4B24: RF Systems - Coursework

CNN : 5592G

Abstract

Impedance matching is important, ensuring maximum power transfer between parts of a network. It can also be used to ensure maximum gain and minimum noise figure. Keeping the bandwidth over which these networks are effective is also important for communication systems. In this report the matching networks are designed and analyzed for the ATF-10100 transistor, with different choices of topolgies being compared and contrasted.

1 Introduction

A receiver for a communications system is fed by a 50Ω antenna, and has an amplifier based on the ATF-10100 transistor. This amplified signal is to be fed into the rest of the receiver which has an input impedance of 50Ω. The design brief states that the system needs to provide maximum gain at minimum nose figure at an operating frequency of 5.2 GHz, meaning input and output matching networks are needed to ensure minimum noise figure at input and maximum gain at output.

A secondary consideration is that he bandwidth of the system be as wide as possible, to allow good performance at a range of operating frequencies, not just at 5.2 GHz.

In this report the input and output matching networks will be designed and the different choices compared to each other using bandwidth, insertion and return loss and robustness as figures of merit. Also, the effects of standard values of components and tolerances on the design networks will be investigated before conclusions are drawn.

2 Characteristics of the ATF-10100 transistor

2.1 Stability

The K-Δ test states that an amplifier is unconditionally stable if and only if:

$$K = \frac{1 - |S_{11}|^2 - |S_{22}|^2 + |\Delta|^2}{2|S_{11}S_{22}|} > 1 \quad \text{and} \quad |\Delta| = |S_{11}S_{22} - S_{12}S_{21}| < 1$$

Figure 1 shows the K factor for the transistor over a range of frequencies. At 5.2 GHz, our frequency of interest, the K factor is less than 1, meaning it is not unconditionally stable and so the device is potentially unstable. Therefore, in designing our matching circuits, we must ensure that the resulting Γ_S and Γ_L lie outside of the stability circles.

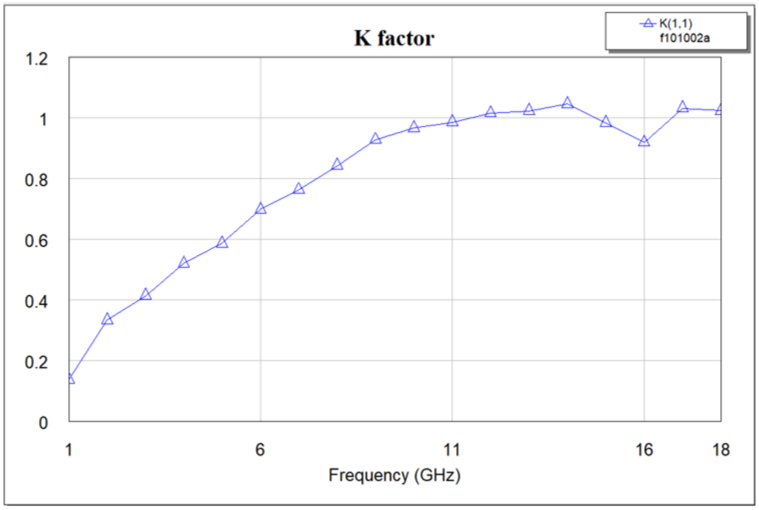

Figure 1: K factor plot over frequency for the ATF-10100 transistor

2.2 S parameters

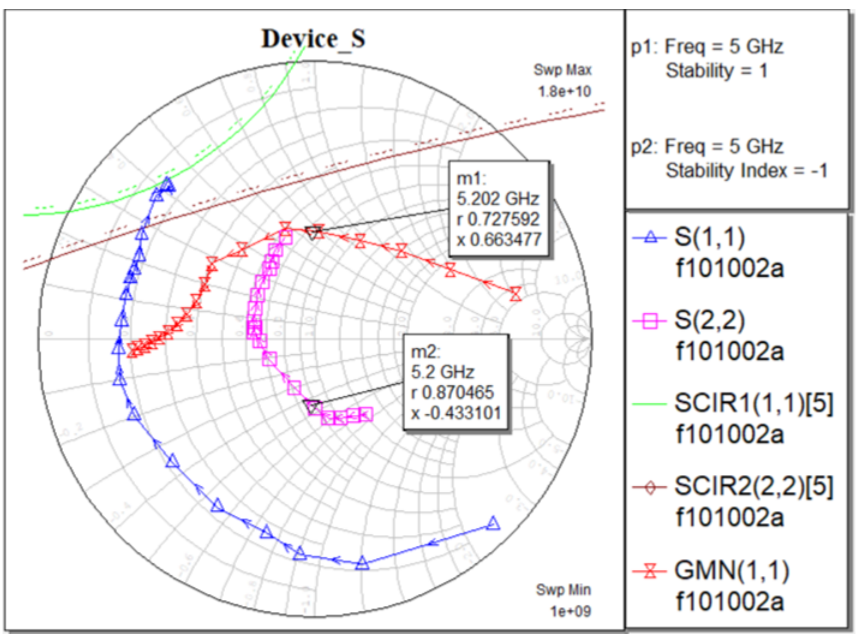

Figure 2: Smith chart of the the ATF-10100 S parameters, input stability circle (green), Output stability circle (brown), and optimum gain for minimum noise figure (red)

Figure 2 shows a plot of the transistors S_{11} and S_{22} parameters, as well as stability circles and the gain required for minimum noise figure. The dotted lines on the stability circles mean that the resulting Γ_S must lie outside the circle and Γ_L inside the circle. This information is used to create the matching networks.

3 Input Impedance matching

For an operating frequency of 5.2GHz, the minimum noise figure is 0.702dB, and is achieved by choosing the gain whose gain circle just touches the noise figure circle, and then designing a matching circuit that results in a reflection coefficient equal to the point of contact on the smith chart. AWR can plot these points for a range of frequencies, and this is the red trace in 2. Marker m1 shows that this is a normalized impedance of $0.727592+0.663477j$, equivalent to $36.3796+33.17385j$ at 50Ω or a reflection coefficient, $\Gamma_S = 0.3867\angle 91.31°$

3.1 Matching using stubs

The AWR software can perform the matching calculations for us, and give us several choices on topologies we can use. One such method is the use of a length of a transmission line and an open circuit stump, as introduced in lectures.

Matching calculation in lectures uses normalized impedance and gives answers as fraction of a wavelength. In order to convert this transmission line dimensions, the wavelength of the signal must be known. If using microstrip technology which is common on PCBs, the wavelength is governed by the relative permeability (dielectric constant) of the substrate, height of substrate as well as the the width and thickness of the track. The impedances phase is governed by the track length. Therefore, all micro strip parameters bar length must be specified to get a nominal impedance of 50 Ω, and then the length is calculated to achieve the correct phase.

Throughout this report, we will use the data and information from PCB manufacture house PCB Train[2]. They suggest using 4 layers with the substrate FR4 (which has a relative permeability of 4.5), and say that using 1 oz copper (which gives a thickness of 35 microns after platting) and a substrate height of 0.22 mm between copper track and ground layer gives and impedance of 50 Ω when a track width of 0.40 mm is used. Plugging these values when matching yield the following matching stub, shown in Table 1

Microstrip Width	0.4071 mm
Transmission line length	15.187 mm
Transmission Line Impedance	$50 \angle 40.064\ \Omega$
Stub length	3.5054 mm
Stub Impedance	$50 \angle 169.30\ \Omega$

Table 1: Physical properties of the input matching stub

3.2 Matching using lumped elements

Another solution is to match using a network of lumped elements, such as inductors and capacitors. AWR gives several choices, one of which is a L-section Low Pass filter.

While the primary concern for this design is maximum gain with minimum noise figure, another criteria is for the system to have a bandwidth as wide as possible. One possible solution for that is to use a N section matching network which is designed to give a maximum flat response.

All 3 designs are shown in Figure 3.

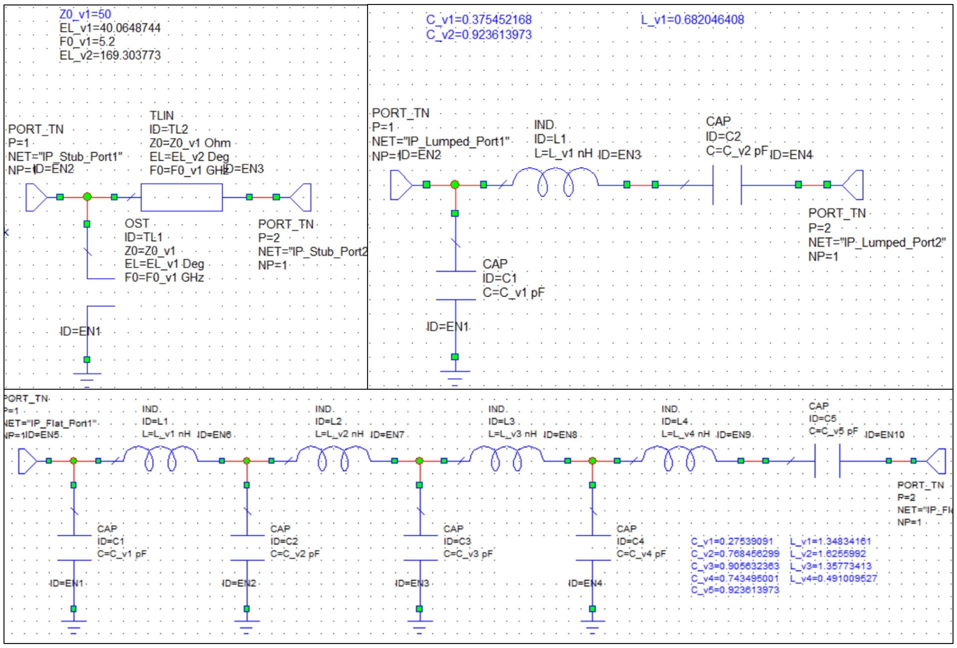

Figure 3: Input matching networks: Stub (top left), L-section (top right) and max flat (bottom)

3.3 Evaluating matching networks

Two key figures of merit for matching circuits are the insertion loss and return loss.

Insertion loss is a measure of how much power the matching circuit uses and is given by:

$$IL(dB) = 10\log\left(\frac{P_i}{P_t}\right) = 10\log\left(S_{21}\right)$$

Ideally, as little power as possible is lost in the matching network, meaning for a good match the value should be zero.

Return loss is a measure of how much power is reflected by the matching network and is given by:

$$RL(dB) = 10\log\left(\frac{P_r}{P_t}\right) == 10\log\left(S_{11}\right)$$

Ideally, the matching networks reflects as little power as possible, meaning the smaller the value the less power is reflected and more is sent through the matching network.

Figure 4 shows the insertion loss and return loss for the 3 matching networks. Around the operating frequency of 5.2GHz, there is a large negative return loss for the stub and lumped impedance match, meaning all the power is transmitted through the matching network. However, the bandwidth for the return loss is quite narrow, meaning if the frequency drifts around 5.2 GHz, the return loss is larger so more power is reflected by the matching network. The max flat trace doesn't have as small return loss at 5.2 GHz, but the response is flatter meaning more predictable and constant behavior around the operating frequency.

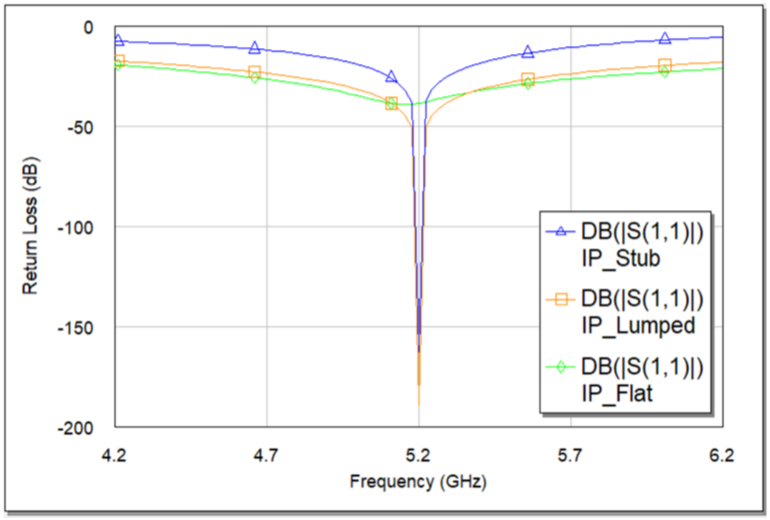

Figure 4: Return losses for the stub matching network (blue), lumped L section network (orange) and max flat network (green)

4 Output Impedance matching

From the lecture notes, the gain of the output matching network is given by:

$$G_L = \frac{1 - |\Gamma_L|^2}{|1 - S_{22}\Gamma_L|^2}$$

This gain is maximized when $\Gamma_L = S_{22}^*$. At 5.2 GHz, $S_{22} = 0.2355\angle - 93.61°$ and so $\Gamma_L = 0.2355\angle 93.61$, which is equivalent to an impedance of $43.52325 + 21.65505j$. This impedance can again be put into the matching wizard which gives a choice of toplogies to choose from, all with different performances. If the source is this complex impedance and the load 50, lumped component matching can be used, such as the networks shown in Figure 5.

Looking at the return losses, as shown in Figure 6, both lumped element networks have good return loss at 5.2 GHz, with the more complex network have a better return loss at frequencies around the operating frequency. The max flat however performs poorly, with the return loss being at maximum at 5.2 GHz, which is not only bad for impedance matching, but could cause the system to become unstable due to the conditional stability of the transistor at 5.2 GHz.

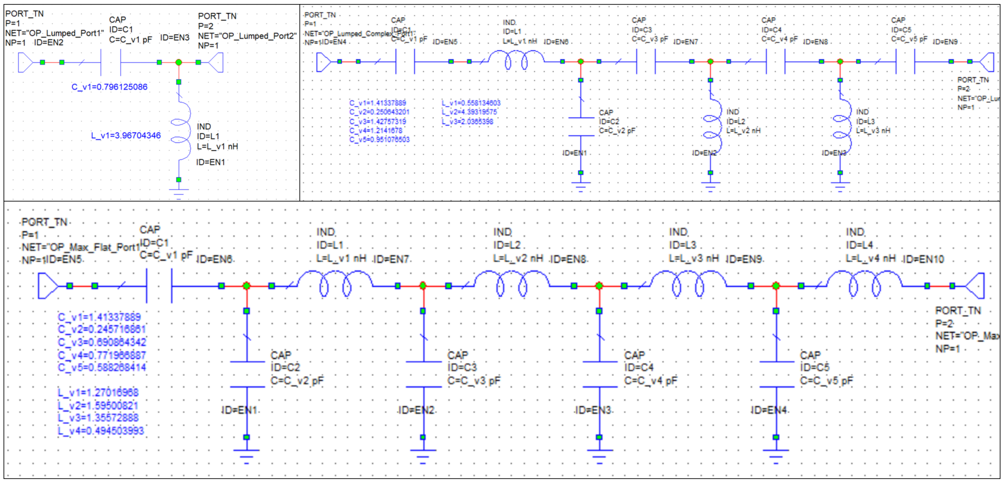

Figure 5: Output
matching networks: L-section (top left), 4 section design (top right) and max flat (bottom)

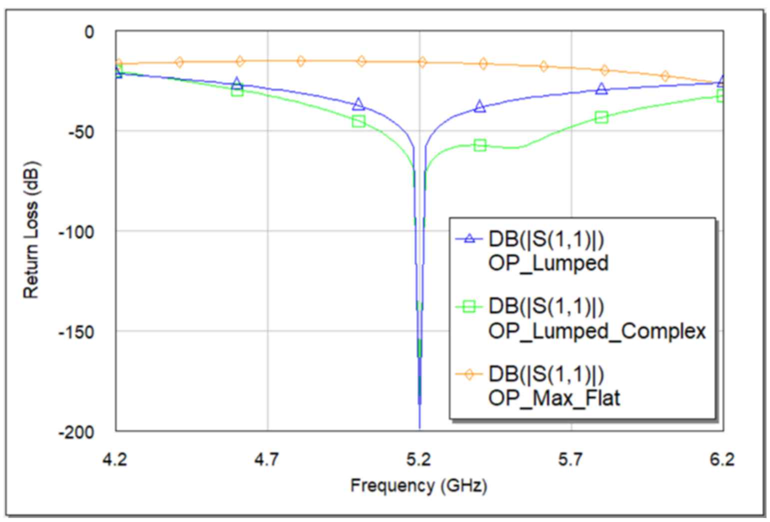

Figure 6: Return losses
for the simple matching network (blue), complex network (orange) and max flat network (green)

5 Initial design

A design using a stub input match and 4 section output match was chosen. The insertion and return losses are shown in Figure 7. The positive insertion loss is due to the gain of the circuit and both insertion and return loss are quite flat, meaning the circuit has quite a wide bandwidth.

Figure 8 shows that the resulting S_{11} and s_{22} parameters lie outside and inside the stability circles of the ATF-10100 transistor, sowing that the design is stable.

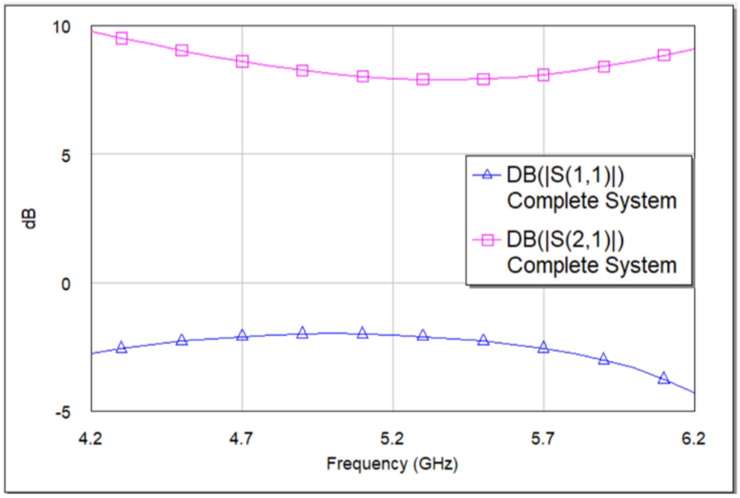

Figure 7: Insertion (pink) and return (blue) loss for the complete network

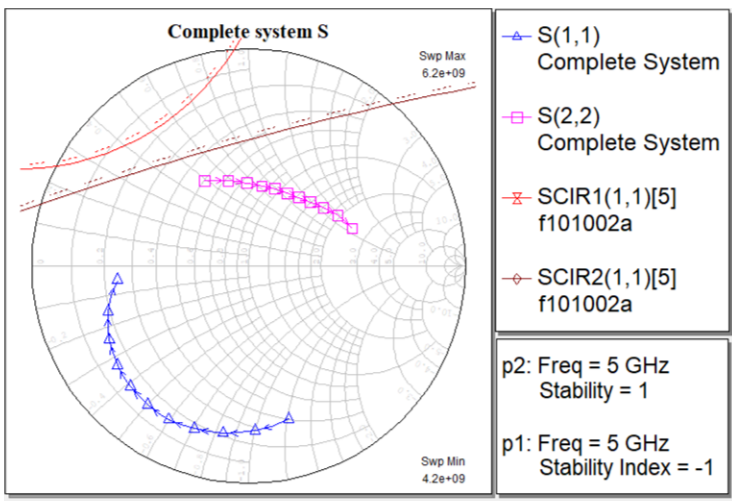

Figure 8: Smith chart for the designed notworks parameters with the ATF-10100 stability circles, showing the design is stable.

6 Investigating Lumped elements in matching

One option for the matching networks is to used Lumped elements, such as inductors and capacitors. The matching wizard gives this component values which may not be available as standard values that can be purchased. If the matching network is designed with non-standard values but then constructed with standard values close to those values, its performance will change. Using manual matching in AWR's matching wizard we can see how using standard values affects matching performance.

For example, at the input we could match the input using a lumped capacitor and inductor network as shown in Figure 3. The component values it returns are not standard values and cannot be purchased from general vendors. One solution is to used standard values found o popular distributors such as Farnell. Values that where found on Farnell were are shown in Table 2.

Component	Exact Value	Standard Value	% difference
C_1	0.92379 pF	0.91 pF	1.49 %
C_2	0.37552 pF	0.39 pF	- 3.86 %
L_1	0.68218 nH	0.68 nH	0.32 %

Table 2: Exact and standard values for the lumped input matching network

The percentage difference in one of the capacitor values is quite big with respect to the others. A closer value can be achieved by combining two capacitors in series of values 0.7 and 0.8 pF, both available on Farrell. This results in a total capacitance of 0.373 pF and is only 0.67% different from the calculated value.

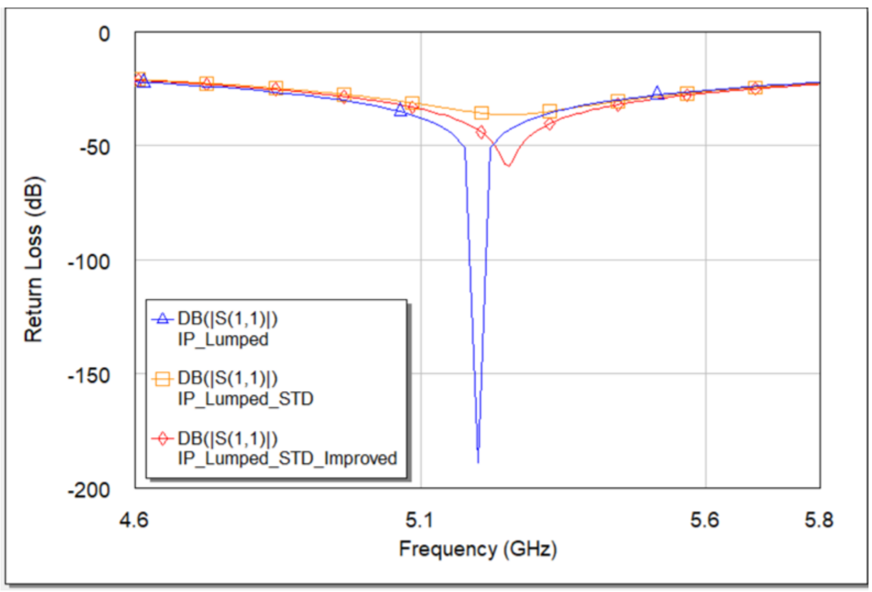

Figure 9: Return losses for 3 sets of lumped components:
The exact values (blue), standard values (orange) and the "improved" standard values" (red)

Figure 9 shows the insertion and return losses for all 3 of these matching networks: The ideal, the standard value and the standard value with extra capacitors. It can be seen that the ideal one as no return loss at 5.2 GHz, the standard value network performs much worse, having a return loss of -35.47 dB at 5.2 GHz. The adjusted design performs slightly better, with a higher return loss of -43.11 dB, around 8 dB better. However using additional values will make the network more sensitive the component tolerance, a weakness of using lumped matching networks. Another considering is the type of component, with RF-specific component being more suited to higher frequencies but can be more expensive.

7 Investigating stub matching

When the software computes the lengths of the micro strip, it needs to know the wavelength inside the micro strip. It therefore defines a width, thickness and dielectric constant. Other EDA tools, such as KiCAD have tools which allows you to specify conductor roughness and dielectric loss factor using there PCB calculator tool. Online tools, such as All About Circuits microstrip impedance tool [1], give the equations that govern the microstrip impedance. Of course when this matching network is manufactured, there will be certain tolerances in track dimensions, dielectric constant and board thickness.

PCB train gives a tolerance of ±10% in its fabrication and using the equations for micro strip impedance given by [1], we can investigate how the impedance changes as the width, thickness, height and relative permeability change. To do this, a python script has been written that varies each of these parameters and impedance against percentage change in parameter value, which can be found at [3]. The plot is shown in Figure 10.

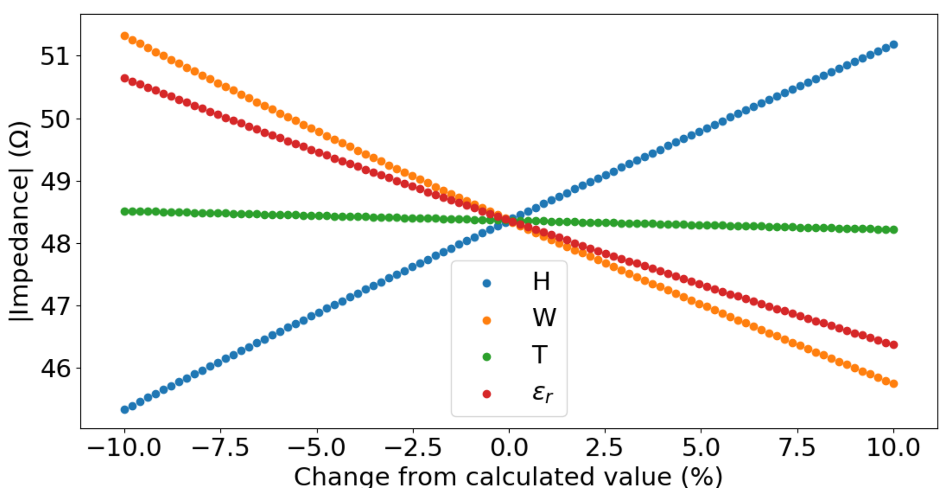

Figure 10: How the magnitude of the impedance changes with track dimensions: height above ground plane (H), track thickness (T), track width (W), and relative permabilty of the substrate (ϵ_r)

Firstly, AWR and the impedance matching calculate give different values for impedance, with AWR saying its 50 Ω and the impedance calculate saying its 48.4 Ω. This could be down to different models being used to calculate the impedance, such as how they take fringing fields into account. Using the 48.4 Ω value as the nominal value, we see that changing the thickness of the track has little effect in impedance, but Height, width and relative permeability have a large effect, causing the impedance to varying between 51 and 46 Ω. The max percentage changes are shown in Table 3.

So a ±10% change in physical properties at worst can affect the impedance by ±6%. Depending on design criteria, this may or may not be acceptable as changes in the impedance will also change the magnitude of the S_{11} scattering parameter and therefore the magnitude of the return loss, while variation in the length will affect its phase and therefore the frequency at maximum return loss it reached.

Track Dimension	Max % change in Z	
	Increase	Decrease
Height	5.763	6.329
Width	6.031	5.472
Thickness	0.243	0.373
ϵ_r	4.632	4.189

Table 3: Percentage change in impedance due to tolerances

8 Conclusions

From this design exercise it was found that:

- AWR is a power electronic CAD tool that allows for matching networks to be designed quickly, as well as allowing the user to compare the merits of different networks by looking at insertion and return loss.
- While a large bandwidth is important in communications applications, using AWR "max flat" option, while giving a constant return loss, sacrifices the size of the return loss, with it being greater than other, narrower band options.
- Lumped elements calculated by AWR can be purposely manufactured but at a high cost. Using standard values makes designed cheaper but alters there performance, both in terms of size of return loss and the frequency at which minimum return loss is met. Improvements can be made by combing standard values to get close to the desired value.
- If using transmission line structures to impedance match, care must be taken as tolerances in the production can alter the matching performance and impedance of the line. If the design is space limited, care must also be taken in how bends in transmission line are designed to minimize reflection, as well as avoiding coupling between microstrips.

Suggestions for future work include:

- Investigate how the return loss changes with tolerances in microstrip parameters, and extend this investigation into component tolerances, not just the difference due to using standard values.
- Come up with a quantitative measure of bandwidth, and then use that and a specified desired bandwidth for the system, to aid the choice in matching network used for the system.

References

[1] Microstrip Impedance Calculator: `https://www.allaboutcircuits.com/tools/microstrip-impedance-calculator/`

[2] PCB Train Controlled Impedance: `https://www.pcbtrain.co.uk/resources/controlled-impedance`

[3] GitHub to pyhton script and AWR analysis:`github.com/BaileyBrookes/4B24_RF_Systems.git`