UNIVERSITY OF TWENTE.

EMC Lab Report

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1 Self-Inductance

We will refer to the examined configurations as such:

- Configuration A: The wire is placed as close to the ground plane as possible. Small Inductive Loop.
- Configuration B: The wire is held at a maximum distance from the ground plane. Big Inductive Loop.

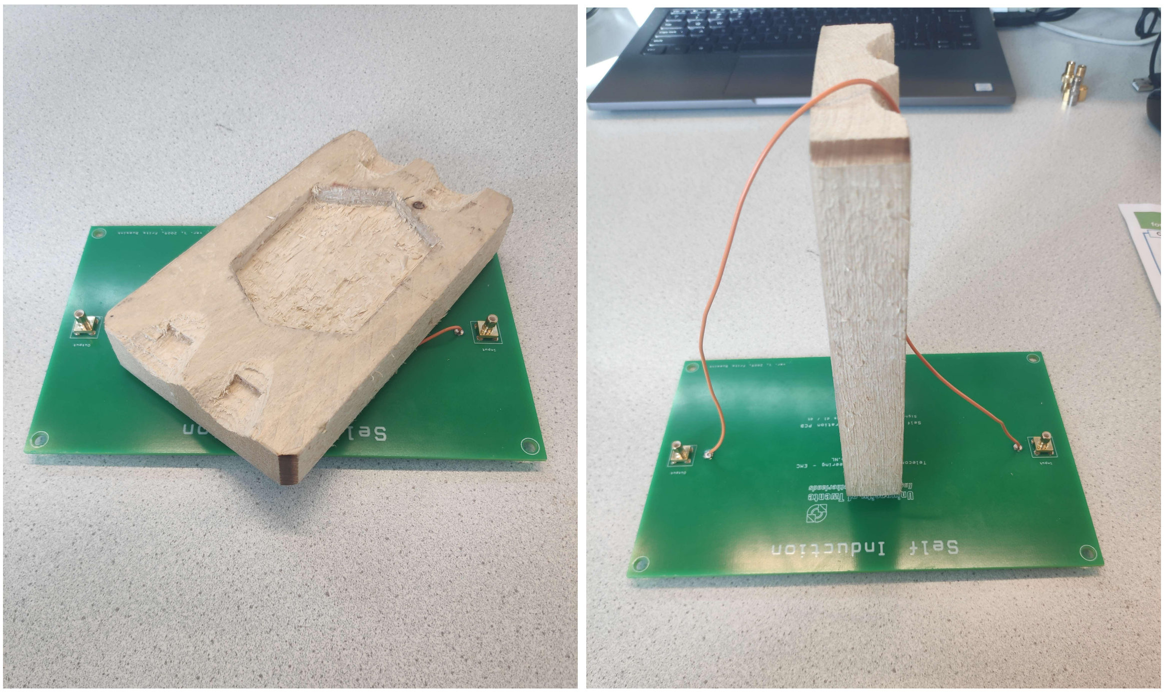


Figure 1: Configuration A (Left) and Configuration B (Right).

1.1 Signal Transfer

Question 1: Describe the differences between the two configurations. In which configuration would high-frequency signal transfer be problematic and what creates this bottleneck?

Answer: In Configuration A, the wire is placed as close to the ground plane as possible, which creates a smaller inductive loop. This results in lower self-inductance and a better transfer of high-frequency signals. In Configuration B, the wire is held at a maximum distance from the ground plane, creating a larger inductive loop. This results in higher self-inductance and poorer transfer of high-frequency signals due to the increased impedance in the circuit. This is verified by the measurements plotted in Figure 2. The bottleneck that creates this problem is the increased impedance in the circuit due to the larger inductive loop.

Question 2: The scattering coefficient stops monotonically decreasing at some frequency point. How do you explain this change?

Answer: One possible explanation for this change in behavior is the presence of a resonance in the system. By storing and plotting (Figure 3) the absolute value of the magnitude (not in dB) we can see that there is a small frequency shift between the resonant frequency for Configuration A and B. In Configuration A, where we have a smaller inductive loop, the value of the scattering coefficient stops motonically decreasing earlier than it does in Configuration B.

Question 3: Given that the scattering coefficient $|S_{21}|$ can be related to the lumped inductance L_w by

$$L_w(f) = \frac{R_0}{f\pi}\sqrt{\frac{1}{|S_{21}|^2} - 1}$$

calculate the difference in the lumped inductance from the two setups for three frequency points

Answer:

- $f = 10.0056238 MHz$: $|S_{21_A}| = 0.9932119$ - $|S_{21_B}| = 0.9811111$ - $L_{w_A} = 186.288 nH$ - $L_{w_B} = 313.629 nH$

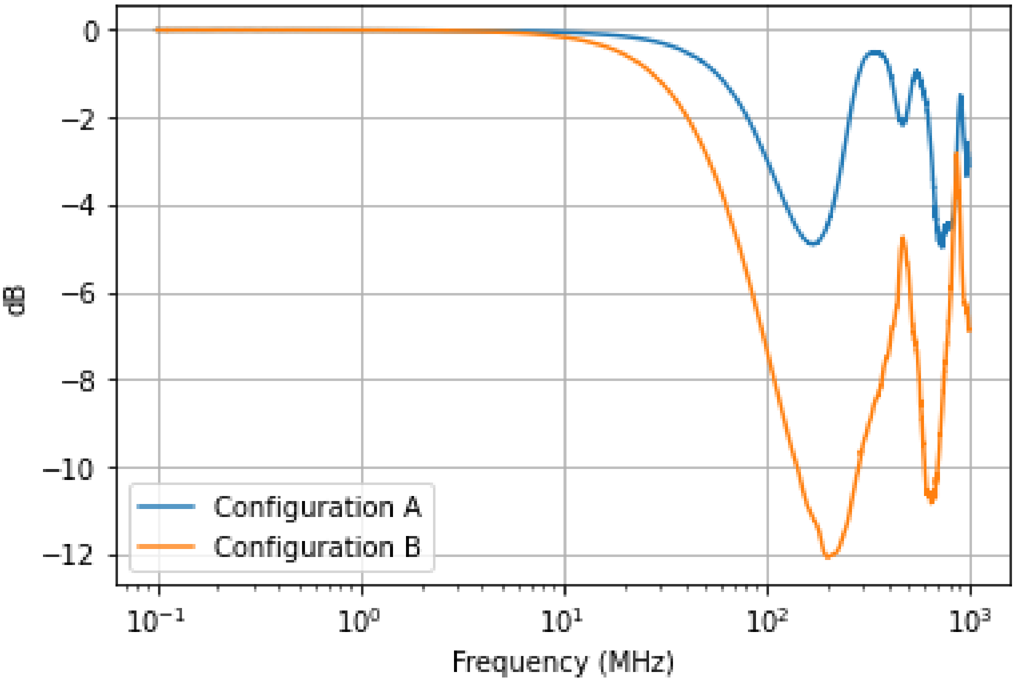


Figure 2: The $|S_{21}|$ parameter measured in dB for both configurations.

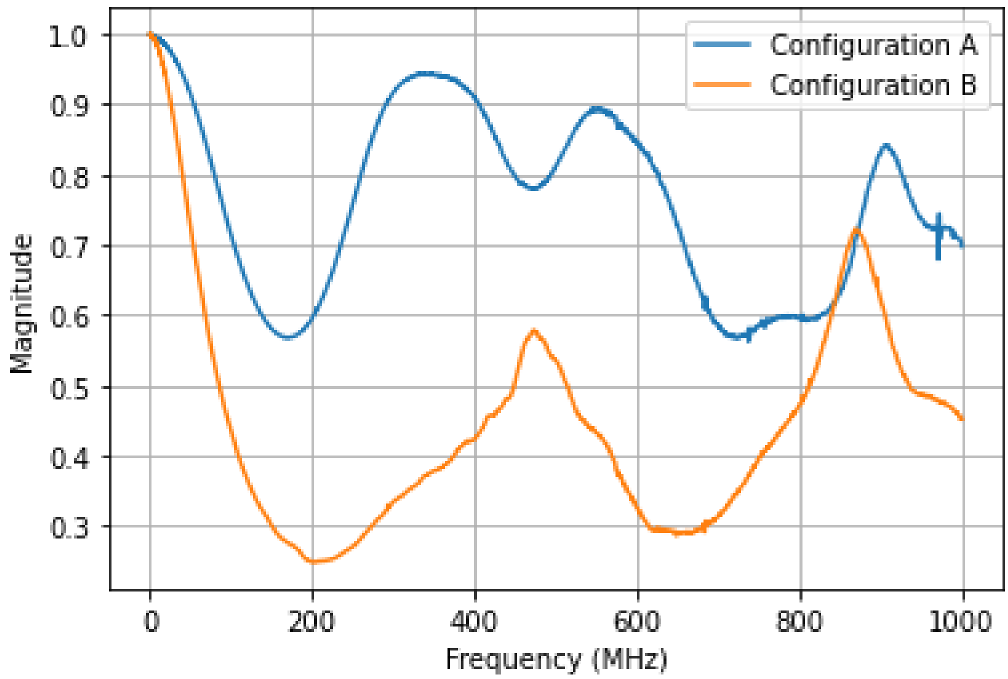


Figure 3: The $|S_{21}|$ parameter for both configurations.

- $f = 50.0103557 MHz$: $|S_{21_A}| = 0.9147676$ - $|S_{21_B}| = 0.7262080$ - $L_{w_A} = 140.543nH$ - $L_{w_B} = 301.270nH$
- $f = 100.0843690 MHz$: $|S_{21_A}| = 0.7140348$ - $|S_{21_B}| = 0.4334157$ - $L_{w_A} = 155.920nH$ - $L_{w_B} = 330.649nH$

Question 4: Find an approximate expression for the inductance of a square loop and calculate the inductance for: a side length $d = 12cm$ and a wire radius $r = 1mm$. Compare the results with the one found previously with the use of $|S21|$.

Answer: We use the following expression to approximate the inductance of a square loop

$$L_{loop} = d[\frac{\mu_0}{\pi} ln(\frac{d}{r}) + \frac{\mu_0}{4\pi}]$$

And the result is $L_{loop} = 241.8nH$ which is not that far off from the measured values.

Question 5: Assuming that a time measurement was performed with a pulse signal as input, what do you expect that will happen to the signal at the output in the case with the largest inductance?

Answer: In the case with the largest inductance (i.e., Configuration B, where the wire is held at a maximum distance from the ground plane), we would expect to see a **longer rise time** and a **longer pulse width** at the output compared to the case with smaller inductance (Configuration A, where the wire is placed as close to the ground plane as possible). This is because a larger inductance in the circuit will result in a slower rate of change of the current in response to a voltage input, as the inductor will resist changes in current flow. This can be described by the known equation

$$V = L\frac{dI}{dt}$$

If a pulse is to serve as input into the circuit, the inductance will cause a delay. This effect is commonly observed in circuits with large inductance values and is known as "inductive ringing" or "inductive kickback".

1.2 Radiation Effects

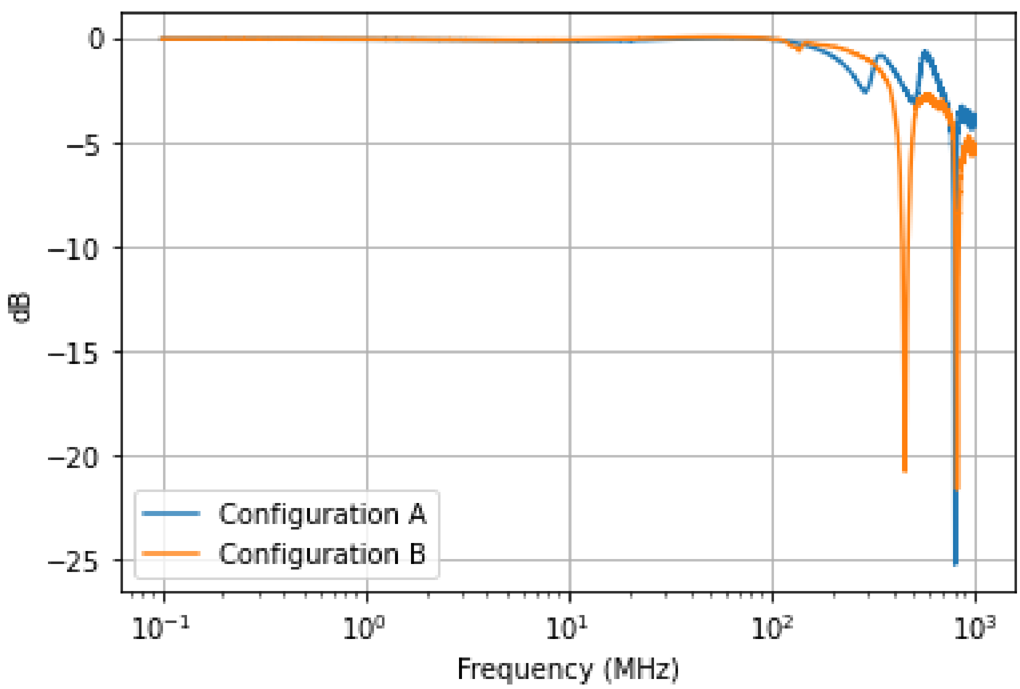


Figure 4: The $|S_{11}|$ parameter measured in dB for both configurations.

Question 1: What difference do your observe between the two configurations?

Answer: Configuration B shows 2 nulls, one at approx. 400 MHz and one at 800 MHz, both reach $-20dB$. Configuration A shows a single null at 800 MHz which reaches $-25dB$.

Question 2: In the case for the wire being suspended far from the ground plane you observe some nulls. What do they show? What dictates the frequency for which those nulls exist?

Answer: In configuration B we have larger loop inductance which in turn leads to lower resonant frequencies. That is why we observe a null at 400 MHz.

Question 3: In which configuration will there be more electromagnetic radiation? Why could this be a problem for nearby electronics?

Answer: Configuration B would radiate at both resonant frequencies, making it a worse EMI source.

Question 4: In which of the two configurations will this system be more susceptible to incident electromagnetic interference?

Answer: Configuration B, where the wire is held at a maximum distance from the ground plane creating a bigger inductive loop, is likely to be more susceptible to incident electromagnetic interference (EMI). This is because the larger loop area in Configuration B can couple more effectively with external electromagnetic fields, and induce higher voltages or currents in the loop, leading to greater susceptibility to EMI.

Question 5: Extend the conclusions found in the previous questions to a PCB application involving traces and ground planes.

Answer: In a PCB, traces can act as inductive loops and generate electromagnetic radiation that can couple with nearby electronics and cause EMI. Ground planes can help reduce the amount of radiation by providing a low impedance return path for the currents in the traces, and acting as a shield to attenuate external electromagnetic fields.

Question 6: What would happen if a return conductor is not provided?

Answer: If a return conductor is not provided, it would result in an open circuit. In configuration B, without a return conductor, the loop formed by the single wire would act as an antenna and emit electromagnetic radiation. This could cause EMI issues. In addition, the lack of a return conductor could also lead to an increase in the inductance of the loop, as the current flowing through the wire would experience a larger magnetic field due to the absence of the return conductor.

2 Lenz' Law

To conduct the experiment, the test setup shown in Figure 5 was used. A pulse was provided as input using the Signal Generator, with the following characteristics

Frequency	127kHz
Amplitude	2Vpp
Pulse Width	1.059us
Rise Edge	8.4ns

The measurements are shown in Figure 6.

Question 1: From your measurements, explain the differences in the settling times of the signal for each trace.

Answer: As seen in Figure 6, paths 1 and 3 which are far away from the ground plane show increased settling times compared to paths 5,6 and 7. Paths 1 and 3 also show occurrences of overshoot, since the signal exceeds the desired amplitude before settling (this is also visible in path 5, albeit smaller).

Question 2: It can be observed that the traces that are nearby the ground plane (so their return path), have a much shorter settling time. Why is this the case?

Answer: When a signal propagates on a trace that is far from the ground plane, the return path for the signal is not well-defined, and the signal experiences a higher impedance path, which can result in reflections and ringing. This leads to longer settling times for the signal.

On the other hand, when a signal propagates on a trace that is near the ground plane, the return path for the signal is well-defined, and the signal experiences a lower impedance path. This helps to reduce reflections and ringing, leading to a shorter settling time for the signal.

Question 3: Explain why the position of the trace over the ground plane is important (i.e. why traces should be placed at the middle of a wide ground plane, and not at the edges).

Answer:

- **Return Path:** When a signal propagates along a trace, it generates an electromagnetic field that induces a current flow in the ground plane, which provides the return path for the signal. The current flow in the ground plane generates a magnetic field that opposes the original signal, and this magnetic field is strongest directly under the trace. If a trace is placed too close to the edge of the ground plane, the current flow in the ground plane is limited by the edge, and the return path for the signal becomes more restricted, which can increase the impedance of the signal path. In contrast, if the trace is placed in the middle of a wide ground plane, the current flow in the ground plane is less restricted, which reduces the impedance of the signal path.
- **Shielding:** Placing traces at the edges of the ground plane can increase the susceptibility of the circuit to electromagnetic interference (EMI). This is because the edge of the ground plane can act as an antenna, picking up unwanted signals from the environment. Placing traces in the middle of a wide ground plane can help to reduce the susceptibility to EMI by shielding the circuit from external electromagnetic fields.

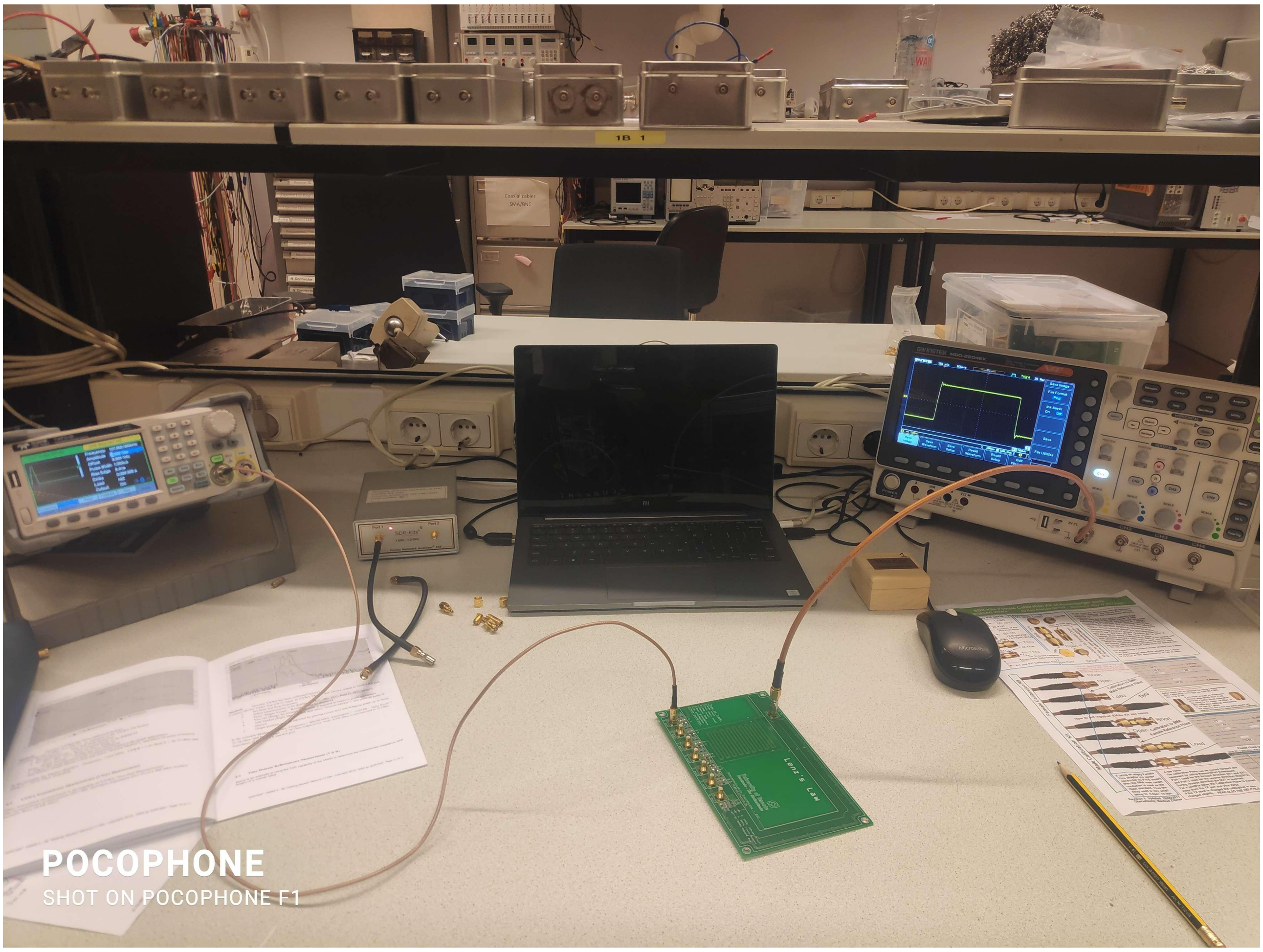


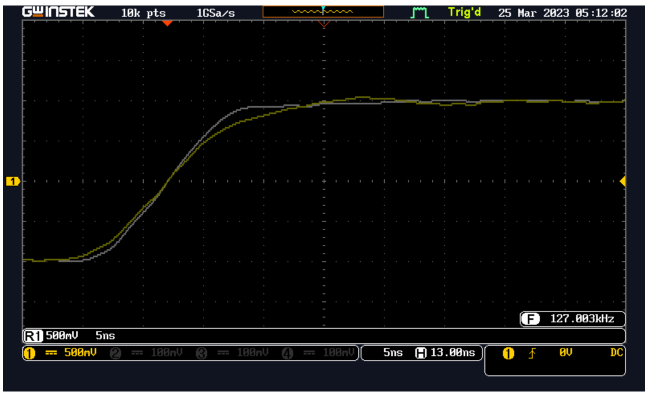
Figure 5: Test Set Up used for Exercise 4: Signal Generator on the left, Test PCB in the middle and Oscilloscope on the right.

(a) The start of the original pulse. Signal generator directly connected to oscilloscope.

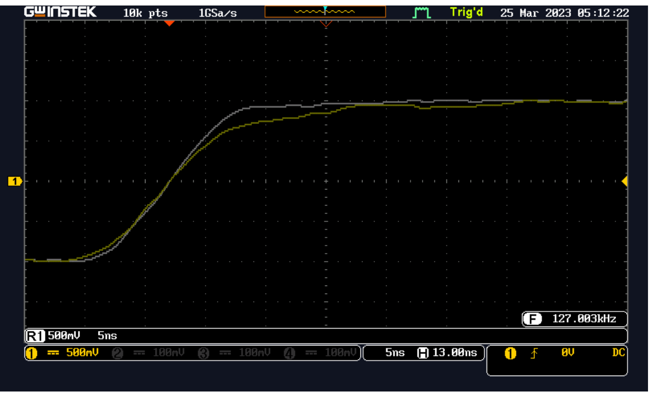
(b) Signal going through path 1 - Wide Short Trace (far from ground plane).

(c) Signal going through path 3 - Wide 'Meandering' Trace (far from ground plane).

(d) Signal going through path 5 - Trace on Edge of Ground Plane.



(e) Signal going through path 6 - Trace on Ground Plane (no adjacent Guard Traces).



(f) Signal going through path 7 - Trace on Ground Plane with adjacent Guard Traces.

Figure 6: The pulse zoomed at its beginning to inspect rise and settling time. In Figures (b)-(f), the original pulse is juxtaposed to compare.

3 Packaging Parasitics and Non-deal Behavior of a Capacitor

3.1 Vias

The measurements are shown in Figure 9.

Vias	f_c	f_0	$S_{21}(f_0)$	C_d	L_s	R_s	Q-factor at f_c
10mm Track	5.53MHz	65.70MHz	-47.89dB	1.151nF	5.096nH	0.1 Ohm	248.068
5mm Track	5.55MHz	81.24MHz	-50dB	1.147nF	3.347nH	0.079 Ohm	316.495
1mm Track	5.47MHz	111.46MHz	-52.95dB	1.163nF	1.753nH	0.056 Ohm	443.948
Multiple Vias	5.59MHz	137.82MHz	-52.63dB	1.139nF	1.171nH	0.058 Ohm	428.077
No Via	5.58MHz	180.26MHz	-51.6dB	1.14nF	0.684nH	0.065 Ohm	379.835 [1ex]

Question 1: Document the cut-off frequency f_c for which $|S_{21}| = -3dB$ and the resonant frequency for which the null depths occur.

Answer: Results in table above.

Question 2: . Calculate the actual capacitance C_d and the stray inductance L_s using:

$$C_d = \frac{1}{f_c R_0 \pi}$$

$$L_s = \frac{1}{(2 f_0 \pi)^2 C_d}$$

Answer: Results in table above.

Question 3: It is also possible to calculate the equivalent series resistance (ESR) of the capacitor using:

$$R_S = \frac{R_0 |S_{21}(f_0)|}{2}$$

where $|S_{21}(f_0)|$ is the forward gain at the resonant frequency.

Answer: Results in table above

Question 4: Calculate the Q-factor for every capacitor. What does the value of the Q-factor imply about the performance of the board?

Answer: Calculated at cut-off frequency f_c using

$$Q = \frac{1}{\omega_c * C_d * R_s}$$

Results in table above.

Question 5: For the capacitor without a via, use the values measured and the model presented in the lecture slides to simulate the transfer function. Compare it to the original measurement and comment on the results.

Answer: We plot the Bode diagram of the impedance function of the circuit equivalent to a non-ideal capacitor (series stray inductance, capacitance and ESR)

$$Z = j\omega L_{lead} + R_s + \frac{1}{j\omega C}$$

The result is shown in Figure 7. We can see that the resonant frequency appears at $1.13 \times 10^9 \frac{rad}{s} = 179.8MHz$ which is very close to the experimental value of $f_0 = 180.26MHz$. Here we also visualise the phase shift from which occurs at the resonant frequency, after which the capacitor starts behaving like an inductor.

Question 6: By examining the five different ground path configurations, it can be argued that the stray inductance can be decomposed in three parts, the intrinsic inductance of the capacitor (L_i), the track inductance (L_{0d}) and the via inductance (L_v). This can be formulated as:

$$L_s = L_i + L_{0d} + L_v$$

The topology examining this is found in the Lab Manual. From which configuration is it possible to extract the intrinsic inductance Li? Estimate the value

Answer: We consider the stray inductance calculated for capacitor no.5 to be the intrinsic inducatance of the capacitor

$$L_i = 0.684nH$$

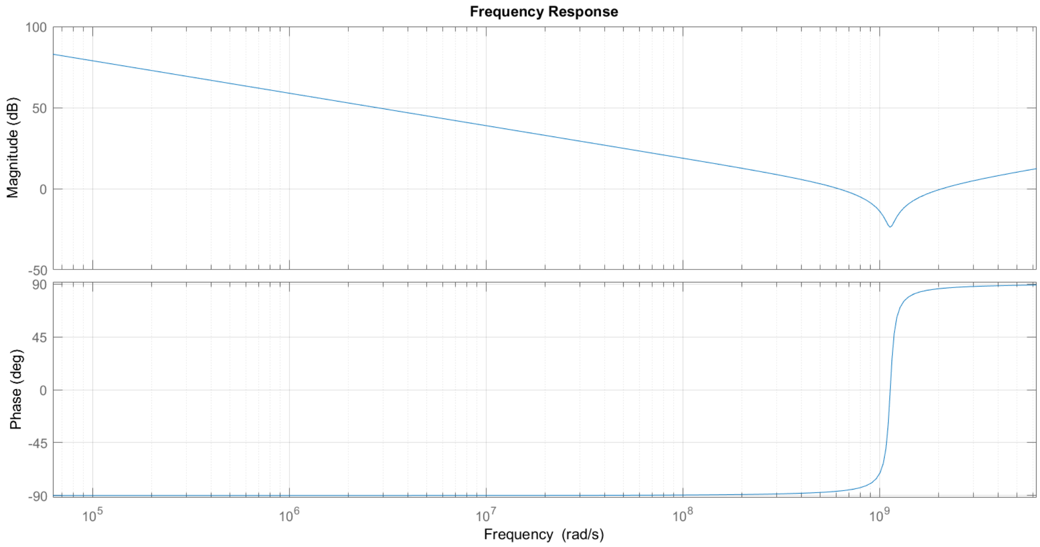


Figure 7: The Bode diagram of $Z = j\omega L_{lead} + R_s + \frac{1}{j\omega C}$ for the No Via capacitor.

Question 7: By constructing a system of equations, estimate the PUL inductance L_0 and the via inductance L_v.

Answer: First we notice that capacitor 4 is connected to ground through 3 vias. Also even if the track length connecting the lead to the vias is not specified, we take it to be 1 mm. Based on this, from capacitors 3 and 4 we get the following

$$L_i + \frac{L_u + L_0}{3} = 1.171nH$$

and

$$L_i + L_u + 1 \times L_0 = 1.7531nH$$

These 2 equations lead to $L_u + 1 \times L_0 = 1.461$ and $L_u + 1 \times L_0 = 1.069$ which cannot both be true so we take the average $L_u + 1 \times L_0 = 1.265nH$. Then from capacitor 2 we get

$$L_i + L_u + 5 \times L_0 = 3.347nH$$

which leads to the result $L_0 = 0.3495nH/mm$. So finally we get:

- $L_i = 0.684nH$
- $L_0 = 0.3495nH/mm$
- $L_u = 0.9155nH$

The results are verified since

$$L_i + L_u + 10 \times L_0 = 5.0945nH$$

which is the expected result for capacitor 1 (10mm Track).

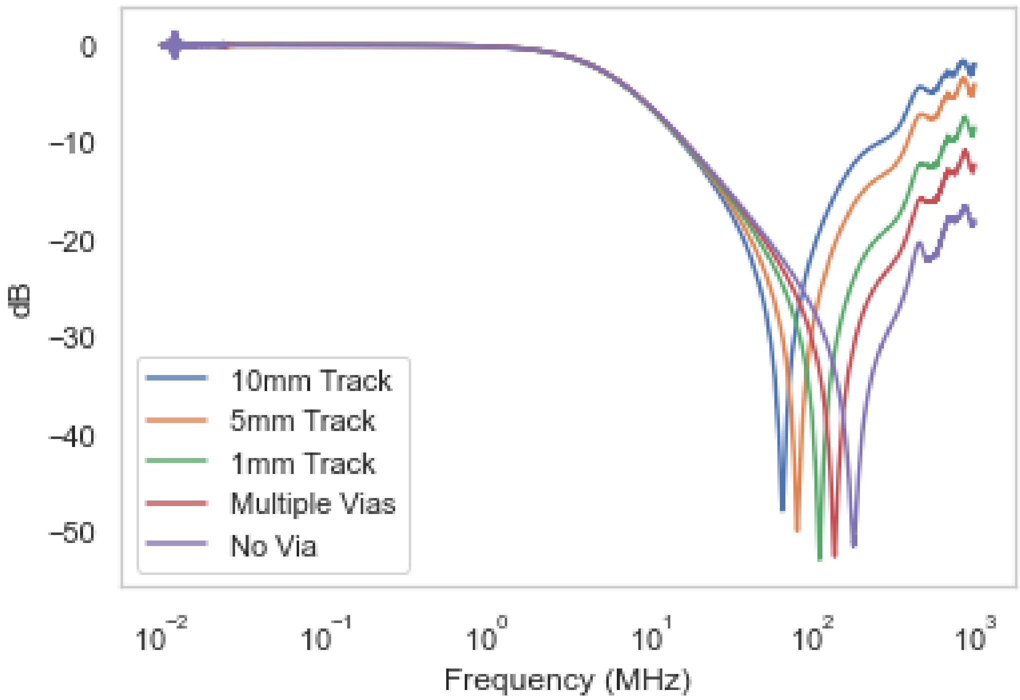


Figure 8: Vias: The $|S_{21}|$ parameter measured in dB for $1nF$ capacitors with different connection.

3.2 Capacitance Value

The measurements are shown in Figure 9.

Question 1: What is the effect of the capacitor value on L_s and R_s? Comment how those effects also extend to the Q-factor.

Answer: Listed below are the L_s, R_s and Q-factor (calculated at 1MHz) values for 100nF, 10nF, 1nF and 100 pF capacitors. The stray inductance stays for all the capacitors, which is expected since it is dependent, not

Cap.	L_s	R_s	Q at 1MHz
100nF	0.698nH	0.025 Ohm	59.799
10nF	0.76nH	0.021 Ohm	654.455
1nF	0.717nH	0.063 Ohm	2164.413
100pF	0.636nH	0.12 Ohm	10840.701

Table 1: Capacitor Characteristics

on the capacitance, but the leads (geometry and way of being grounded as examined earlier). The ESR increases for lower capacitance values but stays relatively unimportant (<1 Ohm). Also, the smaller the capacitance value, the higher the Q-factor. The stray inductance does not affect the Q-factor, as it stays approximately equal. The fact that ESR is higher for lower capacitance values tends to lower the value of the Q factor but is not enough to negate the effect of the smaller capacitance)

Question 2: How does the value of the capacitor affect the resonant frequency? How does that impact the use of large capacitor values in high frequency designs?

Answer: The resonant frequency is the value for which the impedances corresponding to the capacitance and the stray inductance are equal, that is

$$f_0 = \frac{1}{2\pi\sqrt{L_s C}}$$

Since all 5 capacitors are Ceramic Multi-Layer capacitors connected to ground in the same manner, it can be assumed that L_s is approximately equal. So the value of the resonant frequency decreases as capacitance increases. This means that capacitors with smaller capacitance values keep performing ideally for higher frequencies than capacitors with high capacitance values. In high-frequency designs, attention must be given, since higher capacitance values might seem desirable at a first glance in order to reduce high-frequency emissions, but if by selecting a capacitor with a higher capacitance value, the resonant frequency ends up being lower than the frequency of the signal, then the signal could be increased instead of decreased.

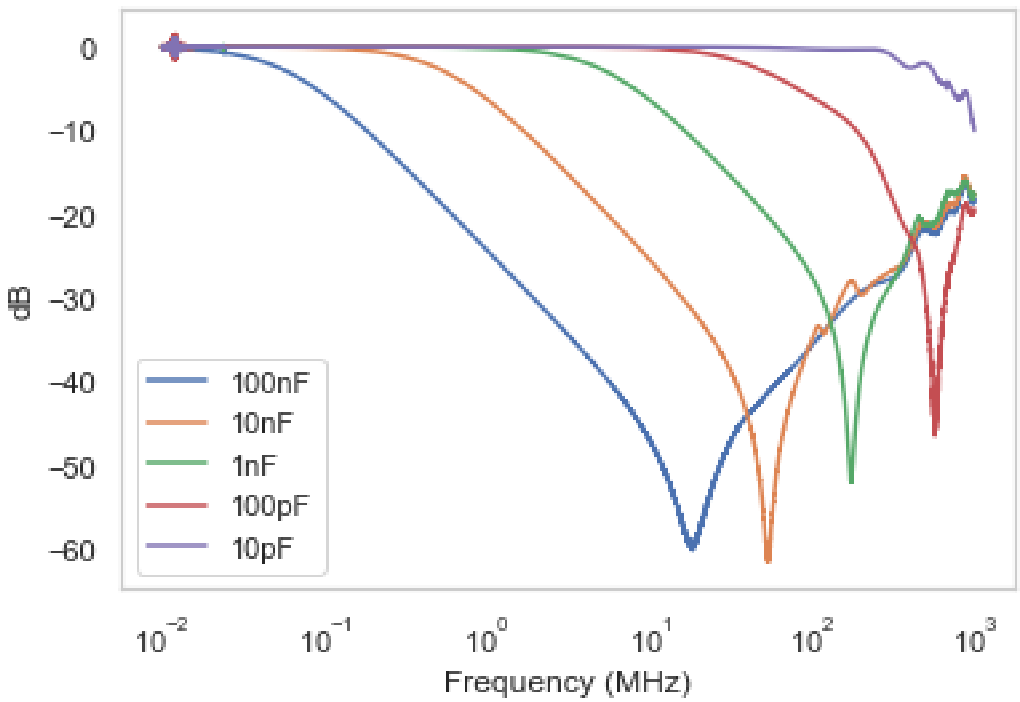


Figure 9: Capacitance Value: The $|S_{21}|$ parameter measured in dB for capacitors with different value.

3.3 Dielectric Material

The measurements are shown in Figure 10.

Question 1: Formulate a conclusion about how the dielectric affects the performance of the capacitor.

Answer: Electrolytic capacitors provide us with impedance that decreases with frequency as wanted but not at a rate of -20dB/dec which is described by the ideal capacitor impedance equation $Z = \frac{1}{j\omega C}$. They are also characterised by a larger resonant frequency compared to Plastic and Ceramic capacitors. Plastic and Ceramic capacitors express near-ideal behaviour but are characterised by lower resonant frequencies, beyond which they start acting like inductors.

Question 2: Which capacitors are best suited for which applications?

Answer: Electrolytic capacitors maintain their capacitive (not ideal, since the slope observed is not -20dB/dec but smaller) behaviour for higher frequency values, but essentially provide us with lower capacitance values. They are prefered for low-frequency applications and this is why they are usually the best alternative for suppression in the conducted emission frequency range. Ceramic and Plastic capacitors are much more similar in behaviour, as seen in the plotted data too. They are preferred for mid and high frequency applications and thus are typically used for suppresing noise in the radiated emission frequency range.

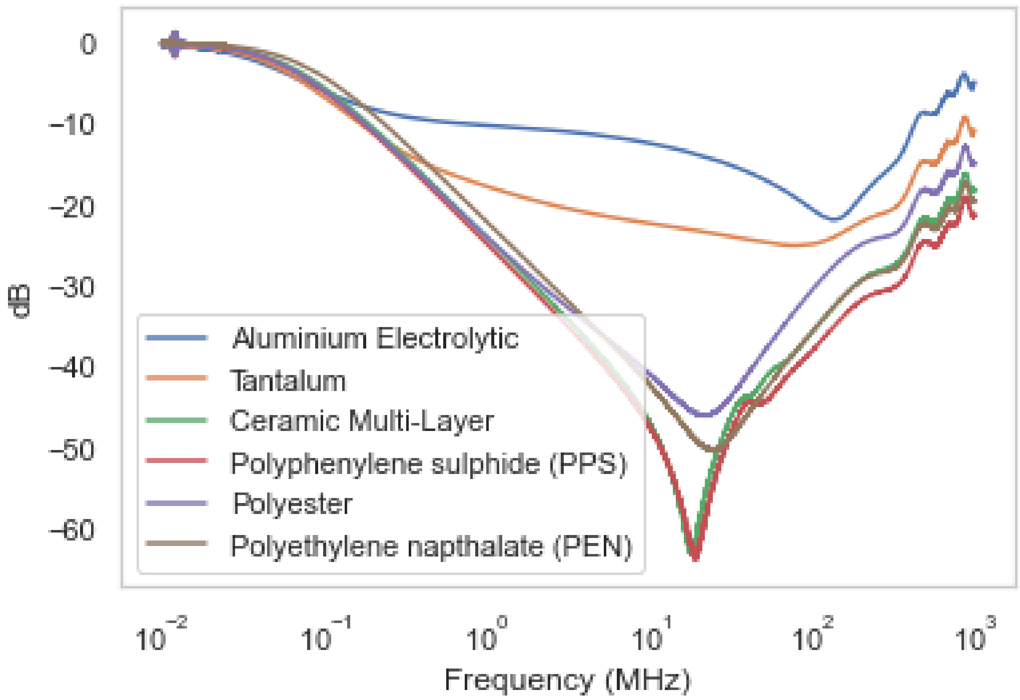


Figure 10: Dielectric Material: The $|S_{21}|$ parameter measured in dB for capacitors with different dielectric material.

3.4 Package

The measurements are shown in Figure 11.

Question 1: Perform the same analysis as in the Vias section to estimate the stray inductance and the ESR of the capacitors.

Answer: Listed below are the stray inductance and ESR values.

Cap.	L_s	R_s
100nF	2.804nH	0.023 Ohm
10nF	3.055nH	0.176 Ohm
1nF	4.257nH	0.134 Ohm
100pF	4.115nH	0.173 Ohm

Table 2: Radial Leaded

Cap.	L_s	R_s
100nF	0.717nH	0.018 Ohm
10nF	0.819nH	0.021 Ohm
1nF	0.69nH	0.066 Ohm
100pF	0.655nH	0.135 Ohm

Table 3: SMD

Question 2: Compare the parasitics between the two different package types and formulate conclusions about their applications.

Answer: So as we can see in Figure 11, for the same value of capacitance, SMD capacitors have a higher resonant frequency f_0 than the corresponding Radial Leaded capacitors. This is attributed to the larger inductive loop created by the larger leads of the Radial Leaded capacitors which leads to a higher value of L_{lead} and thus to a larger stray inductance (as can be verified from the measurements in the above question) and a smaller value of f_0.

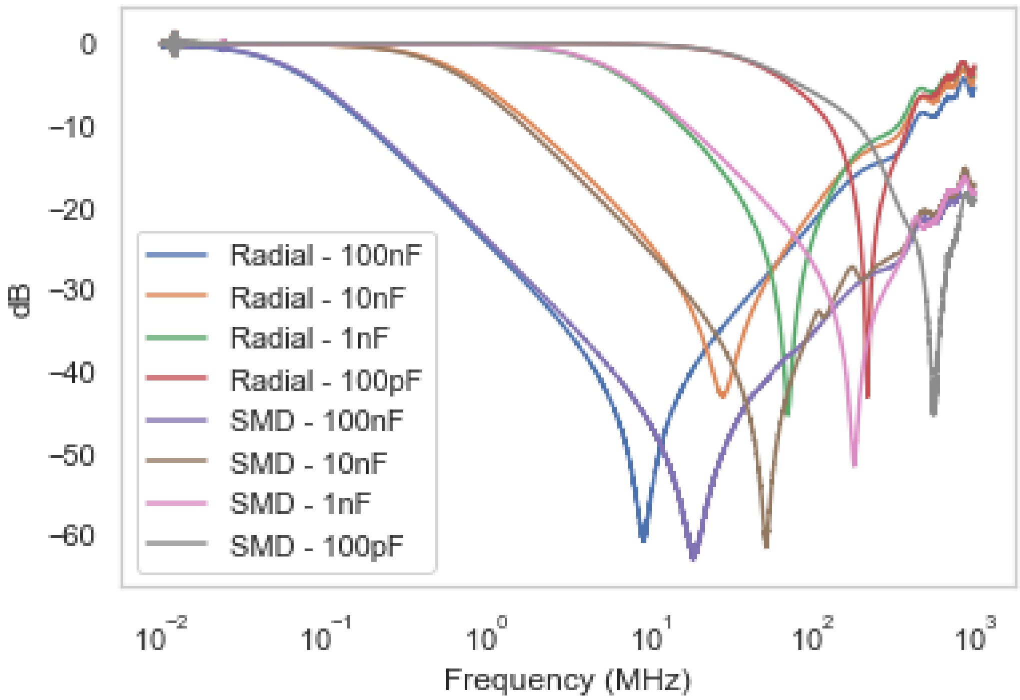


Figure 11: Package: The $|S_{21}|$ parameter measured in dB for Radial Leaded and SMD capacitors (various capacitance values).

4 Grounding of Filters

The results are shown in Figure 12.

Question 1: Which of the filter implementations achieve the required attenuation? Compare the performance of each implementation.

Answer:

- The floating filter (filter no. 1), as expected, is not at all effective in attenuating the signal.
- The filter grounded using a pigtail (filter no. 2) shows improvement compared to filter no.2 but still, achieves only an attenuation of $-18dB$ for a frequency of $10mHZ$. It does not achieve the required attenuation and would only distort the input signal, not filter it as desired. Grounding using a pigtail is not considered a reliable enough connection to ground.
- The grounded and partially shielded filter (filter no.3) achieves considerably improved performance compared to filter no.3 but also does not achieve the required attenuation of $5odB$. It only reachhes $38dB$.
- The properly grounded and shielded filter (filter no.4 achieves an attenuation of $-60dB$ and is the only implementation which satisfies the respective requirement.

Question 2: Mention two performance degrading phenomena that occur due to the use of a pigtail ground scheme.

Answer:

- **Inductance:** A pigtail ground connection has a higher inductance than a direct connection to ground. Inductance can cause impedance in the ground connection, which can affect the performance of the filter. Higher inductance can result in higher noise and interference in the circuit, which can reduce the attenuation achieved by the filter. The longer the pigtail wire, the higher the inductance will be, which can lead to more significant performance degradation. So the higher the frequency, the higher the impedance due to inductance and the more our pigtail connections starts becoming an equivalent to an open connection. That is why in higher frequencies, as seen in Figure 12, filter no.2 performance approaches the performance of filter no.1 which is floating.

- **Ground loop:** Current flows in a loop through the wire ground connections. Ground loops cause noise and interference to appear in the circuit, which can affect the performance of the filter. Because grounding is done with a pigtail, the length of the ground wire is longer, and there is a greater likelihood of ground loops forming. This results in degraded performance and reduced effectiveness of the filter.

Question 3: In the case of the grounded and partially shielded filter, does the loop size of the feed wires impact performance?

Answer: When the loop size is large, it can act as an antenna and pick up electromagnetic interference (EMI) from the surrounding environment. This interference can be coupled into the filter circuit, degrading its performance. This effect is more pronounced at higher frequencies where the wavelength is shorter, and the size of the loop relative to the wavelength becomes more significant. Minimizing the loop size of the feed wires can help to reduce the impact of EMI and improve the performance of the filter.

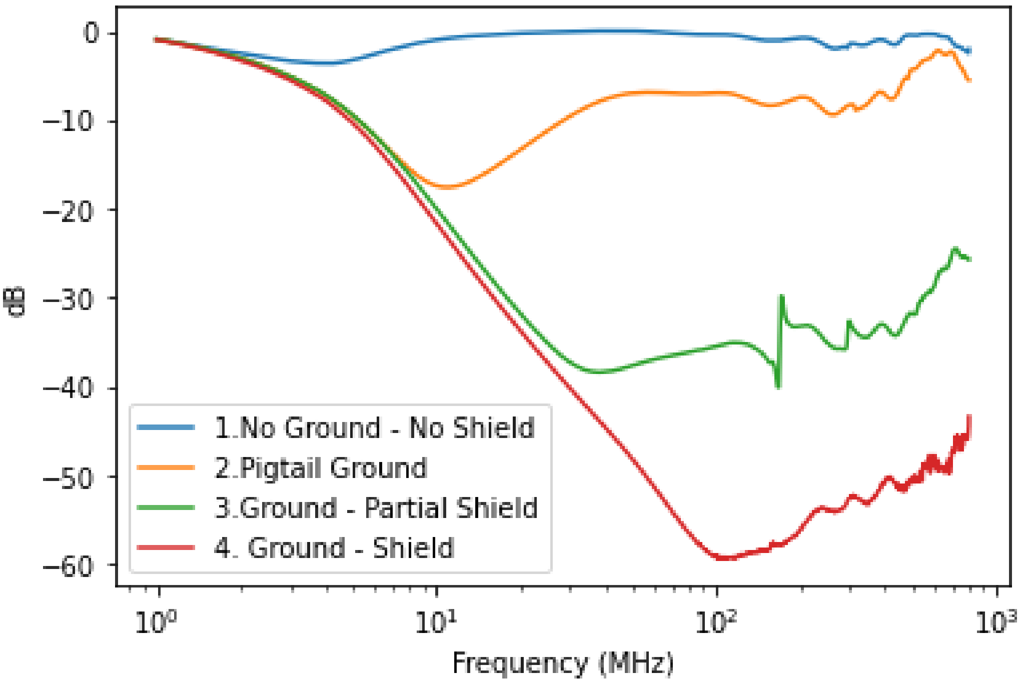


Figure 12: The $|S_{21}|$ parameter measured in dB for the 4 seperate filter implementations examined in Ex. 6.

5 Discontinuities

5.1 Microstrip Discontinuities

The three configurations used to investigate the effects of discontinuities in microstrips.

- A: A trace with $Z_0 = 50$ Ohm
- B: A thinner trace with $Z_0 = 100$ Ohm
- C: A trace with two sections: a wide one with $Z_0 = 50$ Ohm and a thinner one with $Z_0 = 100$ Ohm

Question 1: Compare the signal transfer of the three microstrips. Explain why each configuration has a different response.
Answer: The plotted results can be seen in Figure 13. Configurations A and B exhibit similar behaviour but Configuration C, even though the resonant frequency is similar, reaches $-46dB$ while A and B reached $> -30dB$.

Question 2: Using the equations provided in Chapter 4.2 of C.R. Paul, calculate the characteristic impedance using : $\epsilon_r = 4.4$, $h = 1.5875$ mm and $w = 3$ mm. Assume that the thickness t is negligible.
Answer: Since $\frac{w}{h} \geq 1$ then according to equation (4.41a) of C.R. Paul we get,

$$Z_C = \frac{120\pi}{\sqrt{\epsilon_r'}}[\frac{w}{h} + 1.393 + 0.667ln(\frac{w}{h} + 1.444)]^{-1} = 43.98Ohm$$

Question 3: How does the Z_0 found in [2] converge with the nominal value of 50 Ω?
Answer: The approximation yields a result of 43.98 Ohm. There is a considerable deviation from the nominal value of 50 Ohm.

Question 4: Calculate the velocity of propagation u and the PUL inductance and capacitance l and c assuming a effective relative permittivity $\epsilon_r' = 3.6$.
Answer: The following formulas are used

$$u = \frac{1}{\sqrt{\mu\epsilon}} = \frac{1}{\sqrt{\mu_0\epsilon_r'\epsilon_0}} = 1580061.746m/s$$

$$l = \frac{Z_C}{u} = 27.838\mu H/m$$

$$c = \frac{1}{Z_C u} = 14.39nF/m$$

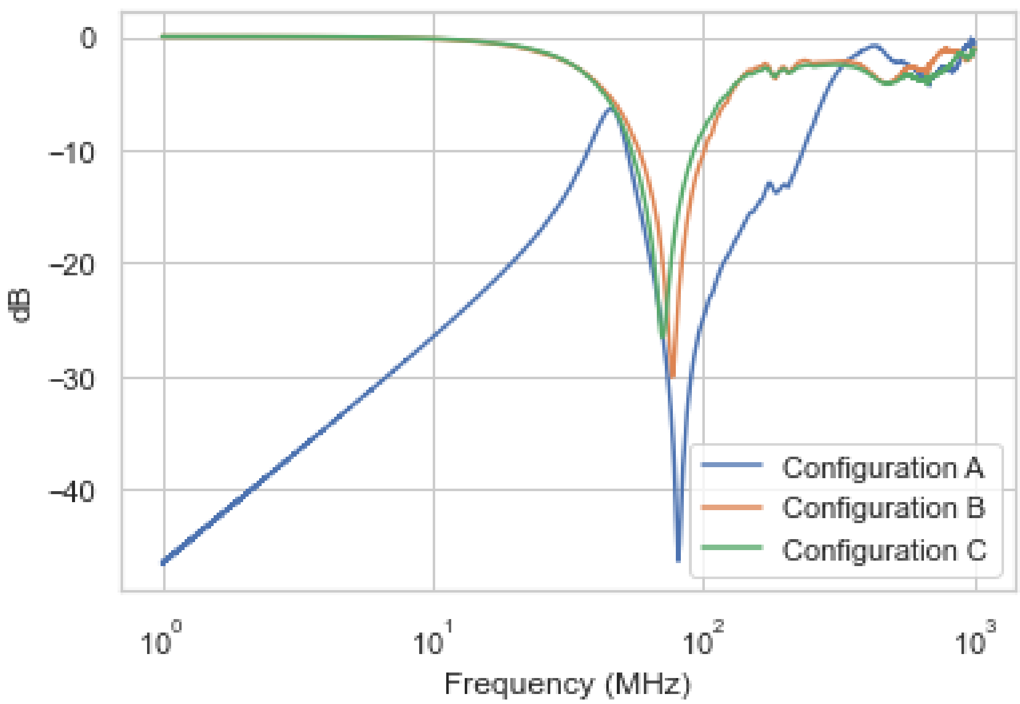


Figure 13: The $|S_{21}|$ parameter measured in dB for the 3 configurations examined in the first part of Ex. 8. Note: Configuration A low frequency behaviour might be due to procedural error.

5.2 Stubs

Question 1: When both stubs are left open ended, two nulls are found in the measurement of $|S_{21}|$. What determines those frequency points?

Answer: When the stubs are left open-circuited, they act as resonators that can reflect the signal back to the source. This reflection can interfere with the transmission of the signal through the main transmission line, causing the observed nulls in the S21 frequency sweep. The frequency of these nulls corresponds to the resonant frequency of the stubs. The frequency points are determined by the resonant frequencies of the open-circuited stubs. The resonant frequency of a stub is determined by its electrical length and the characteristic impedance of the transmission line.

Question 2: When only one stub is left open ended, there exist only one null. Why?

Answer: When we short the one stub, we effectively cancel out the resonant effect of that particular stub. This is because the short circuit acts as a virtual ground at the location of the stub, reflecting the signal back to the open end of the stub and canceling out the reflection from the open end. As a result, the null that was associated with the resonant frequency of the stub disappears.

Question 3: Mention some instances where stubs should be implemented to improve performance.

Answer: Having certain stubs with known resonant frequencies branch out of a transmission line can be used to selectively filter out specific frequency bands, while allowing other frequency bands to pass through relatively unimpeded. Smart filters can be designed using that principle.

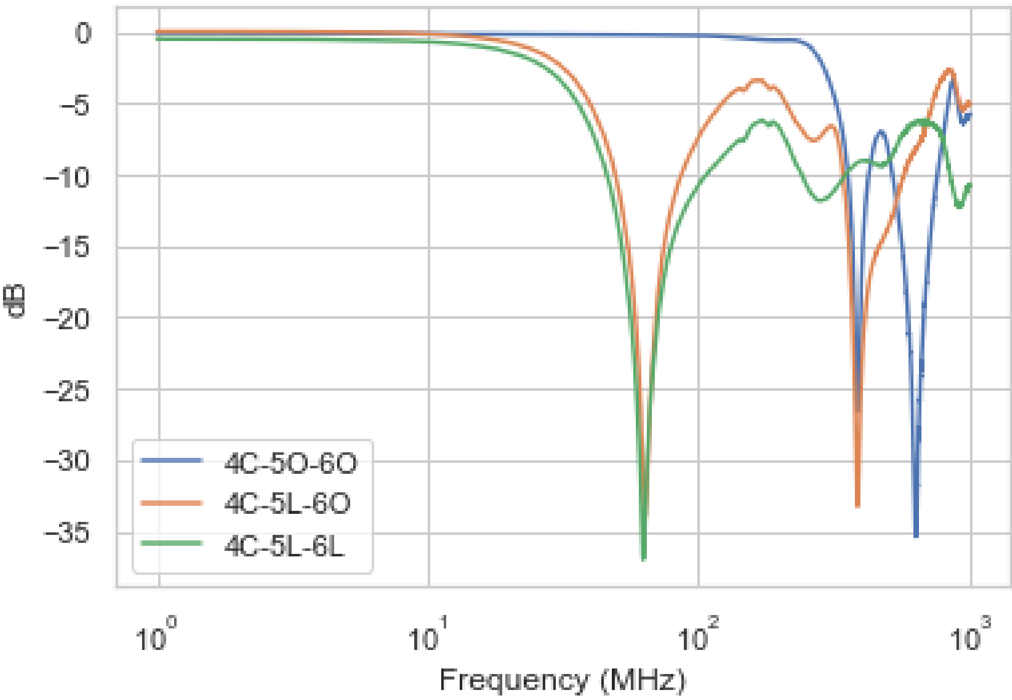


Figure 14: The $|S_{21}|$ parameter measured in dB for the final configuration in the first part of Ex. 8. Here the input port of the VNA is connected to out4.

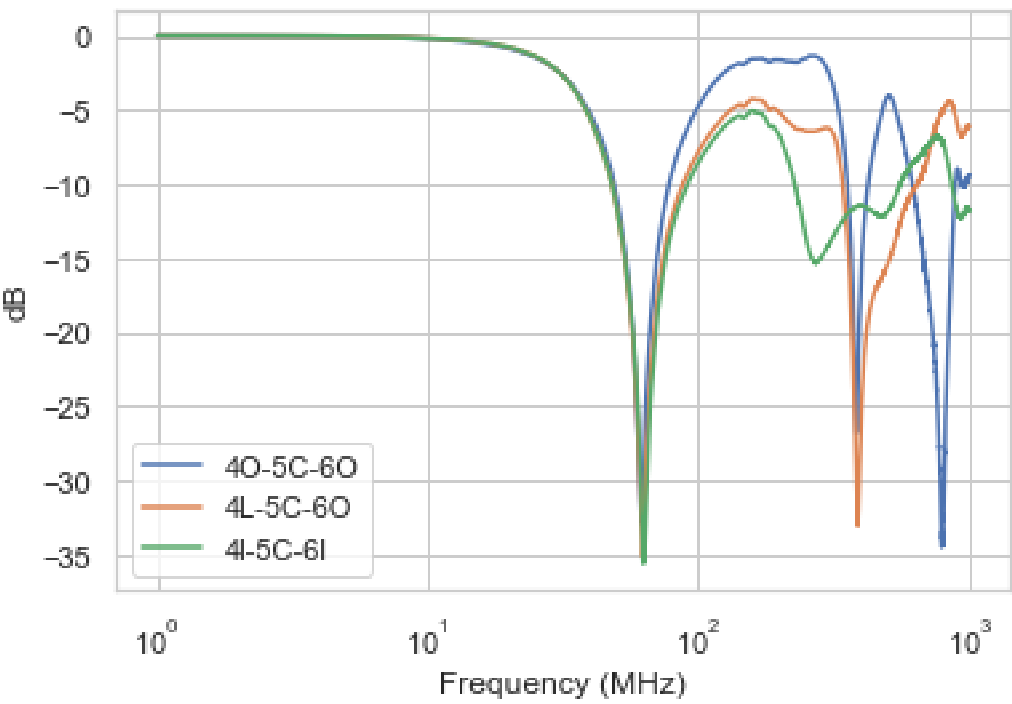


Figure 15: The $|S_{21}|$ parameter measured in dB for the final configuration in the first part of Ex. 8. Here the input port of the VNA is connected to out5.

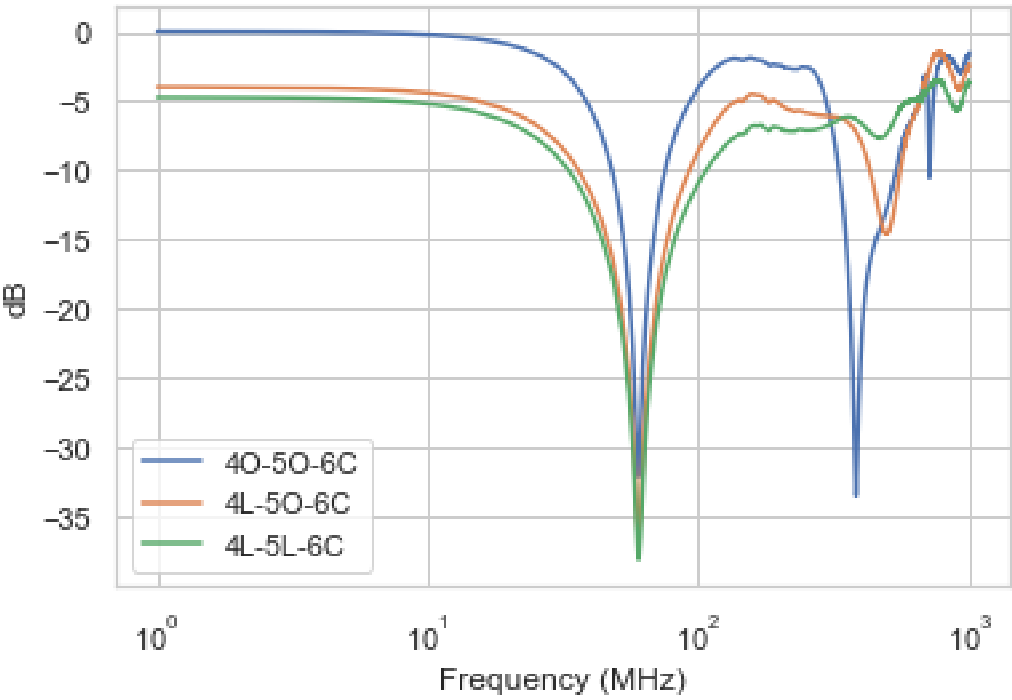


Figure 16: The $|S_{21}|$ parameter measured in dB for the final configuration in the first part of Ex. 8. Here the input port of the VNA is connected to out6.

5.3 Ground Apertures

Question 1: Compare the performance of every trace. What is the effect of ground apertures and how does their size impact performance?

Answer: Regarding Track 1 (trace that crosses a large ground aperture), we observe a null of $-17.5dB$. When SW1 or SW2 is closed, the null does not go away but becomes $-5dB$. The small aperture (Track 3) has a much more minor effect on the signal transfer, merely a $-1dB$ drop is observed.

Question 2: By comparing the configurations with SW1 closed and SW2 closed it can be deduced that a capacitive connection is sufficient. In what scenario such a connection would be useful? What limits the range of frequencies that such an implementation is viable?

Answer: One scenario where a capacitive connection might be useful is in high-speed digital circuits, where maintaining signal integrity and minimizing signal reflections is critical.

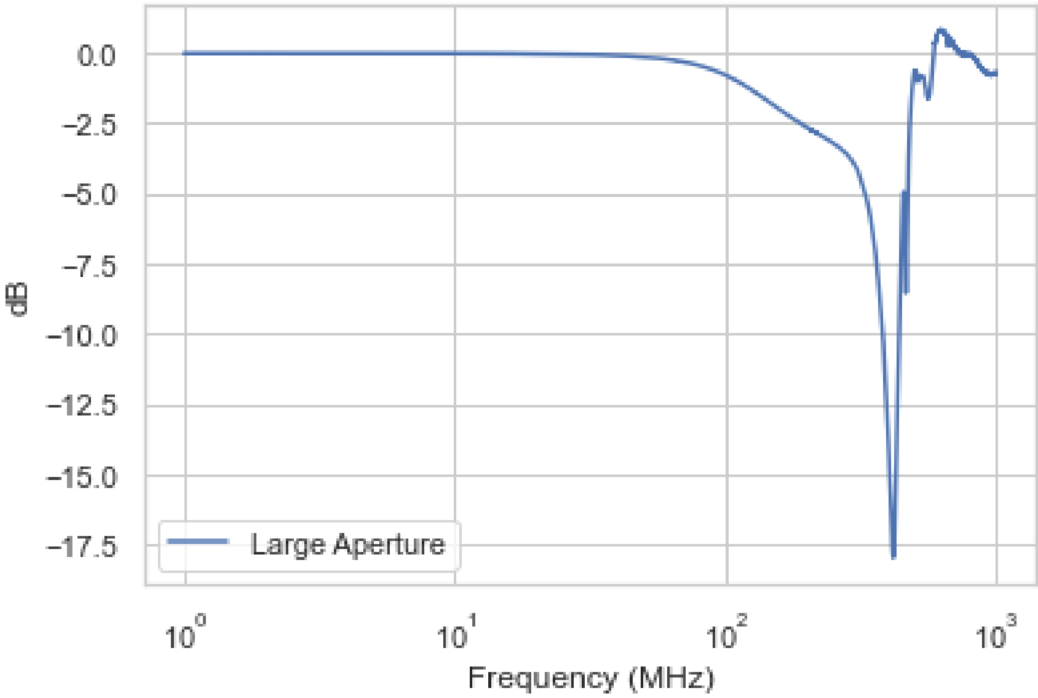


Figure 17: The $|S_{21}|$ parameter measured in dB for Track 1 (trace that crosses a large ground aperture).

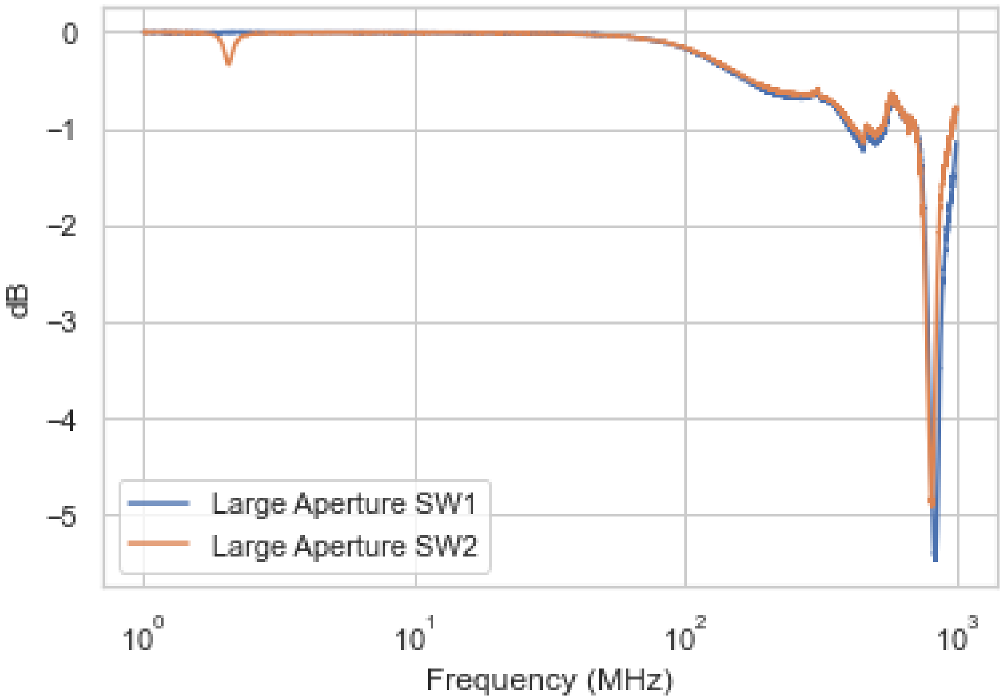


Figure 18: The $|S_{21}|$ parameter measured in dB for Track 1 (trace that crosses a large ground aperture) having closed SW1 and SW2 seperately.

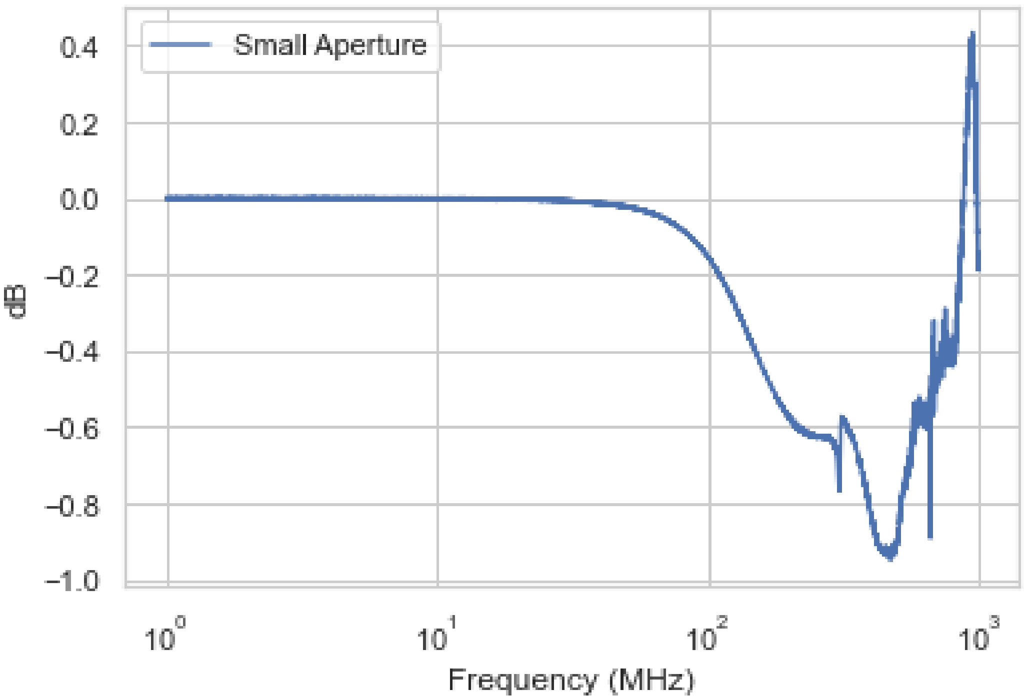


Figure 19: The $|S_{21}|$ parameter measured in dB for Track 3 (trace that crosses a small ground aperture).