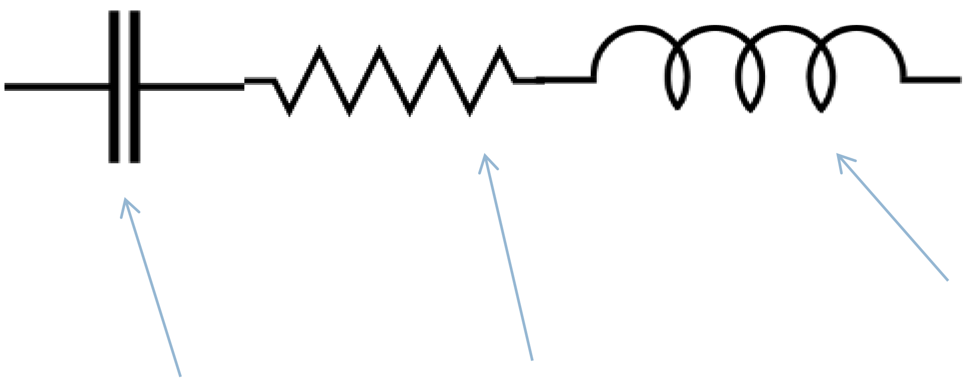
EMBEDDED CAPACITANCE

Presented by

Scott Piper, General Motors with special acknowledgement to Gentex corporation

Case for Embedded Capacitance

Capacitor Equivalent Circuit



Capacitance (Large)

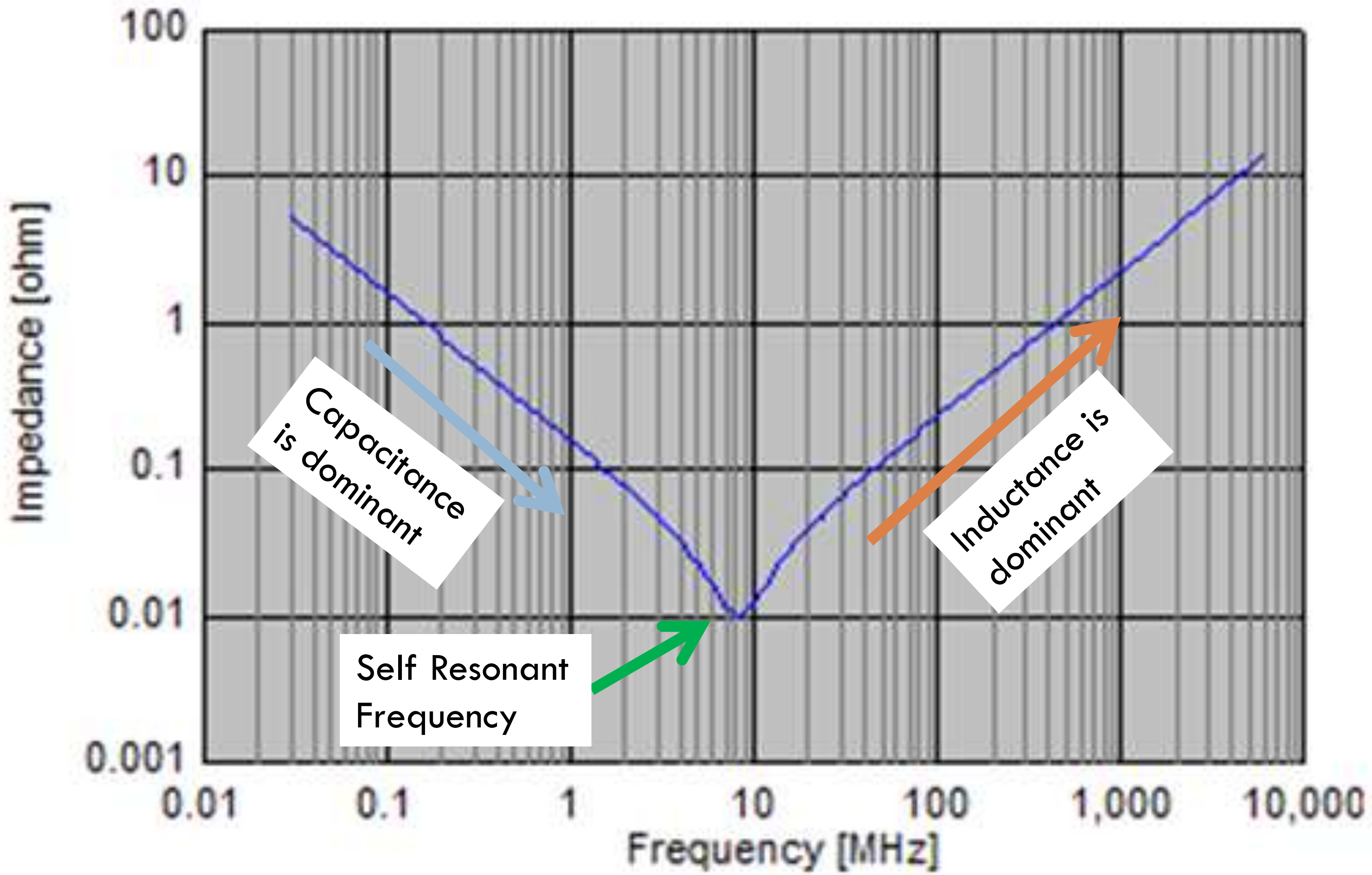
Parasitic Resistance (Small)

Parasitic Inductance (Small)

Capacitance becomes a short circuit at high frequency

Inductance becomes an open circuit at high frequency

Impedance vs. Frequency
1µF 0603 Capacitor



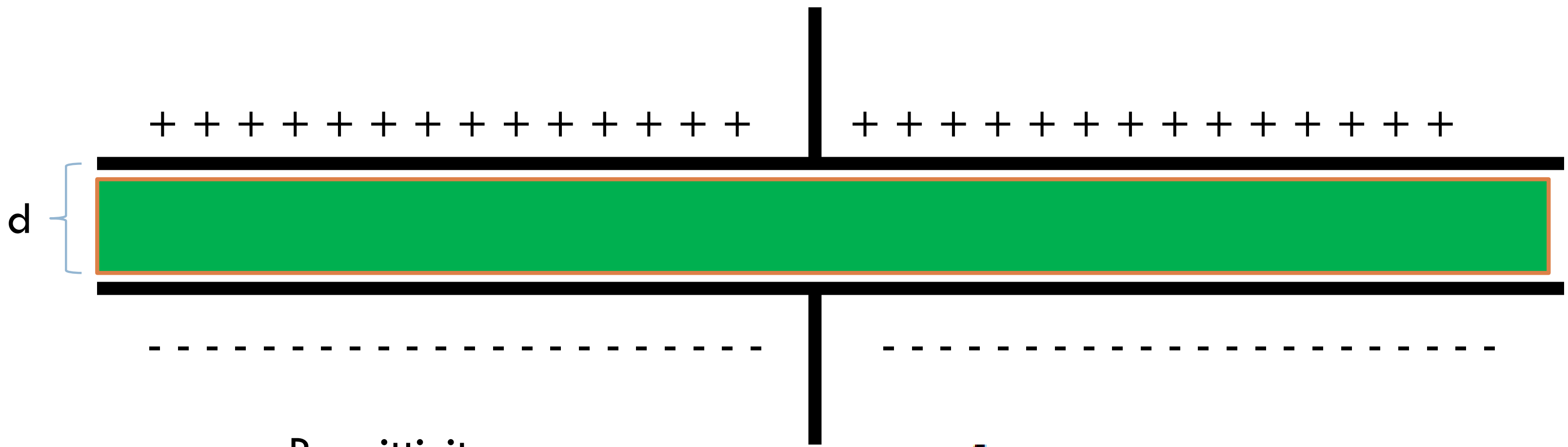
Real Estate

As designs become more complex and microprocessors are required to do more, space near an IC is at a premium

To make things worse, microprocessor speeds are increasing requiring low impedance PDN at high frequency

Concept of embedded capacitance

Parallel Plates Separated by Dielectric



Permittivity Of Dielectric

Plate Area

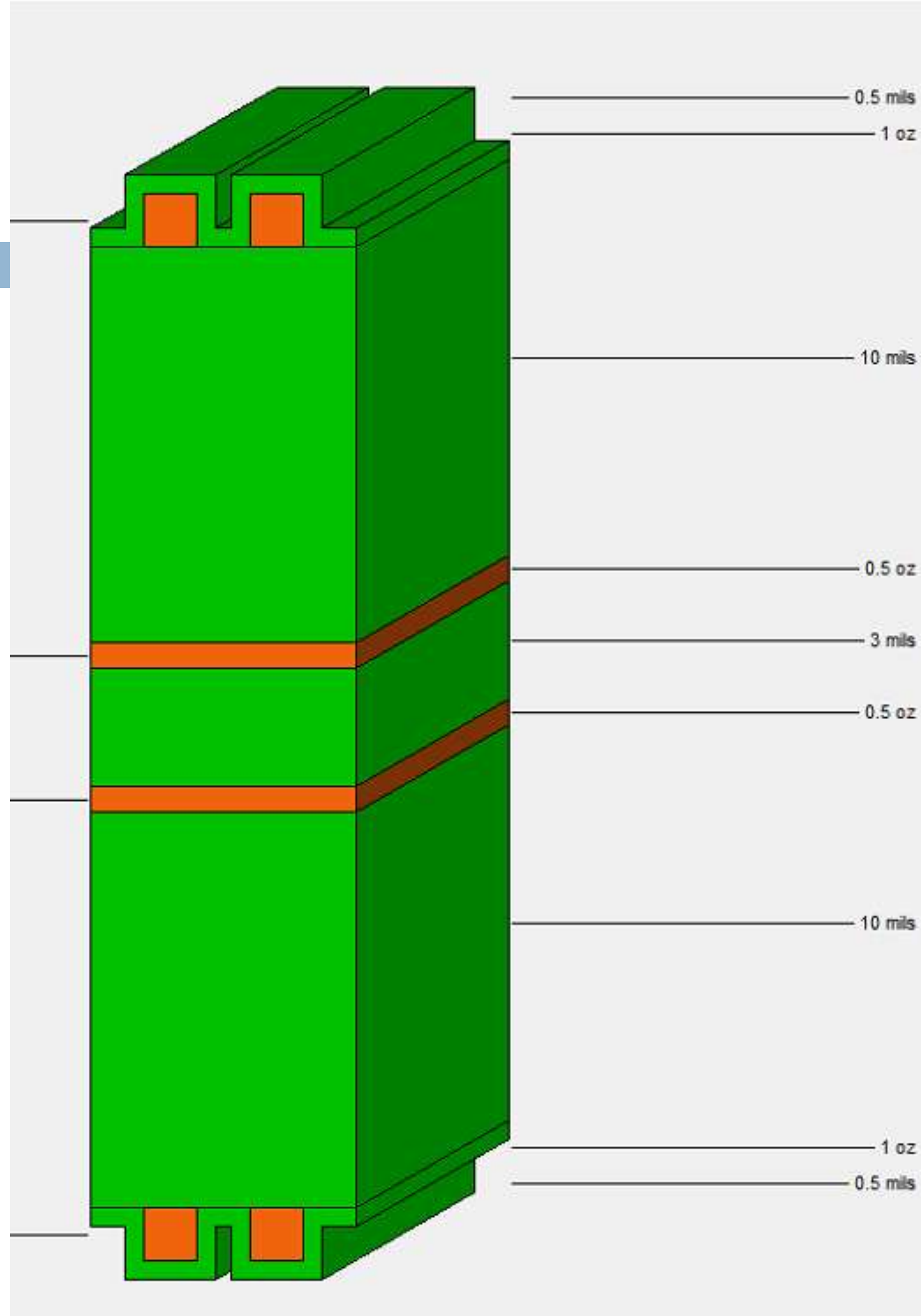
$$c = \frac{\varepsilon A}{d}$$

Capacitance

Plate Separation

Multi-layer PCBs

- Most PCBs are a standard thickness
- More layers in a PCB require the layers to be closer together
  - This results in more capacitance between layers

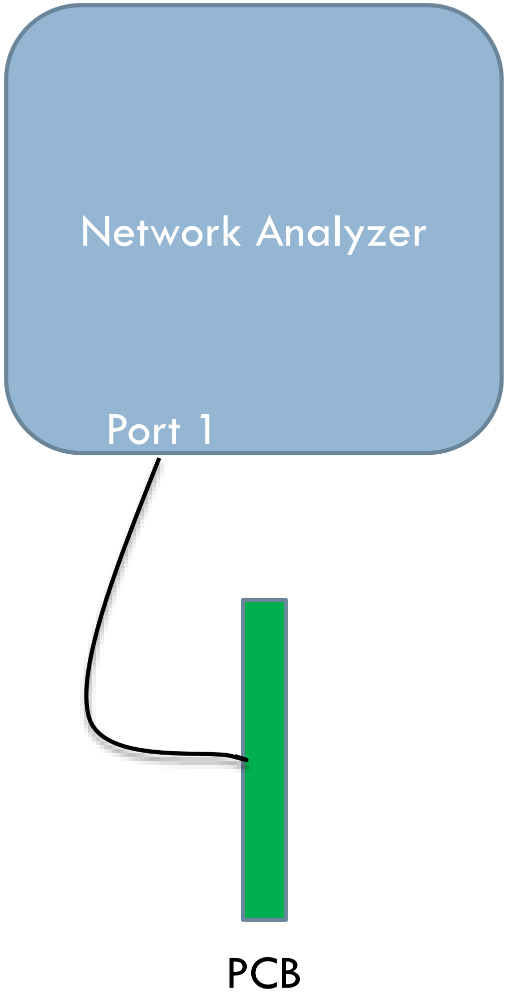


Methodology

Experimental PCB

- PCBs were designed and manufactured for embedded capacitance research
  - Various Dimensions
  - 4 Layer (two planes and two signal layers)
  - Most are FR4 cores
  - Various spacing between planes

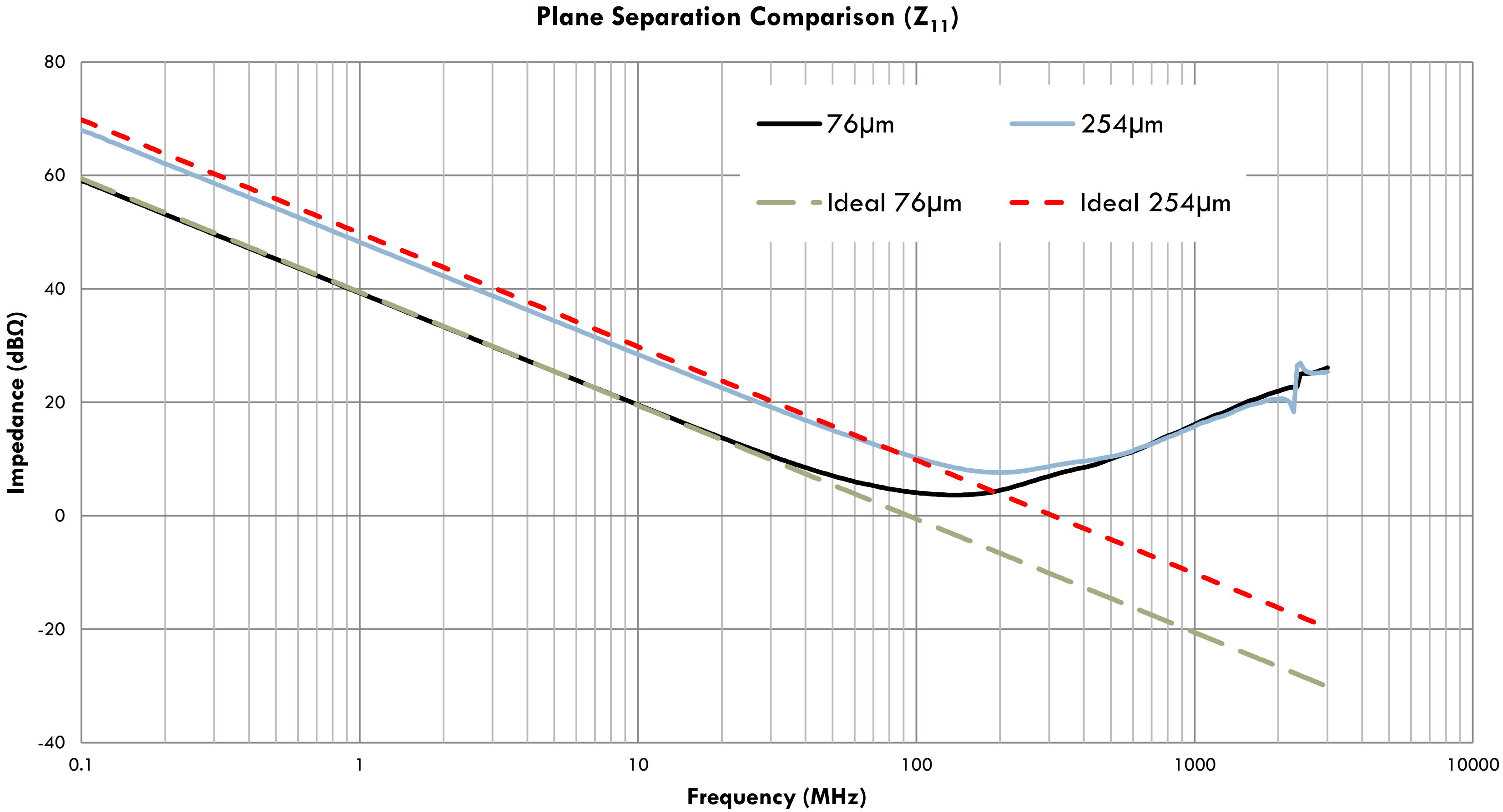
Measurement Methodology



A PCB mounted coaxial connector was used to connect the planes to the network analyzer

Z11 was measured to determine power distribution network (PDN) Impedance

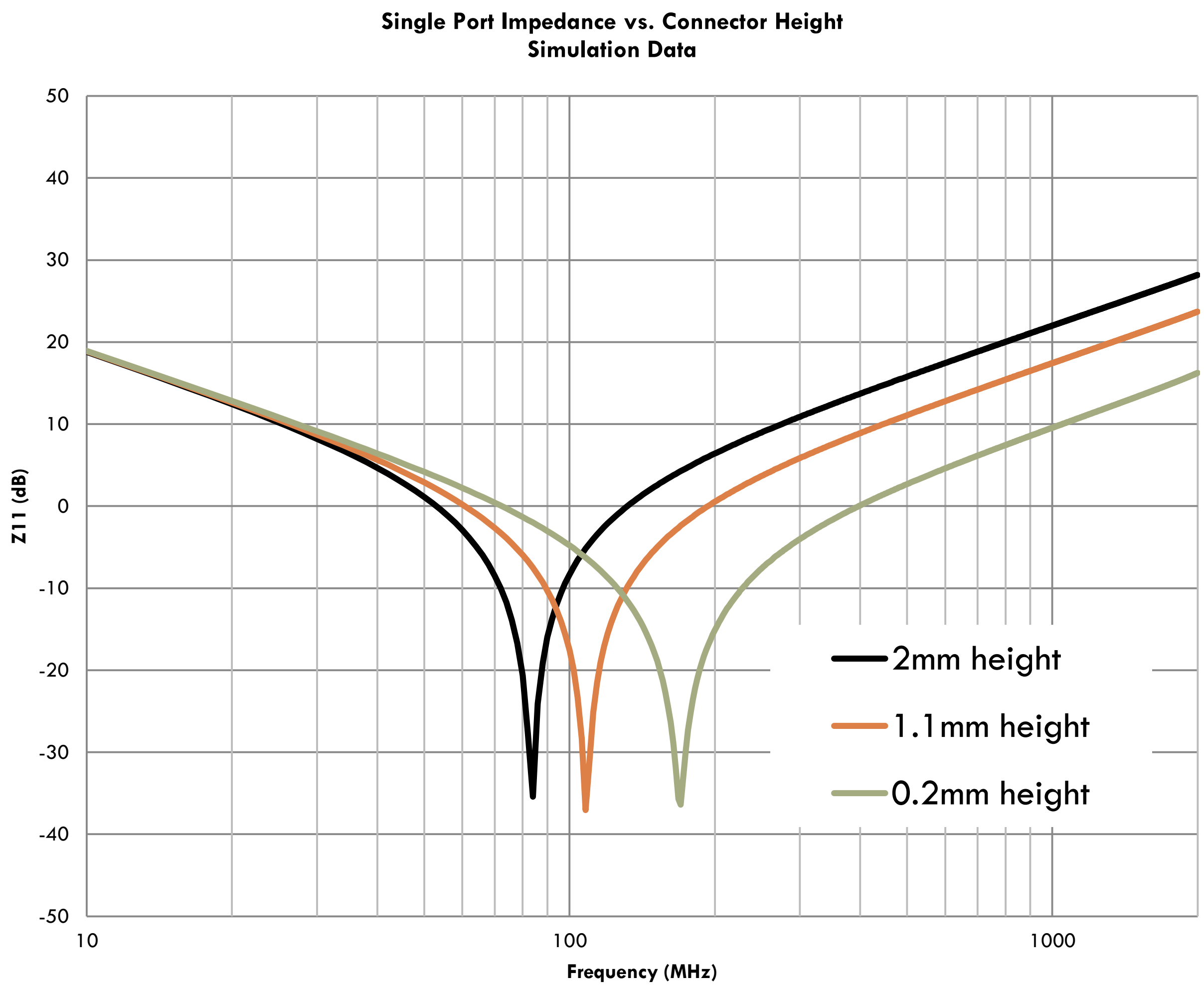
Z11 Measurement Results



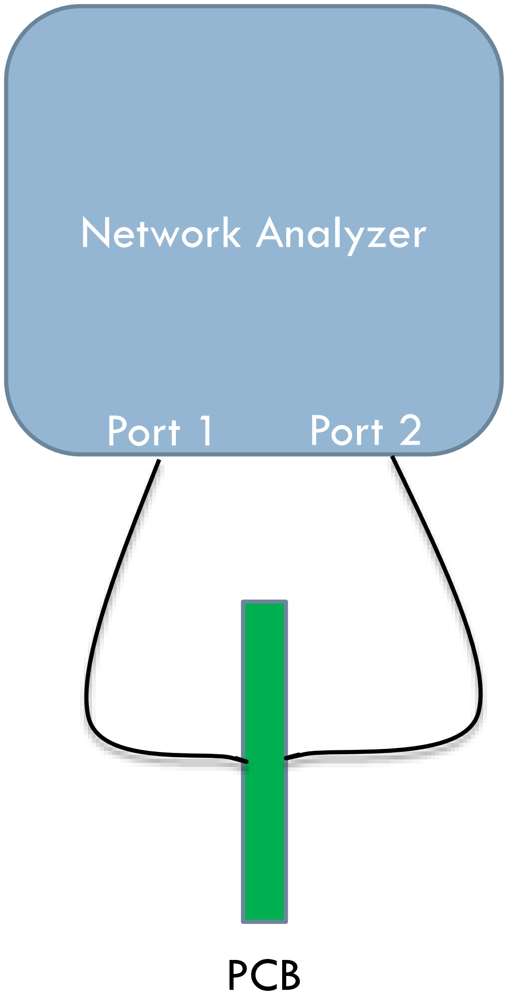
The expectation was to see the narrow plane spacing (76µm) perform better at high frequency
The measurement did not show this

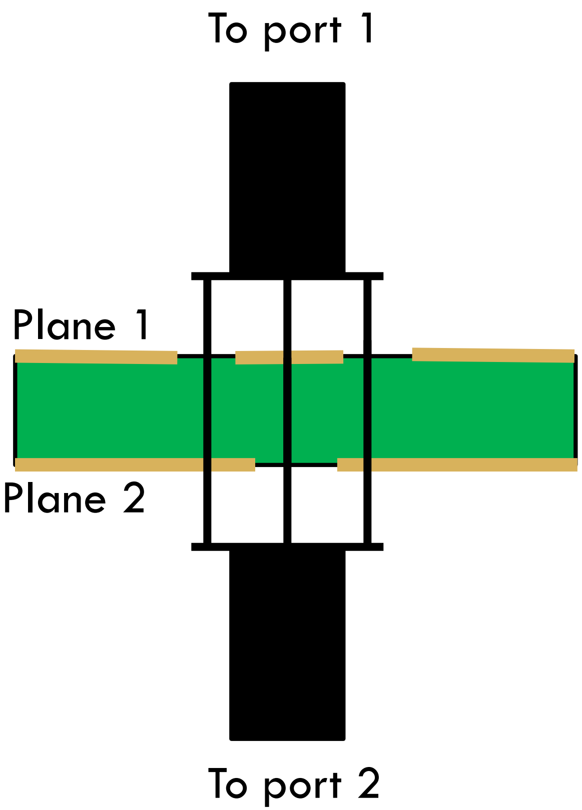
Single port measurement and simulation

- Simulations were performed using the Finite Integration Technique
- It was discovered that the high frequency impedance was dependent upon the height of the coax connector
- 0.2mm height was represented by a port existing between PCB planes

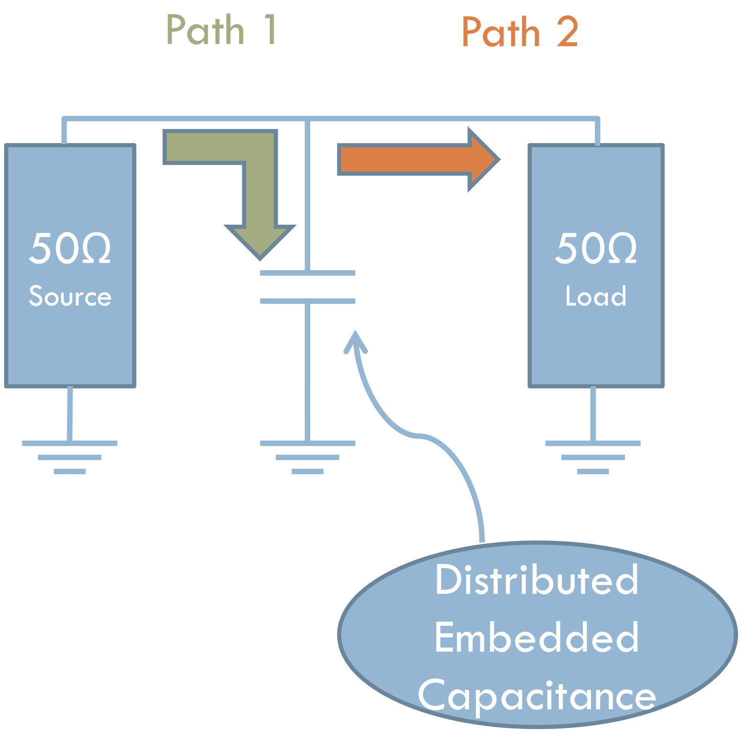


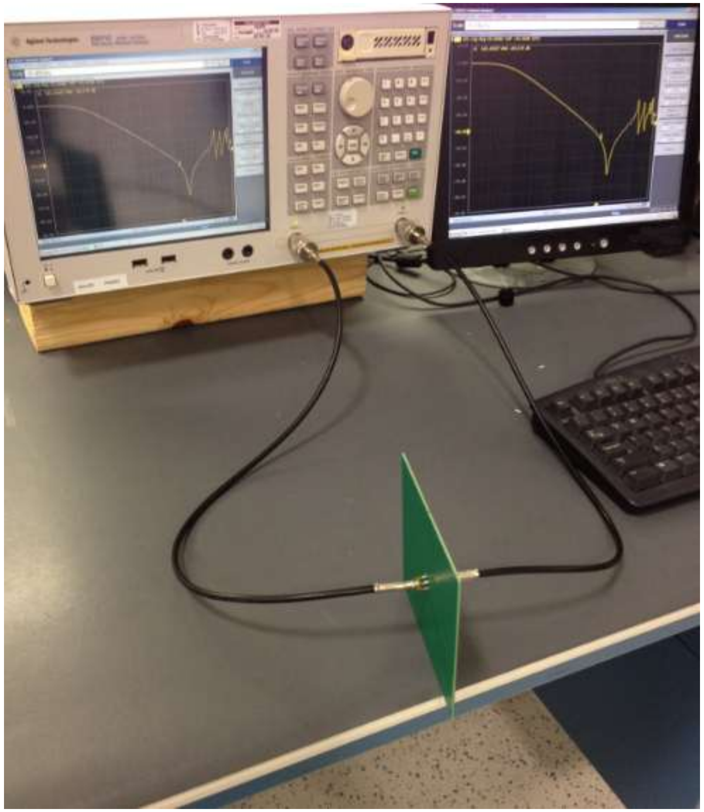
New Measurement Methodology





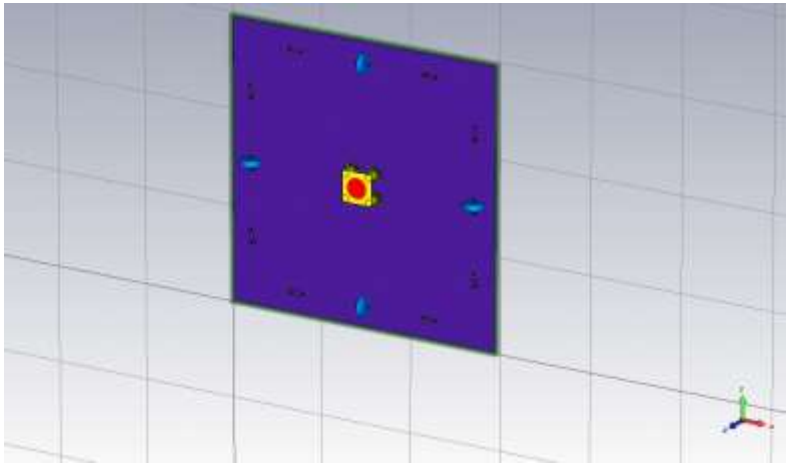
S21 Test Setup



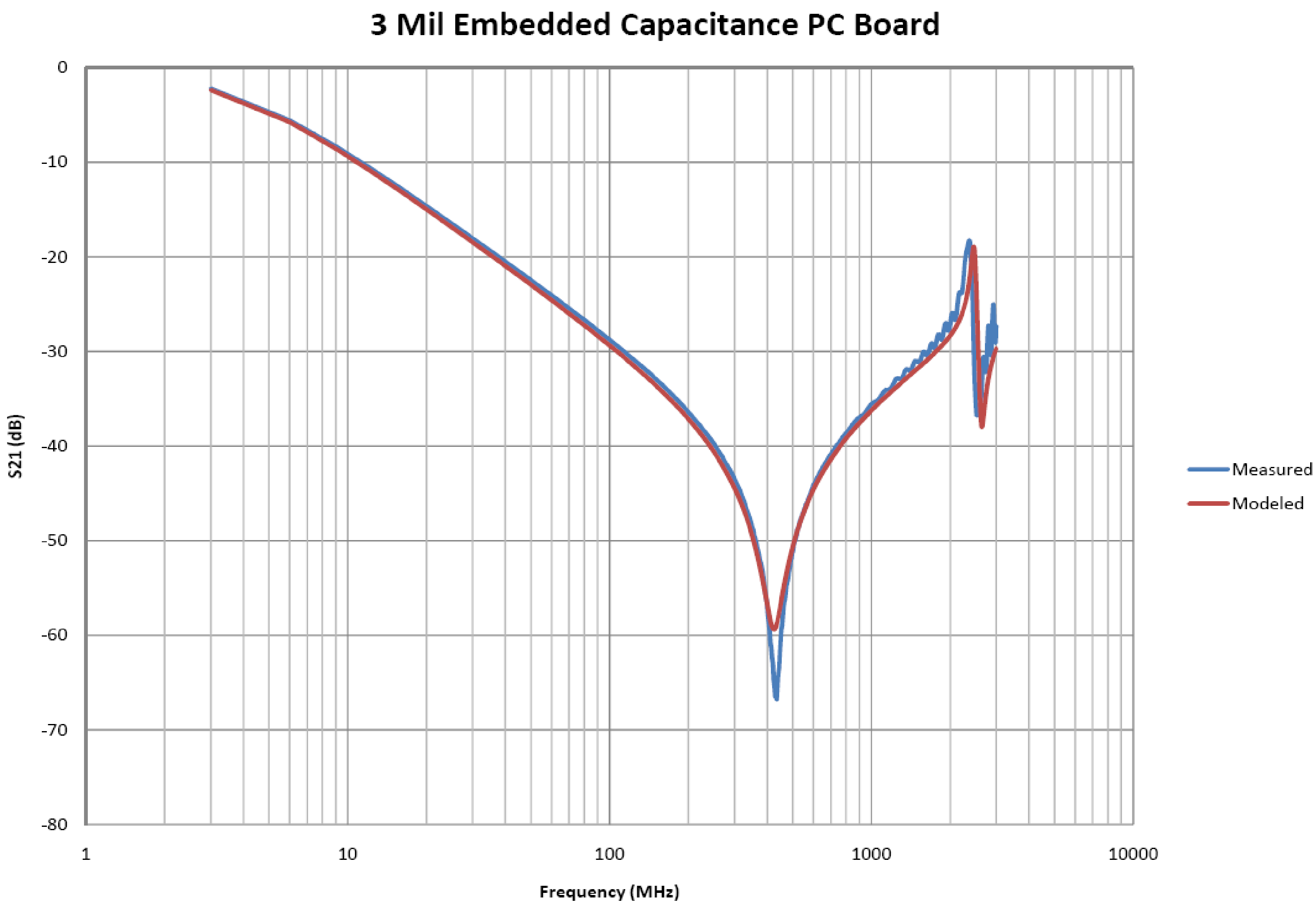


EM Simulation

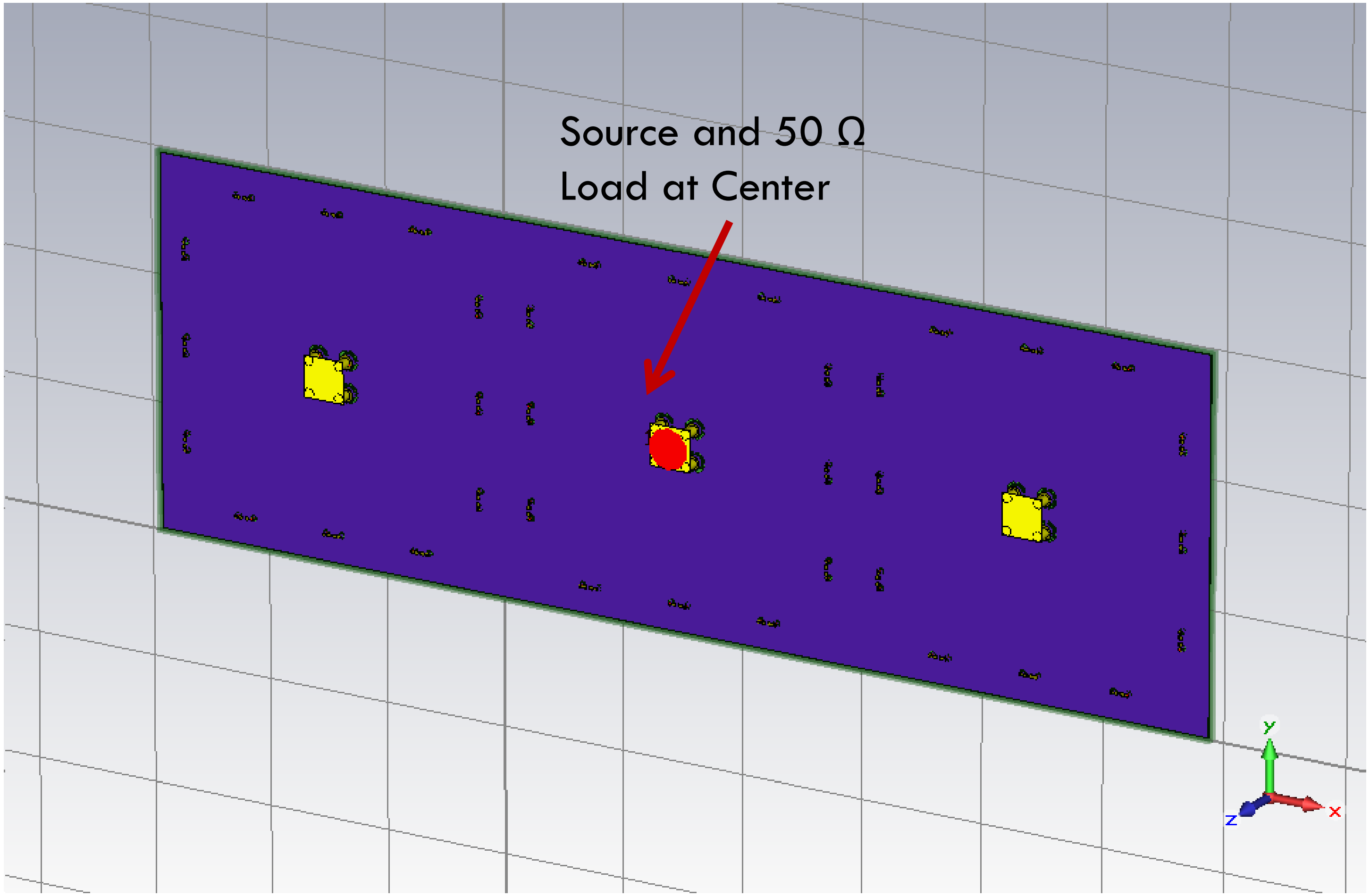
- Technique:
  Full Wave 3D Solver
  Finite Integration Method

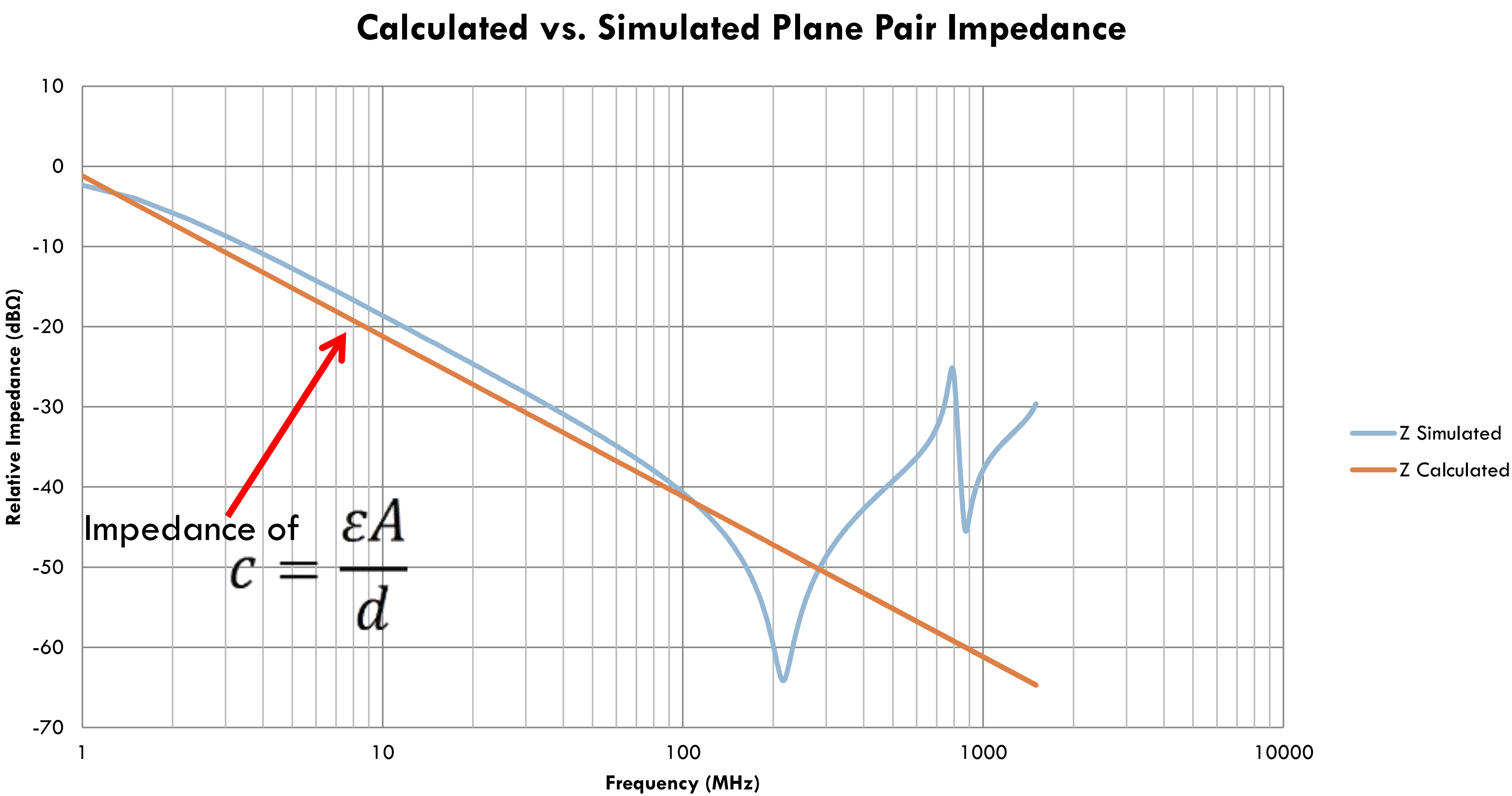


EM Simulation vs. Measurement



6” x 2” PCB with 3 Mils Plane Separation (FR4 Core)



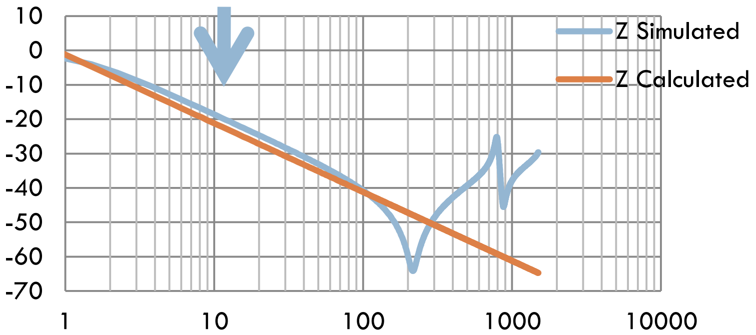


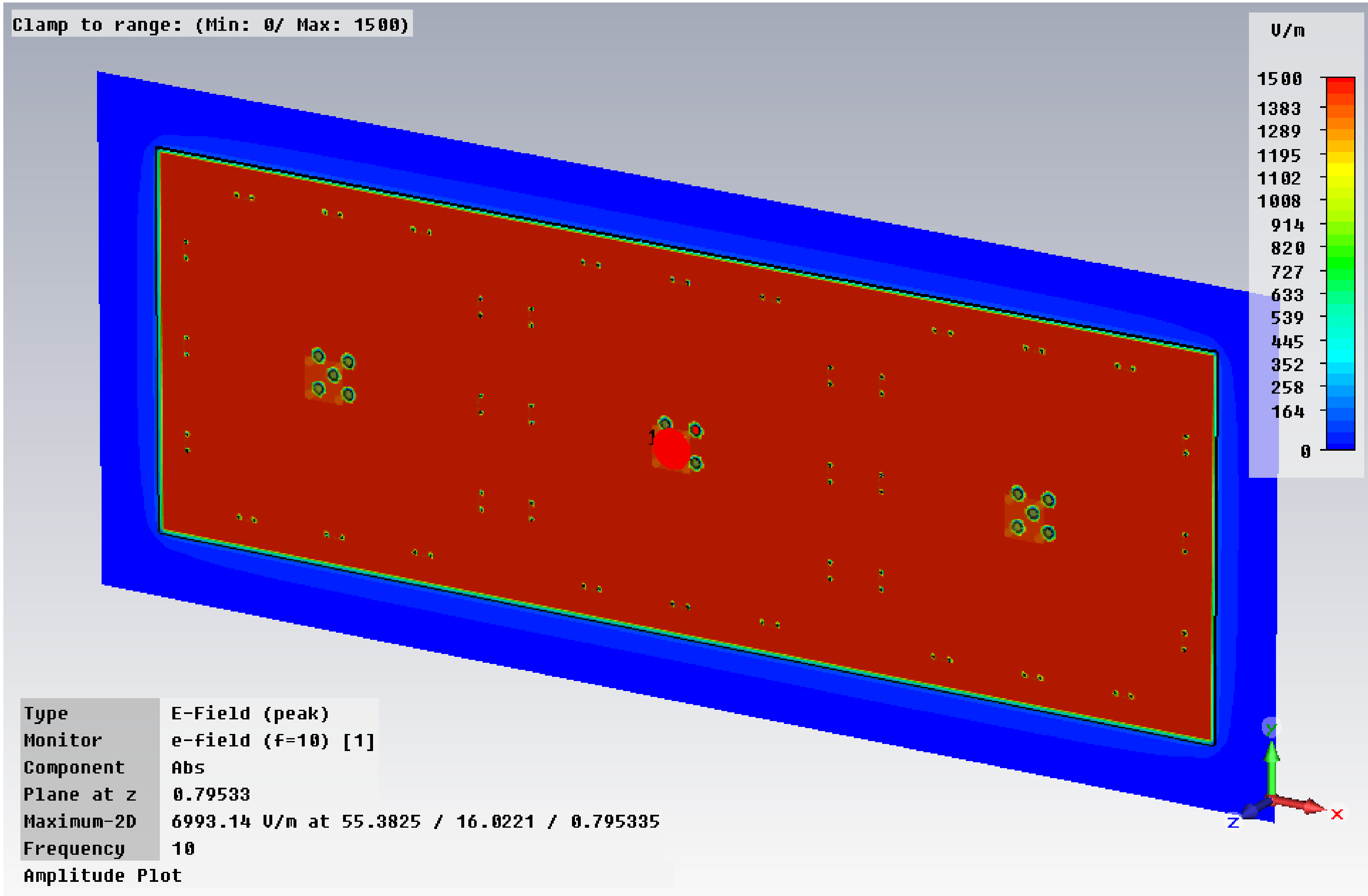
Embedded capacitance works as a parallel plate capacitor at low frequencies but at higher frequencies other factors become dominant

Capacitors

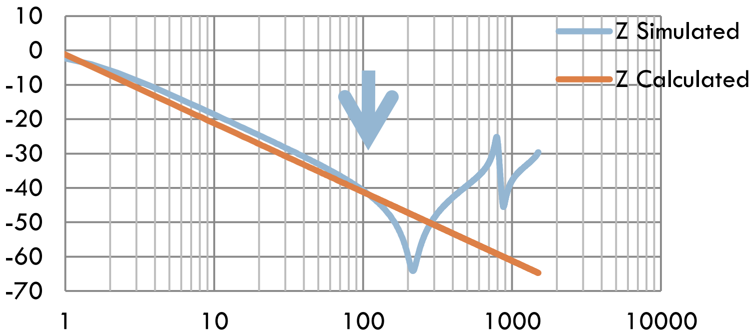
- Energy is stored in a capacitor as an electric field
- In the following field plots
  - A strong electric field indicates the applied energy was used to charge the planes
  - A weak electric field indicates that embedded capacitance was utilized thus generating a magnetic field.

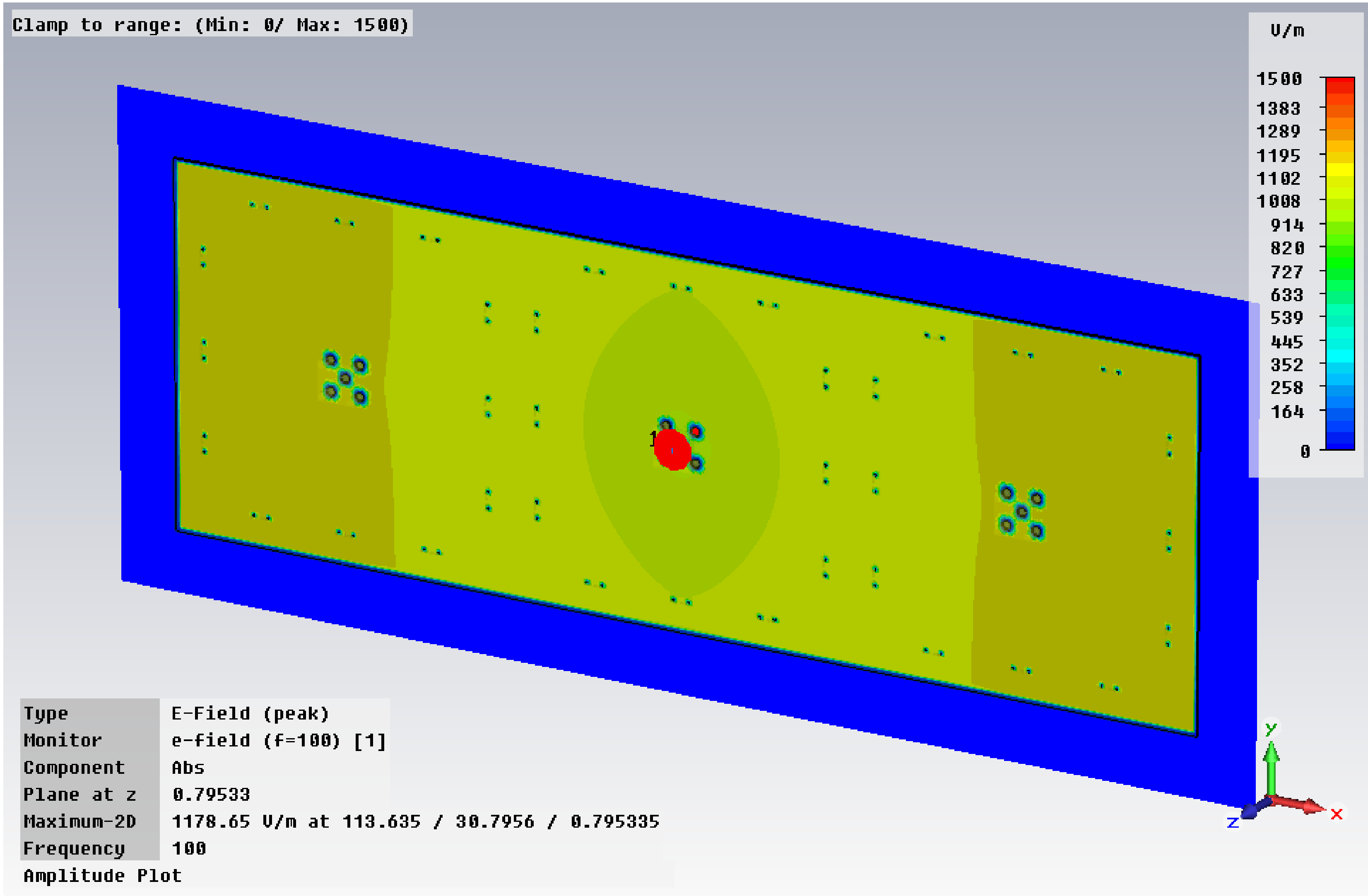
Electric Field at 10 MHz

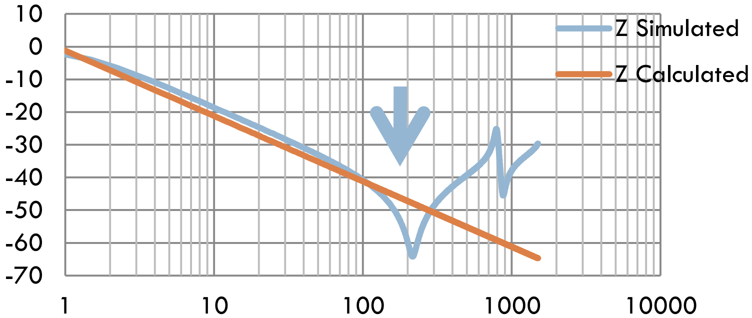




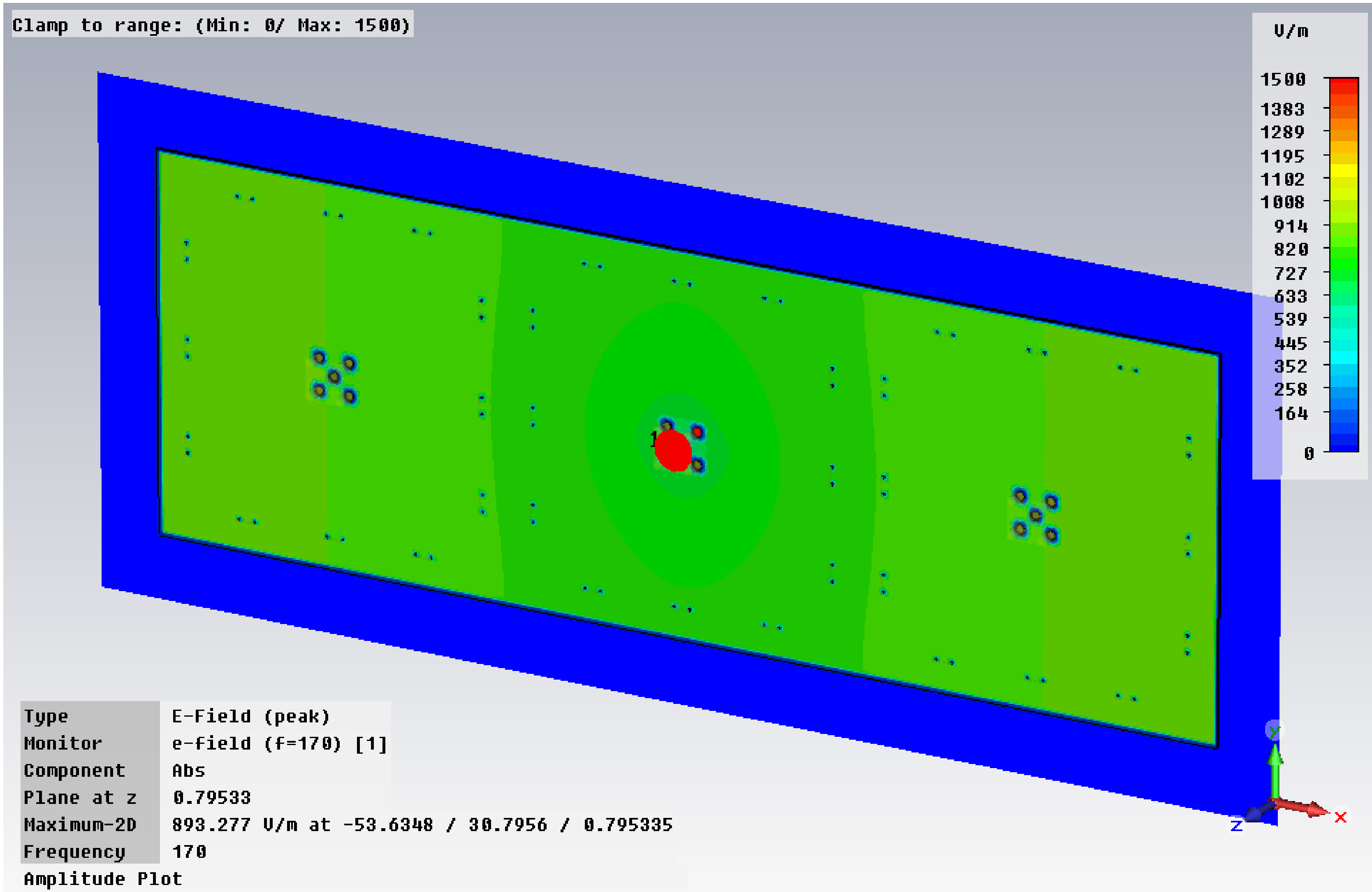
Electric Field at 100 MHz



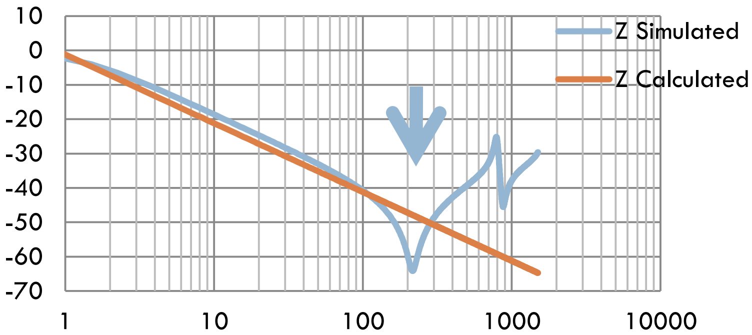


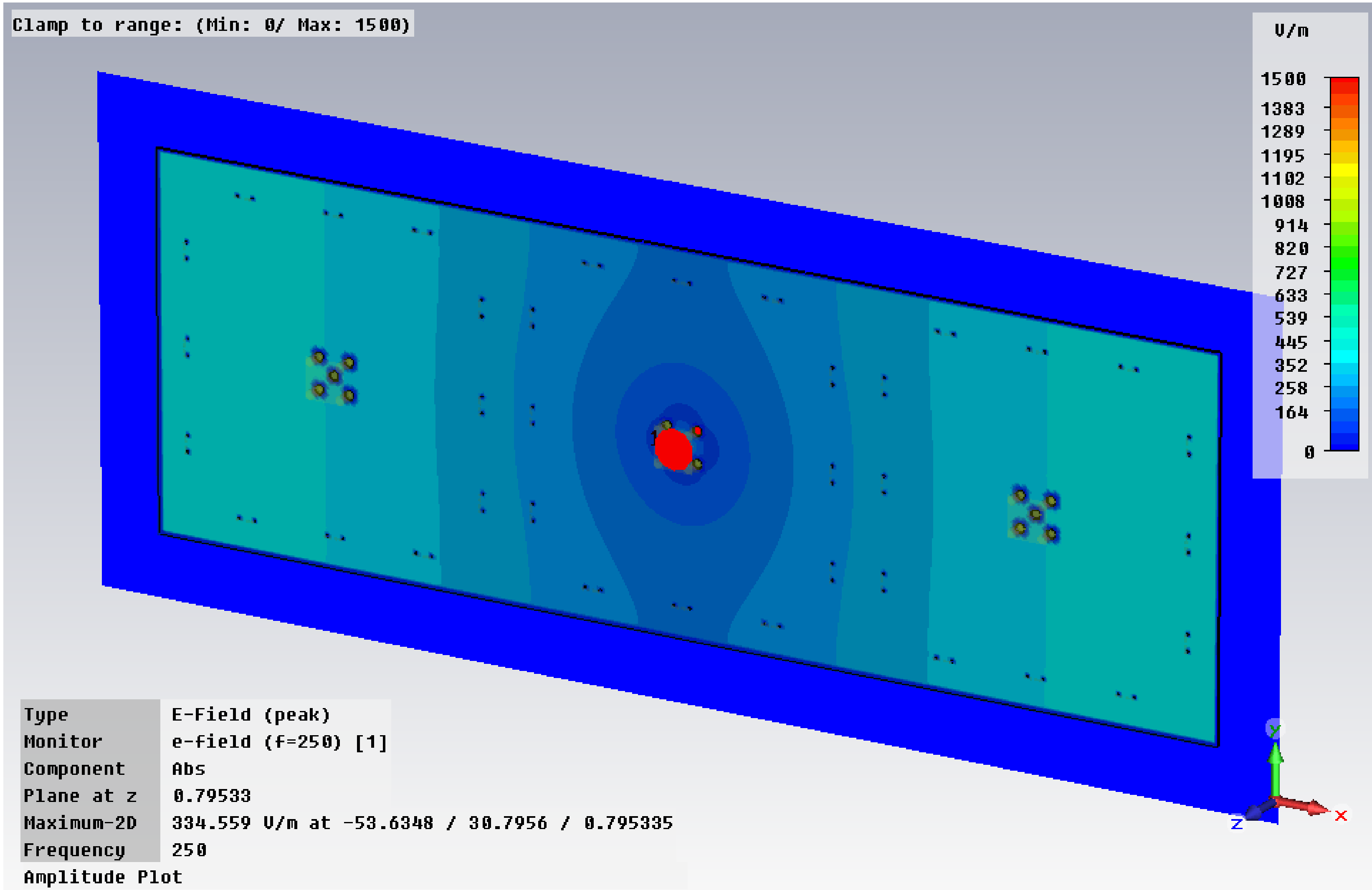


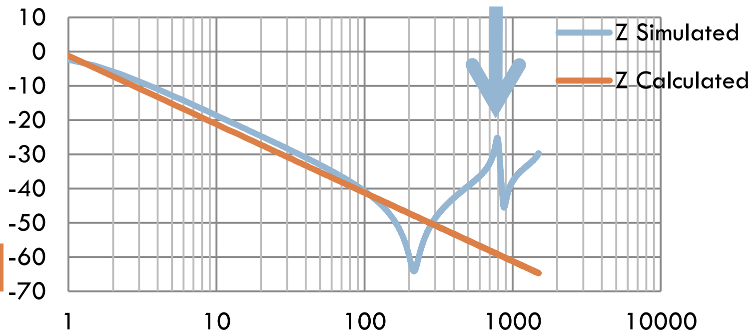
Electric Field at 170 MHz



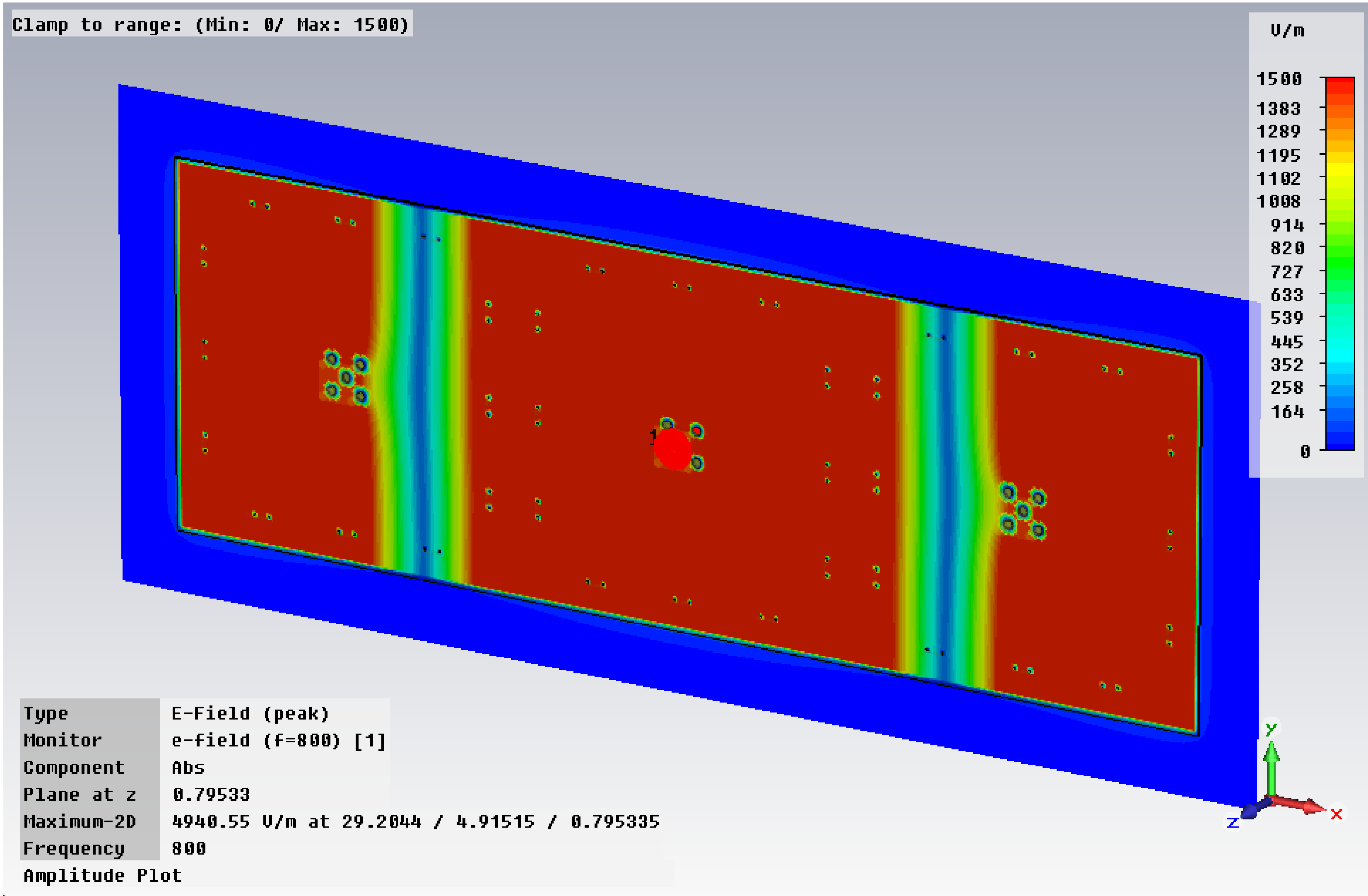
Electric Field at 250 MHz

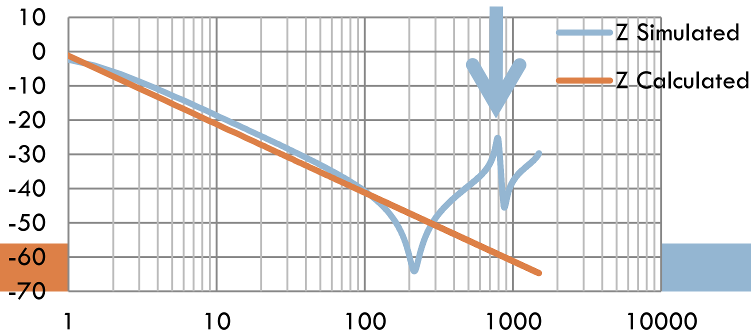




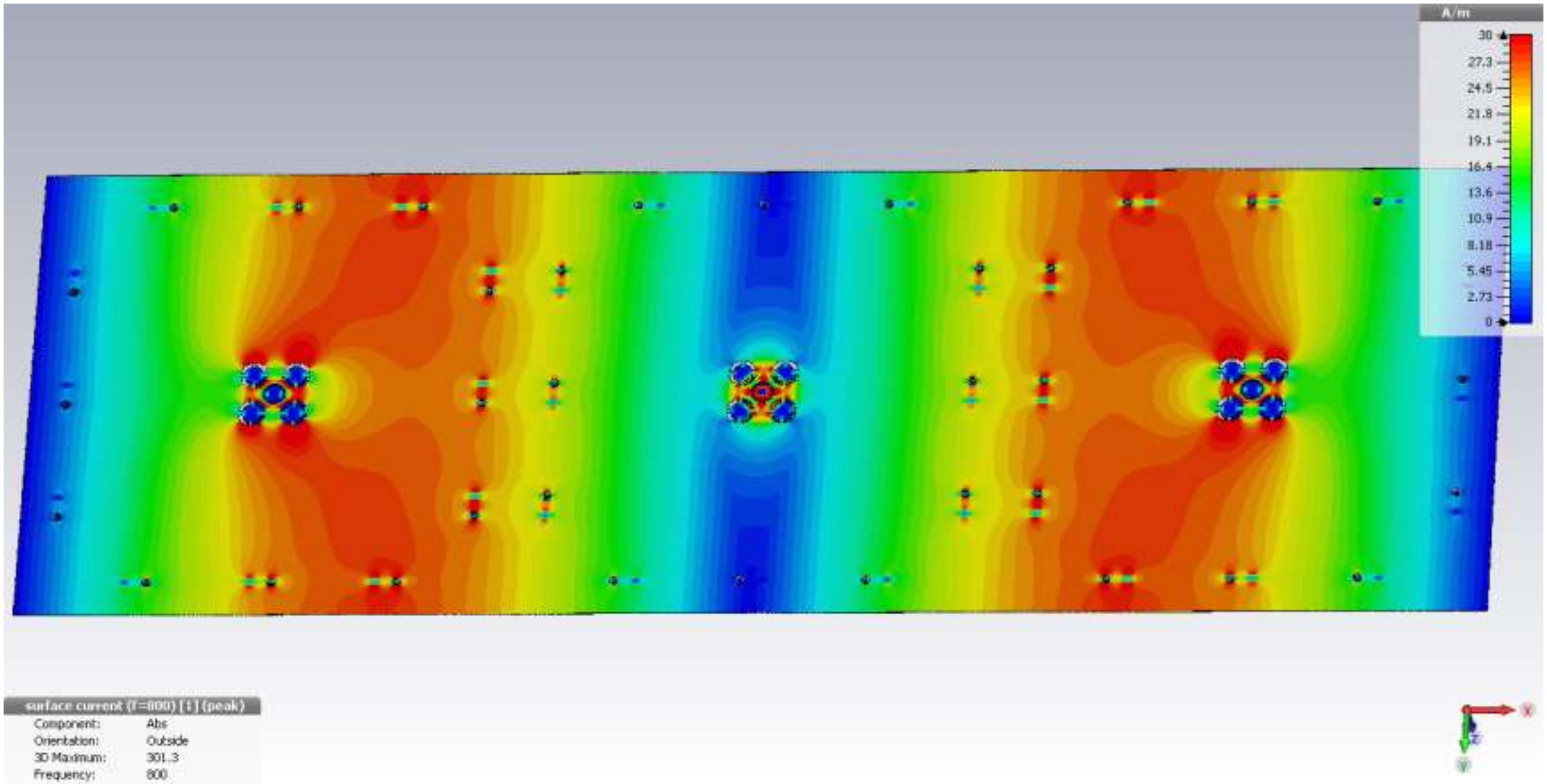


Electric Field at 800 MHz





Surface Current at 800 MHz



Concept of Embedded Capacitance

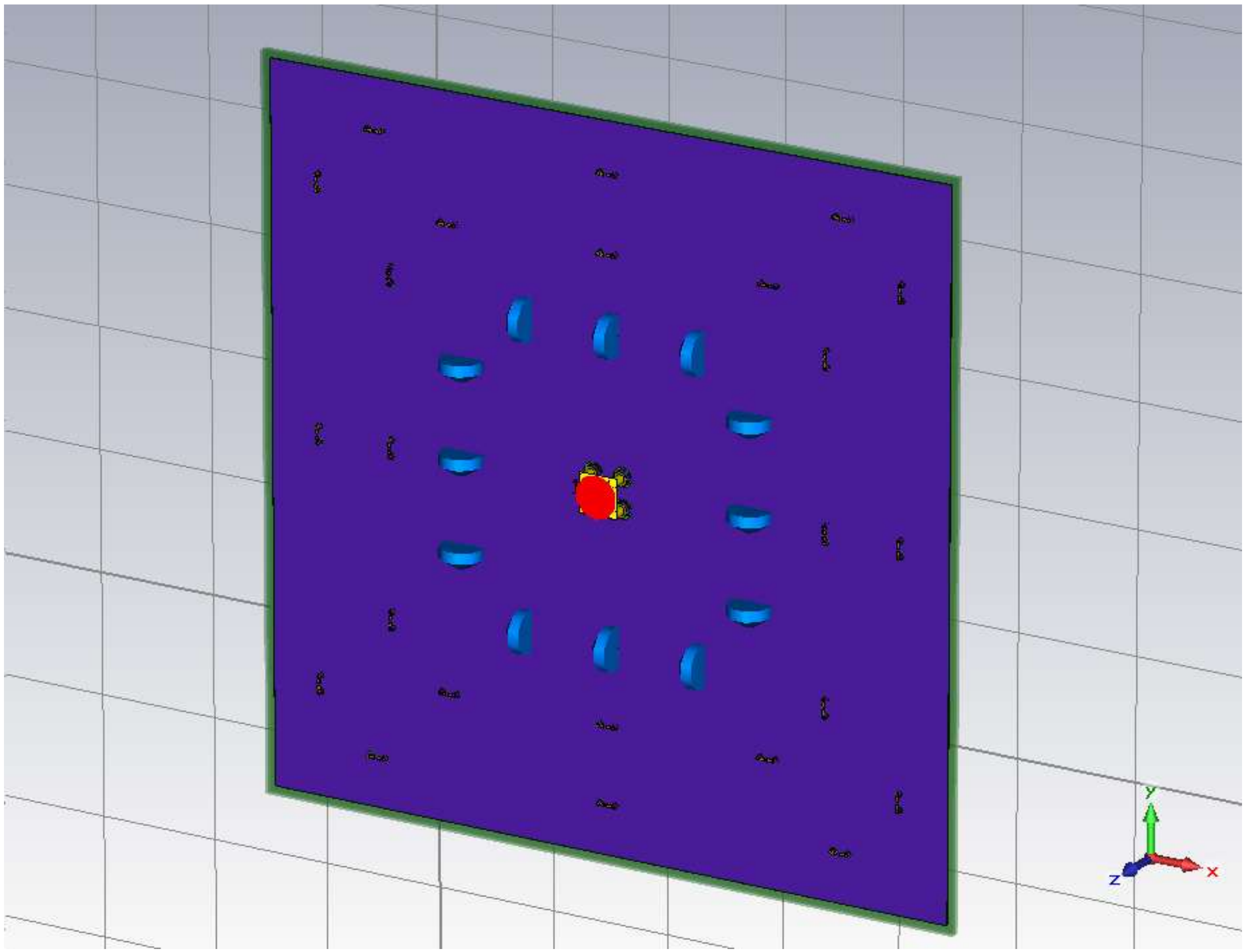
- Below 100 MHz, PCB capacitance is utilized throughout the entire PCB and behaves as an ideal parallel plate capacitor

- Above 100 MHz other factors cause impedance to increase making the PCB not an ideal parallel plate capacitor

PCBs of various dimensions with discrete capacitors

Demonstration

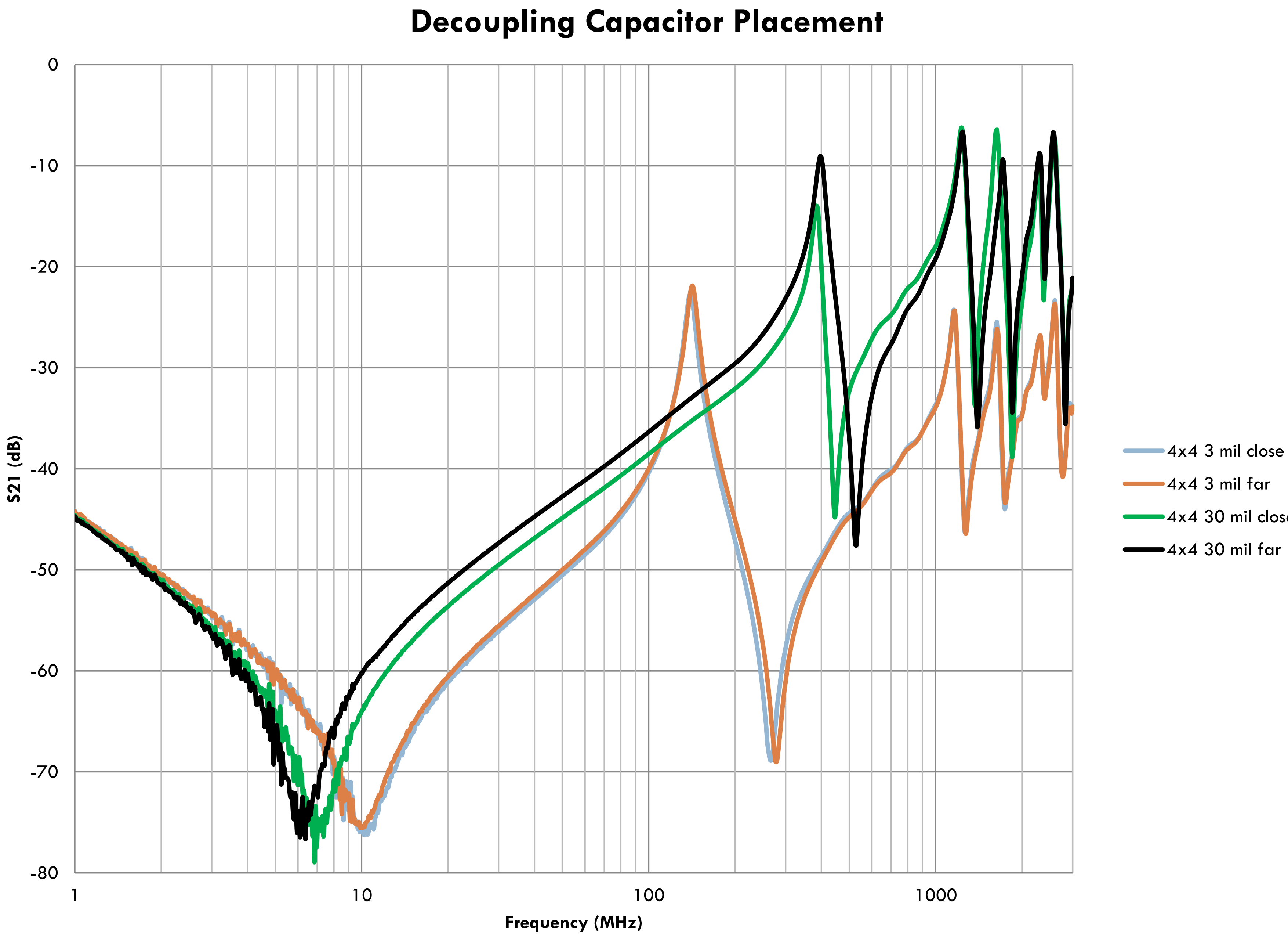
Example



4x4 inch PCB with 2 adjacent plane layers and capacitor pads

Will compare
- 3 mil plane spacing
- 30 mil plane spacing

Each comparison will involve capacitors located
- 1 inch away from the source
- 2 inches away from the source

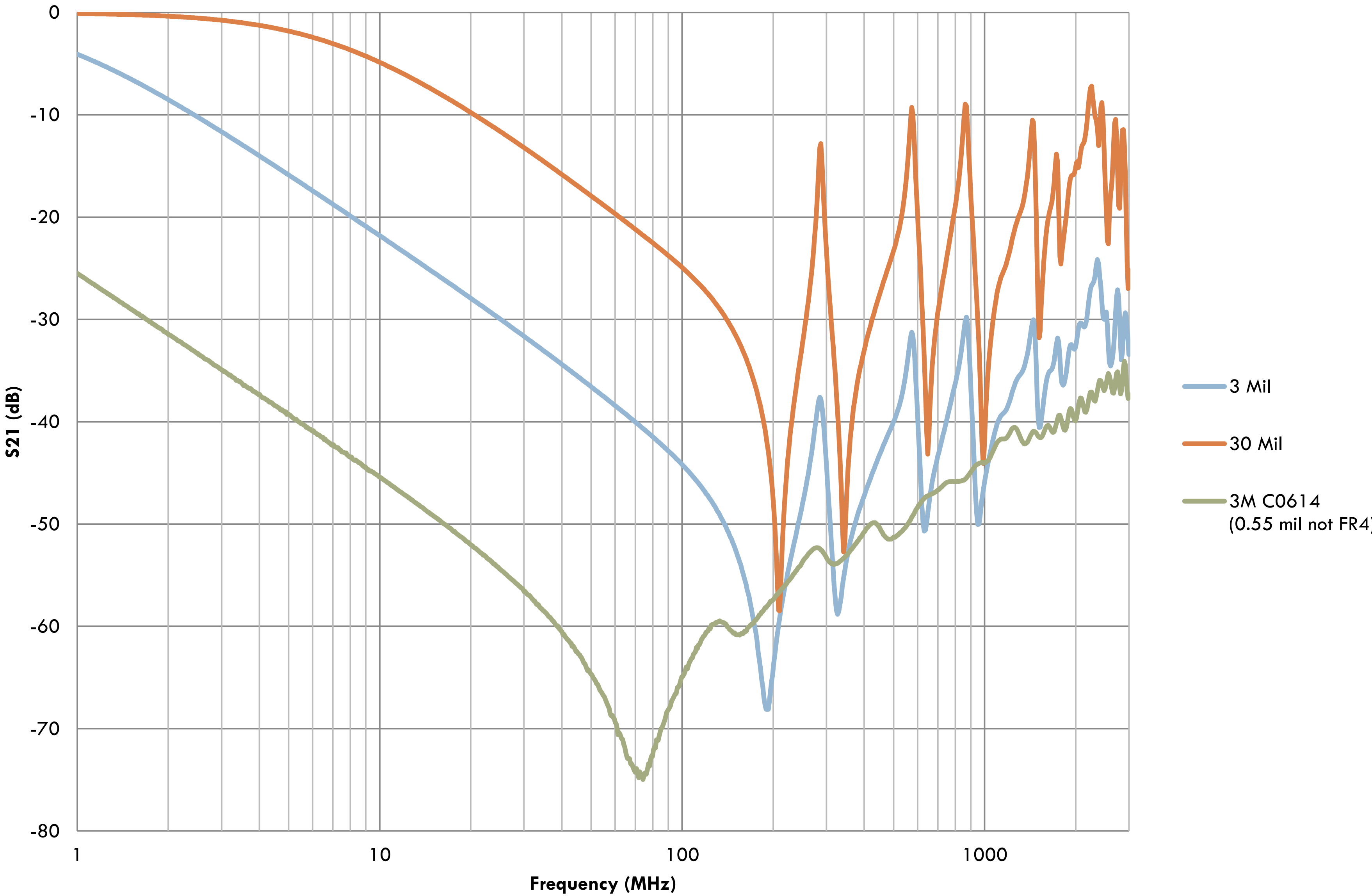

Decoupling Capacitor Placement
0
-10
-20
-30
-40
-50
-60
-70
-80
S21 (dB)
1
10
100
1000
Frequency (MHz)
4x4 3 mil close
4x4 3 mil far
4x4 30 mil close
4x4 30 mil far

Capacitor Location

- As plane distance decreases, distance between the capacitors and the excitation source (or load) becomes less important

PCBs of various dielectric thicknesses and the same dimensions

Measurement of PCBs with Varying Dielectric Thickness
2x8 Inch Dimension

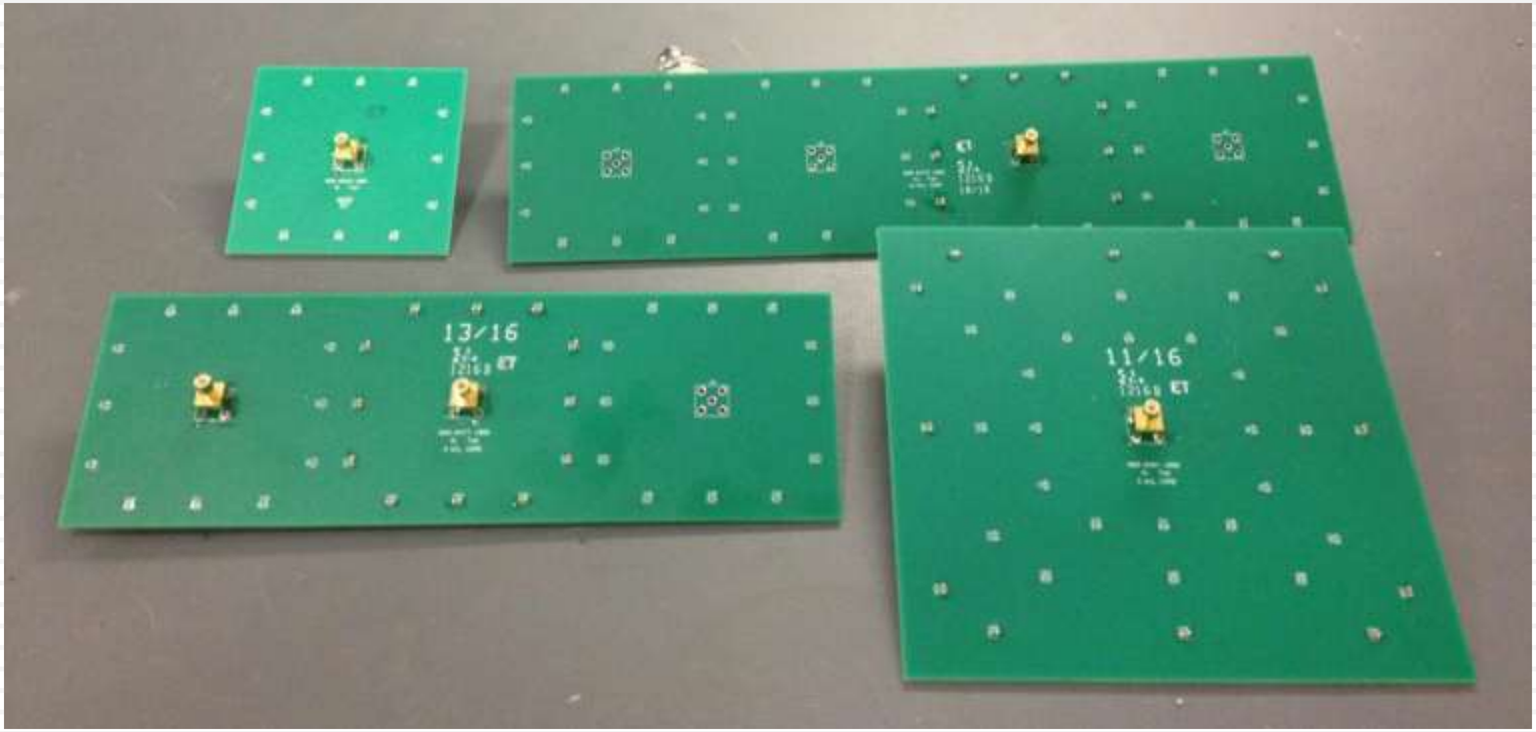


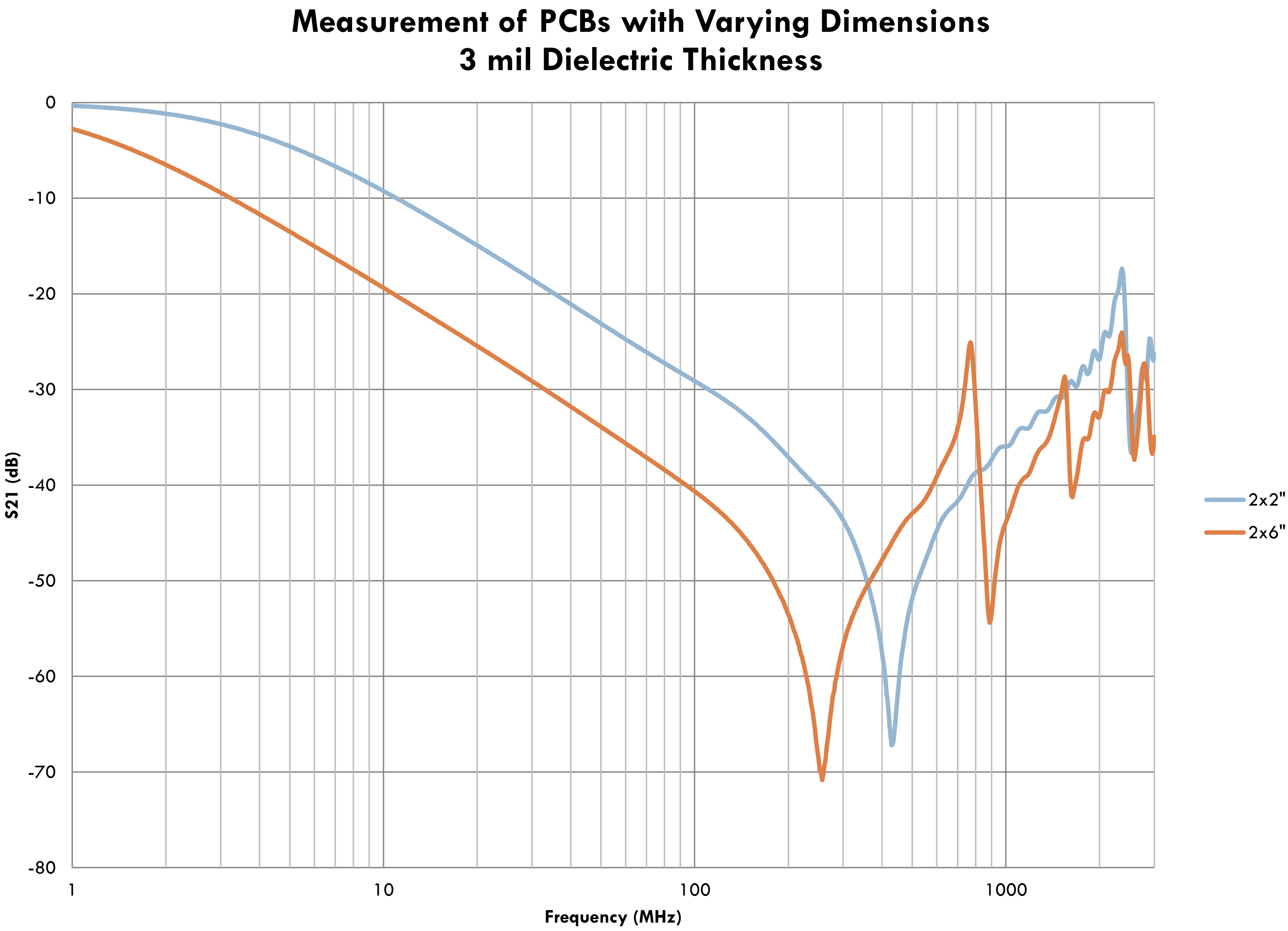
Dielectric Thickness

- Closer plane spacing results in lower plane impedance at low frequencies as well as high frequencies
- Lower Q factor is also achieved by closer plane spacing

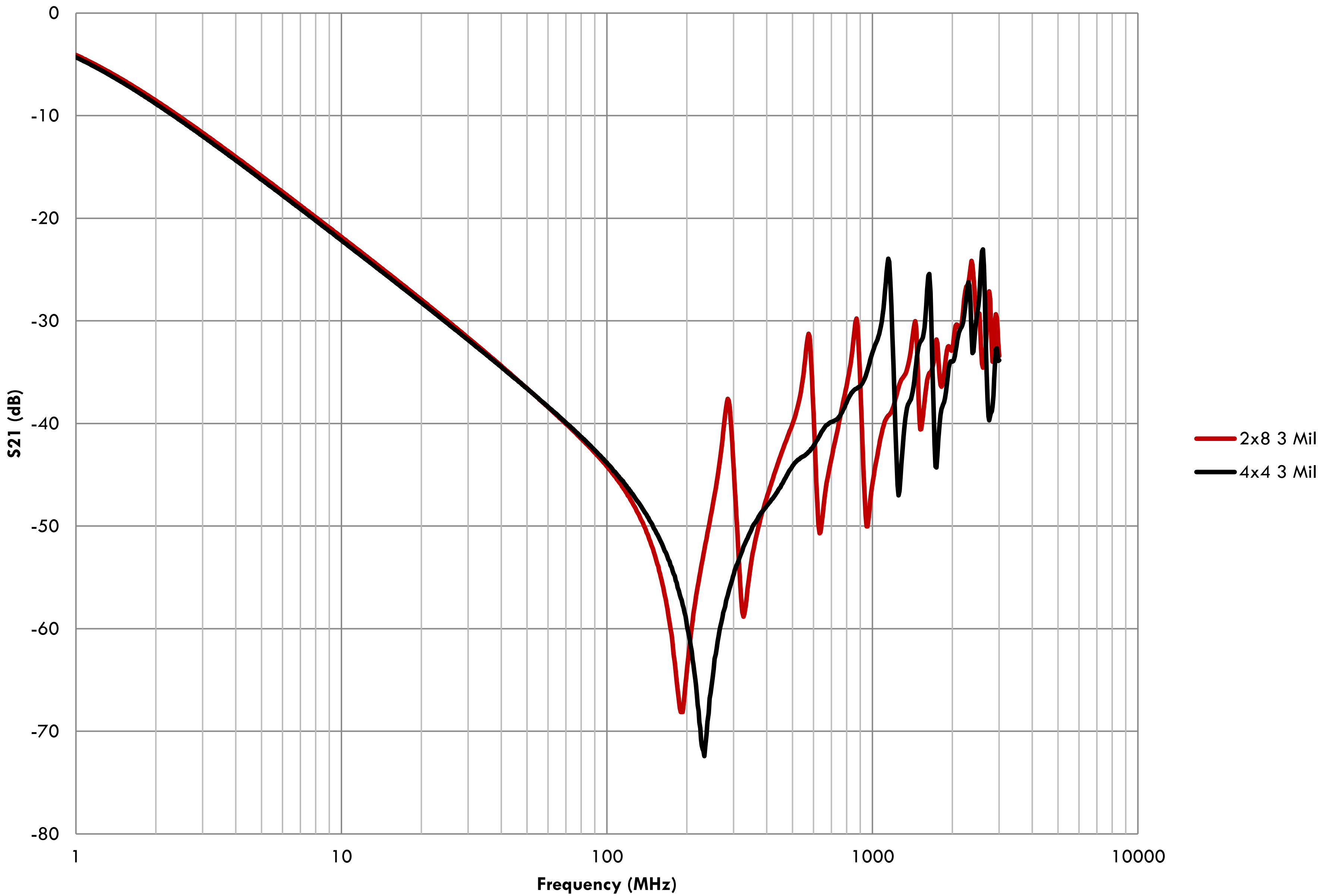
$$Q = \frac{1}{R}\sqrt{\frac{L}{C}}$$

PCBs of various dimensions and the same dielectric thickness




Measurement of PCBs with Varying Dimensions
3 mil Dielectric Thickness
0
-10
-20
-30
-40
-50
-60
-70
-80
S21 (dB)
1
10
100
1000
Frequency (MHz)
2x2"
2x6"

2x8 Inch 3 Mil PCB vs. 4x4 Inch 3 Mil PCB



Plane Area

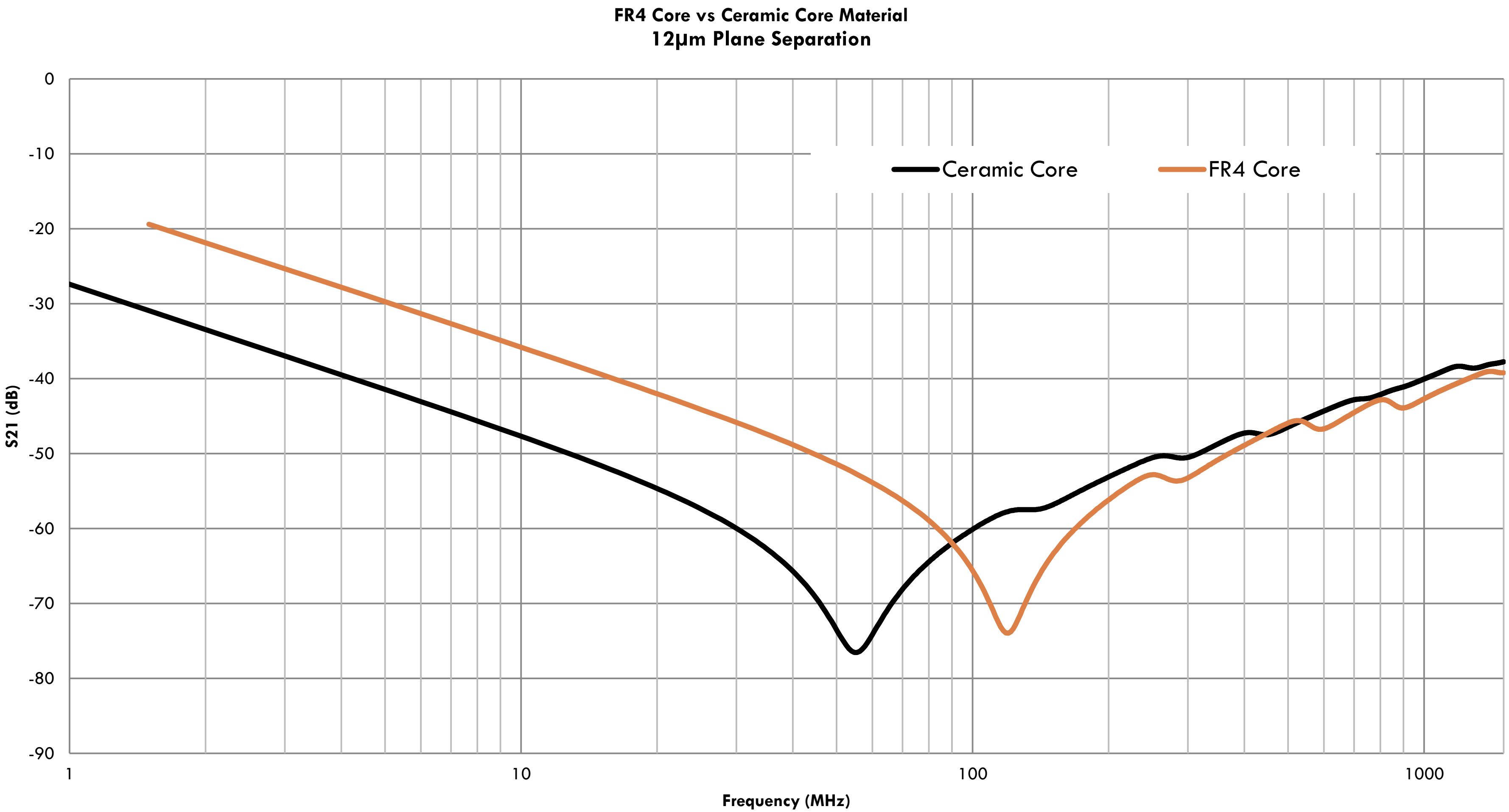
- Increasing PCB size causes lower impedance at low frequencies, but does not affect impedance at high frequencies

- PCBs with identical plane area but different length and width dimensions can have different impedances at high frequency

Impact of Dielectric Material

Ceramic Core Dielectric <3 mil

- Simulation results

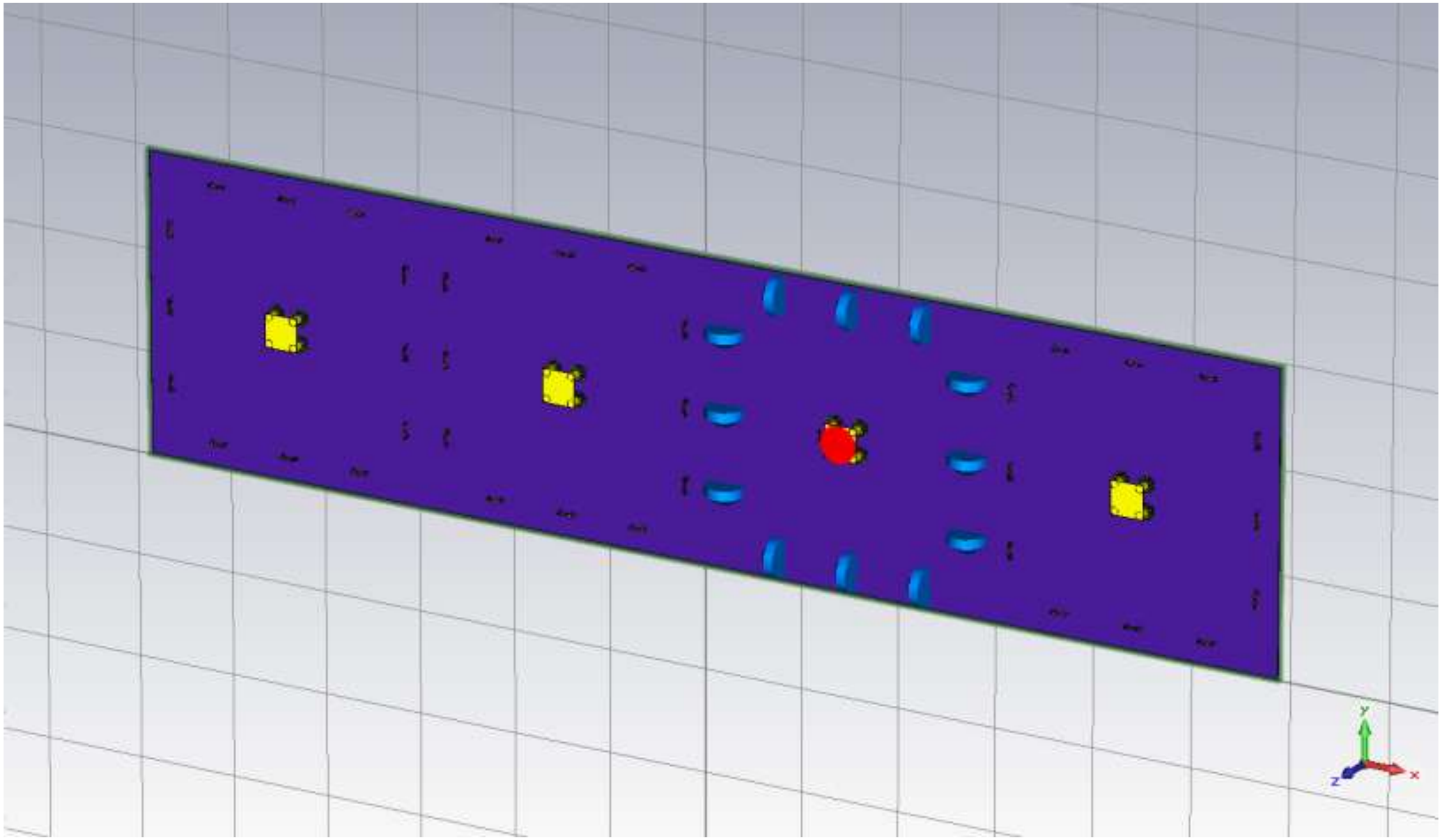


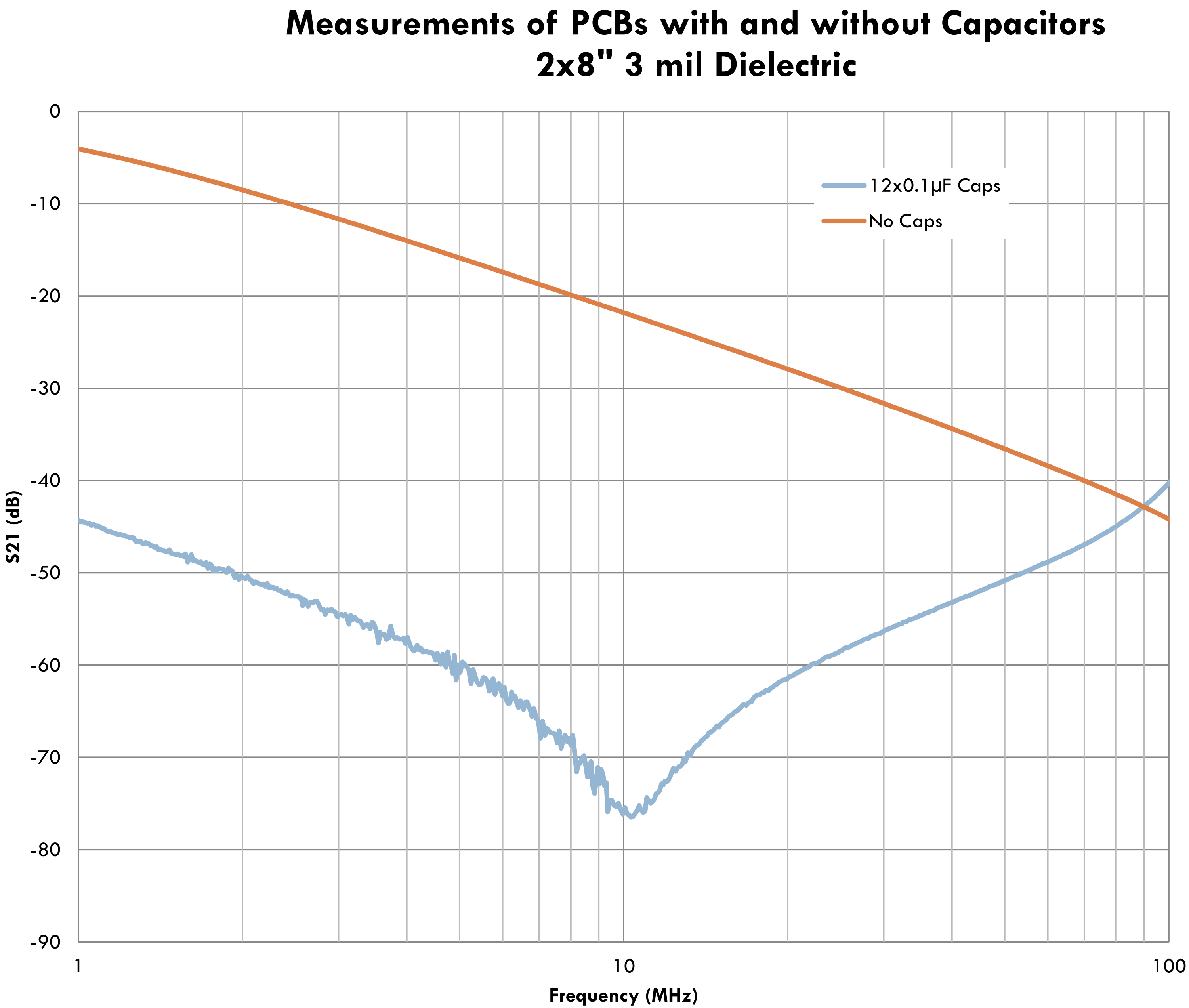
Dielectric Material

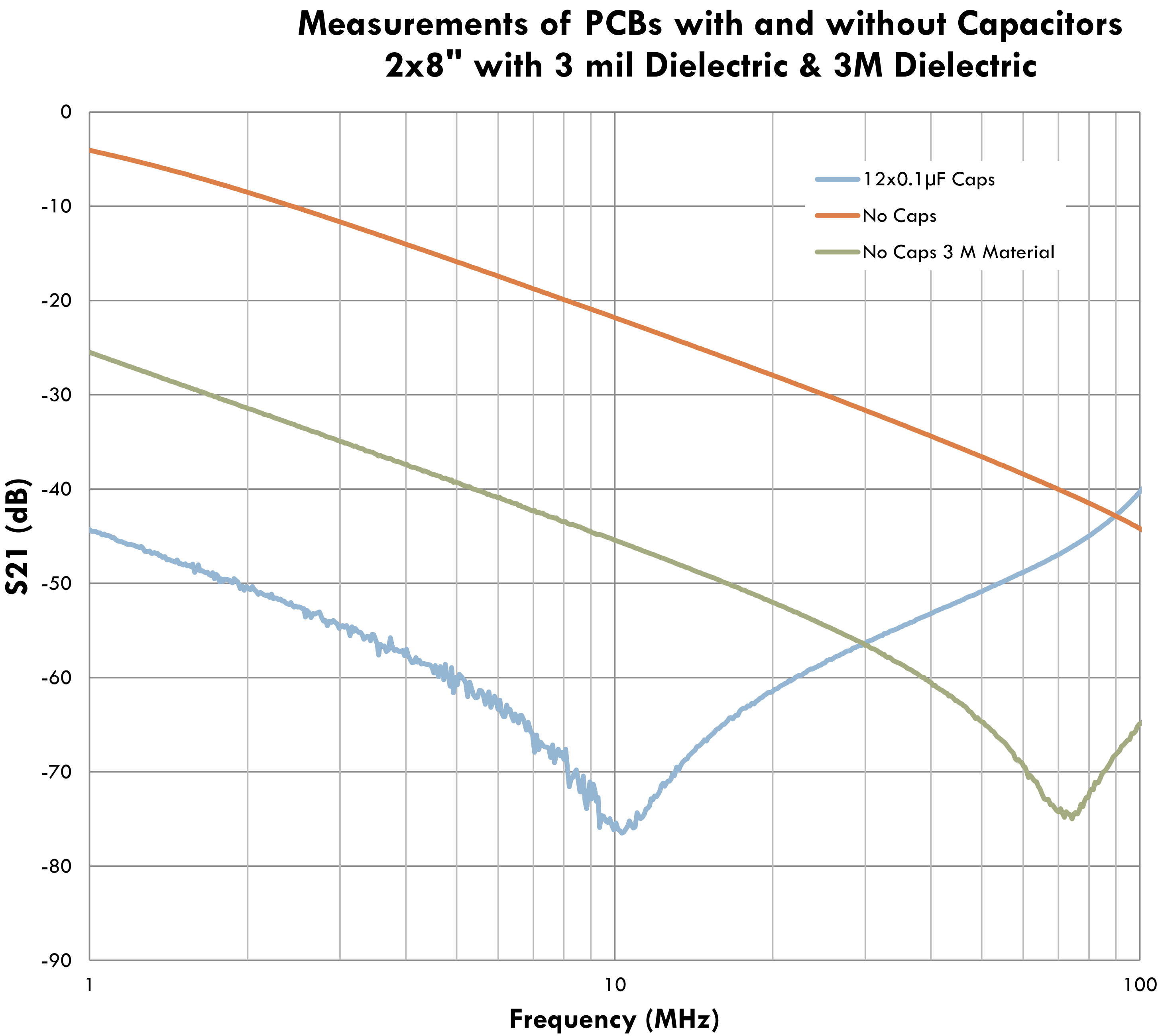
- Higher permittivity materials definitely have their advantages at lower frequency
- At higher frequency (in this case around 200MHz and up) the core material does not provide lower impedance
- Remember: closer plane spacing DOES impact high frequency impedance
- New materials can make it easier (cost effective) to manufacture PCBs with very close layers

PCBs of various dimensions with discrete capacitors

12 x 0.1µF capacitors added




Measurements of PCBs with and without Capacitors
2x8" 3 mil Dielectric
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
S21 (dB)
1
10
100
Frequency (MHz)
12x0.1µF Caps
No Caps

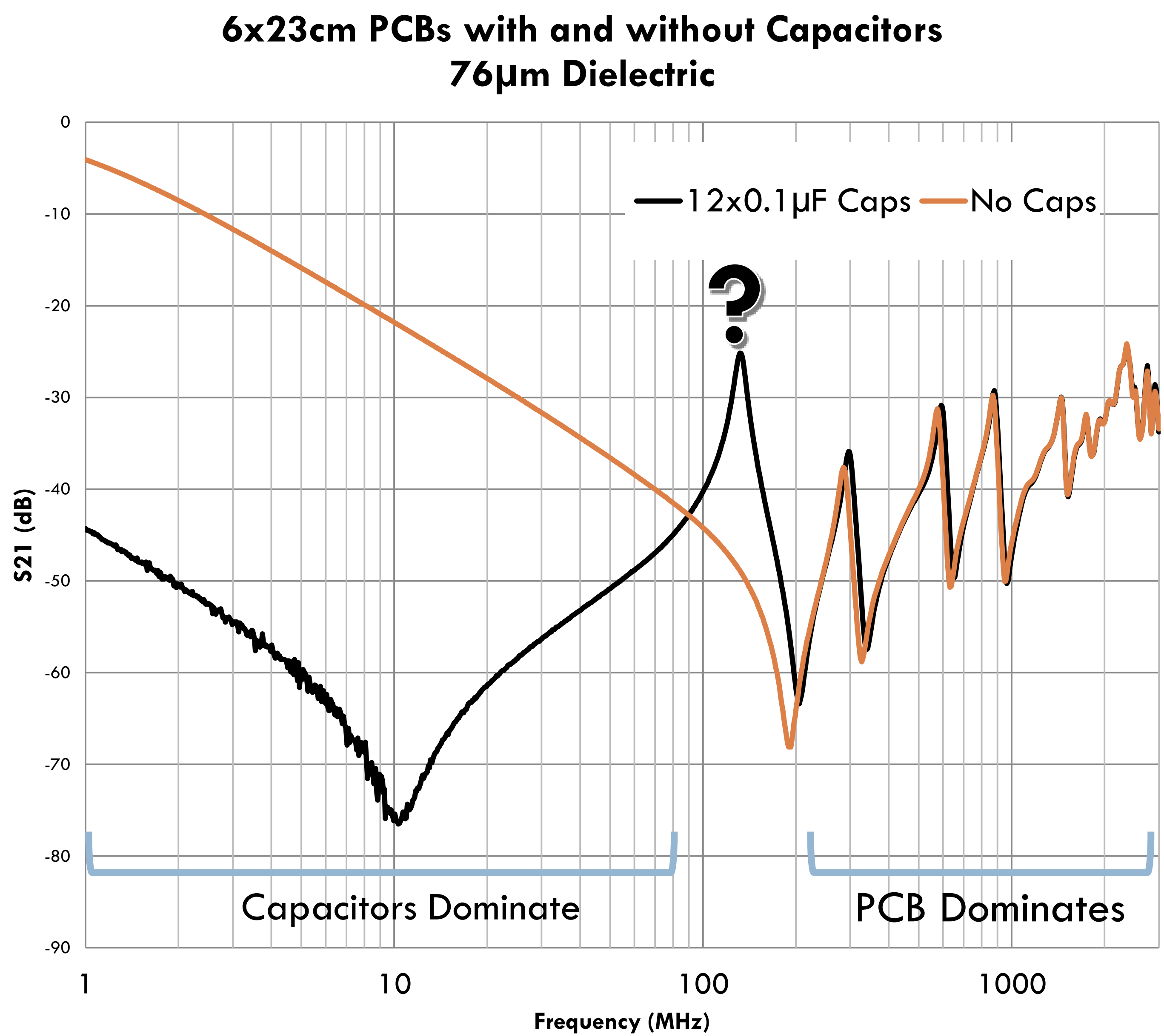

Measurements of PCBs with and without Capacitors
2x8" with 3 mil Dielectric & 3M Dielectric
S21 (dB)
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
1
10
100
Frequency (MHz)
12x0.1µF Caps
No Caps
No Caps 3 M Material

The Concept

Discrete chip decoupling capacitors provide low impedance at low frequencies (<100 MHz) but not at higher frequencies due to ESL

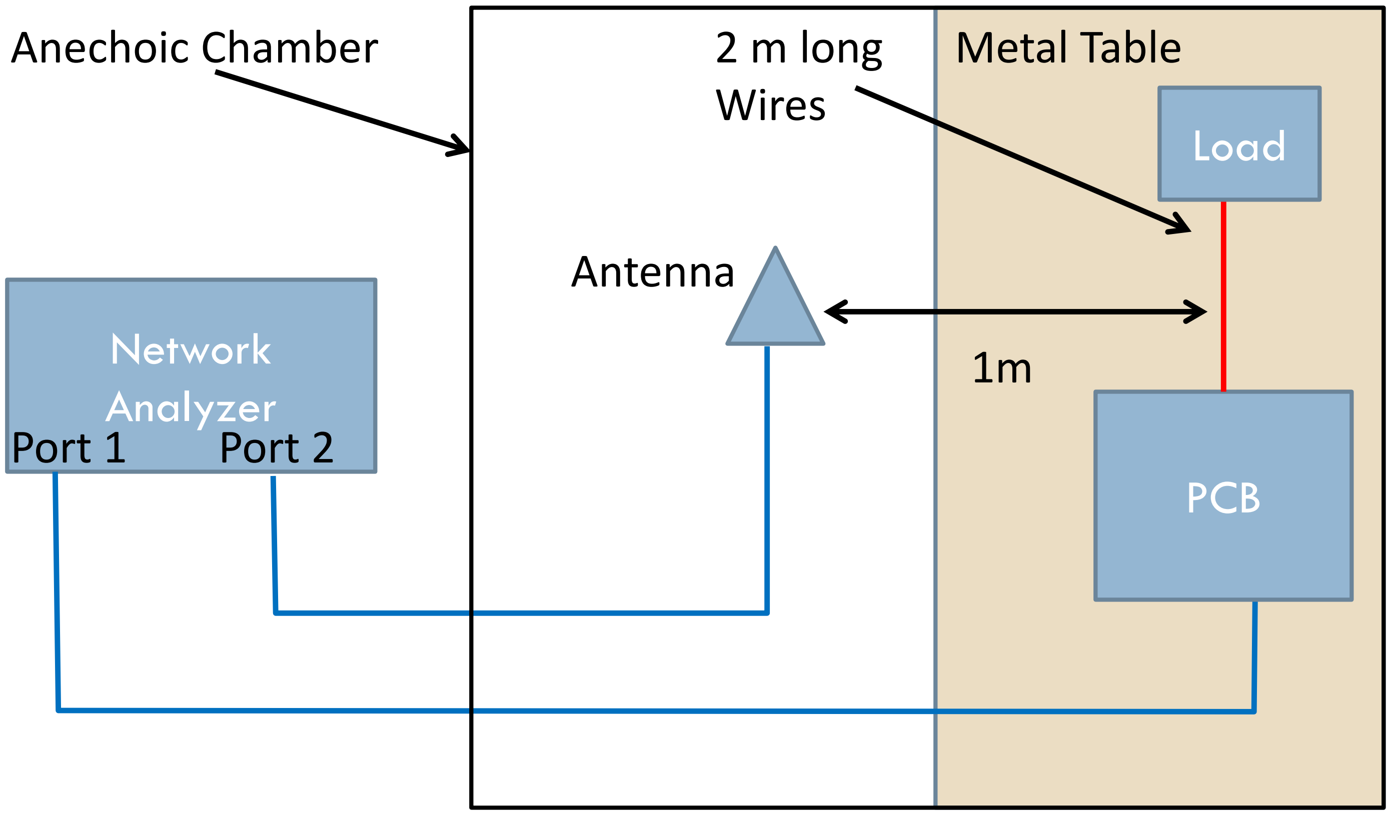
Embedded capacitance provides low impedance at high frequencies but typically do not perform as well as discrete capacitors in their usable range

Why not use both?

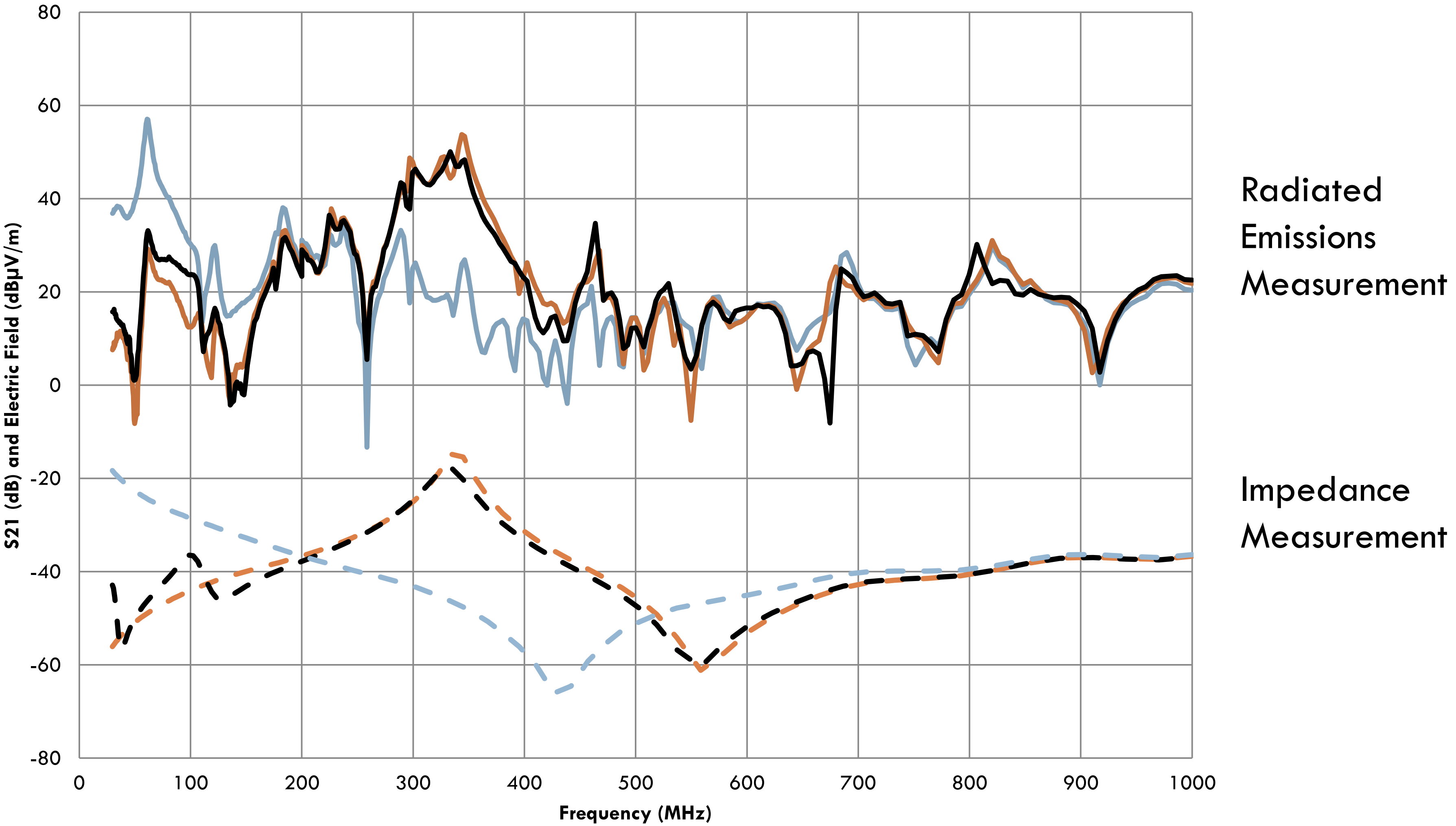

6x23cm PCBs with and without Capacitors
76μm Dielectric
12x0.1μF Caps
No Caps
S21 (dB)
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
1
10
100
1000
Frequency (MHz)
Capacitors Dominate
PCB Dominates
?

Radiated Emissions caused by plane resonance

Radiated Emissions Setup



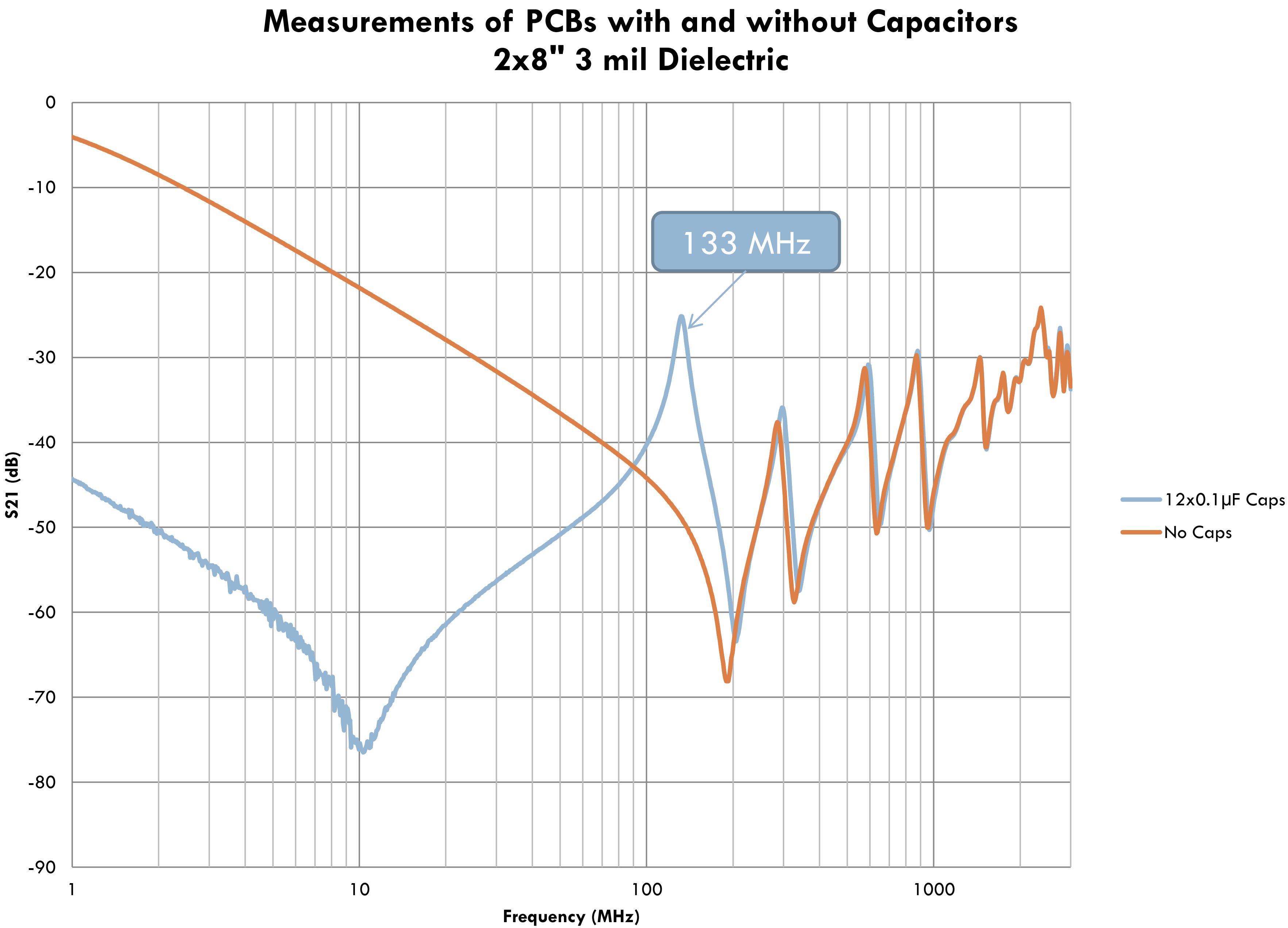
Comparison Between Decoupling Analysis and Radiated Emissions



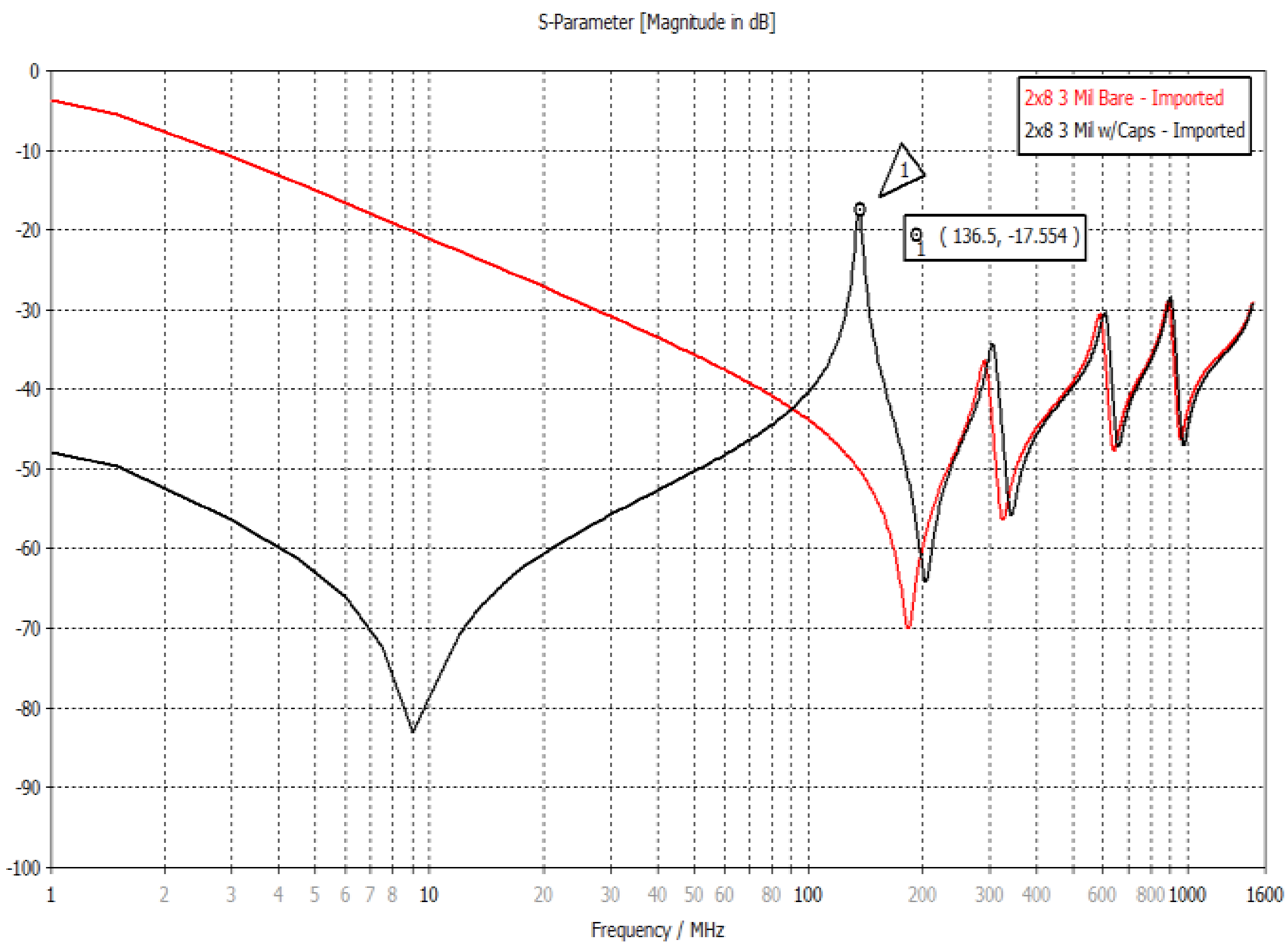
Radiated Emissions vs. PCB Impedance

- The measurement shows correlation between plane resonance and emissions
- Inadequate PDN impedance may cause excessive emissions
- PCB geometry is an important factor in emissions results

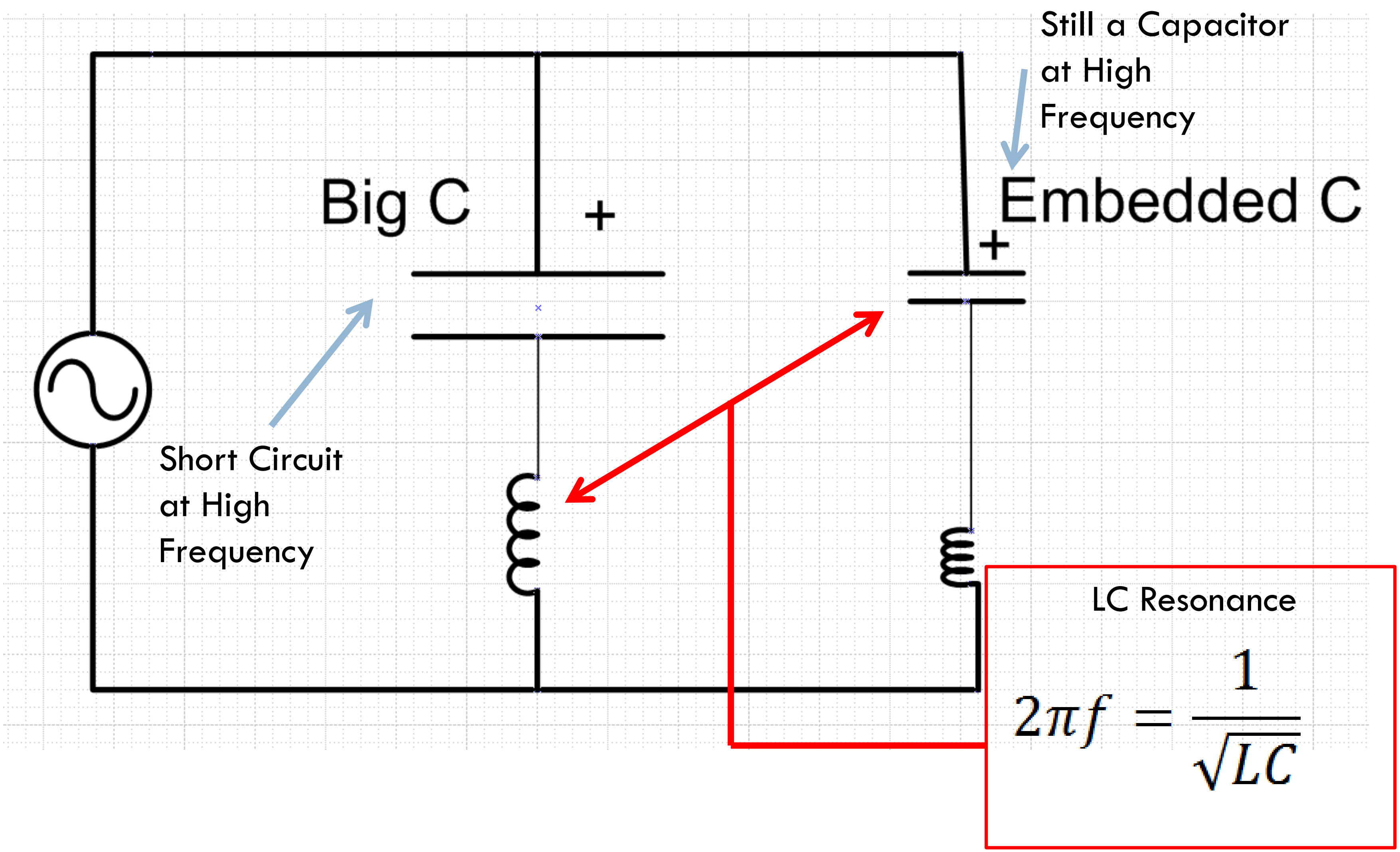
Changing PCB resonance frequency


Measurements of PCBs with and without Capacitors
2x8" 3 mil Dielectric
133 MHz
S21 (dB)
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
1
10
100
1000
Frequency (MHz)
12x0.1µF Caps
No Caps

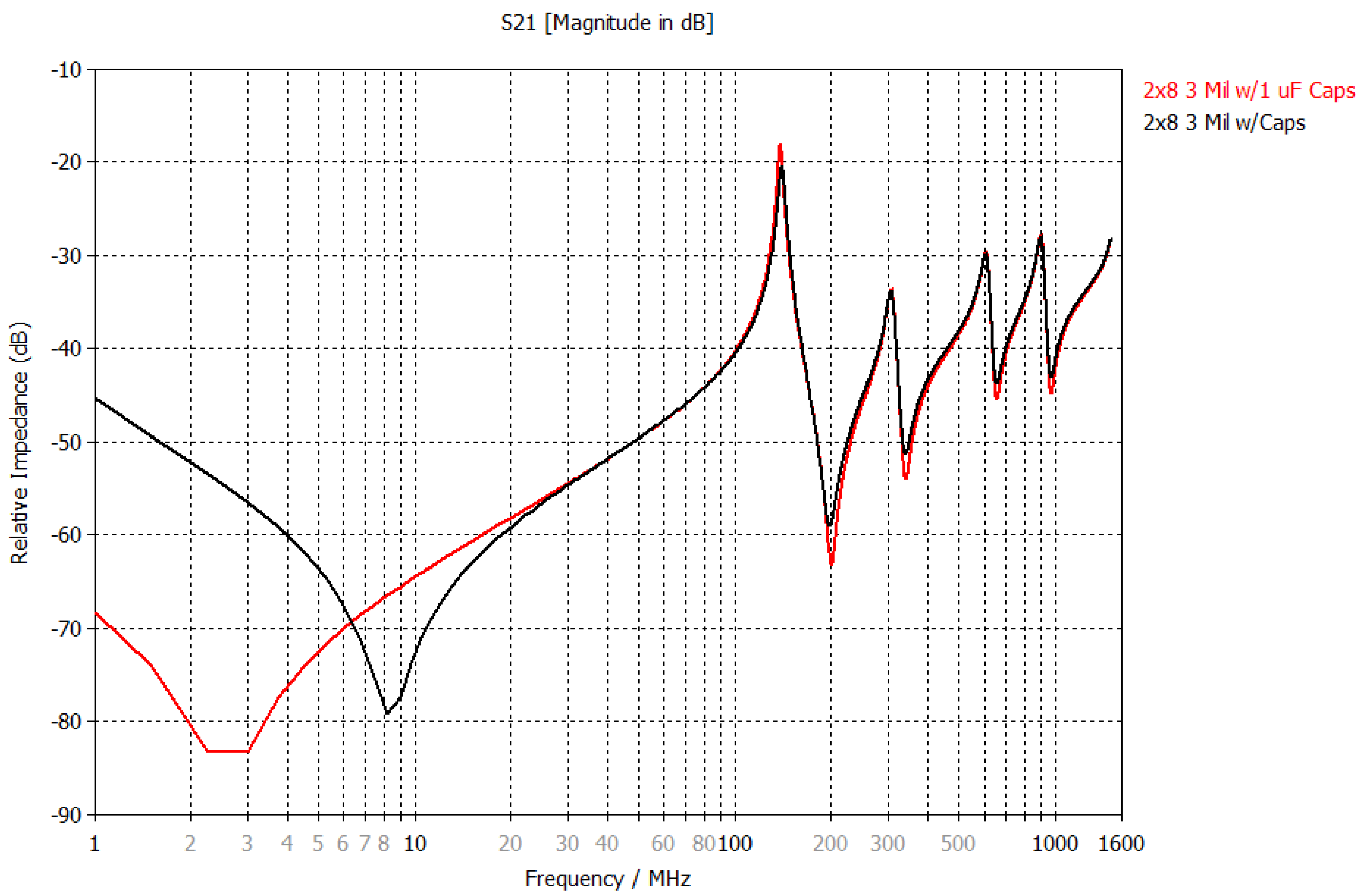
2x8" 3 Mil Simulation Results



Equivalent Circuit



0.1 µF vs. 1 µF Capacitor Values



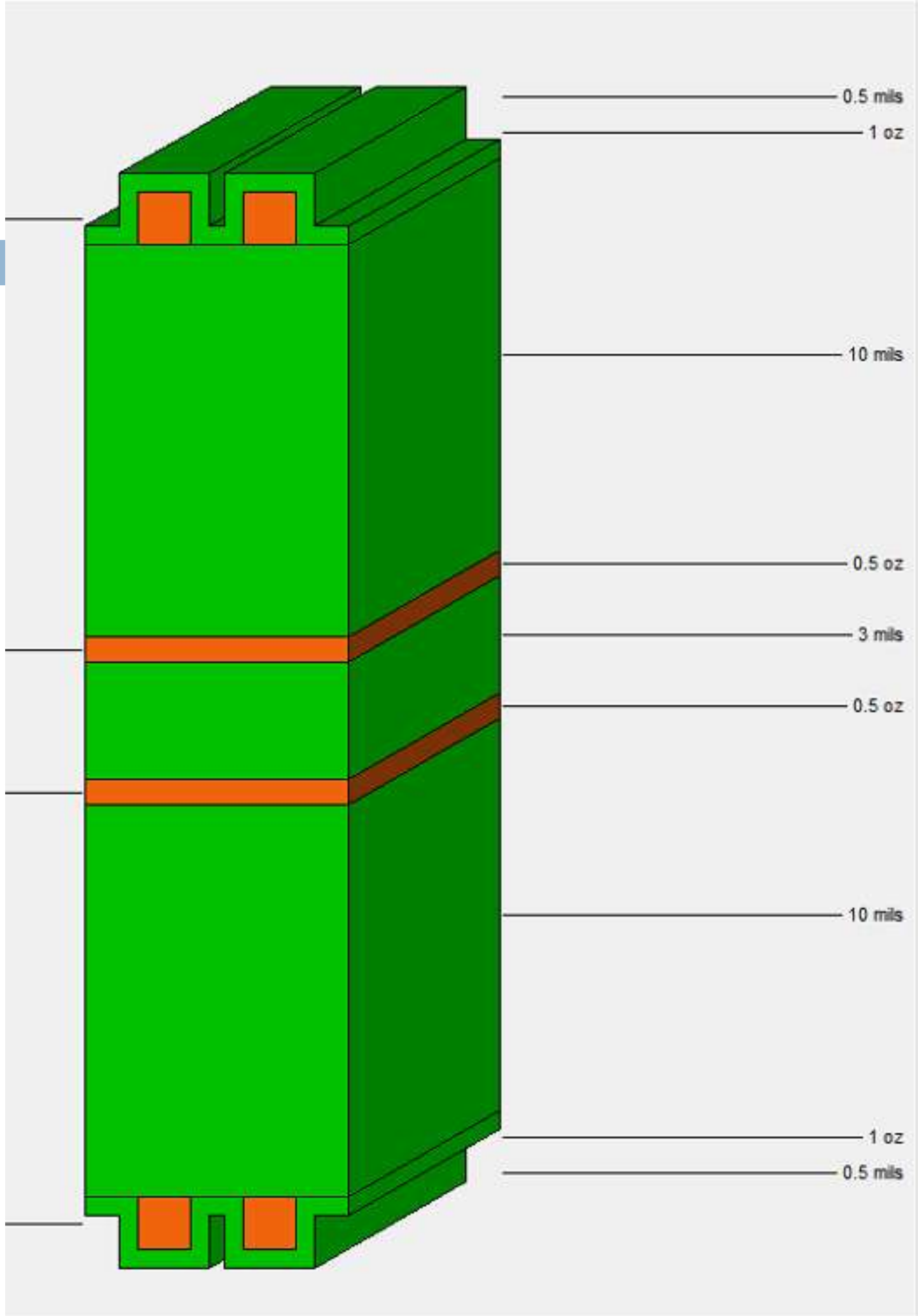
Discrete Capacitors and Embedded Capacitance

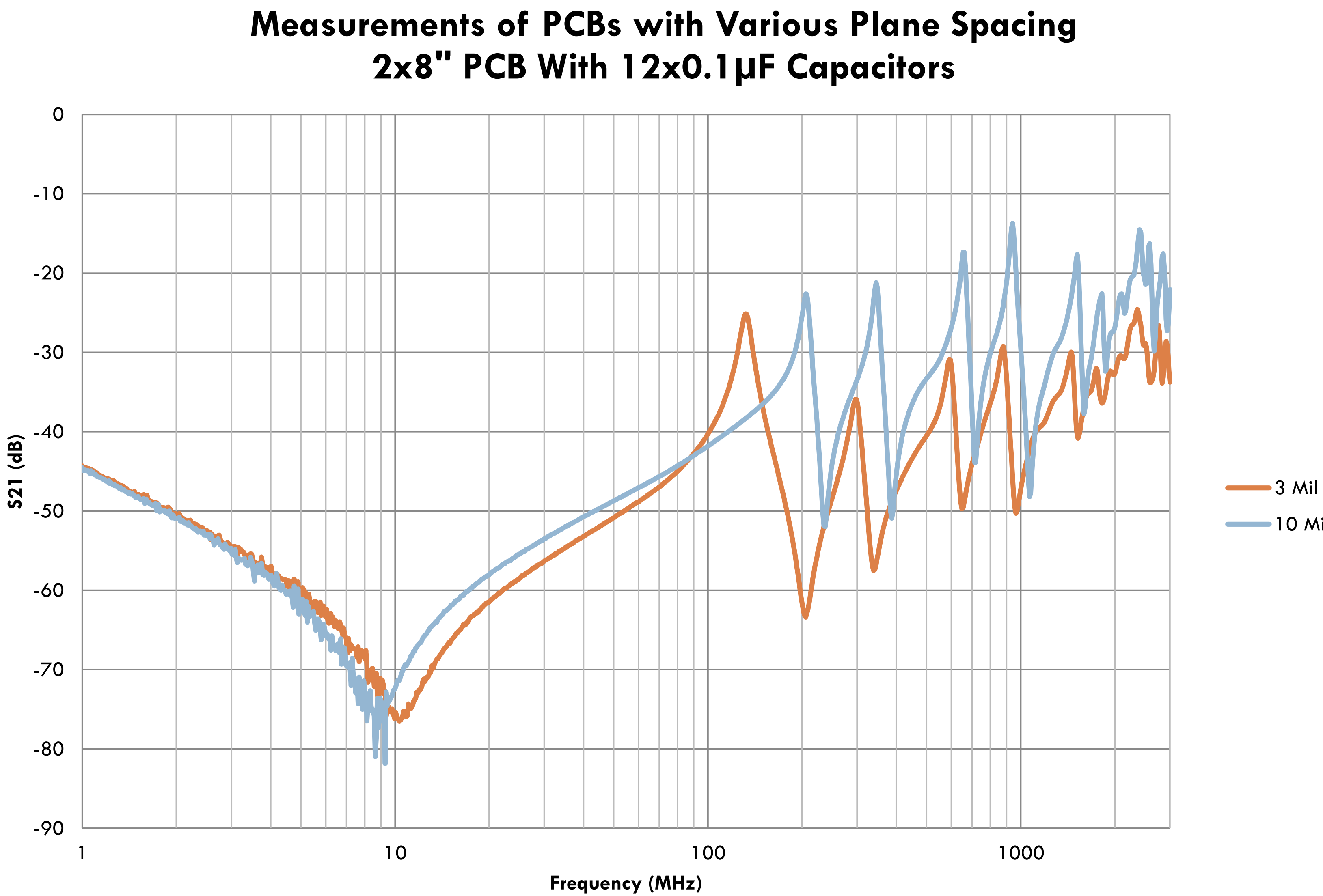
- Discrete capacitors and embedded capacitance can interact causing a parallel resonance raising PCB impedance at some frequencies even as low as 130 MHz for a 2x8” PCB

- This resonance is caused by the embedded capacitance and the ESL of the capacitor
  - The value of the capacitor is not important

Manipulation of the first parallel resonance

#1 Change Plane Spacing

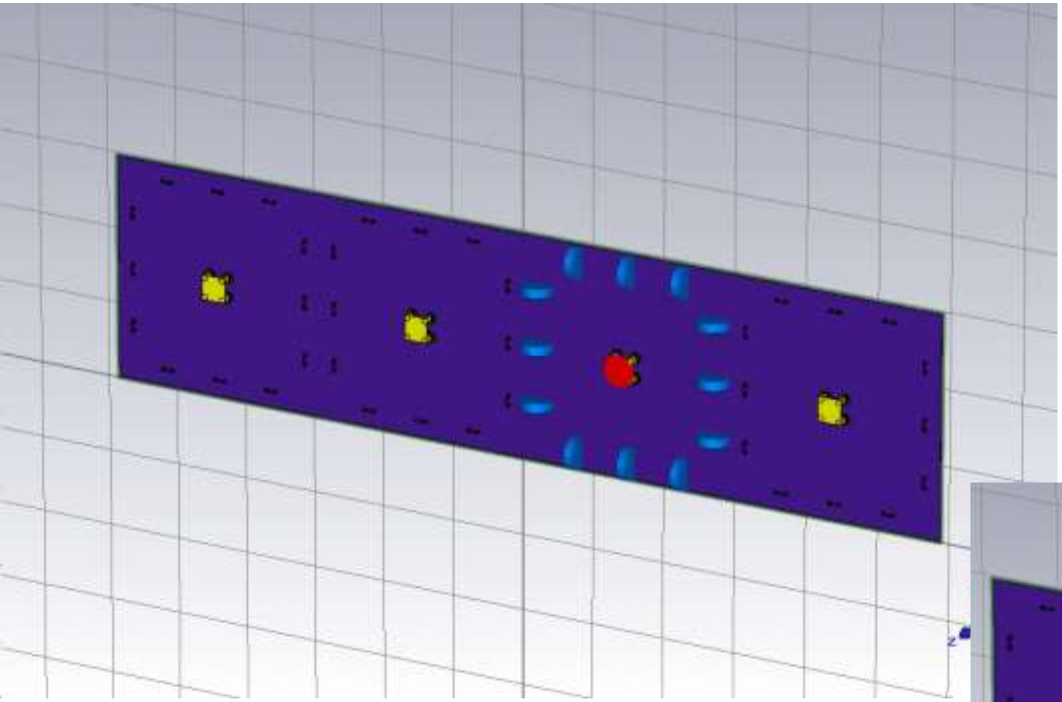


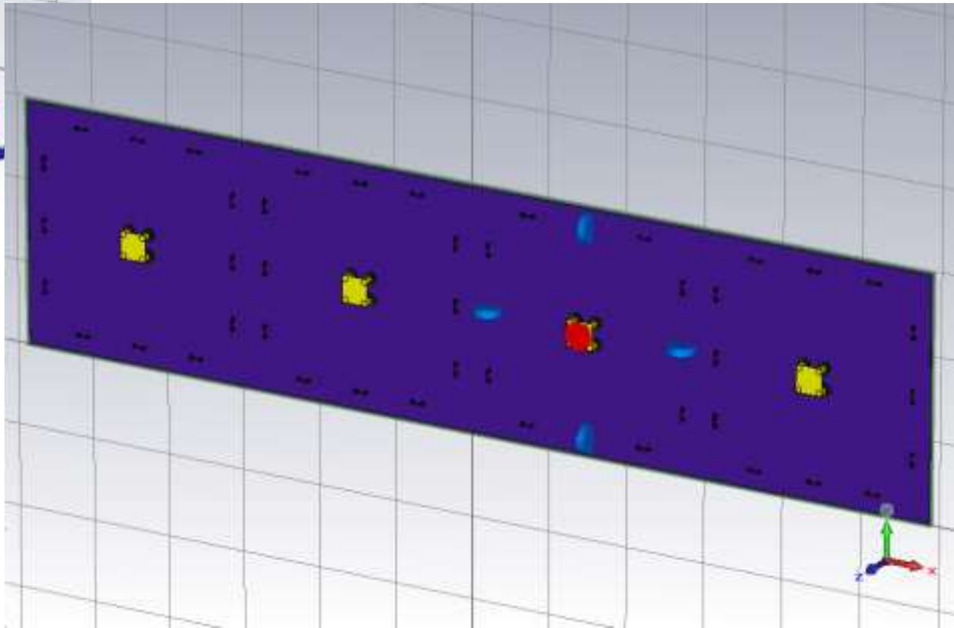


$$2\pi f = \frac{1}{\sqrt{LC}}$$

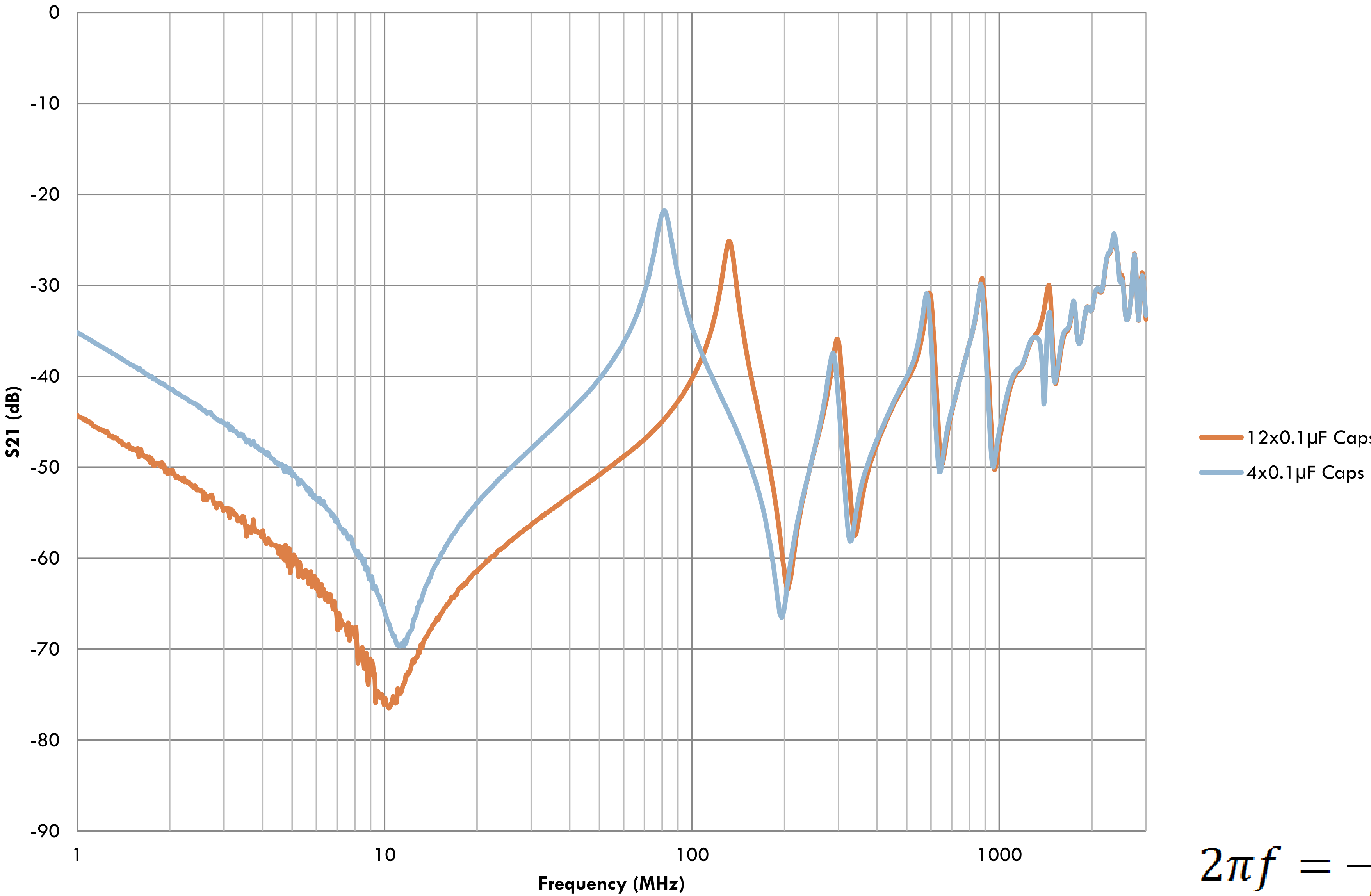
Changing plane spacing changes capacitance

#2 – Change Number of capacitors





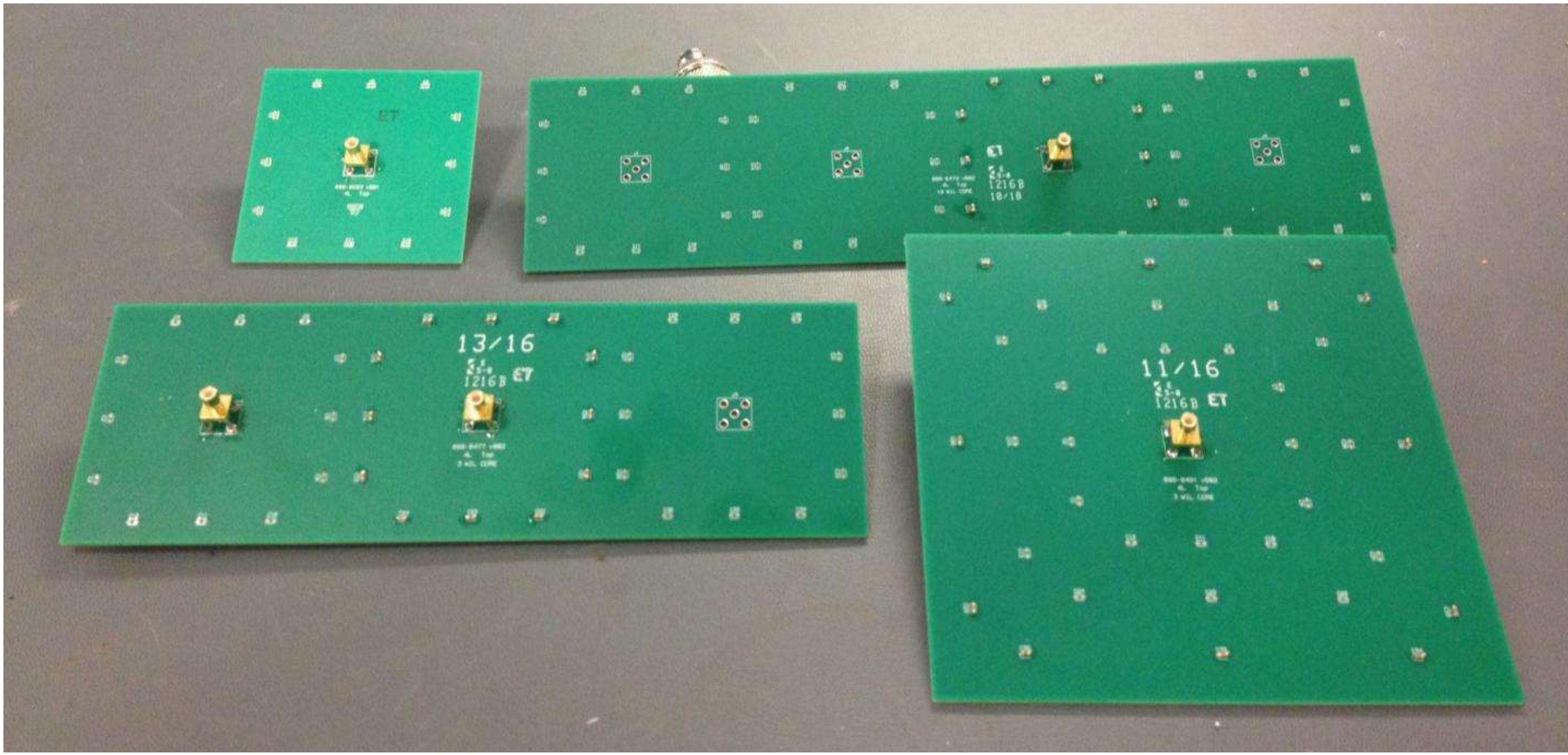
Measurements of PCBs with Various Number of Capacitors
2x8" PCB With 3 Mil Plane Spacing



$$2\pi f = \frac{1}{\sqrt{LC}}$$

Changing the number of capacitors changes inductance

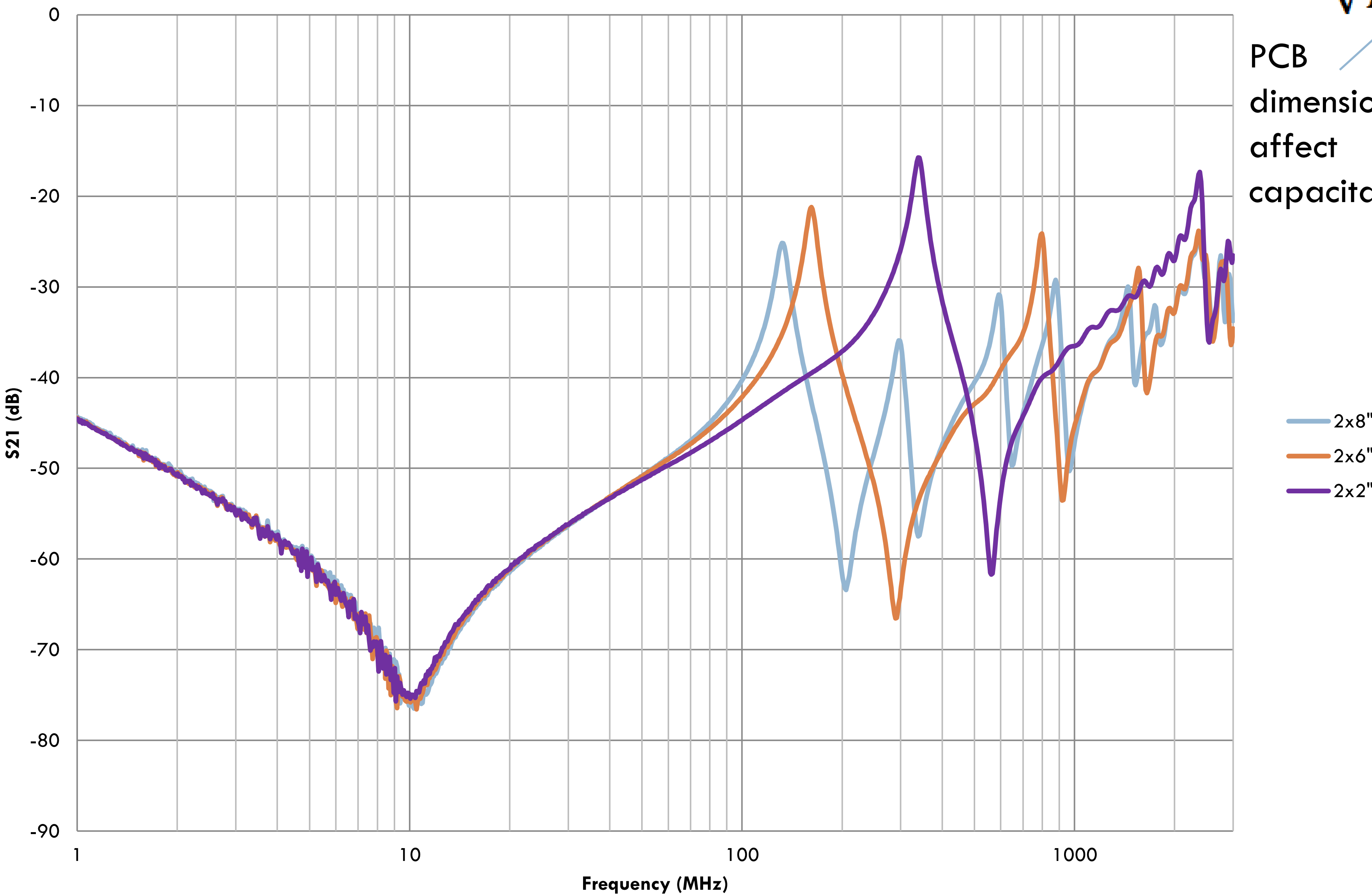
#3 Change PCB Dimensions



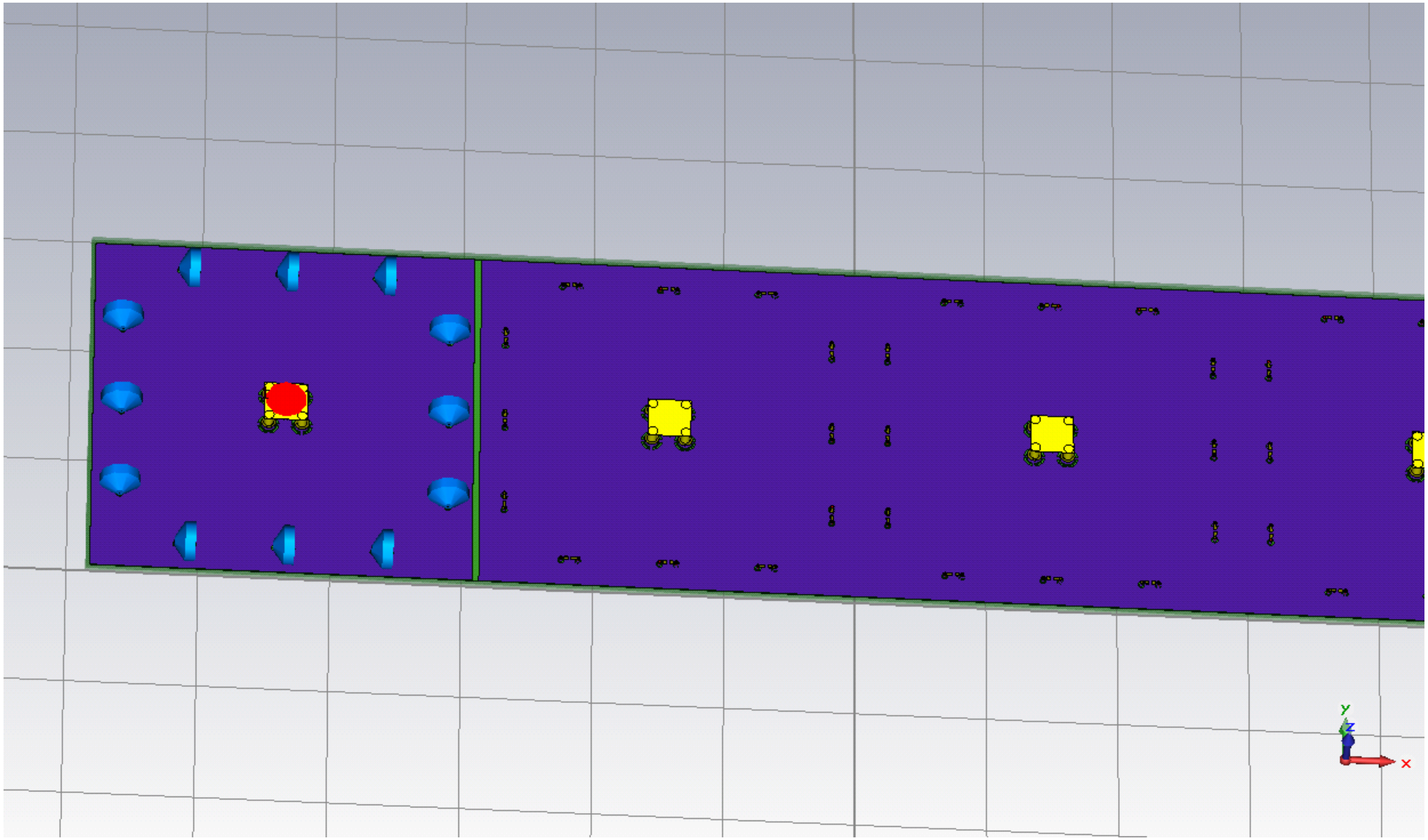
Measurement of PCBs with Varying Dimensions
3 mil Dielectric Thickness with 12x0.1µF Capacitors

$$2\pi f = \frac{1}{\sqrt{LC}}$$

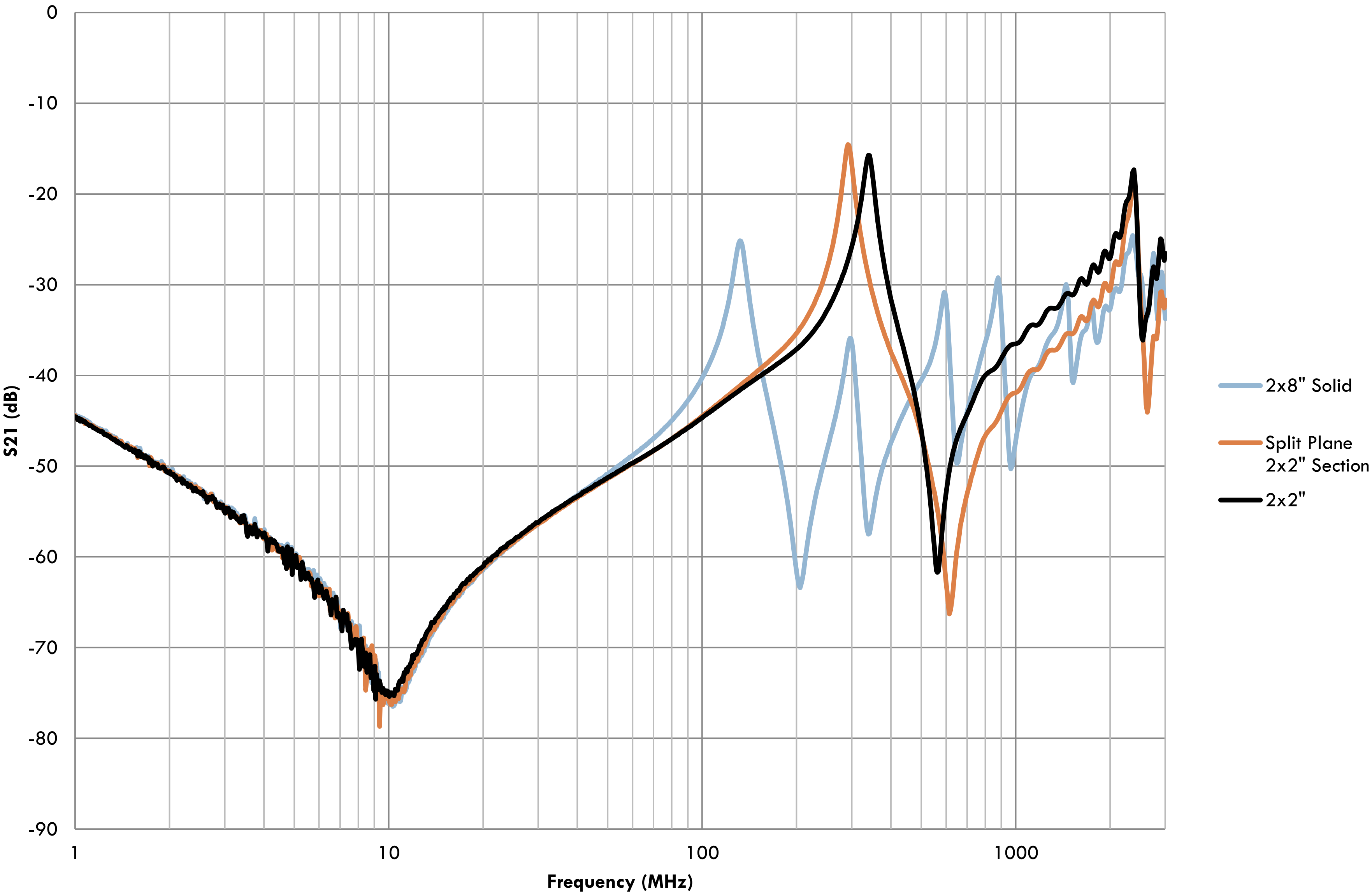
PCB dimensions affect capacitance



One Plane Split



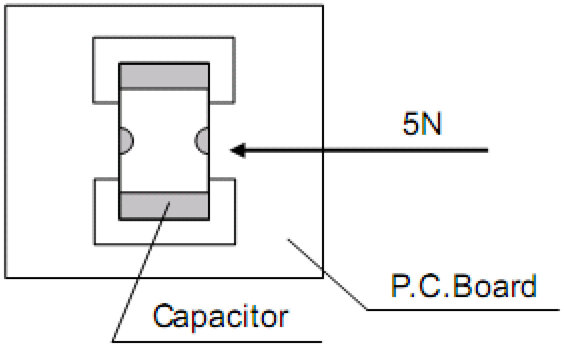
Measurement of PCBs with Varying Dimensions
3 mil Dielectric Thickness with 12x0.1µF Capacitors

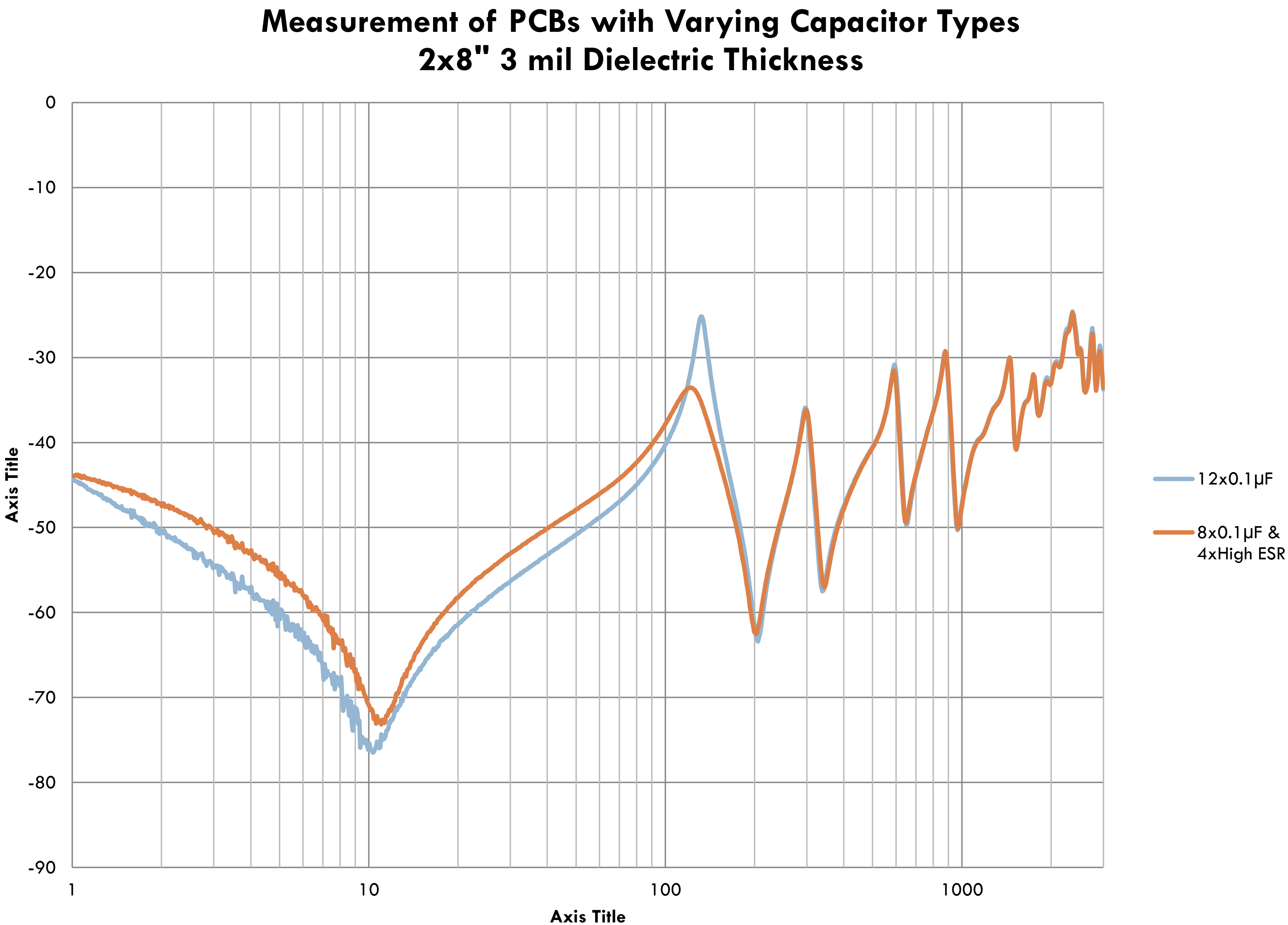


Splitting the plane will decrease the plane area causing a lower capacitance value

#4 - High ESR Capacitors

- 0603 Size capacitors made by TDK
- Center terminal is not connected to anything
- Contains up to 1.2 Ohms of series resistance
- More expensive than standard capacitors but benefit can be seen by replacing some standard capacitors with high ESR capacitors





Resistance in series with the capacitor will create loss at the resonant frequency

Parallel Resonance due to Embedded Capacitance

- **Further plane spacing** = higher frequency resonance
- **More capacitors** = higher frequency resonance
- **Smaller planes** = higher frequency resonance
- **More Series Resistance** = less resonance

Is a higher frequency resonance better than a lower frequency resonance?
….. It depends!

Summary

- Plane impedance can be determined using EM simulation and measuring equipment but plane connections may cause error
- PCB Power/Ground Plane Separation
  - Below resonant frequency, the PCB planes behave as a parallel plate capacitor and the capacitance can be easily calculated
  - Above resonant frequency, plane impedance is more complicated and it depends on several factors including PCB geometry
- Dielectric Material
  - Higher permittivity materials cause higher capacitance below the PCB resonance which can be useful in PDN design
  - Higher permittivity materials do not make a significant difference in PDN impedance at high frequency but the close plane spacing which generally accompanies high permittivity materials make a great difference
- Adding Discrete capacitors
  - PCB embedded capacitance for most devices still can't provide low impedance PDN compared to discrete capacitor components on PCBs
  - Using embedded PCB capacitance along with discrete capacitors can be a good solution but will cause a resonance at a frequency depending on the number of capacitors and the amount of PCB capacitance.