Design and Fabrication of a Microstrip Bandpass Filter in LTCC

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By

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Abstract

The goal of the project was to design and fabricate a bandpass filter with a center frequency of 25GHz with a 2GHz bandwidth. The first step was to do the calculation to design a bandpass filter to meet these specifications along with the properties of the Dupont™ GreenTape™ 9K7. HFSS was then used to verify the results from the initial calculations. There was a significant error between the two results, so more tweaking was done to the calculations to get a better center frequency. After a final design was decided, the fabrication process started. Low Temperature Co-Fired Ceramics (LLTC) was used for fabrication since that was the fabrication processed used on the research project. Three bandpass filters were fabricated, and the best filter had a 2.15% error from the simulation results. The soldering done to each of the boards was the key difference between the results of each bandpass filter.
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Chapter 1: Introduction

Bandpass filters only allow signals in a range of frequencies to pass. This is defined as the bandwidth of the filter. In a perfect bandpass filter, the cutoff is perfect at the edges of the bandwidth. Real bandpass filters have a slope after the bandwidth. Each type of filter design produces a different slope. The most popular ones are Bessel, Butterworth, Chebyshev and Elliptic. Bandpass filter is designed by designing a low pass filter prototype first and then transforming it into a bandpass filter. To design a filter with lumped elements as a microstrip line circuit, it must be transformed into transmission lines. The bandpass filter being fabricated has a center frequency of 25 GHz, a bandwidth of 8% (24GHz – 26GHz) and be 50Ω matched at the input and output. The low pass filter prototype should be an equal-ripple Chebyshev filter with a ripple level of 0.5 dB and have a rejection of at least 40dB at twice the cutoff frequency (50GHz). It is fabricated in LTCC using Dupont 9K7 ($\epsilon_r = 7.5$), with a thickness of 0.2286mm, as the substrate. Silver is used as the conductor.

Chapter 2: Bandpass Filter Design

A. Lowpass Filter Prototype

The low pass filter prototype is designed as an equal-ripple Chebyshev with a ripple of 0.5dB and a rejection of at least 40dB at twice the cutoff frequency. The center frequency (25GHz) is used as the cutoff frequency for the low pass filter. Attenuation for an equal-ripple Chebyshev filter is a function of N which is below.

$$\text{Attenuation} = 10 \log_{10} \left[ 1 + e \cosh \left( \frac{N}{\cosh^{-1} \left( \frac{f}{f_c} \right)} \right)^2 \right]$$

where, \( e = 10^{\frac{\text{Ripple Level}}{10}} - 1 \)

The N is chosen based on the requirements of the rejection. Figure 1 shows this equation for multiple values of N. In this graph 1.0 on the x-axis represents twice the cutoff frequency since it is normalized then one is subtracted from it. The value of N is chosen based
on which graph is closest to 40dB at 1.0 on the x-axis. The graph must be above or at 40dB since the requirement is to have a rejection ratio of at least 40dB at twice the cutoff frequency. The graph for \( N = 5 \) equals 40dB at a normalized frequency of 1.0 based on Figure 1.

![Figure 1. Attenuation vs. Normalized Frequency for Equal-Ripple Filter Prototypes (0.5dB ripple) [1]](image)

The values of \( N \) greater than 5 also satisfy the rejection requirement but it would increase the price of the design since more components would be used. This would also increase the size of the design. Therefore, the lowest \( N \) value that meets the requirements is used in the design.

Element values are given based on \( N \). The values are based on the input and output matched impedance is one and the cutoff frequency in radians is one. These values can be transformed to meet the design requirements. Figure 2 shows the values of the elements for each \( N \). As \( N \) increases, so does the number of elements used in the design. For \( N = 5 \), there are seven elements including \( g_0 \). Each \( g \) value is assigned to an inductor or capacitor depending on whether a T or pi-model is used. The T-model starts with a series element and the pi-model starts with a shunt element (Figure 3).
The T-model was chosen to design the low pass filter prototype, so the low pass filter prototype has three inductors and two capacitors. Impedance and frequency transformations were performed on each element to get the final low pass filter prototype design. The equations used were

\[ L_m = \frac{Z_0 g_m}{\omega_c} \]
\[ C_m = \frac{g_2}{\omega_c Z_0} \]
The final values for the elements are listed in Table 1.

Table 1. Element Values in Lowpass Filter Prototype

<table>
<thead>
<tr>
<th>Element</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_0 )</td>
<td>50Ω</td>
</tr>
<tr>
<td>( L_1 )</td>
<td>542.97pH</td>
</tr>
<tr>
<td>( C_2 )</td>
<td>156.56fF</td>
</tr>
<tr>
<td>( L_3 )</td>
<td>808.76pH</td>
</tr>
<tr>
<td>( C_4 )</td>
<td>156.56fF</td>
</tr>
<tr>
<td>( L_5 )</td>
<td>542.97pH</td>
</tr>
<tr>
<td>( R_6 )</td>
<td>50Ω</td>
</tr>
</tbody>
</table>

The transfer function of the low pass filter prototype is found by finding the ABCD matrix of the circuit. The ABCD matrix for each element is multiplied together to find the bandpass filter ABCD matrix.

\[
\begin{bmatrix}
1 & j\omega L_1 \\
0 & 1
\end{bmatrix}
\begin{bmatrix}
1 & 0 \\
1 & 1
\end{bmatrix}
\begin{bmatrix}
1 & j\omega L_3 \\
0 & 1
\end{bmatrix}
\begin{bmatrix}
1 & 0 \\
1 & 1
\end{bmatrix}
\begin{bmatrix}
1 & j\omega L_5 \\
0 & 1
\end{bmatrix}
\]

The transfer function is found from the ABCD matrix by using the equation to find \( S_{21} \) from ABCD parameters.

\[
S_{21} = \frac{2}{A} + \frac{B}{50} + C \times 50D
\]

The magnitude of \( S21 \) in dB is plotted versus frequency to get the transfer function graph (Figure 4). The transfer function of the low pass filter prototype shows that the cutoff frequency is 25 GHz and at twice the cutoff frequency the attenuation is 48.4 dB. This proves
that the calculations and the impedance and frequency transformations were performed correctly and that it can be transformed into a bandpass filter now.

![Transfer Function of Low Pass Filter Prototype](image)

**Figure 4. Transfer Function of Lowpass Filter Prototype**

**B. Bandpass Filter Transformation**

The elements of the lowpass filter prototype are transformed when it is transformed into another type of filter. For a bandpass filter, each inductor is transformed into an inductor and capacitor in series and each capacitor is transformed into an inductor and capacitor in parallel. The transformations for the bandpass filter are represented in Figure 5.

![Bandpass Filter Design](image)

**Figure 5. Bandpass Filter Design**
The equations for each element are,

\[ L_1 = \frac{Z_o g_1}{\omega_c \Delta} \quad \quad C_1 = \frac{\Delta}{\omega_c Z_o g_1} \quad \quad L_2 = \frac{\Delta Z_o}{\omega_c g_2} \quad \quad C_2 = \frac{g_2}{Z_o \omega_c \Delta} \quad \quad L_3 = \frac{Z_o g_3}{\omega_c \Delta} \]

\[ C_3 = \frac{\Delta}{\omega_c Z_o g_3} \quad \quad L_4 = \frac{\Delta Z_o}{\omega_c g_4} \quad \quad C_4 = \frac{g_4}{Z_o \omega_c \Delta} \quad \quad L_5 = \frac{Z_o g_5}{\omega_c \Delta} \quad \quad C_5 = \frac{\Delta}{\omega_c Z_o g_5} \]

Table 2. Values from Bandpass Filter Transformation

<table>
<thead>
<tr>
<th>Element</th>
<th>Value</th>
<th>Element</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>L₁</td>
<td>6.787 nH</td>
<td>C₁</td>
<td>5.971 fF</td>
</tr>
<tr>
<td>C₂</td>
<td>1.957 pF</td>
<td>L₂</td>
<td>20.71 pH</td>
</tr>
<tr>
<td>L₃</td>
<td>10.10 nH</td>
<td>C₃</td>
<td>4.009 fF</td>
</tr>
<tr>
<td>C₄</td>
<td>1.957 pF</td>
<td>L₄</td>
<td>20.71 pH</td>
</tr>
<tr>
<td>L₅</td>
<td>6.787 nH</td>
<td>C₅</td>
<td>5.971 fF</td>
</tr>
</tbody>
</table>

The transfer function of the bandpass filter is found using the same equation to find the

\[ S_{21} \]

from the ABCD matrix of the circuit.

\[
\begin{bmatrix}
1 & j\omega L_1 + \frac{1}{j\omega C_1} \\
0 & 1
\end{bmatrix}
\begin{bmatrix}
1 & \frac{1}{j\omega C_2 + \frac{1}{j\omega L_2}} \\
0 & 1
\end{bmatrix}
\begin{bmatrix}
1 & \frac{1}{j\omega L_3 + \frac{1}{j\omega C_3}} \\
0 & 1
\end{bmatrix}
\begin{bmatrix}
1 & \frac{1}{j\omega C_4 + \frac{1}{j\omega L_4}} \\
0 & 1
\end{bmatrix}
\begin{bmatrix}
1 & \frac{1}{j\omega L_5 + \frac{1}{j\omega C_5}} \\
0 & 1
\end{bmatrix}
\]

The ban pass filter transfer function is in Figure 6. The center frequency of the bandpass filter is 25GHz and the bandwidth is 24 to 26 GHz. It is working because at 1GHz past the bandwidth, the attenuation is below -40dB.
C. Impedance Inverters

The inductors and capacitors in series need to be converted to parallel inductors and capacitors to be able to perform the transmission line representation calculations. Kuroda’s Identifies transform are used to make this conversion but they only work on low pass filters because they only state how inductors transform into parallel capacitors. Impedance inverters can be used on both inductors and capacitors in parallel. The parallel inductance and capacitance are calculated with the following formulas. $Z_i$ represents the impedance of the line, which is 50Ω.

$$L_{p1} = Z_i^2 C_1$$  $$L_{p3} = Z_i^2 C_2$$  $$L_{p2} = Z_i^2 C_2$$

|S21| [dB]  Band Pass Filter Transfer Function
\[ C_{p1} = \frac{L_1}{Z_1^2} \quad C_{p3} = \frac{L_2}{Z_1^2} \quad C_{p5} = \frac{L_5}{Z_1^2} \]

Table 3. Values from Impedance Inverters

<table>
<thead>
<tr>
<th>Element</th>
<th>Value</th>
<th>Element</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(L_{p1})</td>
<td>14.93 pH</td>
<td>(C_{p1})</td>
<td>2.715 pF</td>
</tr>
<tr>
<td>(C_2)</td>
<td>1.957 pF</td>
<td>(L_2)</td>
<td>20.71 pH</td>
</tr>
<tr>
<td>(L_{p3})</td>
<td>10.02 pH</td>
<td>(C_{p3})</td>
<td>4.040 pF</td>
</tr>
<tr>
<td>(C_4)</td>
<td>1.957 pF</td>
<td>(L_4)</td>
<td>20.71 pH</td>
</tr>
<tr>
<td>(L_{p5})</td>
<td>14.93 pH</td>
<td>(C_{p5})</td>
<td>2.715 pF</td>
</tr>
</tbody>
</table>

A transmission line with the length \(\lambda/4\) must be added on each side of the new parallel components.

![Figure 7. Bandpass Filter Design after Impedance Invertors](image)

D. Transmission Line Representation

Richard’s Transformation is used to convert the parallel components into parallel transmission lines. The resistance of each stub is calculated using the following equations.

\[ Z_0 L_n = \omega L_n \]

\[ Z_0 C_n = \frac{1}{\omega C_n} \]
Table 4. Values from Richard’s Transformation

<table>
<thead>
<tr>
<th>Element</th>
<th>Value (Ω)</th>
<th>Element</th>
<th>Value (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z_oL_1$</td>
<td>2.345</td>
<td>$Z_oC_1$</td>
<td>2.345</td>
</tr>
<tr>
<td>$Z_oL_2$</td>
<td>3.253</td>
<td>$Z_oC_2$</td>
<td>3.253</td>
</tr>
<tr>
<td>$Z_oL_3$</td>
<td>1.574</td>
<td>$Z_oC_3$</td>
<td>1.574</td>
</tr>
<tr>
<td>$Z_oL_4$</td>
<td>3.253</td>
<td>$Z_oC_4$</td>
<td>3.253</td>
</tr>
<tr>
<td>$Z_oL_5$</td>
<td>2.345</td>
<td>$Z_oC_5$</td>
<td>2.345</td>
</tr>
</tbody>
</table>

The length of each stub is $\lambda/8$. The capacitors are represented with open circuit stubs and the inductors are represented with short circuit stubs.

The ABCD matrix is then calculated again to get the S11 and S21 parameters to make sure that all the calculations are still correct.
D. Fifth Order versus Third Order Bandpass Filter

Fifth order filters are more precise than third order bandpass filters. The tradeoff for fifth order bandpass filters is that there are more elements than in third order bandpass filters. Since third order bandpass filters require less material, they are more cost effective. Both order filters are compared to make sure that a third order filter is still precise enough for the project. The same calculations are performed for $N = 3$ (third order bandpass filter).
The fifth order bandpass filter is better than the third order bandpass filter as expected.

The point on the S21 of the third order bandpass filter and 1GHz past the bandwidth is used to
determine if it is an acceptable design. At 23 and 27GHz the bandpass filter only passes approximately -20dB through. Based on the results, the third order bandpass filter will be used for the rest of the project.

D. Microstrip Design

The W/d ratio can be found since the characteristic impedance ($Z_o$) and the dielectric constant $\varepsilon_r$ are known. There are two equations for the W/d ratio: one for W/d < 2 and one for W/d > 2. The equation for W/d > 2 is used since width would be negative with the other equation.

$$\frac{W_n}{d} = \frac{2}{\pi} \left[B_n - 1 - \ln(2B_n - 1) + \frac{\varepsilon_r - 1}{2\varepsilon_r} \left\{\ln(B_n - 1) + 0.39 - \frac{0.61}{\varepsilon_r}\right\}\right]$$

Where,

$$B_n = \frac{377\pi}{2Z_oL\sqrt{\varepsilon_r}}$$

Dupont™ GreenTape™ 9K7 is used in the design for the dielectric. The thickness of the dielectric is 0.2286 mm and the dielectric constant is 7.5.

<table>
<thead>
<tr>
<th>Element</th>
<th>Width (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z_oL_1$ and $Z_oC_1$</td>
<td>12.0</td>
</tr>
<tr>
<td>$Z_oL_2$ and $Z_oC_2$</td>
<td>8.00</td>
</tr>
<tr>
<td>$Z_oL_3$ and $Z_oC_3$</td>
<td>12.0</td>
</tr>
<tr>
<td>$Z_o(\lambda/4)$ – Transmission Line</td>
<td>0.283</td>
</tr>
</tbody>
</table>
Figure 12. Microstrip Representation of Bandpass Filter.

The circles represent a short in the stub to ground.

Chapter 3: HFSS Analysis

A. Initial Analysis

The initial analysis was done using the dimensions that were calculated in Chapter 2. ANSYS HFSS was used for the RF simulations. Simulations were done before fabrication because the equations that were used don’t account for all the factors, such as the thickness of the metal. The bandpass filter design is put on top of the substrate with the ground plane below the substrate. To make the fabrication easier the short circuit connections were removed and \( \frac{\lambda}{4} \) was added to the length. When \( \frac{\lambda}{4} \) is added to an open circuit stub it acts like a short circuit stub. The initial design is shown in Figure 13. The thickness of the bandpass filter is 15\(\mu\)m and the thickness of the ground plane is 30.48\(\mu\)m.

![Figure 13. Initial HFSS Design, Top Down View](image)

The design was simulated from 20 to 30 GHz. The S21 and the S11 were plotted to review the results. The center frequency was \(~22.5\)GHz. The design will have to be tweaked since 10% error of the center frequency is not acceptable. S21 at the center frequency is \(~5.5\)dB. This is also not acceptable since ideally it should be zero. The bandwidth was determined by taking the center frequency and subtracting -3dB to find the boundaries. Using this definition, the bandwidth is \(~0.57\)dB. This results in 71.5% error using this definition to find...
the bandwidth.

B. Redesign of the Bandpass Filter

The bandpass filter was redesigned with the initial calculations. Since there was an approx. 2.5GHz difference between the designed center frequency and the simulated center frequency, the calculations were performed again in MATLAB with the designed center frequency at approx. 27.5GHz. This is done to shift the center frequency closer to the intended frequency.

After the redesign, the center frequency is 23.6GHz. The error is 5.6% so slight tweaking of the design can now be used to get the center frequency within 5% of 25GHz. The bandwidth
is approx. 0.5GHz using the definition of 3dB down from the center frequency. If the bandwidth is calculated as the range of S21 above -10dB, then the bandwidth is approx. 1.9GHz. The bandwidth has also improved with the redesign. S21 at the center frequency is -3.2723GHz, which has also improved since it is closer to zero.

Figure 16. Redesign of the Bandpass Filter Simulation Results

The comparison between the two designs is shown in Figure 17.
C. Final Design

Small changes were made by decreasing the width of the stubs. These changes were made until the results were within 5% error. The final design is shown in Figure 18.

The final center frequency is approx. 23.7dB with an error of 5%. At the center frequency, $S_{21}$ is -3.2858GHz. The bandwidth is 0.5GHz using the definition of 3dB less than the center frequency. The bandwidth is approx. 2.1GHz if the definition of the $S_{21}$ graph above -10dB is used.
Figure 19. Final Bandpass Filter Design Results

Figure 20. Initial Redesign vs. Final Design
Chapter 4: LTCC Fabrication

Low Temperature Co-Fired Ceramics (LTCC) is a multi-layer glass ceramic substrate. The substrate is co-fired at low temperatures with low resistance metal conductors. LTCC has many advantages including stability at high frequency and a high accuracy of shrinkage tolerance.

The first step in the process of fabrication is to prepare the GreenTape 9K7 squares by cofiring them in the oven for 30 minutes. After this is done, the layers with vias are punched out with the hole punch machine in Figure 21.

![Multi Punching Machine](image)

Figure 21. Multi Punching Machine

Once the vias have been bunched in all the layers, then Gold 505 is used to fill in the vias. This is done by putting the gold ink on each layer and then using a squeegee to make sure all the vias are filled.
The next step is to let all of them dry for 10 minutes in the 80°C oven. Next, screens are used with a machine to print the gold on to the top and or bottom of each layers.

Since, the bottom layer has gold printed on the top and bottom side of the board, it is cooked for 5 minutes in between each side being done.
Once each layer is done, they all cook for 10 minutes in the oven, with the top layer cooking for 20 extra minutes. Once all layers are done cooking, they are stacked and wrapped up to put in a vacuum sealer.
After the board has been vacuum sealed together it gets laminated.

![Figure 27. LTCC Lamination Machine](image)

When the board has finished lamination, it is then cut to the desired size and the fired overnight.

![Figure 28. Cut Bandpass Filters Before Final Cofire](image)
Chapter 5: Results

Before the bandpass filters were tested, SMA connectors were soldered on so that it would be able to connect to the cables on the VNA.

The boards were tested with a VNA and calibration was done before any measurements were taken. All bandpass filters were tested and then the results shown below are based on board two since it gave the best results.
The center frequency of the results from testing is approx. 23.3 GHz. Since the center frequency of the simulation was approx. 23.8 GHz, there was a 2.15% error. The bandwidth of the results from testing was approx. 1.56 GHz, which was 22% error, which was improved from the 70% error in the simulation. The transmitted power also only got up to approx. -9.5dB.
Chapter 6: Conclusion

One of the reasons for less transmitted power in the fabricated bandpass filter, is the solder that is used and the connector. When I tested all the bandpass filters, the filter with the most solder had the least amount of transmitted power. It went down by approx. 3dB which is a significant change. If the connectors had been soldered on with less solder, I would have expected the results to have been better. The SMA connector could have also led to some issues since the frequency range of the SMA connector was only to 26.5 GHz. Since it was at the end of its frequency range it could have affected the transmitted power more. If more designs were fabricated, I would get a 2.92mm connector since it has a large frequency range.

Overall, it was good results for the first fabrication, but more designs would need to be done for a final design. More simulations would need to be done before another board was fabricated. I would also do more testing on the fabricated board with a good solder job to get the best possible measurements to compare. While the solder played a role in the decrease in transmit power, it was not the only factor.
References

%Initial Low Pass Filter Design

clear all;

g0 = 1; %R0
G1 = 1.7058; %L1
G2 = 1.2296; %C2
G3 = 2.5408; %L3
G4 = 1.2296; %C4
G5 = 1.7058; %L5
G6 = 1; %R6

fc = 25*10^9; %cutoff frequency
wc = 2*pi*fc;
Z0 = 50;

%Lumped components transformed to correct cutoff frequency and Z0
R0 = g0*Z0
L1 = (Z0*g1)/wc
C2 = g2/(wc*Z0)
L3 = (Z0*g3)/wc
C4 = g4/(wc*Z0)
L5 = (Z0*g5)/wc
R6 = g6*Z0

%ABCD Matrix
syms XL1;
syms YC2;
syms XL3;
syms YC4;
syms XL5;

M1 = [1 XL1; 0 1];
M2 = [1 0; YC2 1];
M3 = [1 XL3; 0 1];
M4 = [1 0; YC4 1];
M5 = [1 XL5; 0 1];
M = M1*M2*M3*M4*M5;

%Transfer Function
f = 0;

for k = 1:1:101
    w = 2*pi*f;
    XL1 = w*i*L1;
YC2 = w*i*C2;
XL3 = w*i*L3;
YC4 = w*i*C4;
XL5 = w*i*L5;

%Taken from M [A,B;C,D]
A(k) = XL1*YC2 + YC4*(XL1 + XL3*(XL1*YC2 + 1)) + 1;
B(k) = XL1 + XL3*(XL1*YC2 + 1) + XL5*(XL1*YC2 + YC4*(XL1 + XL3*(XL1*YC2 + 1)) + 1);
C(k) = YC2 + YC4*(XL3*YC2 + 1);
D(k) = XL3*YC2 + XL5*(YC2 + YC4*(XL3*YC2 + 1)) + 1;

%Transfer Function |S21| in dB
T(k) = 10*log(abs(2/(A(k)+B(k)/50+C(k)*50+D(k))));

f = f + 1*10^9;
end

%Plot
f = [0:1:100];
w = 2*pi*f;

figure(1)
plot(f,T)
title('Transfer Function of Low Pass Filter')
xlabel('Frequency [GHz]')
ylabel('Attenuation [dB]')

figure(3)
A = (1-T);
plot(f,A)

%Bandpass Filter Transformation
fo = 25*10^9;
wo = 2*pi*fc;
w2 = 26*10^9*2*pi;
w1 = 24*10^9*2*pi;
delta = (w2-w1)/(wo);

%Bandpass Lumped Elements Transformation
L1 = (g1*Zo)/(wo*delta)
C1 = delta/(wo*g1*Zo)
L2 = (delta*Zo)/(wo*g2)
C2 = g2/(wo*delta*Zo)
L3 = (g3*Zo)/(wo*delta)
C3 = delta/(wo*g3*Zo)
L4 = (delta*Zo)/(wo*g4)
C4 = g4/(wo*delta*Zo)
L5 = (g5*Zo)/(wo*delta)
C5 = delta/(wo*g5*Zo)

%ABCD Matrix
syms X1;
syms Y2;
syms X3;
syms Y4;
syms X5;

M1 = [1 X1; 0 1];
M2 = [1 0; Y2 1];
M3 = [1 X3; 0 1];
M4 = [1 0; Y4 1];
M5 = [1 X5; 0 1];

M = M1*M2*M3*M4*M5

%Transfer Function
f = 0;

for k =1:1:201
    w = 2*pi*f;
    X1 = w*i*L1 + 1/(i*w*C1);
    Y2 = w*i*C2 + 1/(i*w*L2);
    X3 = w*i*L3 + 1/(i*w*C3);
    Y4 = w*i*C4 + 1/(i*w*L4);
    X5 = w*i*L5 + 1/(i*w*C5);

%Taken from M [A,B;C,D]
    A(k) = X1*Y2 + Y4*(X1 + X3*(X1*Y2 + 1)) + 1;
    B(k) = X1 + X3*(X1*Y2 + 1) + X5*(X1*Y2 + Y4*(X1 + X3*(X1*Y2 + 1)) + 1);
    C(k) = Y2 + Y4*(X3*Y2 + 1);
    D(k) = X3*Y2 + X5*(Y2 + Y4*(X3*Y2 + 1)) + 1;

%Transfer Function |S21| in dB
    T(k) = 10*log(abs(2/(A(k)+B(k)/50+C(k)*50+D(k))));
    %T2(k) = 20*log10(abs(sqrt(D(k)/A(k))*(sqrt(A(k)*D(k))-sqrt(B(k)*C(k)))));

    f = f + 0.5*10^9;

end

%Plot
f = [0:0.5:100];
w = 2*pi*f;

figure(2)
plot(f,T)
hold on
%plot(f,T2)
title('Transfer Function of Bandpass Filter')
xlabel('Frequency [GHz]')
ylabel('|S21| [dB]')
ylim([-120 5])