3322ENG – Electromagnetic Waves and Propagation

Assignment 2: Engineering RF Design

Jessy Barber – s5138877

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Contents

Griffith UNIVERSITY

1. Introduction

Quadrature demodulators are used in communication system networks for the purpose of receiving and recovering information from a distant radio transmitter. This demodulation technique uses two sinusoidal signals that are 90° out of phase to recover information on a third signal that is received from the transmitter. The key component to this demodulation circuit is a component subsystem which generates a pair of sinusoidal signals at required phases.

Quadrature demodulators, also known as quadrature couplers and branch-line couplers, are designed to either act as power combiners or dividers. In this assignment, the branch-line couplers will be used as power dividers, receiving an input sinusoid, and splitting this sinusoid between 3 network ports. The benefit of using such a demodulation technique, is that signals can be divided without reflection or power dissipation as long as the input port is matched to corresponding output ports. A quadrature demodulator circuit contains 4 network ports, port 1 (S_{11}) contains the input sinusoid, port 2 and 3 (S_{21}, S_{31}) act as the power divider, splitting the sinusoid into two equal power sine waves, ninety degrees out of phase with each other, and port 4 (S_{41}) which acts as the isolated port. In the network this port will power match port 1 and will be grounded outside of the network.

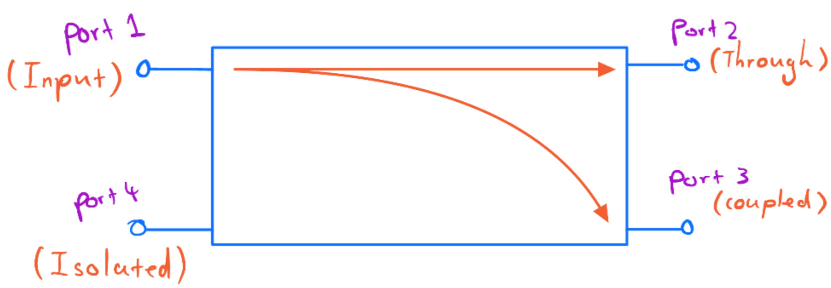


Figure 1: Four Port Network

The purpose of this experiment is to design two different versions of the branch-line coupler, one to facilitate a narrowband of signals, and one for a wider bandwidth of signals. To do this, two different designs will be used, a traditional branch-line coupler, and a double-box branch-line coupler. Both of these coupler designs will be based on the specified printable circuit board (PCB) product, the Astra MT77, with characteristic outlined in the specifications section.

2. Specifications

The goal of this experiment is to design two different versions of a branch-line coupler circuit, one with a narrow bandwidth and one with a wider bandwidth. S_{21} and S_{31} need to be equal in power, and S_{11} and S_{41} should be equal in power in an ideal system to represent the power loss. It is specified that one of the port S_{21} or S_{31} should be in phase with the single input signal S_{11}, and one should be ninety degrees out of phase with the input signal. The Specifications for the Astra MT77 board are shown below:

Characteristic impedance (ohms)	Centre frequency (hertz)	Relative permittivity	Thickness (millimetres)
25	7.53×10^8	3.000	0.7600

Table 1: Astra MT77 Design Characteristics

3. Design Process

1) Read literature on quadrature demodulation and branch-line couplers.
2) Identify alternative designs of the branch-line coupler that influence the frequency response, particularly the bandwidth.
3) Learn how to simulate a transmission line microstrip circuit in the simulation software PUFF.
4) Identify the PCB specifications of the Astra MT77 and its characteristics including characteristic impedance, centre frequency, relative permittivity, and thickness.
5) Conduct calculations to find any new characteristic impedances of transmission line components and use this to find the length of each component.
6) Edit the board specifications field in the board section of PUFF and add the parts list in the parts section.
7) Build the circuit in the layout section and add the scattering parameters S_{11}, S_{21}, S_{31} and S_{41} in the plot section.
8) Edit the x and y axis dimensions to a suitable slice of the response and plot the response using the plot section.
9) Observe the response between S_{11} and S_{41}, and then the response between S_{21} and S_{31}.
10) Record the frequency bandwidth between +/- 10 degrees phase difference of S_{21} and S_{31}, or at the first point from the centre where S_{31} is greater than S_{21} by 1dB.
11) Record the power and phase change of each of the ports.

4. Design Calculations

A Jupyter notebook file (appendix ii and iii) was created to help assist with the calculations. This notebook handles the calculations for finding the width (w), effective relative permittivity (ε_{eff}), propagation velocity (μ_p), guide wavelength (λ_g) and length (l).

The first step is to calculate A and B:

$$A = \frac{Z_o}{60}\sqrt{\frac{\varepsilon_r + 1}{2}} + \frac{\varepsilon_r - 1}{\varepsilon_r + 1}\left(0.23 + \frac{0.11}{\varepsilon_r}\right), \qquad (1.0)$$

$$B = \frac{377\pi}{2Z_o\sqrt{\varepsilon_r}}, \qquad (1.1)$$

From here, there are two possible equations to determine the width of the component:

$$SmallRatio = \frac{8e^A}{e^{2A} - 2}, \qquad (1.2)$$

$$BigRatio = \frac{2}{\pi}\left[B - 1 - \ln(2B - 1) + \frac{\varepsilon_r - 1}{2\varepsilon_r}(\ln(B - 1) + 0.39 - \frac{0.61}{\varepsilon_r})\right], \qquad (1.3)$$

Now the width can be determined dependent on the outcome of the following:

$$w = \{ \begin{matrix} SmallRatio * Thickness, & if\ SmallRatio \leq 2 \\ BigRatio * Thickness, & if\ BigRation \geq 2 \end{matrix}, \qquad (1.4)$$

Now that the width has been determined, the effective permittivity is given as:

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2\sqrt{1 + 12(\frac{h}{w})}}, \qquad (1.5)$$

Assuming the speed of light (c) = 3.00*10^8ms^{-1}, the propagation velocity is calculated as follows:

$$\mu_p = \frac{c}{\sqrt{\varepsilon_{eff}}}, \qquad (1.6)$$

And the wave guide as:

$$\lambda_g = \frac{\mu_p}{f}, \qquad (1.7)$$

Finally, the length of the component can be found:

$$l = \frac{\lambda_g}{4}, \qquad (1.8)$$

5. Proposed Designs

The final designs chosen for this experiment are the single-box branch-line coupler for the narrowband and a double-box branch-line coupler for the wideband. The dimensions for the PCB are outlined below, along with the dimensions of the microstrip transmission lines. The Astra MT77 plate is predominantly made from ultra-loss laminate composition of materials such as fibre glass, resin, and copper (ISOLA, 2021). It should be noted that both designs have an isolated port. For the sake of simulation, the GND will be placed at the output of port 4 and not in the circuit design.

Table 2: Transmission Line Components

Transmission Line Components	
$Z_o\ (Tline\ A)$	$l = 61.83mm,$ $w = 4.99mm,$ $h = 0.76mm,$ $\varepsilon_{eff} = 2.595$
$\frac{Z_o}{\sqrt{2}}(Tline\ B)$	$l = 60.9mm,$ $w = 7.61mm,$ $h = 0.76mm,$ $\varepsilon_{eff} = 2.675$
$(1+\sqrt{2}) * Z_o(Tline\ C)$	$l = 64.76mm,$ $w = 1.41mm,$ $h = 0.76mm,$ $\varepsilon_{eff} = 2.366$
$\sqrt{2} * Z_o(Tline\ D)$	$l = 62.9mm,$ $w = 3.17mm,$ $h = 0.76mm,$ $\varepsilon_{eff} = 2.508$

Since the PUFF simulation software does not allow for rotation of components, the design of the double-box branch-line coupler is geometrically impossible. Therefore, for T-lines C and D, a value of $l = 63.5mm$ will be used.

Single-box branch-line coupler:

The single-box branch-line coupler consists of 2 T-line A components and 2 T-line B components connected in a square. Each component aims to represent $\frac{\lambda}{4}$ even though each component has different lengths and widths. Below is a diagram representing the component connections of the single-box branch-line couple in a four-port network, and to scale on a PCB.

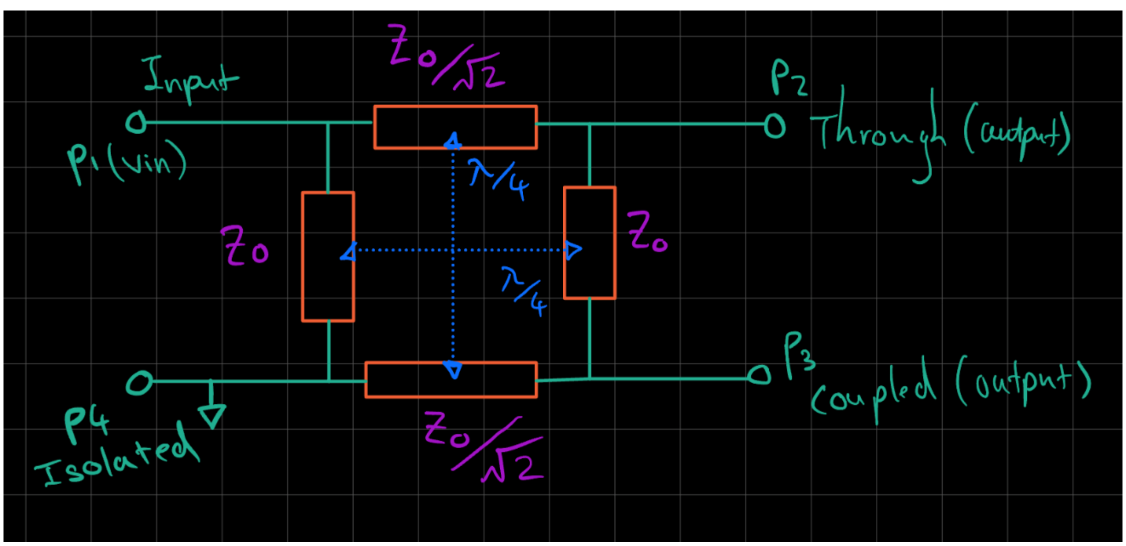


Figure 2: Single-Box Branch-Line Coupler Design

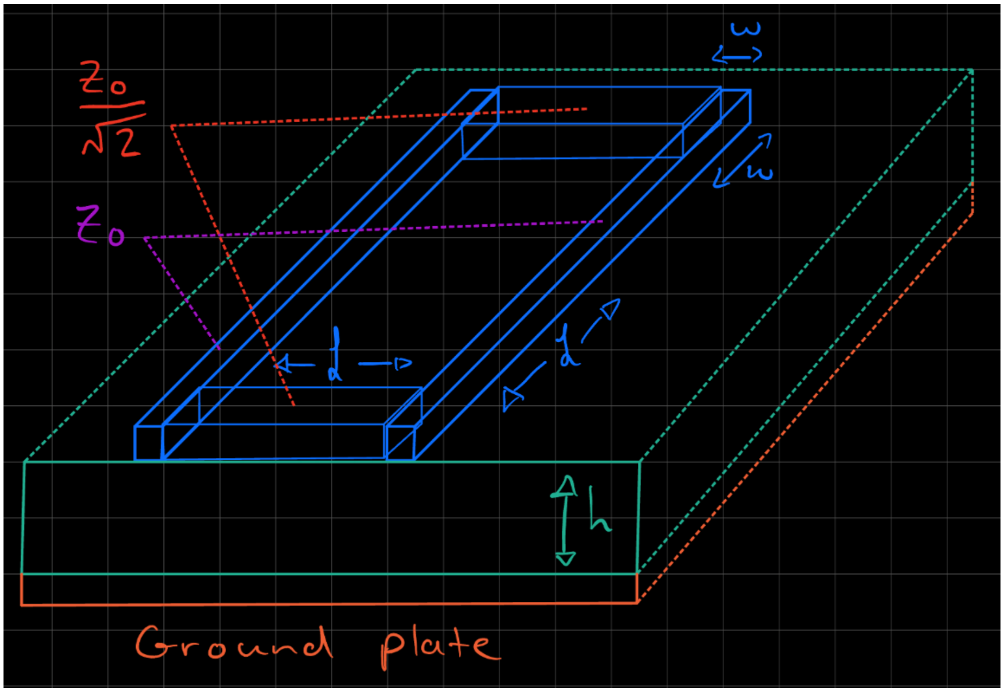


Figure 3: Single-Box Branch-Line Coupler PCB Design

Double-box branch-line coupler:

The double-box branch-line coupler consists of T-line components A, C and D, and is connected in a "double" box pattern as seen below. This coupler handles the wider frequency bandwidth between S_{21} and S_{31}. Since the signal travels an additional $\frac{\lambda}{4}$ to get to port two, this port will now be an extra ninety degrees out of phase.

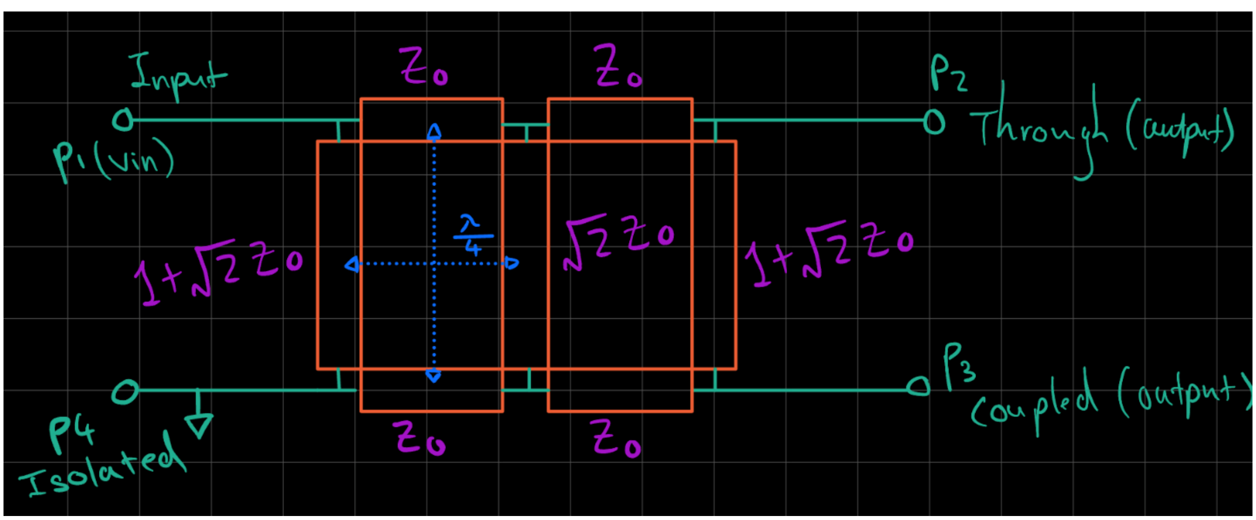


Figure 4: Double-Box Branch-Line Coupler Design

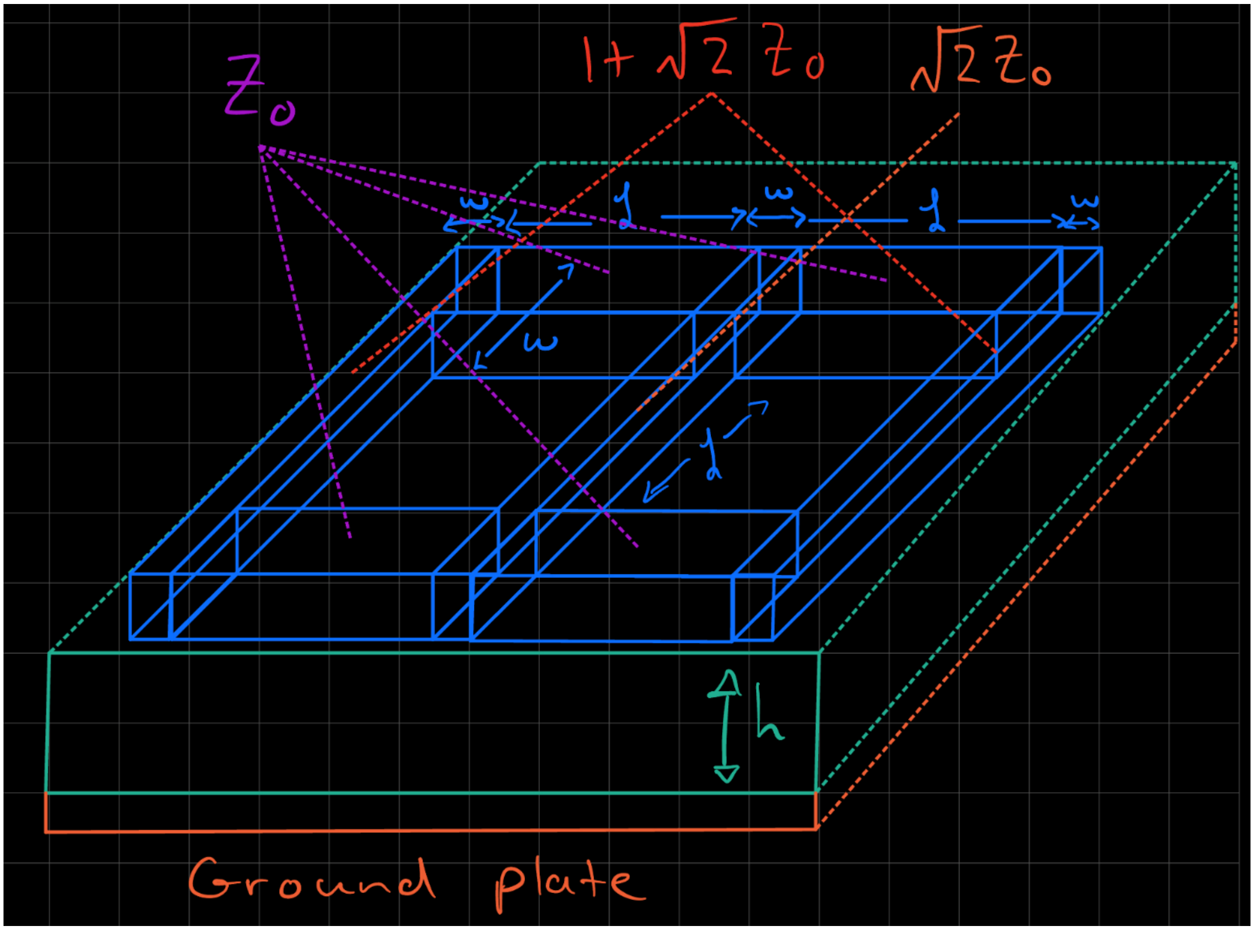


Figure 5: Double-Box Branch-Line Coupler PCB Design

6. Method of Testing

Below are the expected values for the single-box branch-line coupler and double-box branch-line coupler as per the assignment description. All of these values occur at the centre frequency point.

Single-Box Branch-Line Coupler Expected Results						
S_{11} (dB)	**S_{21}(dB)**	**S_{31}(dB)**	**S_{41}(dB)**	**$\angle S_{21}$(°)**	**$\angle S_{31}$(°)**	**f_c (MHz)**
$= S_{41}$	-3dB	-3dB	$= S_{11}$	90	180	753
Double-Box Branch-Line Coupler Expected Results						
S_{11} (dB)	**S_{21}(dB)**	**S_{31}(dB)**	**S_{41}(dB)**	**$\angle S_{21}$(°)**	**$\angle S_{31}$(°)**	**f_c (MHz)**
$= S_{41}$	-3dB	-3dB	$= S_{11}$	180	90	753

Table 3: Expected Results

It should be examined the bandwidth of S_{21} / S_{31} should be wider in the double-box branch-line coupler than in the single-box branch-line coupler. Port 2 or 3 should also be in phase with port 1, and there should be a ninety-degree phase difference between port 2 and 3.

7. Results of Tests

Below lists the test results for both proposed designs after simulation in PUFF.

Single-Box Branch-Line Coupler Simulated Results									
S_{11} (dB)	S_{21} (dB)	S_{31} (dB)	S_{41} (dB)	S_{21}/S_{31} BW (MHz)	$\angle S_{11}$ (°)	$\angle S_{21}$ (°)	$\angle S_{31}$ (°)	$\angle S_{41}$ (°)	f_c (MHz)
-67.33	-3.01	-3.01	-67.33	191.312	-89.7	-91	-179	-2.3	748
Double-Box Branch-Line Coupler Simulated Results									
S_{11} (dB)	S_{21} (dB)	S_{31} (dB)	S_{41} (dB)	S_{21}/S_{31} BW (MHz)	$\angle S_{11}$ (°)	$\angle S_{21}$ (°)	$\angle S_{31}$ (°)	$\angle S_{41}$ (°)	f_c (MHz)
-36.46	-3.01	-30.1	-36.45	221.096	88.5	178.7	88.7	-1.1	752.8

Table 4: Simulated Results

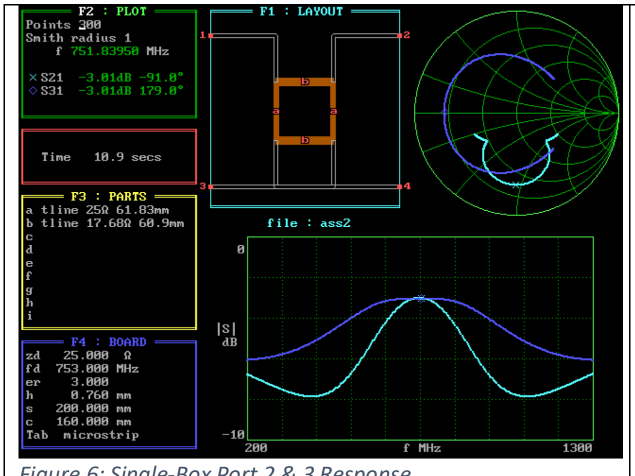


Figure 6: Single-Box Port 2 & 3 Response

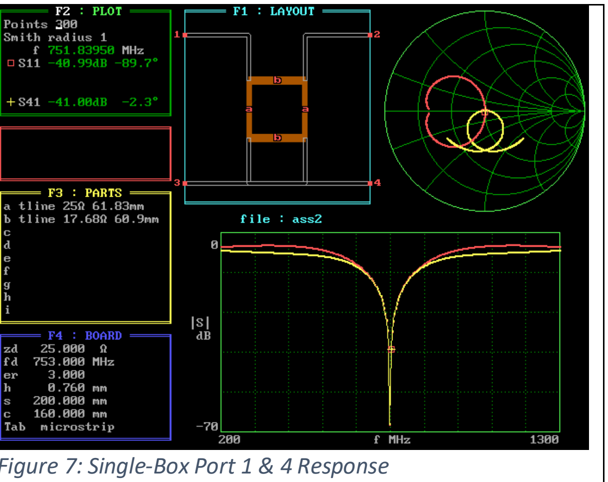


Figure 7: Single-Box Port 1 & 4 Response

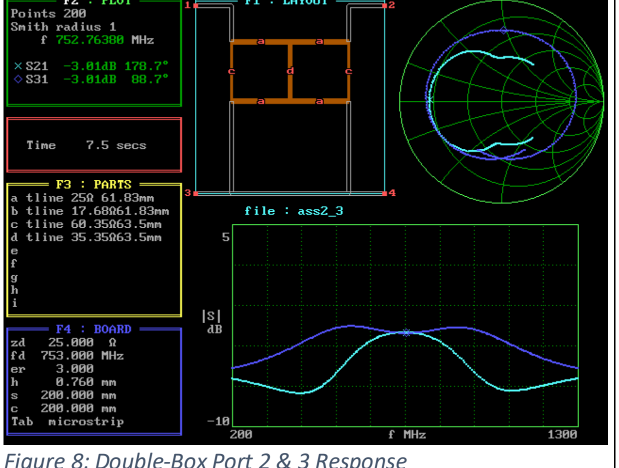


Figure 8: Double-Box Port 2 & 3 Response

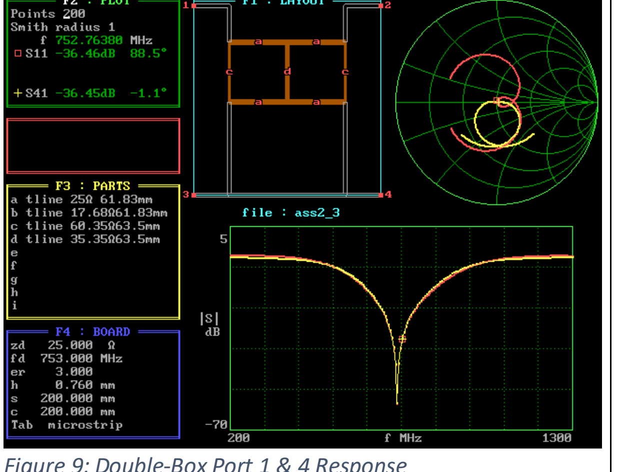


Figure 9: Double-Box Port 1 & 4 Response

See appendix iv and v for overlayed figures.

8. Evaluation of Results

Evaluating the results from both the single-box branch-line coupler and the double-box branch-line coupler, all of the desired results for the proposed designs have been met. There is an equal power split between ports 2 and 3 of the network for both designs, and they are both close to ninety degrees out of phase with each other. In the single-box branch-line coupler, port 2 is in phase with port 1, and in the double-box branch-line coupler port 3 is in phase with port 1. Port 4 is receiving identical power to port 1, which will be grounded after exiting the network, acting as the isolated port. There is clearly an increase in bandwidth for the double-box design at 221 MHz, which is a 14.5% increase from the 191.312 MHz bandwidth of the single-box design.

9. Recommendations

It is clear after analyzing the PUFF simulation results that the proposed designs were successful in meeting the assignment criteria. However, the designs can be better. The main issue in the designs is that 14.5% increase in bandwidth isn't a very large increase. An option to improve this percentage would be to decrease the bandwidth of the single-box branch-line coupler. This could be done by re-evaluating the components at the design phase and decreasing the transmission lines from $\frac{1}{4}\lambda$ to around $\frac{1}{9}\lambda$. Another option would be to use a different simulation software that allows rotation of parts. This is because a compromise was made in the design of the double-box coupler since transmission lines C and D were different lengths. The lengths were made the same using the mean length of the two components so that the circuit could be connected properly. This change may improve the accuracy of the phase angles of all ports in the network.

10. Appendix

Appendix i: Design Specification Sheet (S5138877)

student number	characteristic impedance (ohms)	centre frequency (hertz)	relative permittivity	thickness (millimetres)	product
5198493	21	9.45×10^8	4.380	0.5080	Kappa 438
5174738	23	1.04×10^9	3.565	0.5100	I-Tera MT40
5138877	25	7.53×10^8	3.000	0.7600	Astra MT77
5125369	25	9.02×10^9	3.000	0.0635	Astra MT77
5168300	25	7.48×10^9	3.050	0.0760	RO1200
5143364	25	3.19×10^9	3.050	0.1780	RO1200
5048396	24	3.57×10^8	3.480	1.5000	IS680 AG-348
5080442	25	4.48×10^9	3.050	0.1270	RO1200
5069543	24	5.30×10^9	3.480	0.1010	RO4350B
2901412	25	1.12×10^9	3.000	0.5100	Astra MT77
5175579	25	1.50×10^9	3.000	0.3810	Astra MT77
5174340	25	2.80×10^9	3.050	0.2030	RO1200
5201360	25	3.82×10^8	3.000	1.5000	Astra MT77
5189801	25	3.01×10^9	3.000	0.1905	Astra MT77
5190030	25	1.80×10^9	3.000	0.3175	Astra MT77
2885671	24	1.58×10^9	3.480	0.3380	RO4350B
5142226	23	6.95×10^8	3.565	0.7600	I-Tera MT40
5165637	25	1.50×10^9	3.200	0.3700	TLC-32
5111821	24	3.19×10^9	3.480	0.1680	RO4350B
5130398	25	5.57×10^9	3.050	0.1020	RO1200
5188812	25	2.24×10^9	3.050	0.2540	RO1200
5048831	23	3.52×10^8	3.565	1.5000	I-Tera MT40
5174447	25	7.05×10^8	3.200	0.7900	TLC-32
5166030	21	3.15×10^8	4.380	1.5240	Kappa 438
5143277	21	6.30×10^8	4.380	0.7620	Kappa 438
5178094	25	3.74×10^9	3.050	0.1520	RO1200
5178358	21	4.72×10^8	4.380	1.0160	Kappa 438
5113831	23	2.11×10^9	3.565	0.2500	I-Tera MT40
5099434	24	2.11×10^9	3.480	0.2540	RO4350B
5135470	25	2.25×10^9	3.000	0.2540	Astra MT77
	24	1.27×10^9	3.480	0.4220	RO4350B
	24	1.05×10^9	3.480	0.5080	RO4350B
	24	7.02×10^8	3.480	0.7620	RO4350B
	24	3.51×10^8	3.480	1.5240	RO4350B
	25	4.55×10^9	2.940	0.1270	RT/duriod 6002
	25	2.27×10^9	2.940	0.2540	RT/duriod 6002
	25	1.14×10^9	2.940	0.5080	RT/duriod 6002
	25	7.58×10^8	2.940	0.7620	RT/duriod 6002
	25	3.79×10^8	2.940	1.5240	RT/duriod 6002
	25	1.90×10^8	2.940	3.0480	RT/duriod 6002
	28	5.06×10^9	2.330	0.1270	RT/duriod 5870

Appendix ii: Python Code Part 1

```
In [8]: import numpy as np
        import pandas as pd
```

Variables

```
In [14]: # thickness
         h = 0.76e-3
         # relative permitivitty
         er = 3.000
         # characteristic impedance
         # zo = 25
         # zo = 17.678
         # zo = 60.35
         zo = 35.35
         # centre frequency
         f = 7.53e8

         # constants
         # speed of light
         c = 3e8
```

A, B

```
In [15]: A = zo/60 * np.sqrt((er+1)/2) + (er-1)/(er+1) * (0.23 + 0.11/er)
         B = (377 * np.pi) / (2 * zo * np.sqrt(er))
         print("A = ",A)
         print("B = ",B)

         A =  0.966540823831482
         B =  9.67188628453041
```

Small Ratio / Big Ratio

```
In [16]: smallratio = (8 * np.exp(A)) / (np.exp(2*A) - 2)
         bigratio = (2/np.pi)*(B-1-np.log(2*B-1)+((er-1)/(2*er))*(np.log(B-1)+0.39-(0.61/er)))
         print("Small Ratio = ", smallratio)
         print("Big Ratio = ", bigratio)

         Small Ratio =  4.28255927446747
         Big Ratio =  4.1665790942867895
```

Determine width (w)

```
In [17]: if smallratio <= 2:
             w = smallratio * h
         if bigratio >= 2:
             w = bigratio * h
         print("w = ", w)

         w =  0.00316660011165796
```

Eeff

```
In [18]: eeff = ((er + 1)/2) + ((er - 1)/(2*np.sqrt(1+12*(h/w))))
         print("e eff = ", eeff)

         e eff =  2.507669122547131
```

Appendix iii: Python Code Part 2

Propagation Velocity / Guide Wavelength

In [7]:
```
ug = c / np.sqrt(eeff)
lg = ug / f
print("Propagation Velocity = ", ug)
print("Guide Wavelength = ", lg)
```

```
Propagation Velocity =  195045779.9516189
Guide Wavelength =  0.2590249401747927
```

Length

In [28]:
```
l = lg / 4
print("Length = ", l)
```

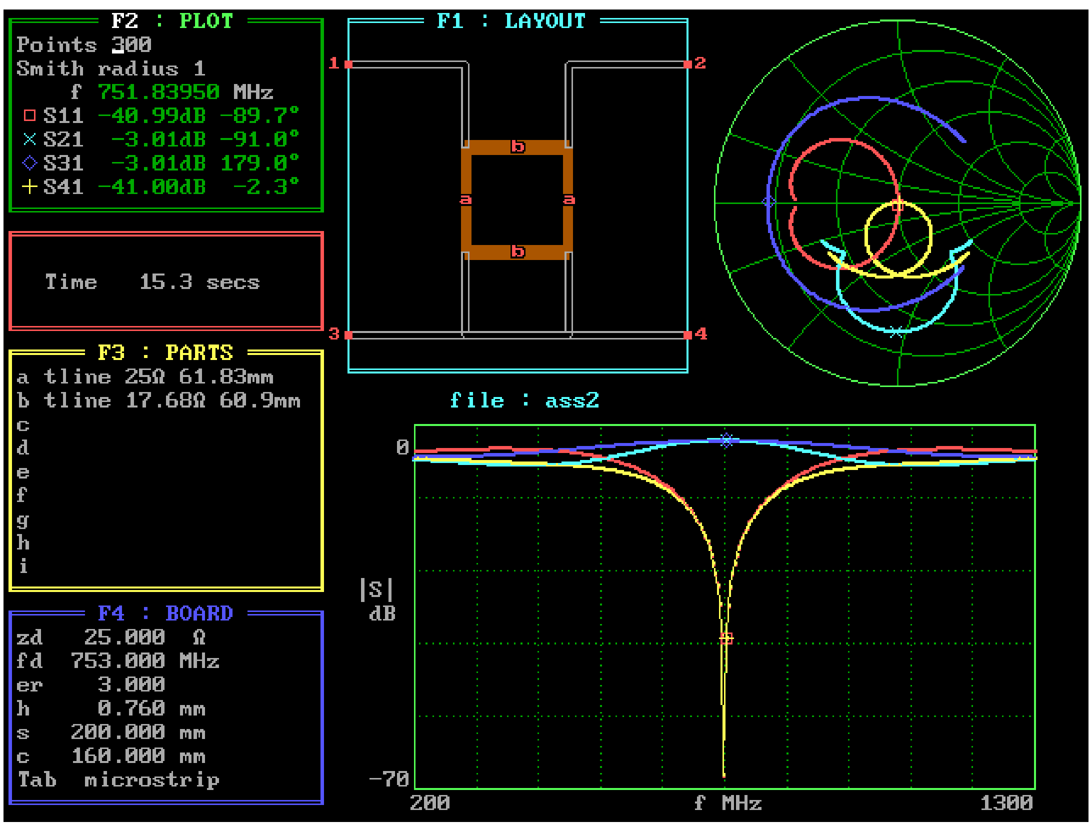
```
Length =  0.06090260270743159
```

In [29]:
```
df = pd.DataFrame({
    'Characteristic':[r'$\epsilon r$', 'c', 'f', 'Zo', 'Zo/sqrt(2)', r'$\epsilon eff$','h', 'w', 'l'],
    'Value':[er, c, f, zo, zo/np.sqrt(2), eeff, h, w, l]
})
df
```

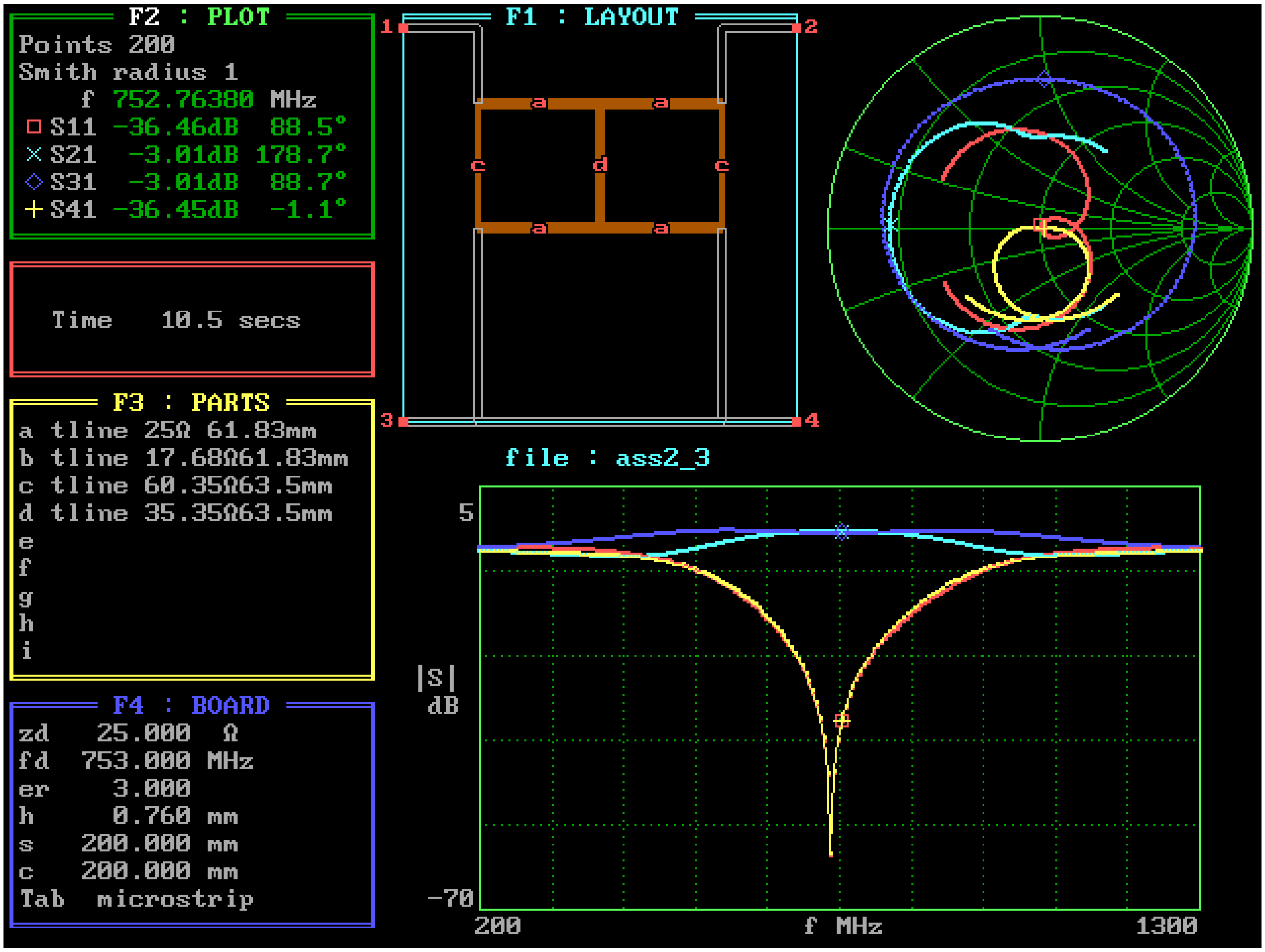
Out[29]:

	Characteristic	Value
0	ϵr	3.000000e+00
1	c	3.000000e+08
2	f	7.530000e+08
3	Zo	1.767800e+01
4	Zo/sqrt(2)	1.250023e+01
5	ϵeff	2.674612e+00
6	h	7.600000e-04
7	w	7.617078e-03
8	l	6.090260e-02

Appendix iv: Single-Box Branch-Line Coupler Overlayed Signals



Appendix v: Double-Box Branch-Line Coupler Overlayed Signals



References

ISOLA. (2021, NA NA). *Astra MT77*. Retrieved from ISOLA: https://www.isola-group.com/pcb-laminates-prepreg/astra-mt77-laminate-and-prepreg/