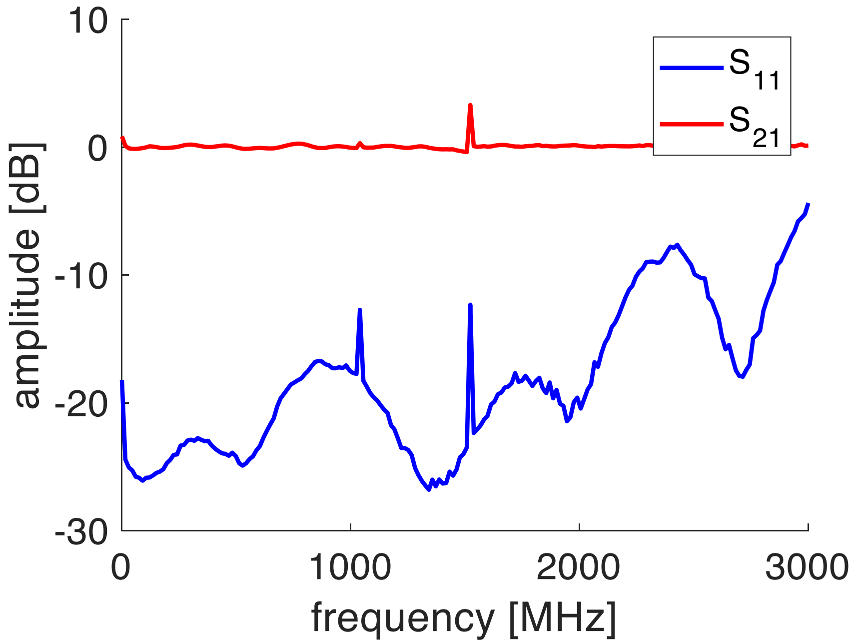
GIANNOPOULOU VALIA

CID: 01933859

1b



In the above graph, one can observe that Reflection is minimized while transmission is maximized. Since the arrangement is a direct connection of the DET and DUT port using a short cable, so the loads are matched and transmission is maximised, this is an expected result. There is a glitch near the 1.5 GHz frequency which probably is due to a discontinuity in the way the VNA takes measurements in the ranges of $f < 1.5\ GHz$ and $f > 1.5GHz$.

2a

For this task, it is important to understand how the Scattering Parameters matrix can be used to derive the impedances of the circuit arrangements. Specifically, as LC resonators are used, the theoretical impedance of such an arrangement will be compared with the one calculated from the Scattering Parameters matrix. The theoretical impedance of an LC resonator is:

$$X = \omega L - \frac{1}{\omega C}$$

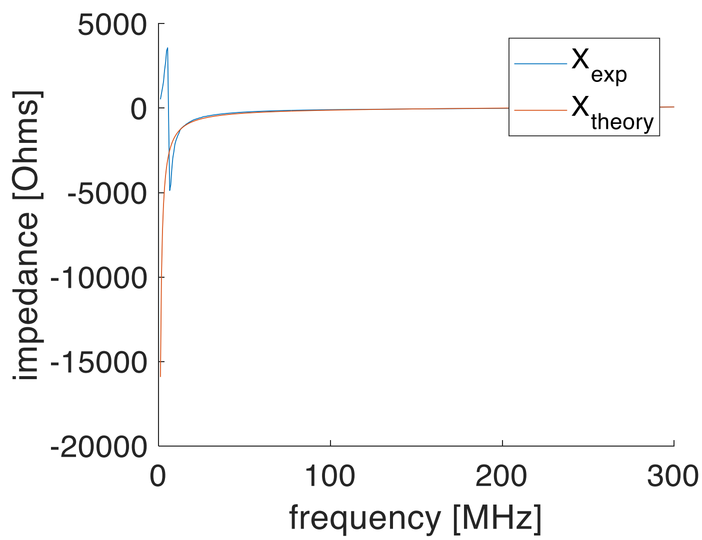
Using the background theory, the same impedance can be measured experimentally using:

$$Z_{LC} = Z_0 * \frac{S_{11} + 1}{1 - S_{11}}$$

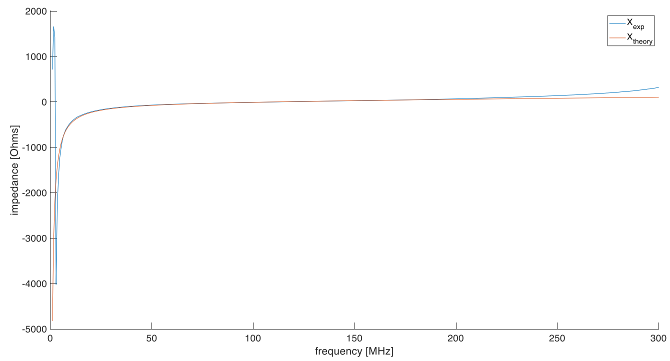
Where $Z_0$is the characteristic impedance of the transmission line and S_{11} is the reflection coefficient.

Multiple measurements were taken with resonators with different capacitances. The graphs of the impedances measured superimposed with the theoretical impedances are shown below:

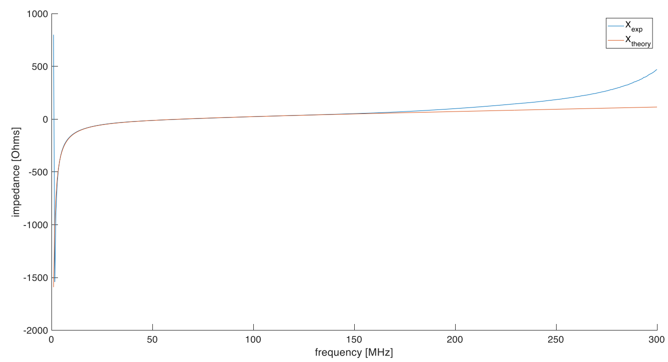
For the 10pF capacitor:



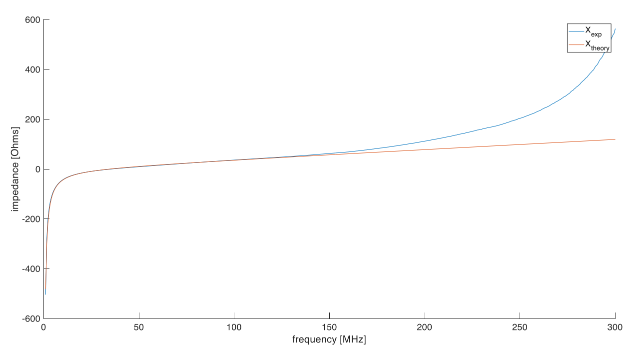
For the 33pF capacitor:



For the 100pF capacitor:



For the 330pF capacitor:



Having the inductance of the arrangements as an unknown, trial and error was used to match the zero-crossing point of the theory and experiment.

The table with the results is the following:

Capacitance(pF)	Inductance(nH)
10	56.9
33	57.4
100	56.2
330	59.6

The inductance seems to have a mostly stable value as expected and any deviations are mostly due to MATLAB resolution differences and human error.

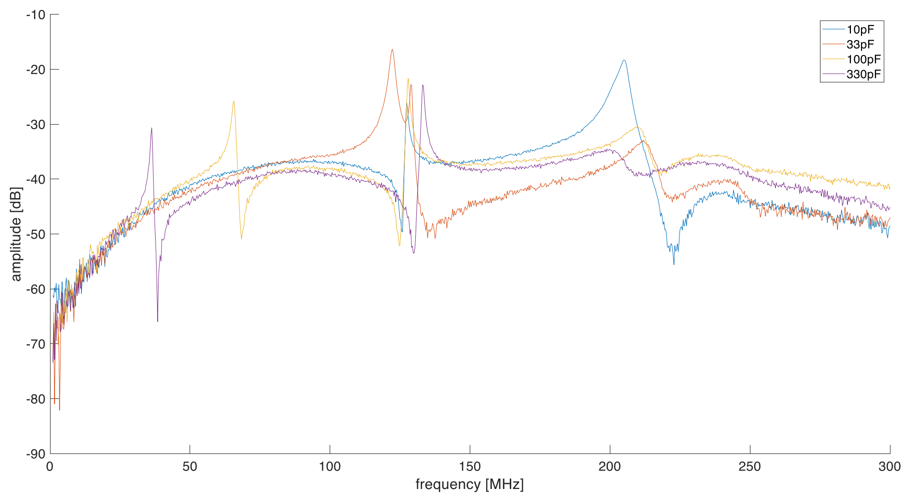
The reason the zero-crossing point is used to measure the inductance is because that is the point where the impedance has no imaginary part and thus the impedance due to the capacitor matches the impedance due to the inductor.

Comparing theory with experiment yields the following deductions. For low frequencies, the system's impedance is affected mostly by the contribution of the capacitor. Any difference between the theory and experiment for these frequencies is due to the VNA being heated up which might create some discrepancies in the low frequencies for the reflection coefficients leading to the deviations shown in the graph for the $10pF$, $33pF$ and $100pF$ capacitor. When these measurements were taken using a cold VNA, these deviations disappeared but the graphs with the differences were included in the report. For the final measurement, a cold VNA was used to show the difference as seen in the graph for the $330pF$ capacitor.

Actual deviations that are not accounted by the theoretical model are observed for high frequencies. After the zero-crossing point, the system starts to act as an inductor as the impedance of the capacitor starts to tend to zero. For high frequencies, parasitic inductances deviate the experimental impedance from the theoretical. The relationship is not linear so these parasitics are not in series with our system. For different capacitances, the effect is either less prominent or more prominent and there seems to be a positive correlation with the capacitance value of the system. This can be attributed to the fact that increasing the capacitance of the resonator, decreases the zero-crossing point which might mean that the parasitics start to have a considerable effect on the system on lower frequencies compared to resonators with a higher zero-crossing point.

2b

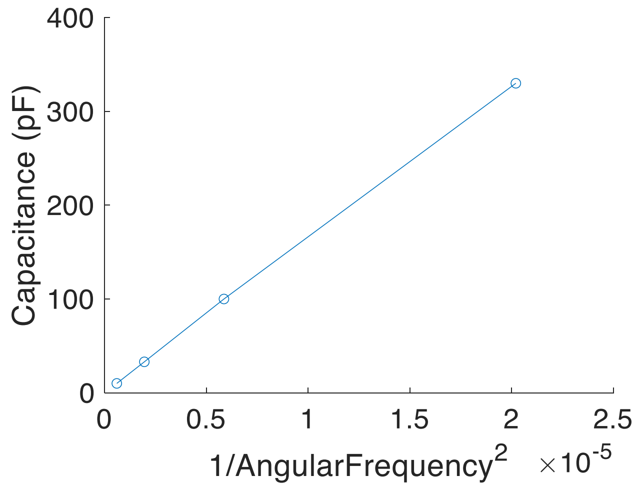
The inductive probes create a magnetic field that interacts with the LC resonators. This interaction is observed through the resonant peaks of transmission. For different capacitor values of the resonator, there are different resonant peaks. The graph with the super-imposed transmission coefficients for different resonators is shown below:



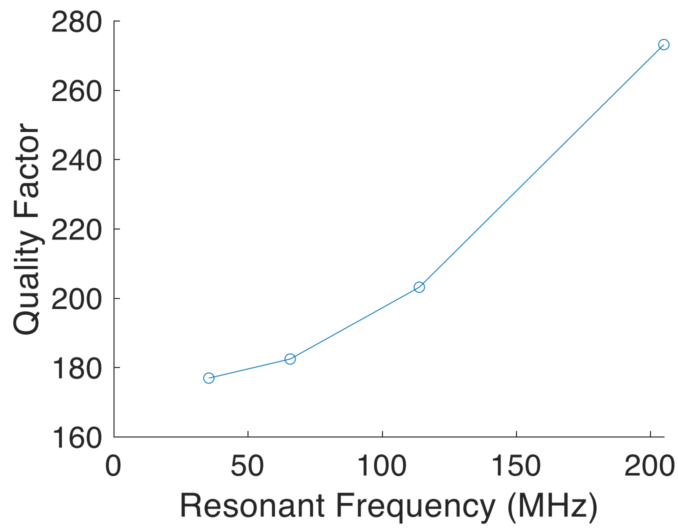
A table with the resonant frequencies for the different capacitors follows:

Capacitance(pF)	Resonant Frequency (MHz)	Δf (MHz)
10	204.9	0.75
33	113.8	0.57
100	65.7	0.34
330	35.4	0.2

Knowing these values, one can calculate the Inductance of the resonator, Quality factor and the equivalent series resistance:

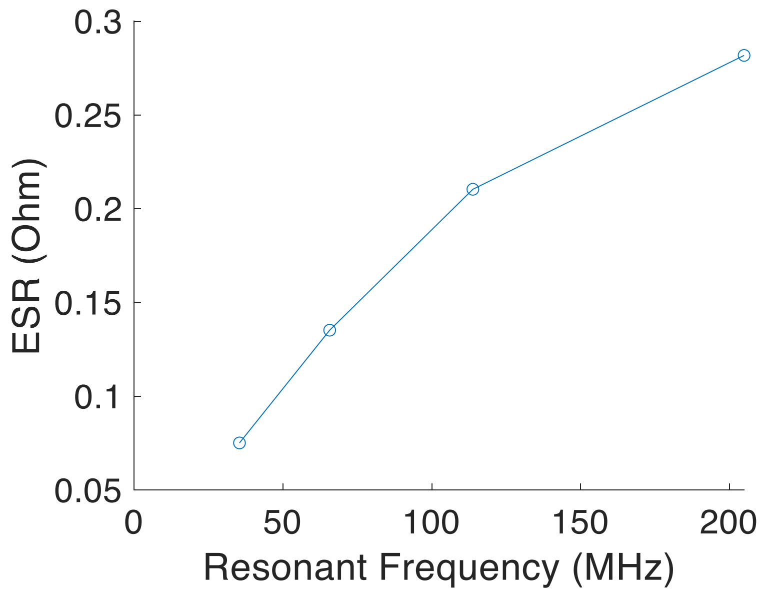


By finding the slope of the graph one can determine the inductance of the resonators. The calculation yields $L = 59.8nH$. The graph is a straight line and that is to be expected as the inductance of the resonators is constant. Below the graph of the Quality Factor over resonant frequency is shown:



The graph is clearly not linear but there is a positive correlation between the quality factor and frequency. This can be an indication that the equivalent series resistance of each resonator varies depending the frequency of operation.

Plotting the ESR values over the resonant frequency yields:

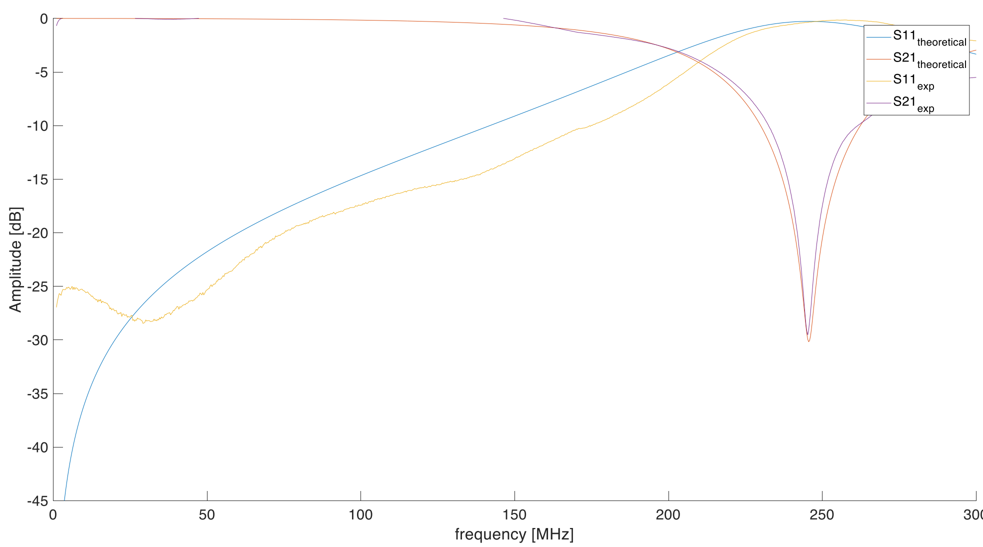


From the graph, it is shown that indeed the Equivalent Series Resistance increases with the frequency of operation. Because the accuracy is limited, it is difficult to conclude on a specific relationship between the aforementioned physical quantities but the linear relationship can be excluded.

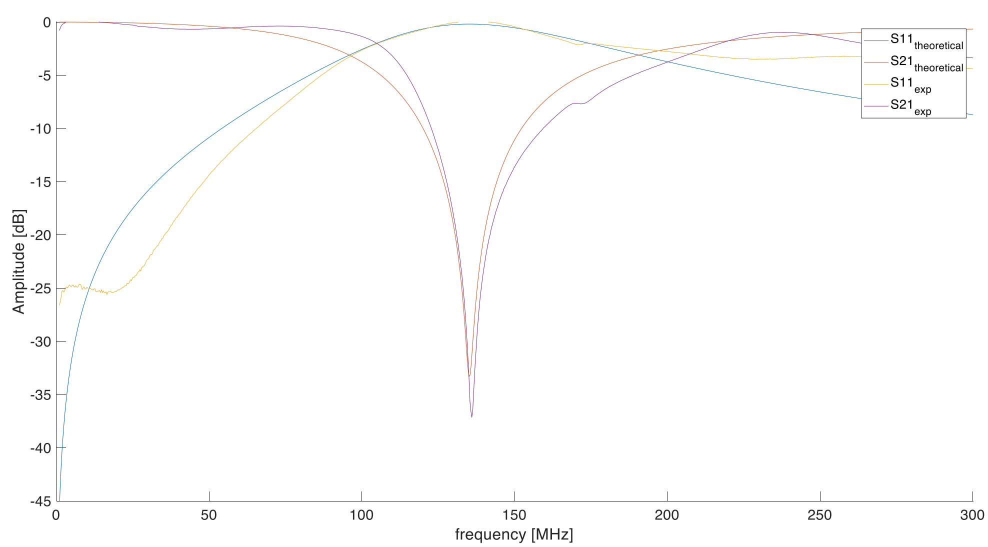
3a

Evaluating the performance of BandStop filters is a good way of understanding how these filters work. By using the background theory, the Scattering Parameters matrix can be calculated to compare experimental results with theory. The graphs of the reflection and transmission coefficients are shown below:

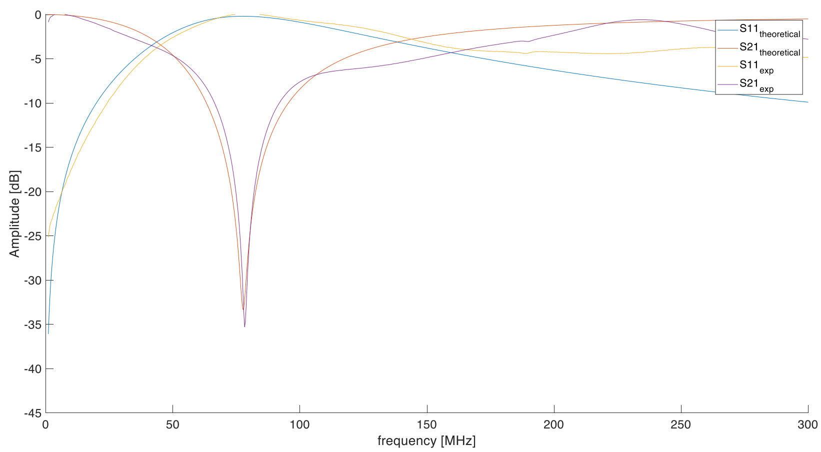
For the 10pF capacitor:



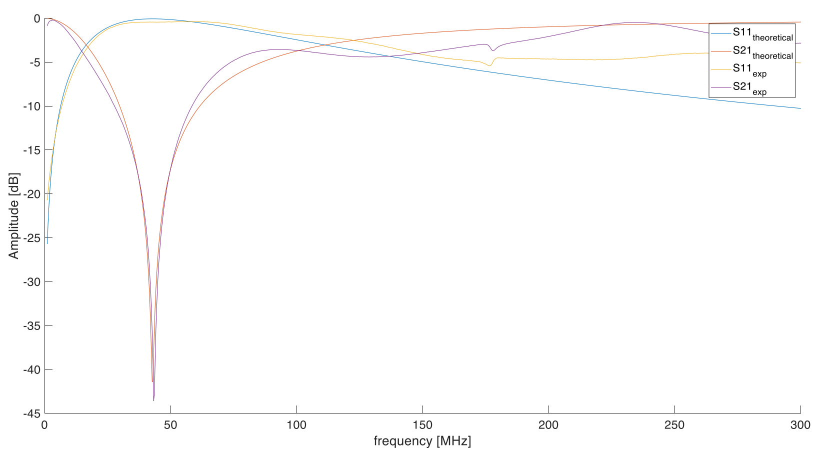
For the 33pF capacitor:



For the 100pF capacitor:



For the 330pF capacitor:

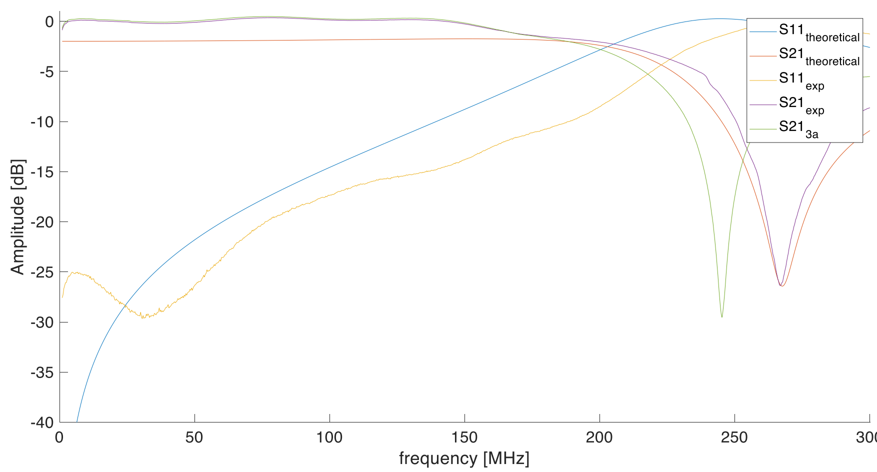


By directly observing the graphs it is clearly discernible that theory and experiment agree in a great extent. For low frequencies the reflection amplitude decays to a value bigger than the theoretical. This is because the VNA has a specific resolution and a value of reflection of 0 would have a quantisation error plus any additive noise would increase that error. Near the resonant frequency of each resonator, the filter works as expected and the transmission is minimised while reflection is maximised so for a small band of frequencies near the resonant, there is no transmission. For higher frequencies, the reflection coefficient measured is higher than the theoretical one which must be due to the added parasitics not accounted for in theory which create a considerable impedance difference between experiment and theory. The inductance used to fit theory to experiment was considerably smaller compared to previous tasks. This is most probably because of added parallel inductance from the transmission lines.

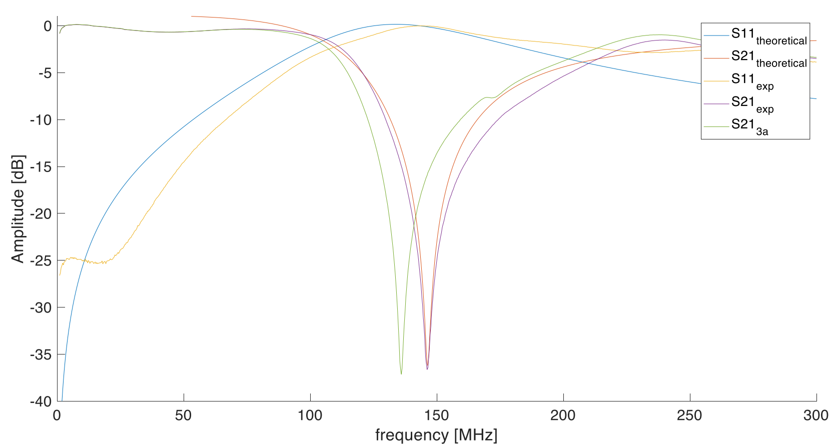
3b

Having verified the effect of band-stop filters, one can proceed by observing how the magnetic field of such filters interact with metal objects and what is the effect on the measured scattering parameters. After taking the measurements for the various capacitances, the graphs below were plotted.

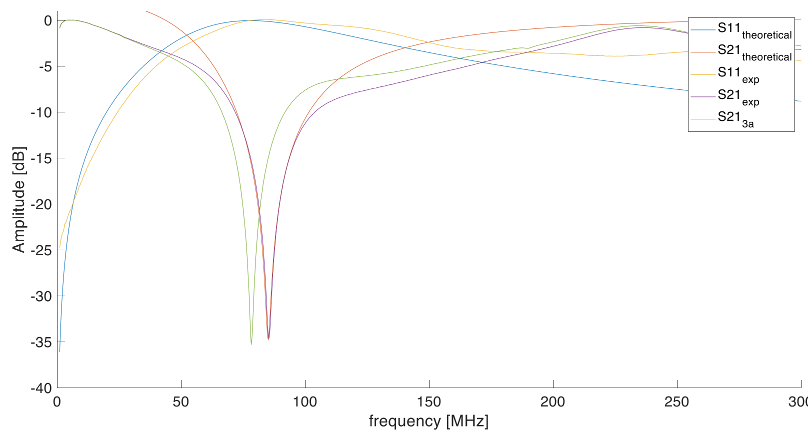
For the 10pF capacitance



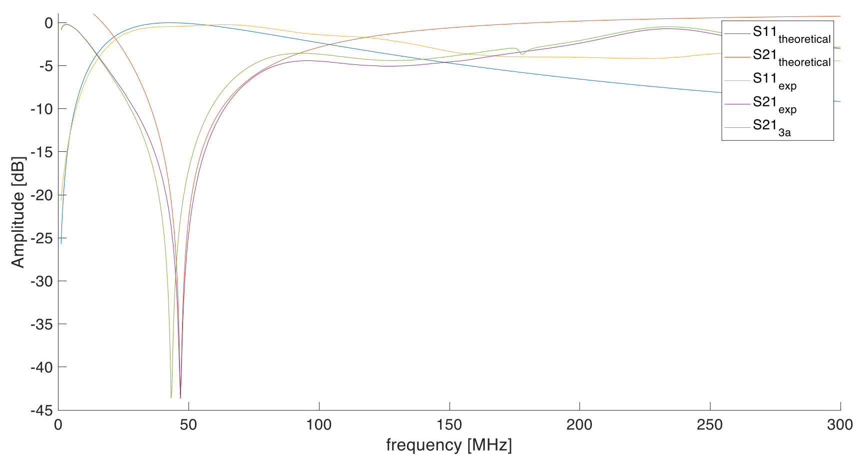
For the 33pF capacitance:



For the 100pF capacitance



For the 330pF capacitance



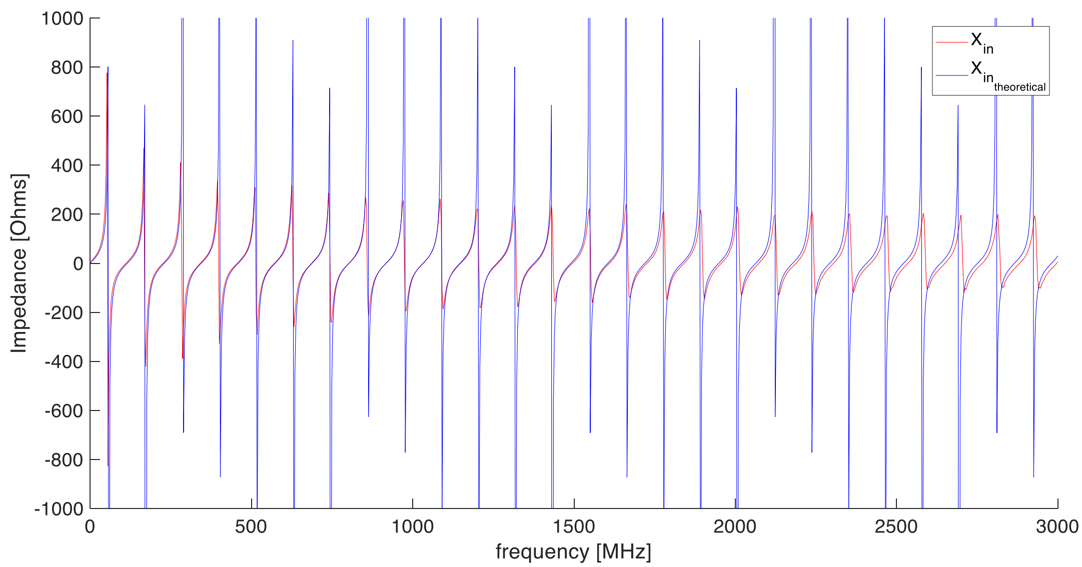
It is clearly visible that theory matches the experimental values. Comparing with the values of task 3a, it can be observed that there is a right-shift of the corner frequency. This indicates a decrease of the apparent inductance of the system. To explain why this happens one needs to consider what magnetic fields are present and how they interact. Initially, there is the magnetic field of the resonator. In presence of the metallic sheet, this field induces eddy currents in the sheet, which means that another magnetic field is created. This field opposes the field of the resonator which is followed by a reduction of the magnetic flux. The inductance of the system is positively related to the magnetic flux meaning that a decrease of the flux leads to a decrease of the apparent inductance which is depicted by the shift of the resonant peak. Knowing the resonant peak of the resonator without the presence of metallic objects is key to analysing the properties of different metals by investigating the shift of the resonant peak. It is important to note that for smaller capacitances, the shift of the resonant peak, with the same metallic object being present, is larger which might mean that the decrease of the inductance is constant in magnitude across all capacitances making the shift proportional to the resonant peak frequency.

4a

For this task, a long cable was measured to be approximately 0.914 meters. By connecting the cable to the DUT port and having the other end be a short circuit, a 0 load impedance is simulated. This configuration has an input impedance that follows the relationship:

$$Z_{in} = jZ_0 tan(kd)$$

Where k is the propagation constant and d is the length of the cable. The superimposed plot of the measured impedance and the theoretical impedance is shown below:

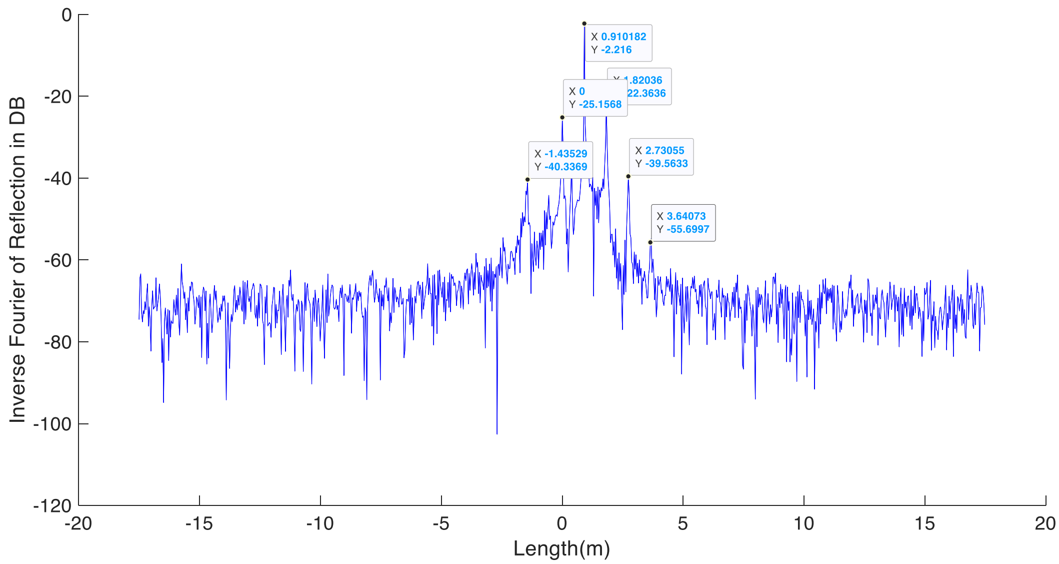


The value of the dielectric constant to fit the experiment was found using trial and error to be $\varepsilon_r = 2.04$

The main observation that can be made from the graph is that for low frequencies theory and experiment are aligned perfectly whereas for higher frequencies there starts to be some growing deviation. This is most probably due to additive parasitics that change the measured impedance. Also note how the theoretical impedance tends periodically to plus and minus infinity whereas the measured impedance does not. This is most probably because S11 never reaches a value of 1 that would make the impedance tend to infinity which is due to some power losses in the transmission line.

4b

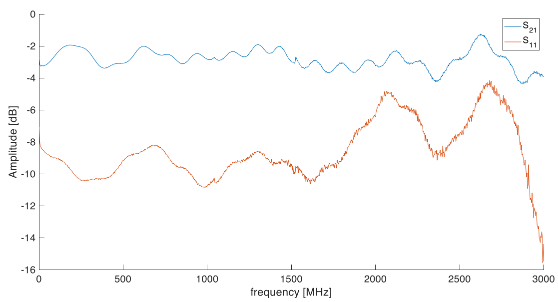
An important property of electromagnetic waves is that their speed is constant, and it is a simple fraction of the speed of light in vacuum determined by the dielectric constant of the medium of propagation. By knowing this important property, one can convert frequency domain data to time domain data and by knowing the velocity of propagation, it can be converted to range data. This is exactly what is done in this task to measure the length of a long cable.

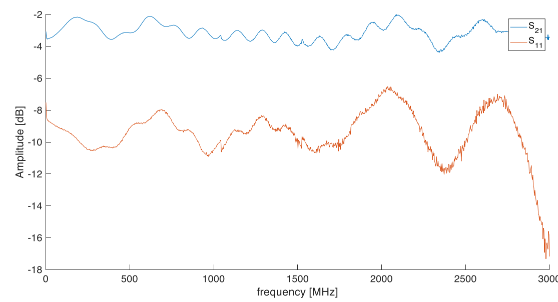


The graph is noisy but has some important peaks. Specifically, the one with the greatest amplitude is at the range of 0.91 which matches the length of our cable. That means that waves of wavelength equal to the length of the cable produce max reflection. All the other peaks of the graph are on multiples of the cable length, a property that resembles standing waves. There is also a peak at the 0m range indicating that there is some considerable reflection happening right on the DUT port. The peaks on the negative ranges can be discarded as it is the result of extending the reflection data on negative frequencies to be able to do the IFFT, so they do not represent meaningful information. The value of ε_r used to match the range data to the actual cable length is $\varepsilon_r = 2.04$ which is exactly the same as the one found on the previous task. As the circuit is left open at the end of the cable, an infinite load is simulated which would imply maximum reflection at all frequencies. The inverse Fourier transform of such an arrangement would yield theoretically a sinc function in the time domain.

5a

In this arrangement, an unmatched splitter is used. That means that any possible orientation is symmetric to each other, and it would not yield different results. The orientation as it is yields $Z_{in} = \frac{Z_0}{2}$ which models an expected reflection to be $S_{11} = -\frac{1}{3}$. This is approximately -9dB which is close to the starting -8dB seen in the graphs below. Any difference might be due to some added load difference at the port of the splitter and possibly to some error in the resistance of the 50 ohm load on one end of the splitter.

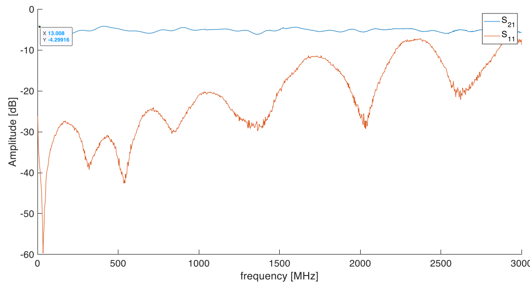


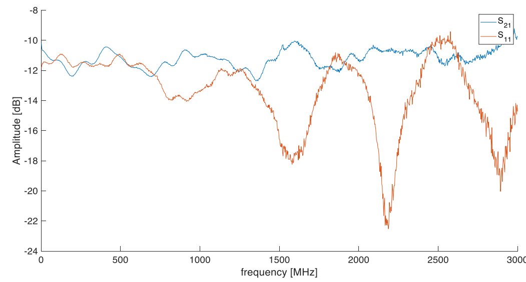


The graphs are extremely similar as expected. At high frequencies there seems to be a sudden increase of reflection possibly due to some additive parasitic resistance at a port of the splitter and afterwards a rapid decrease of it. The expected value of transmission from our model is -3.5dB which is approximately the value seen at the graphs indicating a correct use of a theoretical model.

5b

In this arrangement, a partly matched splitter is used. At two ports of the splitter, there is an added 50 Ohms load which allows for one orientation to have matching loads to achieve minimum reflection and maximum transmission.





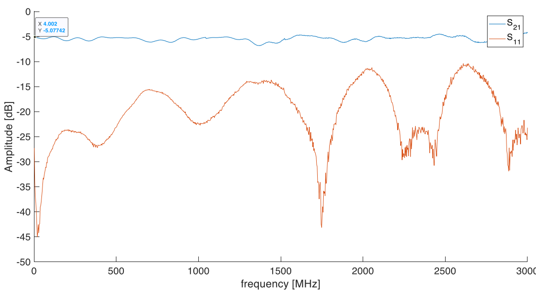
The arrangement on the left is the matched one and on the right is the unmatched one.

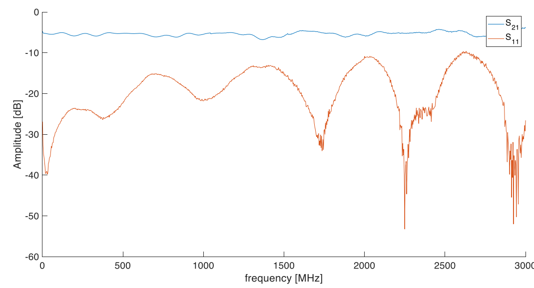
For the first arrangement there are a few things to note. Firstly, indeed for low frequencies the reflection coefficient is close to zero as expected because of the matched loads. It is important to note though that the transmission coefficient is about -4dB which is even lower than in the unmatched case of the previous task. This is because power is dissipated on the resistors of the splitter. The benefit of matching the loads is seen through the much more constant value of the transmission for the whole range of frequencies. For high frequencies, a considerable increase of the reflection is observed which is most probably because of parasitics.

For the unmatched orientation, the shape of the graph is similar to the previous task but because of the added loads, the amplitudes of both transmission and reflection are different. The theoretical model gives a constant reflection of about -12dB which matches the experiment for low frequencies. For higher frequencies there are considerable fluctuations of reflection due to parasitics at the ports of the splitter. This can be a major issue when there is a requirement for bi-directional transmissions so such a splitter would not be optimal in such cases. Note how transmission in the unmatched case fluctuates considerably more than in the matched case.

5c

In the fully matched splitter case, in each port of the splitter there is a load of $\frac{Z_0}{3}$, making $Z_{in} = \frac{Z_0}{3} + \frac{2Z_0}{3} = Z_0$ which matches the loads. This is further verified from the experimental data as shown in the graph below:



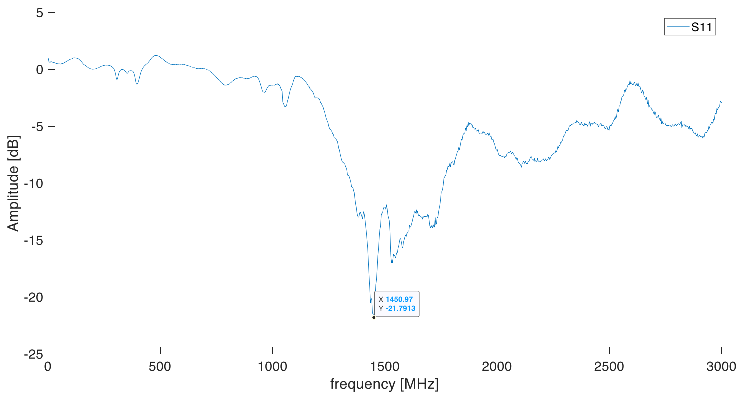


For low frequencies, the reflection is minimized as expected. Because there is a strong dependency on having matched loads, even the slightest impedance difference between ports can create considerable amplitude difference in dB. Again, note how the transmission is mostly constant and at the same amplitudes for both orientations suggesting that bi-directional transmission is achievable using this splitter. Again, for high frequencies the expected deviations are observed in the reflection values due to slight load differences between ports because of the parasitics. Also note that the amplitude of transmission is close to -5dB which is the lowest of the 3 cases making meaning that using this splitter dissipates about 45% of the power of the transmitted signal.

In conclusion, if minimal reflection is not a requirement for a potential system, maximum power is transmitted using an unmatched splitter. If transmission needs to be single-directional, then the partly matched splitter can be used as it ensures minimal reflection and does not dissipate as much power as the fully matched splitter. In the case of bi-directional transmission, a fully matched splitter must be used in expense of a considerable dissipation of power.

6a

A dipole antenna has a current resonance when the total length of the dipole is equal to half the wavelength of the transmitted wave. The expectation is to see a negative peak at a single frequency of the reflection data for each dipole length and that frequency must be closely correlated with the length of the dipole. For example, the reflection data for a dipole antenna of length 8cm is shown below:



A table of the minimum of all the antennae is provided:

Length (cm)	Resonance (MHz)
6	1904.27
7	1733.16
8	1450.97
9	1282.84

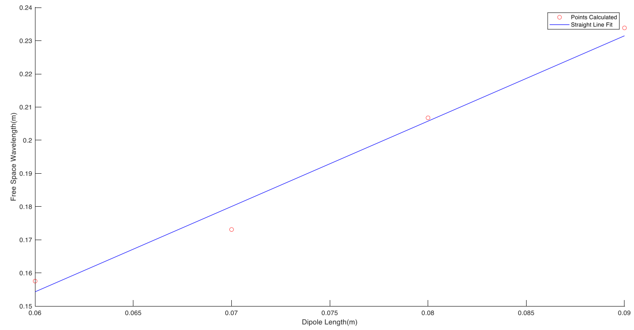
These values can be converted to free space wavelengths using the equation:

$$\lambda_{free} = \frac{c}{f}$$

Because the wave is propagated through a medium that is not the vacuum the actual wavelength of the EM wave will be different. Specifically,

$$\lambda = \frac{\lambda_{free}}{\sqrt{\varepsilon_r}}$$

When plotting a graph of free space wavelength against dipole length, the following results are produced:



The points seem to fit on a straight line and there is no non-linear behaviour. The slope of the line is :

$$\lambda_{free} = m * dipole\_length \text{ where } m = 2.572$$

Also using the actual wavelength of the EM wave we have:

$$\sqrt{\varepsilon_r} * \lambda = m * dipole\_length$$

Giving:

$$\lambda = \frac{m}{\sqrt{\varepsilon_r}} * dipole\_length$$

Having taken into account the medium of propagation means that for resonance:

$$\frac{m}{\sqrt{\varepsilon_r}} = 2$$

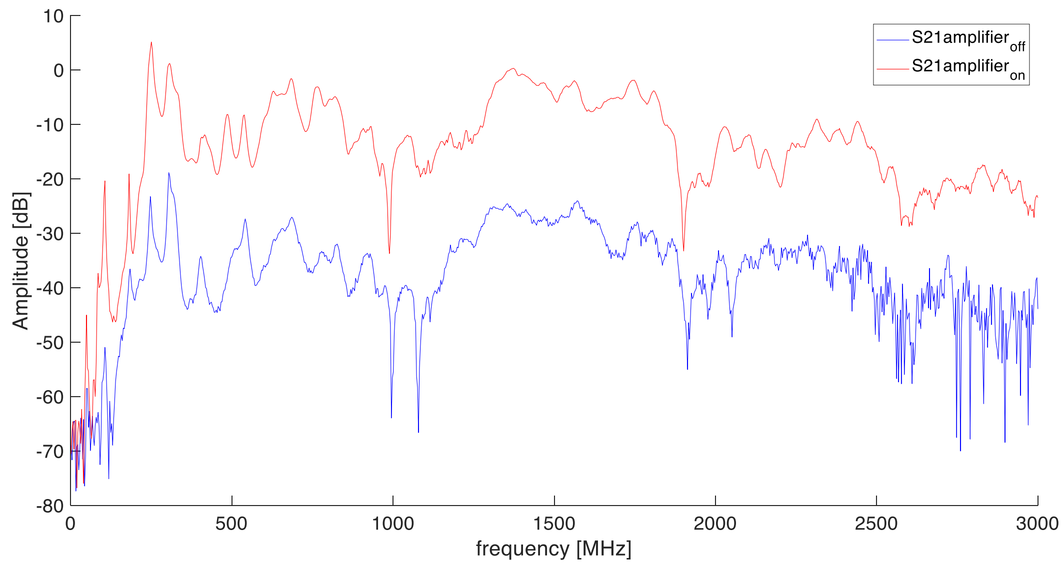
Giving:

$$\varepsilon_r = 1.65$$

This value is much lower than the value 4.4 of the FR4 substrate. This value might be a weighted average of the theoretical permittivity of vacuum and the permittivity of FR4 based on the structure of the antenna.

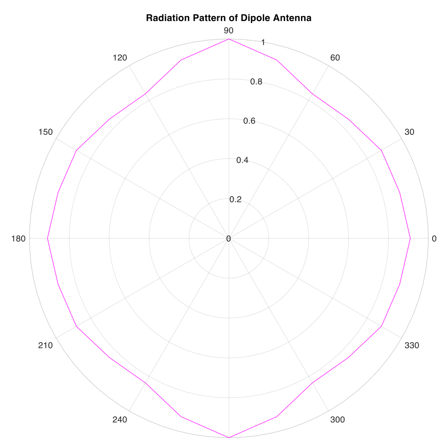
6b

The variation of transmission with the amplifier off and on is shown below:



There is an average difference of 25dB as expected.

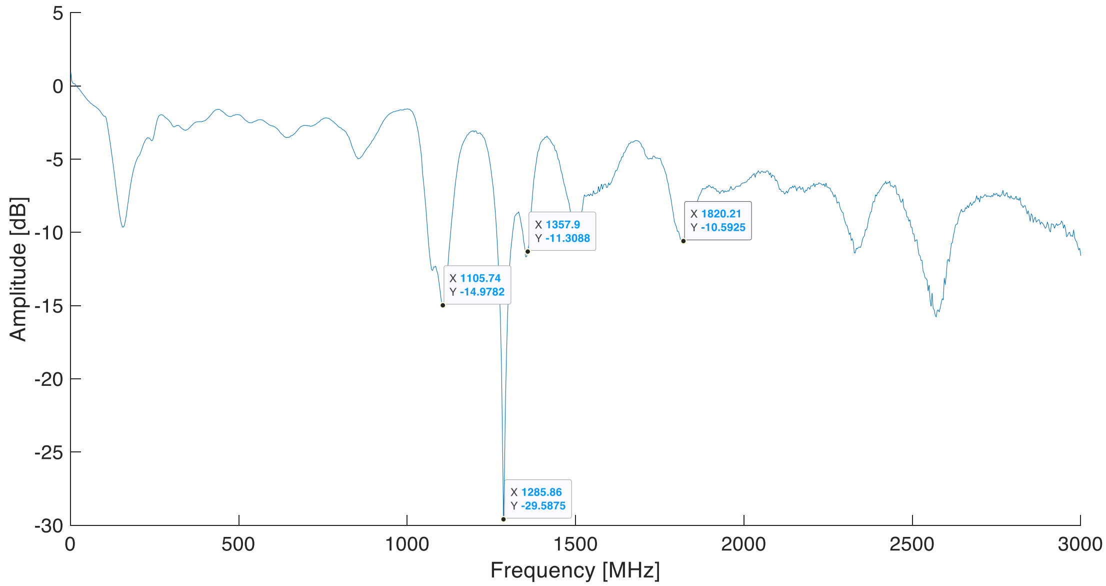
The frequency chosen to extract the transmission values was 1198MHz which is close to the peak found in the previous task for the dipole antenna of 9cm. The polar plot produced is shown below:



The radiation pattern is as expected. All the amplitudes for different angles are close to a normalised value of 1 indicating that the antenna is isotropic. Variations from the theory may be due to human error in positioning the antennae and, also, due to interference from miscellaneous objects in the area of the conduction of the experiment.

7a

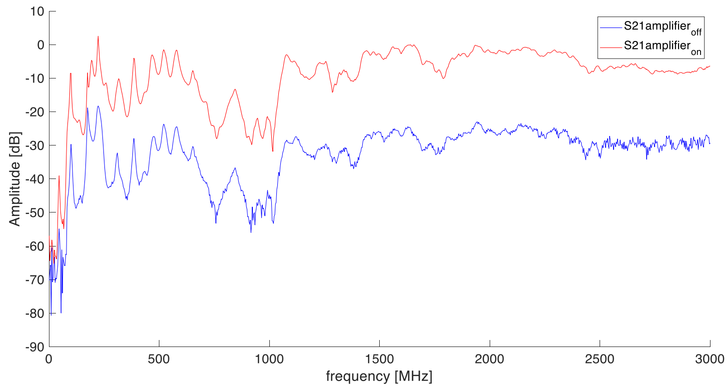
The reflection values for the log-periodic antenna are shown below:



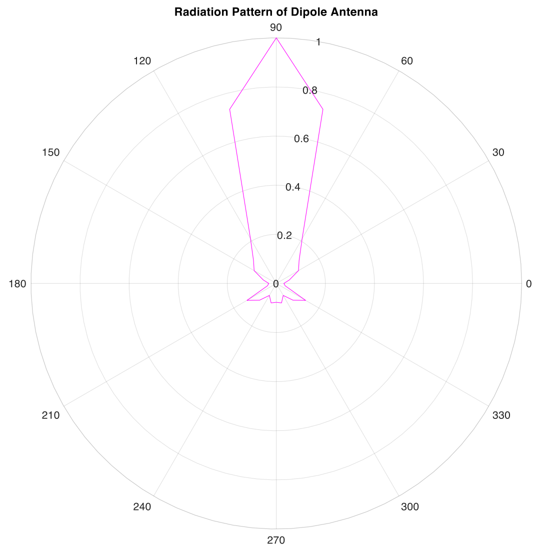
The reflection is minimised at multiple frequencies because the log-periodic antenna is composed by multiple dipole antennae of different lengths. This antenna is useful to transmit information to be received by receivers operating at different frequencies. A considerable difference though is that, for some frequencies the reflection is not minimised to the same extent as in the main negative peak. This is something that should be considered when transmitting information to these frequencies.

7b

One can verify the correct operation of the amplifier using the plot shown below:



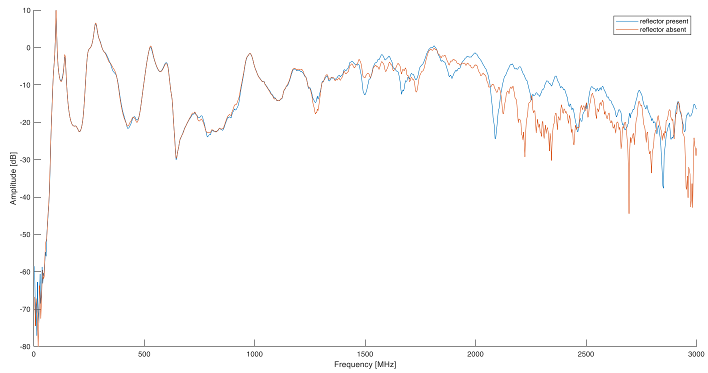
After taking the measurements for angles that represent all possible distinct orientations with respect to the receiver (i.e. facing the receiver and having a 180 degree angle to the receiver) and choosing a frequency of 1478MHz close to the instructed 1.5GHz, one can plot the radiation pattern of the log periodic antenna.



The degrees shown in the plot are relative to the protractor used with 90 being the angle where the antennae face each other and 270 being the angle where they are opposite to each other. The antenna is clearly not isotropic and has its highest transmission power when it is facing the receiver. This means that to transmit a message the transmitter needs to know the position of the receiver which in some cases is desirable. The dipole antennas of the log-periodic antenna interfere with each other to cancel transmission in some directions, but the cancelation is not absolute and that is why there are some small radiations at angles of 210 degrees and 330. To conclude, both antennae work great for their application. A half-wave dipole antenna allows for non-discriminatory transmission at all directions but at a specific frequency whereas a log-periodic antenna allows transmission at some frequencies, but the direction of transmission needs to be parallel and facing the receiver.

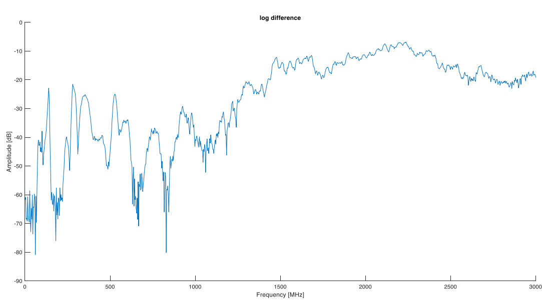
8a

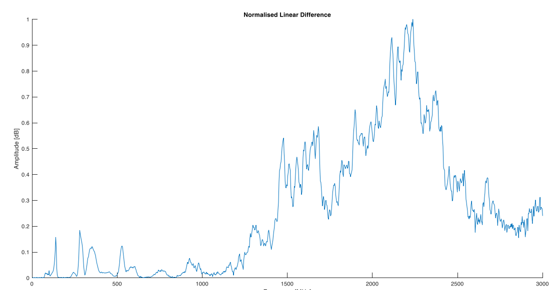
A superimposed plot of the transmission values of the reflector being present and absent is shown below:



As it can be seen there is an extremely close correlation of the two curves for small values of the frequency and they start to deviate at about 1.5GHz. This is the expected behaviour as the reflector reflects high frequency EM waves and small frequency waves pass through it due to the skin effect.

The linear and logarithmic plot of the difference of the two curves is shown below:

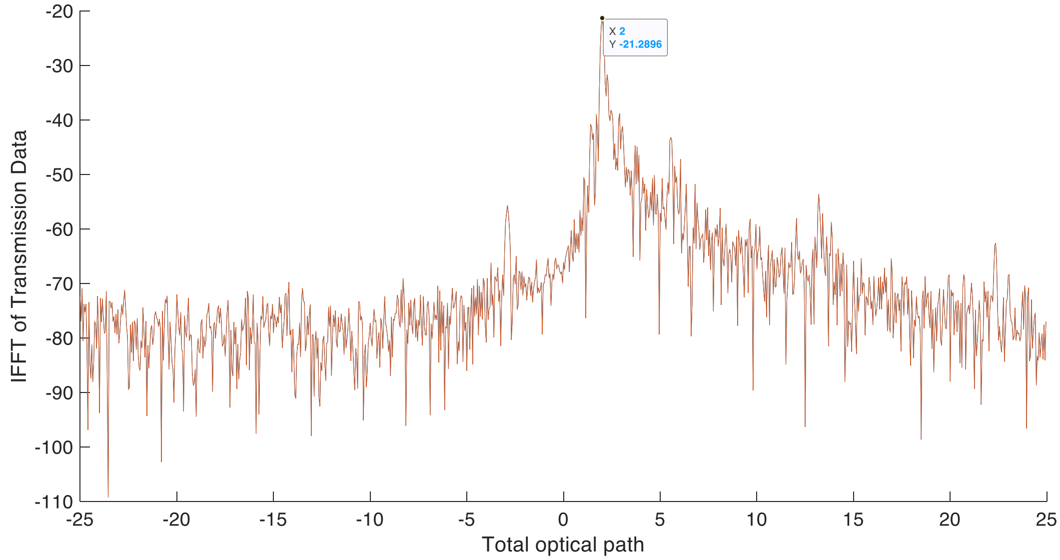




As it can be seen from the logarithmic plot on the left, for small values of the frequency the difference is mostly noise and the amplitude is close to 0. An almost constant difference is observed at higher frequencies where indeed the reflector reflects waves back to the receiver. This is clearer from the normalised linear plot on the right where the maximum difference is observed at a frequency of 2.2GHz.

8b

The procedure used in task 4b to measure the length of the long cable is transferable in this task to measure the position of the reflector. After running the code with the transmission difference data as input, the following graph is generated:



The peak of the graph is at the satisfyingly round value of 2 meters. This range data does not take into account the optical path travelled and uses a permittivity value of 1. This means that the actual EM wave was slower than light throughout its propagation so the actual result should be less than 2 meters. For the experiment, medium cables were used of length 0.48m. The length of the amplifier is approximately 0.06m. The length of the antenna is approximately 0.12m. This gives an optical path of:

$$\sqrt{\varepsilon_r}\sum_{i=1}^{3} L_i = \sqrt{2.04} * (0.48 + 0.06 + 0.12\,) \approx 0.94m$$

Giving a modified range value of:

$$reflector_{distance} = 2 - 0.94 = 1.06m$$

The reflector was positioned accurately at a 1m distance from the antennae so there is a deviation. This is most probably due to accumulated human error in a lot of length measurements and, also, the use of an arbitrary permittivity value which is the same as the one found in task 4a.