter done we should simulate to compare the results we expected with the results we get in order to see the deviations that each software introduces in the results. And, of course, in this section we can also check the differences in time that takes us to run a simulation in each software, which is also a very remarkable characteristic.

Now that we have the simulations, if they correspond to our expected results, we can carry out the manufacturing and see which of them let us manufacture and if they can perform it in a proper way.

Finally, when we have our designs printed on the PCB’s is the moment to see if our software has been able to achieve our requirements. To carry out this part we used a Vector Network Analyzer, in order to get the S-parameters, and a Vector Signal Generator and a Signal Analyzer in order to check the response of the filters with real signals.

1.4 Thesis Outline

The chapter 2 provides a theoretical background of how to design and characterize a filter. It contains how to design a low-pass filter by the insertion loss method, how to transform a lumped element filter into a distributed one and how to measure and what is the meaning of the S-parameters.

Chapter 3 is about the process we have followed to carry out our aim and about the results we have gotten during our process. The figures of the most interesting simulations are shown in this chapter also.
Finally, simulations made with the different software and measurements taken from different manufactured filters are discussed on chapter 4.
2 Theory

In this chapter we will introduce some theory in order to understand some of the concepts we treat during the development of this thesis.

We will introduce concepts like how to design a low-pass filter using the insertion loss method, how to transform the normalized values of a lumped element filter into the real ones, how to implement a filter in microstrip technology using the Richard’s and Kuroda’s transformations, the meaning of the Scattering parameters and how we used our measurement devices.

2.1 Low-pass filter design by the insertion loss method

To carry out this method we need to know our required insertion loss (at the desired frequency), and the cutoff frequency.

The insertion loss is defined as [3]:

\[
IL = 10 \log PLR
\]

where:

\[
PLR = \frac{P_{inc}}{P_{load}}
\]

To implement a butterworth response filter we must know that the power loss ratio is specified by [3]

\[
PLR = 1 + k^2 \left( \frac{\omega}{\omega_c} \right)^{2N}
\]

where

N = order of the filter

\( \omega_c = \) cutoff frequency

From the formula we can get the value of N if we fix some requirements.

Now that we know the order of the filter we must look at the table 1 in order to know the values of the elements (normalized in frequency and impedance) of our filter made by lumped reactive elements [4].
Table 1. Element values for maximally flat low-pass filter prototypes ($g_0 = 1$, $\omega_c = 1$).

<table>
<thead>
<tr>
<th>n</th>
<th>$g_0$</th>
<th>$g_1$</th>
<th>$g_2$</th>
<th>$g_3$</th>
<th>$g_4$</th>
<th>$g_5$</th>
<th>$g_6$</th>
<th>$g_7$</th>
<th>$g_8$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.00000</td>
<td>1.00000</td>
<td>1.00000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1.00000</td>
<td>1.41421</td>
<td>1.41421</td>
<td>1.00000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1.00000</td>
<td>1.00000</td>
<td>2.00000</td>
<td>1.00000</td>
<td>1.00000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1.00000</td>
<td>0.76536</td>
<td>1.84775</td>
<td>1.84775</td>
<td>0.76536</td>
<td>1.00000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>1.00000</td>
<td>0.61803</td>
<td>1.61803</td>
<td>2.00000</td>
<td>1.61803</td>
<td>0.61803</td>
<td>1.00000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>1.00000</td>
<td>0.51763</td>
<td>1.41421</td>
<td>1.93185</td>
<td>1.41421</td>
<td>0.51763</td>
<td>1.00000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>1.00000</td>
<td>0.44504</td>
<td>1.24697</td>
<td>1.80193</td>
<td>2.00000</td>
<td>1.80193</td>
<td>1.24697</td>
<td>0.44504</td>
<td>1.00000</td>
</tr>
</tbody>
</table>

where the $g_k$ has the following definition:

- $g_0$ = generator resistance
- $g_1$, $g_N$ = inductance for series inductors or capacitance for shunt capacitors
- $g_{N+1}$ = load resistance if $g_N$ is a shunt capacitor or load conductance if $g_N$ is a series inductor

### 2.2 Filter transformations

With the aim of get the real values of the capacitor and inductors we have to undo the normalization. We must apply some equations to the values in the table.

To undo the impedance scaling and the frequency scaling we must apply the following formulas [5]:

\[
L'_k = \frac{R_0 L_k}{\omega_c}
\]

\[
C'_k = \frac{C_k}{R_0 \omega_c}
\]

\[
R'_S = R_0 R_S
eq R'_L = R_0 R_L
\]

where $L_k$, $C_k$ and $R_L$ are the component values for the original low-pass filter. And $R_0$ is the value of the source resistance.
2.3 Filter implementation

It is needed a way to transform a lumped element filter into a microstrip filter, so we use a couple of transformations in order to achieve this aim.

Richard’s transformation

To implement a low-pass filter design with microstrip lines we could use the Richard’s transformations, which give us a way to substitute lumped elements by transmission lines, since the reactance of an inductor can be written as

\[ jX_L = jL \tan \beta l \]

and the susceptance of a capacitor can be written as

\[ jX_C = jC \tan \beta l \]

These equations indicate that we can replace an inductor by a short-circuited stub of length \( \beta l \) and characteristic impedance \( L \) and a capacitor can be replaced with an open-circuited stub of length \( \beta l \) and characteristic impedance of \( 1/C \). Unity filter impedance is assumed.

Then, we know the cutoff occurs at unity frequency for low-pass filter prototype, so

\[ \tan \beta l = 1 \]

which gives us a length for our stubs of \( \lambda/8 \), where \( \lambda \) is the wavelength of the line at the cutoff frequency [3].

Thus, we can apply the following substitution in the figure 1 [3]:

![Figure 1. Richard’s transformation.](image-url)
Kuroda’s identities

The four Kuroda identities let us achieve a more practical microstrip filter implementation doing any of the following processes:
- Separate physically transmission line stubs
- Replace series stubs into shunt stubs or vice versa
- Change impractical characteristic impedances into more practical ones.

Here we have the equivalences of 2 kuroda identities we used in the figure 2 [3]:

\[
\begin{align*}
\text{First Identity} & \quad \frac{1}{Z_2} = \frac{Z_1}{Z_1} \\
\text{Second Identity} & \quad \frac{Z_2}{n^2} = \frac{n^2 Z_1}{1/n^2 Z_2}
\end{align*}
\]

Where

\[
n^2 = 1 + \frac{Z_2}{Z_1}
\]

and each box represents a line of length $\lambda/8$ and at $\omega_c$ with the impedance indicated inside the box. The capacitor and inductors represent open-circuited and short-circuited stubs respectively.

### 2.4 Scattering or S-parameters

S-parameters are useful to analyze microwave networks. They give us information about the magnitude and relative phase of the traveling waves on the network [5].
For example, this 2-port network in the figure 3 can be defined as:

![Image of a 2-port network]

**Figure 3. Waves in a 2-port network.**

The equations which define the connection between incident waves ($a_n$) and reflected waves ($b_n$) are [6]:

\[
\begin{align*}
    b_1 &= s_{11} a_1 + s_{12} a_2 \\
    b_2 &= s_{21} a_1 + s_{22} a_2
\end{align*}
\]

Or in a matrix way:

\[
\begin{bmatrix}
    b_1 \\
    b_2
\end{bmatrix} =
\begin{bmatrix}
    s_{11} & s_{12} \\
    s_{21} & s_{22}
\end{bmatrix}
\begin{bmatrix}
    a_1 \\
    a_2
\end{bmatrix}
\]

Where

\[
\begin{align*}
    s_{11} &= \left. \frac{b_1}{a_1} \right|_{a_2=0} \\
    s_{21} &= \left. \frac{b_2}{a_1} \right|_{a_2=0} \\
    s_{22} &= \left. \frac{b_2}{a_2} \right|_{a_1=0} \\
    s_{12} &= \left. \frac{b_1}{a_2} \right|_{a_1=0}
\end{align*}
\]

Note that $a_n = 0$ is equivalent to matching port $n$. 
2.5 Devices used for measurements

Regarding the devices we used to take measurements, we used a Vector Network Analyzer from the company Agilent technologies. The model is N5242A and it can take measurements from 10 MHz till 28.5 Ghz. It can be seen in the figure 4.

![Vector Network Analyzer](image1.png)

Figure 4. Vector Network Analyzer

We used this device with the purpose of measuring the scattering parameters. In order to use this device correctly is needed a calibration of the device first. We get all the parameters from this device and we plot them in Matlab.

It was also used a Vector Signal Generator from the company Rohde & Schwarz. The model is SMU 200A. It can be seen in the figure 5.

![Vector Signal Generator](image2.png)

Figure 5. Vector Signal Generator.
We used this device to create and send real signals through our filter. First, is needed to configure the signals (frequency and amplitude). Then we send them through the filter and we measure them ith the signal analyzer.

And finally, we also used a Signal Analyzer from the company Rohde & Schwarz. The model is FSQ26 and it can measure signals from 20 Hz until 26.5 Ghz. It can be seen in the figure 6.

![Signal Analyzer](image)

**Figure 6. Signal Analyzer.**

We used this device in order to measure the signals sent from our Vector Signal Generator, whether if they come directly from the source or through the filter.
3 Process and results

To start our thesis we fixed all the parameters we were required to design our low-pass filter and this way, we can compare the three software packages.

We used a maximally flat (also called binomial or Butterworth) low-pass filter, because it has a low group delay, and in some applications in communications is unacceptable to have high group delay [6]. The low-pass filter prototype has the following specifications:

- Cut-off frequency \( f_c = 1.8 \text{Ghz} \)
- Insertion loss \( IL = 26 \text{dB} \) at 4.6 GHz

And we are going to implement it in a Teflon substrate with these characteristics:

- Thickness of 0.8 mm
- Relative dielectric constant of 2.54
- Relative permeability of 1
- Dielectric loss tangent of 0.0003

And a copper conductor with the following features:

- Thickness of 35 µm
- Conductivity of \( 1e+50 \text{ S/m} \)
- Surface roughness protrusion height of 0 mm

3.1 Design with lumped elements

In this part we are going to design our filter with lumped elements, thus we use the next formula with our requirements

\[
P_{LR} = 1 + k^2 \left( \frac{\omega}{\omega_c} \right)^{2N}
\]

and we get a forth order filter \( N=4 \) so we are going to have four elements in our lumped design.

Then we get our normalized values for the lumped elements from the table 1.
These values are:

\[
\begin{align*}
g_0 &= 1.0000 \\
g_1 &= 0.7654 \\
g_2 &= 1.8478 \\
g_3 &= 1.8478 \\
g_4 &= 0.7654 \\
g_5 &= 1.0000
\end{align*}
\]

In order to check that the design is correct, we simulated our lumped design in ADS (see figure 7). The calculations done in order to get the value of every lumped element knowing the normalized values can be found in Appendix A.

And we got the following result in the figure 8:

Where, as we expected, we can check that at 1.8 GHz we have approximately the cut-off frequency.
3.2 Microstrip design

Now, we start with the design of the filter in microstrip technology. In order to carry out this we have to transform our lumped element circuit into a distributed element circuit.

The first step is to use Richard’s Transformation where we get our circuit with distributed elements but is not ready yet, since we have to use Kuroda’s identities to get open-circuited shunt stubs and avoid coupling between stubs.

Once we applied the transformations we get all the values for all the characteristic impedances for every microstrip line. These are the values according to the figure 9.

\begin{align*}
Z_1 &= 50 \, \Omega \\
Z_2 &= 115.325 \, \Omega \\
Z_3 &= 88.27 \, \Omega \\
Z_4 &= 27.055 \, \Omega \\
Z_5 &= 120.705 \, \Omega \\
Z_6 &= 37 \, \Omega \\
Z_7 &= 71.68 \, \Omega \\
Z_8 &= 165.315 \, \Omega \\
Z_9 &= 50 \, \Omega 
\end{align*}

Figure 9. Schematic after applying Richard’s and Kuroda’s transformations.
3.2.1 Microstrip design with ADS

Now that we know all the values of the impedances, we use an ADS tool called LineCalc (see figure 10).

![Figure 10. Tool in ADS for microstrip sizes calculation.](image)

In the table 2 we can see the results given by the tool for the design:

<table>
<thead>
<tr>
<th>Strip number</th>
<th>Width</th>
<th>Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.2001 mm</td>
<td>14.3572 mm</td>
</tr>
<tr>
<td>2</td>
<td>0.3966 mm</td>
<td>15.1096 mm</td>
</tr>
<tr>
<td>3</td>
<td>0.7792 mm</td>
<td>14.8580 mm</td>
</tr>
<tr>
<td>4</td>
<td>5.1857 mm</td>
<td>13.9156 mm</td>
</tr>
<tr>
<td>5</td>
<td>0.3462 mm</td>
<td>15.1531 mm</td>
</tr>
<tr>
<td>6</td>
<td>3.4196 mm</td>
<td>14.1269 mm</td>
</tr>
<tr>
<td>7</td>
<td>1.1916 mm</td>
<td>14.6657 mm</td>
</tr>
<tr>
<td>8</td>
<td>0.1032 mm</td>
<td>15.4876 mm</td>
</tr>
<tr>
<td>9</td>
<td>2.2001 mm</td>
<td>14.3572 mm</td>
</tr>
</tbody>
</table>

Table 2. Sizes of the microstrips calculated with ADS.
And we design our microstrip filter with the components called MTEE_ADS, MLOC, MLIN and Term. The result looks like this (see figure 11):

![Figure 11. Filter with distributed components in ADS.](image)

And the layout (see figure 12), ready to print and manufacture has the following shape:

![Figure 12. Layout of the filter with distributed components in ADS.](image)
3.2.2 Microstrip design with Microwave Office

Microwave Office also has a designing tool called TXLINE 2003 which gives us the length and width of every strip line. This tool has the following appearance:

![Figure 13. Tool in Microwave Office for microstrip sizes calculation.](image)

Here, we have to specify the materials parameters, electrical characteristics and the height and thickness in the physical characteristics, in order to get the length and width of every strip line. These are the results given by the tool for the design (see table 3):

<table>
<thead>
<tr>
<th>Strip number</th>
<th>Width</th>
<th>Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.2001 mm</td>
<td>14.3566 mm</td>
</tr>
<tr>
<td>2</td>
<td>0.3970 mm</td>
<td>15.1090 mm</td>
</tr>
<tr>
<td>3</td>
<td>0.7792 mm</td>
<td>14.8574 mm</td>
</tr>
<tr>
<td>4</td>
<td>5.1854 mm</td>
<td>13.9149 mm</td>
</tr>
<tr>
<td>5</td>
<td>0.3461 mm</td>
<td>15.1525 mm</td>
</tr>
<tr>
<td>6</td>
<td>3.4193 mm</td>
<td>14.1262 mm</td>
</tr>
<tr>
<td>7</td>
<td>1.1915 mm</td>
<td>14.6650 mm</td>
</tr>
<tr>
<td>8</td>
<td>0.1032 mm</td>
<td>15.4870 mm</td>
</tr>
<tr>
<td>9</td>
<td>2.2001 mm</td>
<td>14.3560 mm</td>
</tr>
</tbody>
</table>

Table 3. Sizes of the microstrips calculated with Microwave Office.
And we design our microstrip filter with the components called MTEES, MLEF, MLIN and PORT. The result looks like this (see figure 14):

![Figure 14. Filter with distributed components in Microwave Office.](image)

Then, as we did with ADS, we get the layout of the filter. It looks like this (see figure 15):

![Figure 15. Layout of the filter with distributed components in Microwave Office.](image)

### 3.2.3 Microstrip design with HFSS

HFSS does not have a tool to calculate the width and length of a strip line knowing its impedance and the characteristics of the conductor and the substrate. Thus, we used the lengths and widths from ADS and the result looks like this (see figure 16):

![Figure 16. Filter designed in HFSS.](image)
3.3 Simulations results

In this section are found the results of our filters simulation, we can compare the $S_{21}$ parameter of every filter.

In the figure 17 we can see the magnitude of the filter designed with ADS. As we expected it has the cut-off frequency around 1.8GHz. Exactly, we have -3dB between 1.83 GHz and 1.84 GHz. About the slope we can calculate that it goes down approximately by 39.23 dB/GHz. Moreover we can also see that we can use the filter until 4.31 GHz where we have attenuation from -3dB to -60 dB or less, but of course, we can use a wider range depending on how much attenuation we need. Regarding the phase we see in the figure 18 that is linear inside the bandpass.

![Figure 17. $S_{21}$ magnitude of the filter with distributed elements in ADS.](image)

![Figure 18. $S_{21}$ phase of the filter with distributed elements in ADS.](image)
In the figure 19 we can see the magnitude of the filter designed with Microwave Office. As we expected it has the cut-off frequency around 1.8GHz. Exactly, we have -3dB between 1.76 Ghz and 1.775 Ghz. About the slope we can calculate that it goes down approximately by 39.31 dB/GHz. Moreover we can also see that we can use the filter until 4.164 GHz where we have attenuation from -3dB to -60 dB or less, but of course, as we said before, we can use a wider range depending on how much attenuation we need. Regarding the phase we can see in the figure 20 that is linear inside the bandpass.

![Figure 19. S21 magnitude of the filter with distributed elements in Microwave Office.](image1)

![Figure 20. S21 phase of the filter with distributed elements in Microwave Office.](image2)

In the figure 21 we can see the magnitude of the filter designed with HFSS. As we expected it has the cut-off frequency around 1.8GHz. Exactly, we have -3dB between 1.72 Ghz and 1.73 Ghz. About the
slope we can calculate that it goes down approximately by 39.15 dB/GHz. Moreover we can also see that in this case we have a peak in the stopband which reaches almost the value of -50 dB, then we cannot use the filter in the same range as we were using it before. However we can use it until 4.1 GHz if an attenuation higher than 50 dB is not required. Regarding the phase we see in the figure 22 that is linear inside the bandpass.

![Figure 21. S21 magnitude of the filter with distributed elements in HFSS.](image1.png)

![Figure 22. S21 phase of the filter with distributed elements in HFSS.](image2.png)
3.4 Manufacturing

Once we carried out all the simulations we decided to manufacture the filters in ADS and Microwave office, since is not possible to manufacture directly from HFSS, moreover, the design simulated in HFSS has the same strip sizes as the one simulated in ADS because HFSS does not have any tool to calculate strip sizes knowing its characteristic impedance.

In order to do the manufacturing we used a process of photolithography on a PCB (printed circuit board). This is a simple and cheap method used to manufacture filters in microstrip technology. It consists of printing our design on a transparent sheet in order to overlap this printed drawing with our printed circuit board. Once we overlapped the sheet and the board we expose it to UV light during five minutes approximately to remove an acid protection layer from our board, this means that the part of the board overlapped with the printed circuited will not be affected by the UV light. Now, we introduce our board inside an acid which removes copper from the parts which has been affected by the UV light giving us a copper microstrip filter printed on our board.

In figures 23 and 24 can be seen the results of the manufactured filters.

![Figure 23. Filter manufactured with ADS](image1)

![Figure 24. Filter manufactured with Microwave Office.](image2)
3.5 Measurements

3.5.1 Measurements of the filter designed with ADS.

In this section we show measurements of the filter designed with ADS. First of all, we decided to measure basic parameters of a filter like magnitude and phase of the $S_{21}$. The result was measured with our signal analyzer and the data is represented in MATLAB. We can see the appearance of the parameter in figures 25 and 26.

![Figure 25. $S_{21}$ magnitude of the manufactured filter with ADS.](image1)

![Figure 26. $S_{21}$ phase of the manufactured filter with ADS](image2)
As we can see we have the cut off frequency at 1.802 GHz and a calculated roll-off factor of 51.81 dB/GHz. In addition, we have linear phase and as long as we have linear phase we have constant group delay, since group delay is calculated as the first derivative of phase.

We set up our Vector Signal Generator to send two different signals, one Multi Carrier Continuous Wave (MCCW) signal at 2.5 GHz and one CDMA2000 signal at 1.8 Ghz. They were sent through the filter and we compared the result with the signals not filtered. The result was measured with our signal analyzer and the data is represented in MATLAB and it can be seen in the figure 27.

![Figure 27. Measurement with 2 signals through the filter manufactured in ADS.](image1.png)

It can be seen how our MCCW signal has been attenuated in 23 dB approximately.

We also sent a QPSK signal through the filter in order to see how our constellation diagram was affected by the filter when we increase the frequency along the stop-band. The result can be seen in the figure 28.

![Figure 28. Measurement with a QPSK signal through the filter manufactured in ADS.](image2.png)
The red figures represent where the symbols should be in an ideal system and the blue ones represents where we received the symbols actually. As we can see even knowing that the phase of the bandstop is not very linear, symbols does not suffer any phase change that we can appreciate. It can also be seen that as long as we increase the frequency the noise and the power are attenuated, since the symbols are getting closer to the ideal position of the symbol and to the center of the graph where there is no power.

3.5.2 Measurements of the filter designed with Microwave Office.

As in the last section we show measurements of the designed filter, but now it is was designed with microwave office. Then, in order to compare both filters we took the same type of measurements. We start with magnitude and phase of the $S_{21}$. The result was measured with our signal analyzer and the data is represented in MATLAB. We can see the appearance of the parameter in figures 29 and 30.

![Figure 29. $S_{21}$ magnitude of the manufactured filter with Microwave Office.](image)

![Figure 30. $S_{21}$ phase of the manufactured filter with Microwave Office.](image)
As we can see in the figure 29 our cut off frequency is not where we expected because when we printed our design of Microwave Office, we realized it was a little bit smaller and it affected to our cut off frequency. It can also be seen that the magnitude response is not flat, if we would want to use this filter we would need an equalizer to compensate the attenuation suffered by the signal if it is a wide signal. However we calculate our roll-off factor anyway and we get 35.625 dB/GHz. In the figure 30 we can see that our phase is linear (or almost linear) in the band-pass, as we expected, and as we said before it means that we do not have group delay or if we have is very little.

For our next measurement we also set up our Vector Signal Generator to send two different signals, one Multi Carrier Continuous Wave (MCCW) signal and one CDMA2000 signal. As in the previous section we sent them through the filter and we compared the result with the signals not filtered. The result was measured with our signal analyzer and the data is represented in MATLAB and it can be seen in the figure 31.

![Figure 31. Measurement with 2 signals through the filter manufactured in Microwave Office.](image)

It can be seen how our MCCW signal has been attenuated in 25 dB approximately. And also we can appreciate a peak power at 2.2 GHz approximately which makes us think that our filter is also working as an antenna and if we do not want to receive interferences through our filter it has to be shielded, taking into account that the walls are distanced from the filter by three to five substrate thicknesses [8].
For this filter we also sent a QPSK signal through the filter in order to see how our constellation diagram was affected by the filter when we increase the frequency along the stop-band. The result can be seen in the figure 32.

![Figure 32](image.png)

*Figure 32. Measurement with a QPSK signal through the filter manufactured in Microwave Office.*

The red figures represent where the symbols should be in an ideal system and the blue ones represents where we received the symbols actually. As we can see even knowing that the phase of the band-stop is not very linear, symbols does not suffer any phase change that we can appreciate. It can also be seen that as long as we increase the frequency the noise is not attenuated as in the other filter, since the symbols are not getting closer to the ideal position of the symbol. And another remarkable fact is that our symbols are not getting closer to the centre of the graph as before which means that the slope of the stop-band of this filter is not as sharp as the one designed with ADS.
4 Discussion and conclusion

Now, that we went through all three software packages we can make an evaluation of them. We have been focused on the design of the filter in microstrip technology, so that is going to be our main point of reference where we are going to focus all our discussions and conclusions. But before we can say that a remarkable fact could be that all three software packages are quite intuitive to use but is always needed at least a basic guide to know how them works, especially when we want to simulate our design and get results.

The first point we can treat, because it was the main purpose of our thesis, is our roll-off factor in the simulations. As we saw it is almost the same for all three software, so this could not be an important feature to choose one of the software. Once manufactured we can see that our roll-off factor have suffered deviations, in ADS it got better and in Microwave Office got worse.

Now we can treat the fact of designing the filter with lumped elements in order to check if our design has been correctly calculated. It can help us to save some time if we check that the response of our filter is what we expected. This feature is given by ADS and Microwave Office but in HFSS you have to start designing your microstrip design directly.

Another issue could be that ADS and Microwave Office offer us LineCalc and TXLINE 2003, respectively, which give us the possibility of calculating the sizes of the strips. Otherwise, as it happens with HFSS, we need to use a tool apart in order to calculate the width and length of every single strip line. Regarding the results they give us we can compare table 2 and table 3 and see that the results are quite similar; they start to be different from tens of micrometers.

Something else important to consider is how easily and quickly we can draw our design in the software. This theme is more or less the same for ADS and Microwave Office, you just have to choose the elements you want to use and place them in the proper position in order to connect them to each other and give them the values of the lengths and widths. However, in HFSS designing a microstrip filter is something completely different. Designing in HFSS is based in a 3D environment (versus a 2D environment we had in ADS and Microwave office) where you have to place boxes with the shape of the board and the shape of the filter and then give them their dimensions, moreover you have to place the boxes carefully in the proper layer because if the boxes are overlapped the design does not work.

Regarding the feature of getting the layout of our microstrip filter and manufacture it we have to say that ADS and Microwave Office give us the possibility of printing the design and carry out the
manufacturation, whereas in HFSS is not possible to print in real scale; it is a software package just
designed to simulate electromagnetic devices in a 3D environment.

Something else quite relevant is how much time takes us to run a simulation. Both ADS and
Microwave Office just take us some seconds to give us a result when we configure them with default
settings and the same conditions (as the same range of frequency to sweep, same number of steps,
etc…) but HFSS can take us almost one hour to get a result.

Another point to treat is the results which are given by all three software. As it can be seen in figures
14, 16 and 18, where we have represented the magnitude of the parameter S21 simulated by ADS,
Microwave Office and HFSS respectively, the cut-off frequency is not exactly where we expected. In
ADS we have an approximate deviation of +40 MHz, in microwave office an approximate deviation of
-25MHz and in HFSS an approximate deviation of -70MHz.

And the last point, and the most important if what we want is to get a good manufactured filter, is the
comparison of the responses of the manufactured filters. Comparing figures 25 and 29 we can say that
the filter designed with ADS is more similar to what we wanted to design (a Butterworth filter with the
cut off frequency at 1.8 GHz and an attenuation of at least -26 dB at 4.6 GHz). The deviations of the
cut off frequency are approximately 2 MHz for ADS and 100 MHz for Microwave office.

To conclude we can make a table in order to compare all three software packages in an easier way.

<table>
<thead>
<tr>
<th></th>
<th>ADS</th>
<th>Microwave Office</th>
<th>HFSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roll-off Simul.</td>
<td>39.23 dB/GHz</td>
<td>39.31 dB/GHz</td>
<td>39.15 dB/GHz</td>
</tr>
<tr>
<td>Roll-off Manuf.</td>
<td>51.81 dB/GHz</td>
<td>35.63 dB/GHz</td>
<td>Not Manufactured</td>
</tr>
<tr>
<td>Intuitive</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>Lumped elements</td>
<td>YES</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td>Strip Sizes</td>
<td>LineCalc</td>
<td>TXLINE 2003</td>
<td>Does not have</td>
</tr>
<tr>
<td>Easy and Quick</td>
<td>YES</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td>Manufacturing</td>
<td>YES</td>
<td>YES</td>
<td>NO</td>
</tr>
<tr>
<td>Time of Simulation</td>
<td>LOW</td>
<td>LOW</td>
<td>HIGH</td>
</tr>
<tr>
<td>Deviation Simulation</td>
<td>+40 MHz</td>
<td>-25MHz</td>
<td>-70MHz</td>
</tr>
<tr>
<td>Deviation Manufactured</td>
<td>+2MHz</td>
<td>-100MHz</td>
<td>NOT MANUFACTURED</td>
</tr>
</tbody>
</table>
Now, after the whole research, we can say that ADS is the software package which has the best qualities compared to the two others. Since it is quite accurate in the simulations and very good when we have to manufacture. We get the best roll-off factor when we manufacture.
References

Appendix A

Calculations of the values of the lumped elements for the filter made with lumped elements.

As we know from the theory section:

\[ L'_k = \frac{R_0 L_k}{\omega_c} \]
\[ C'_k = \frac{C_k}{R_0 \omega_c} \]
\[ R'_S = R_0 R_S \]
\[ R'_L = R_0 R_L \]

Then:

\[ R'_S = R_0 R_S = 50 \times 1 = 50 \ \Omega \]

\[ L'_1 = \frac{R_0 L_1}{\omega_c} = \frac{50 \times 0.7654}{2 \times \pi \times 1.8 \times 10^9} = 3.38 \ \text{nH} \]

\[ C'_2 = \frac{C_2}{R_0 \omega_c} = \frac{1.8478}{50 \times 2 \times \pi \times 1.8 \times 10^9} = 3.18 \ \text{pF} \]

\[ L'_3 = \frac{R_0 L_3}{\omega_c} = \frac{50 \times 1.8478}{2 \times \pi \times 1.8 \times 10^9} = 8.17 \ \text{nH} \]

\[ C'_4 = \frac{C_2}{R_0 \omega_c} = \frac{0.7654}{50 \times 2 \times \pi \times 1.8 \times 10^9} = 1.35 \ \text{pF} \]

\[ R'_L = R_0 R_L = 50 \times 1 = 50 \ \Omega \]