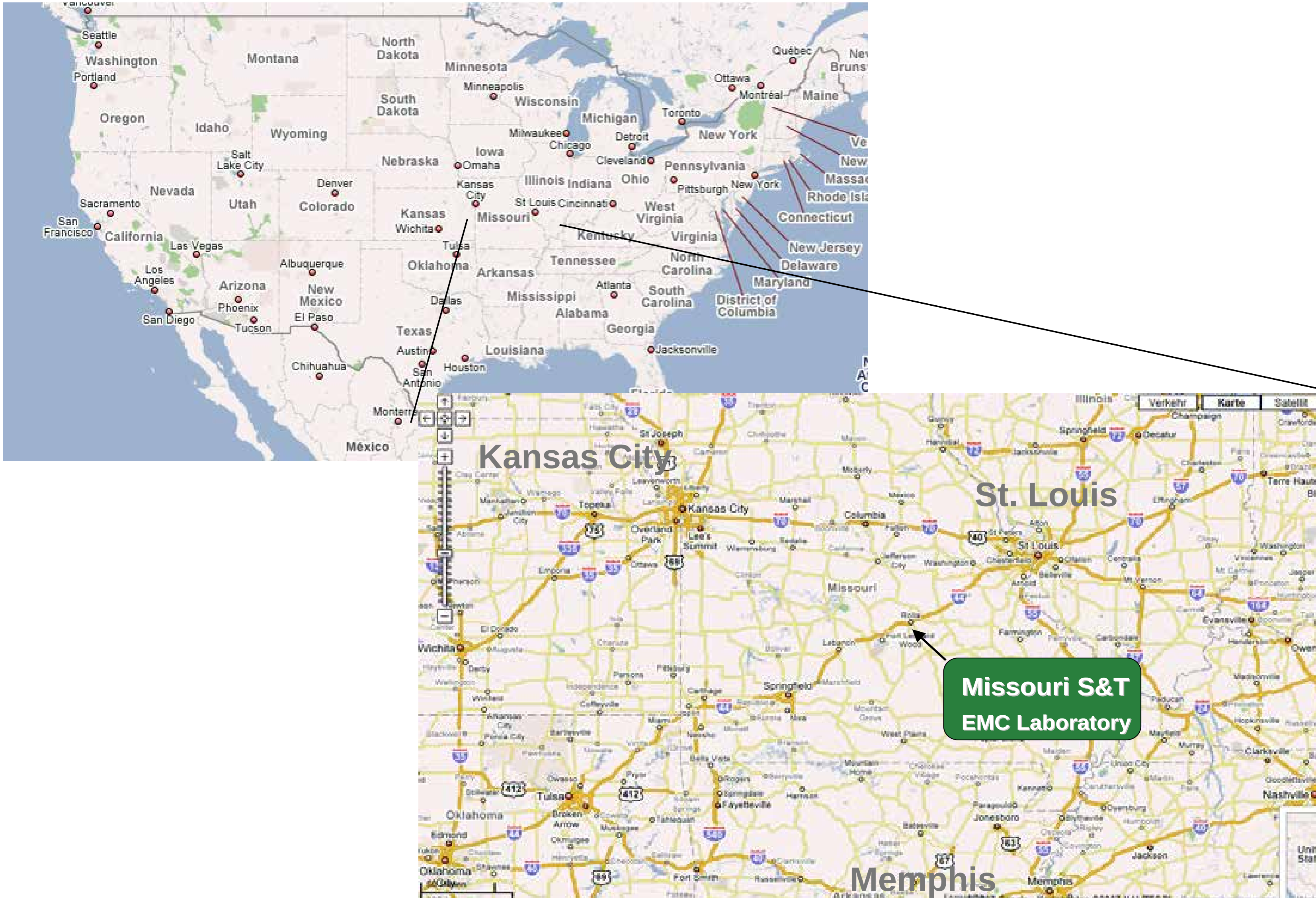
EMC Filter Analysis

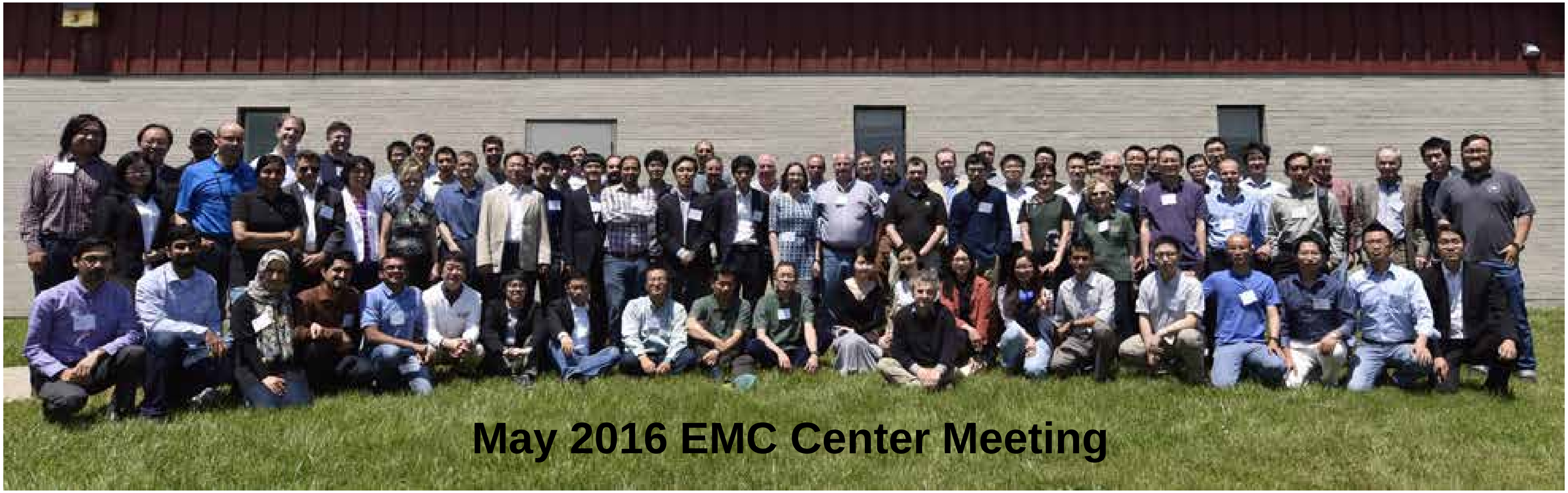
Dr. David Pommerenke with the help of many members of the EMC laboratory

November 2018

EMC laboratory Missouri S&T



The group



- 6 Tenured faculty
- 8 Research faculty
- 4 Adjunct faculty
- 6 Visiting scholars
- Laboratory technician
- >40 students
  - 11 PhD
  - 31 MS
  - 4 undergraduate
- 2 Administrative support

Research partners from industry and government

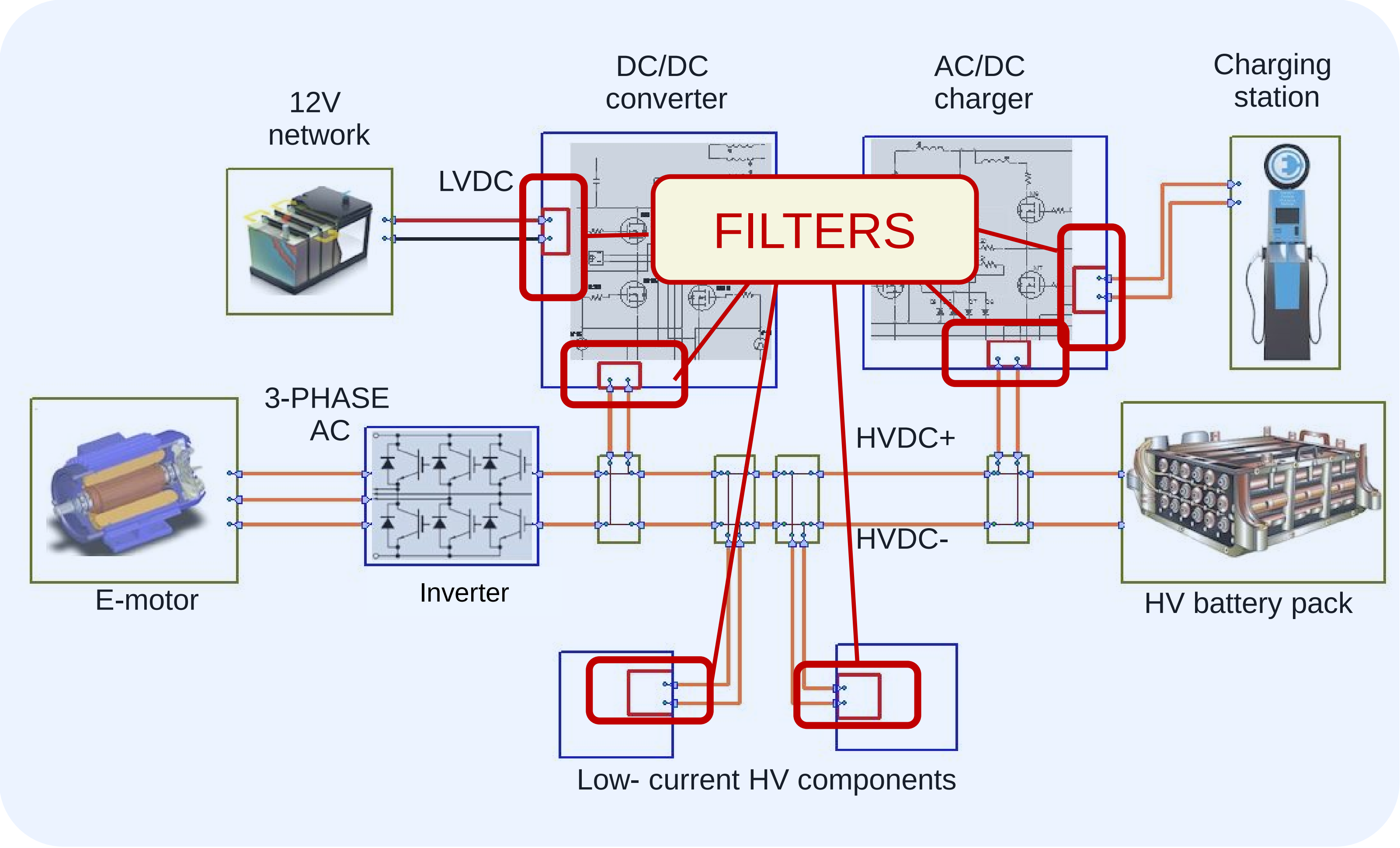
Most projects are in close cooperation with industry

Where are Our Graduates? 105 MS, 53 PhD, 12 Postdocs

And other companies
http://www.emclab.mst.edu/studfac/alumni.html

- **Intel Corporation** **(Total 19: 9-PhD/10-MS)**
  - Oleg Kashurkin, MSEE 2016
  - Ben Orr, PhD 2016
  - Wei Qian, MSEE 2016
  - Xinyao Guo, MSEE 2016
  - Jayong Kool, Ph.D. 2008
  - Vijay Kasturi, MSEE. 2007
  - Juan Chen, MSEE 1999 (Princ. Engin.)
- **Altera** **(Total 5: 4-Ph.D/1-MS)**
  - Xinyun Guo, MSEE 2016
  - Jianmin Zhang, Ph.D. 2007
  - Shishuang Sun, Ph.D. 2006
  - Kundan Chand, MSEE. 2006
- **Apple Computer (Total 20: 10-Ph.D/10-MS)**
  - Abhishek Patnaik, Pd.D. 2018
  - Satyajeet Shinde, PhD 2017
  - Kyoungchoul Koo, PostDoc 2017
  - Guangyao Shen, PhD 2016
  - Guanghua Li, PhD 2015
  - Xu Gao, Ph.D. 2014
  - Tianqi Li, Ph.D. 2014
  - Andriy Radchenko, Ph.D. 2014
  - Kam Keong Ph.D. 2012
  - Frederico Centola, MSEE 2003
- **NVidia**
  - Aukit Bharagava, MSEE. 2010
  - Fan-Keung Chang, MSEE. 2006
  - Chen Wang, Ph.D. 2004
- **Cisco** **(Total 13: 3-Ph.D/10-MS)**
  - Kartheek Nalla, MSEE 2016
  - Chunchun Sui, PhD 2015
  - Natalia Bondarenko, Ph.D. 2015
  - Xiangyang Jiao, MSEE 2015
  - Soumya De, Ph.D. 2012
  - Amendra Koul, MSEE. 2010
- **Motorola**
  - Bivin Varghese, MSEE. 2003
  - Prem Ganeshan, MSEE. 1998
- **Panasonic**
  - Xiao Luo, MSEE. 1999
  - Janet Luo, MSEE. 1998
- **Dell Computer**
  - Arun Chada, Ph.D. 2014
  - Lauren Zhang, MSEE. 1999
- **Google**
  - Suyu Yang, MSEE 2016
  - Jingnan Pan, PhD 2015
  - Ketan Shringarpure, PhD 2014
  - Weifeng Pan, PhD, 2008
  - Sandeep Chandra, MSEE 2007
- **Sandia National Laboratory**
  - Ben Conley, MSEE, 2015
  - Matthew Halligan, PhD 2014
  - Matt Schepers, MSEE. 2010
  - David Carter, MSEE. 2004
- **Broadcom Corporation**
  - Hongyu Li, Ph.D. 2012
  - Liehui Ren, Ph.D. 2011
- **Agilent Technologies**
  - Joe Bishop, M.S. 2011
  - Kuifeng Hu, PhD. 2007
- **Juniper Networks**
  - Qian Liu, MSEE 2016
  - Hui He, MSEE 2015
- **Mentor Graphics Corp.**
  - Aleksandr Gafarov, MSEE 2012
  - Praveen Anmula, MSEE 2009
- **IBM Systems**
  - Matteo Cocchini, MSEE. 2008
  - Michael Cracraft, PhD 2007
  - Xiaoxiong Gu, MSEE. 2002
- **Research in Motion**
  - Gang Feng, PhD 2010
  - Qing Cai, MSEE 2007
- **Lockheed Martin**
  - Jim Feucht, MSEE 2010
- **Amazon**
  - Liang Li, MSEE 2016
- **Semtech Corp.**
  - Li Zhen, MSEE 2011
- **Texas Instruments**
  - Haixiao Weng, Ph.D. 2006

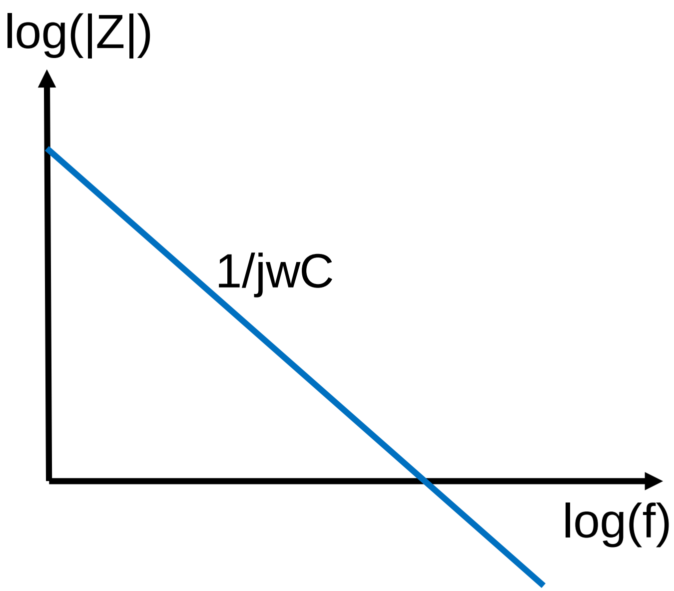
Introduction. EMC Filters in Power Electronics

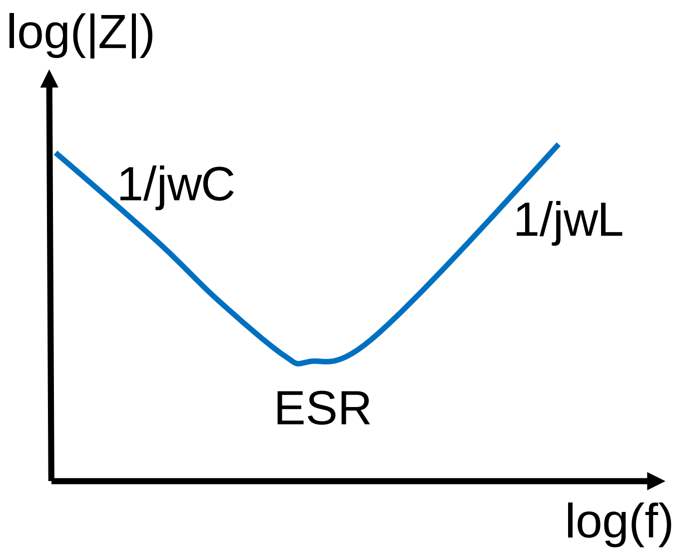


Structure of the talk

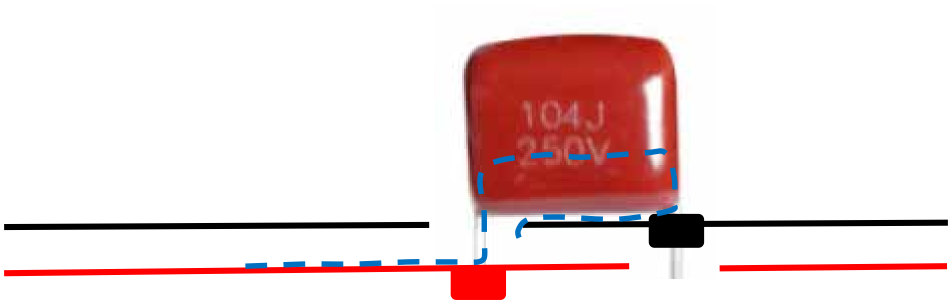
- Different solution path: Circuit, Circuit with parasitics, full wave
- Film Capacitor modeling
- SMT Capacitor modeling
- CMC modeling
- Material property extraction
- Examples of properties of magnetic materials used in EMC

One capacitor

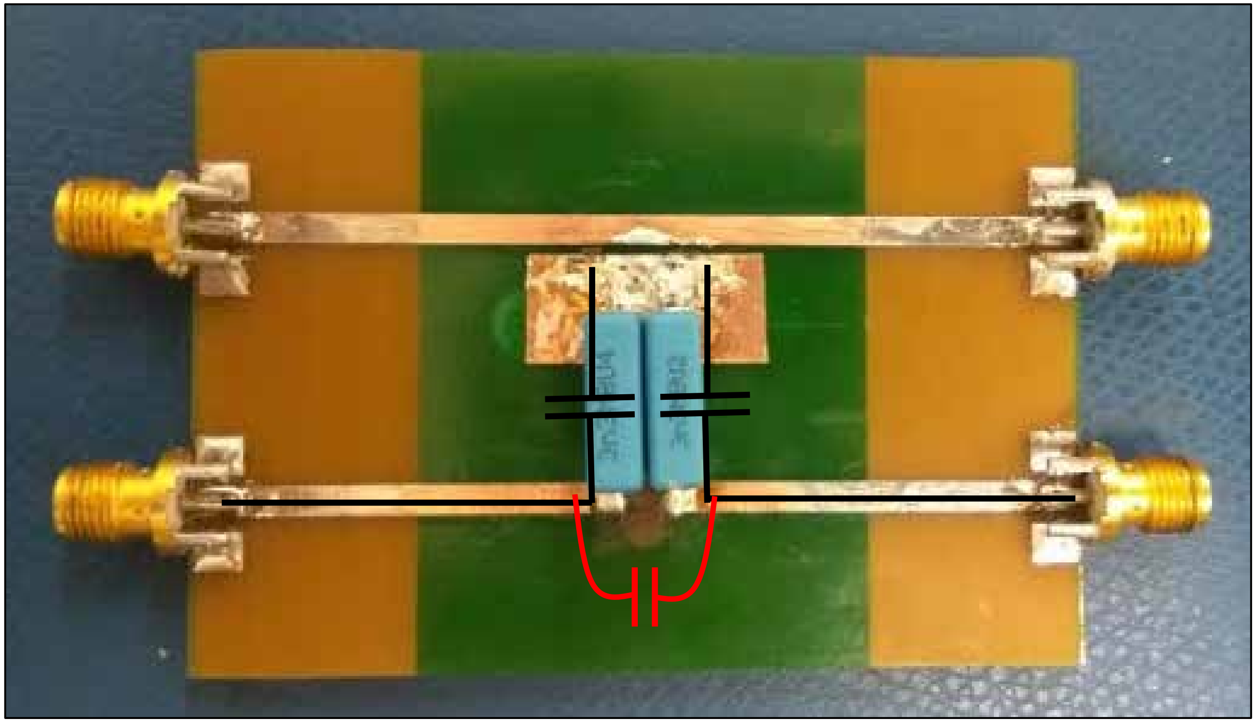




With increased modeling requirement, more and more EM effects need to be considered.



Two capacitors



Capacitive coupling exists between components.

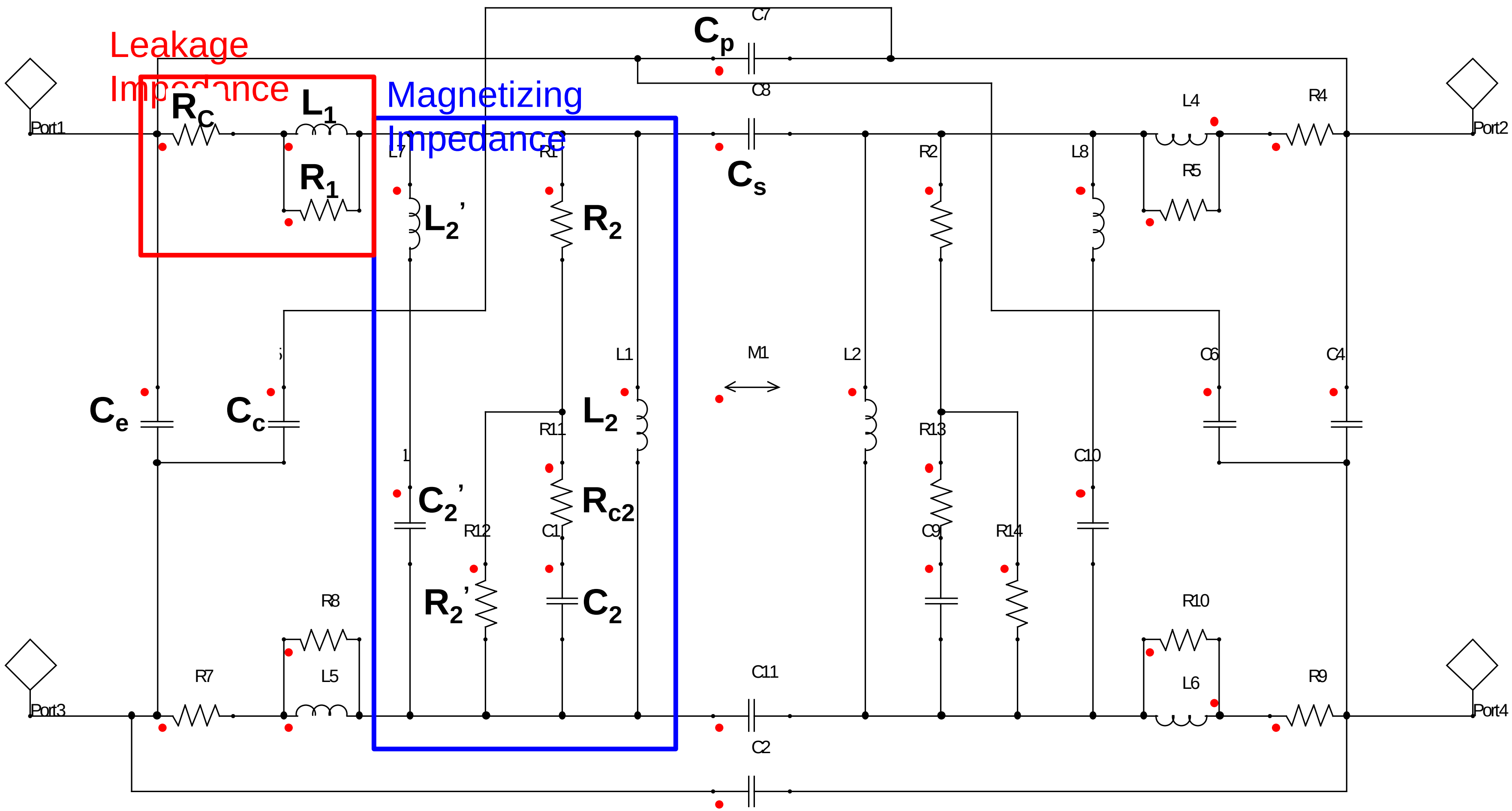
In reality there will be chassis, traces, and other components involved, making the circuit model more complex.

Building a full wave model helps with more accurate evaluation of the coupling, and easier to implement if the modelling strategy is clarified.

CMC characterization: Sounds too simple!

Characterization of EMI Chokes

Circuit Model for Choke as Proposed:

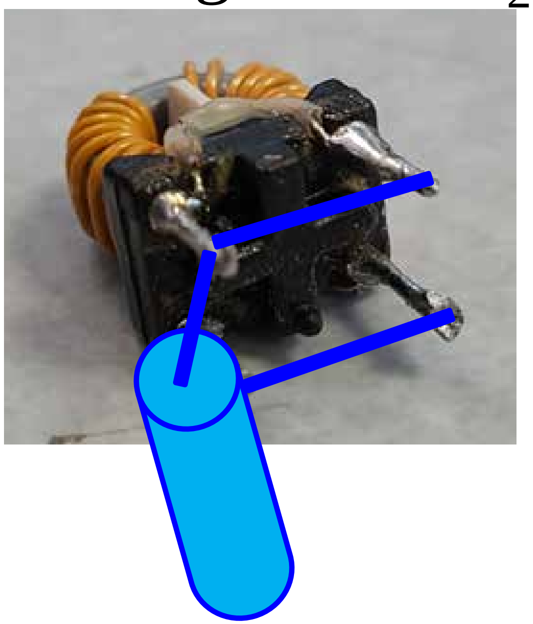


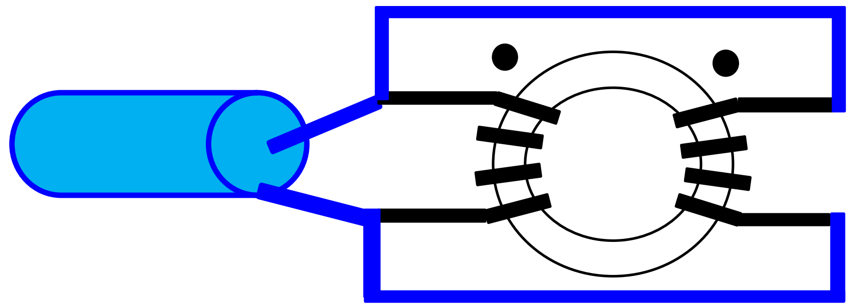
Characterization of EMI Chokes

- Using different connections, open and shorts the value of individual elements or groups of elements can be determined.
- Alternative methods use S-parameters, however, if one element has only a small effect on the S-parameters the extraction is error prone

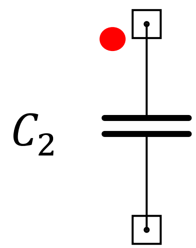
Characterization of EMI Chokes

- Configuration T_2



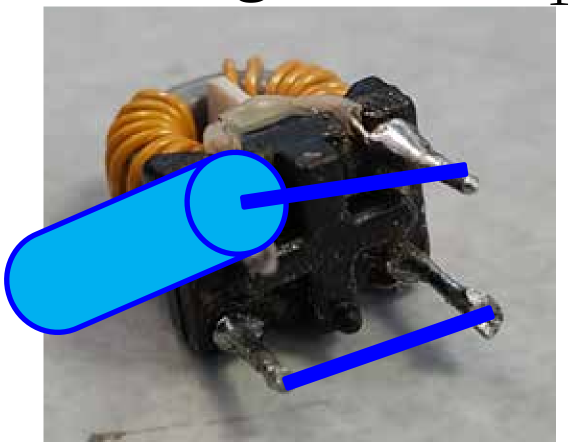


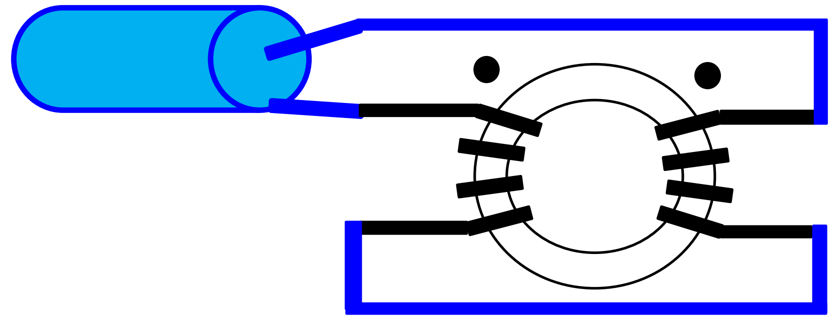
- Equivalent Circuit:



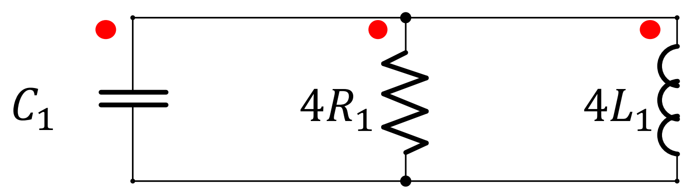
Characterization of EMI Chokes

- Configuration T_1

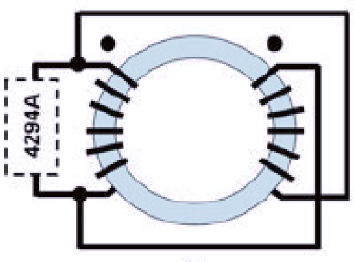


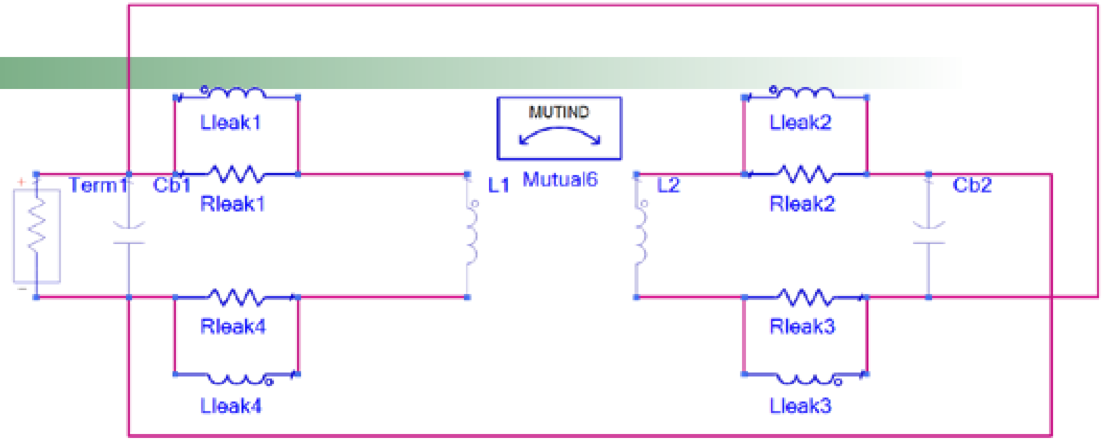


- Equivalent Circuit:

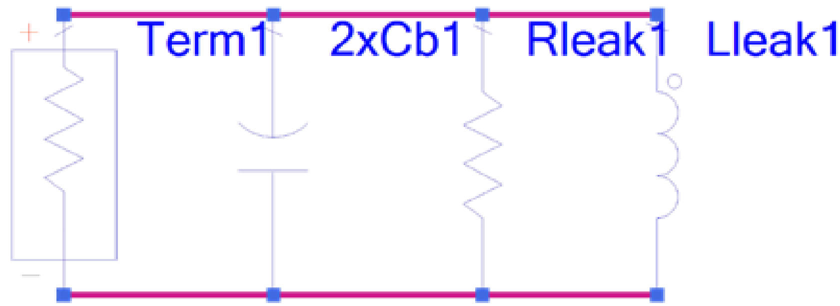


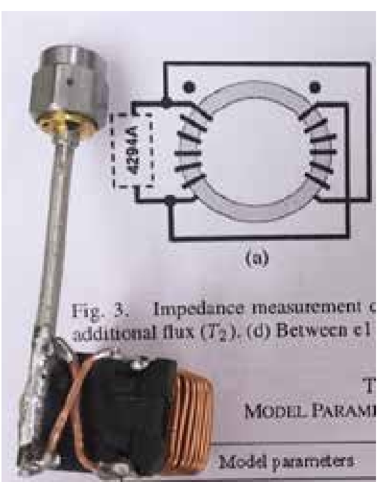
Obtain Z_{leak}, C_b

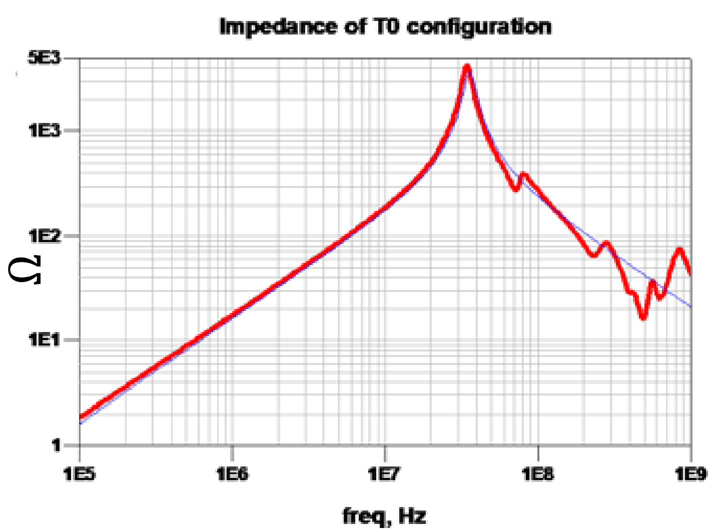




This configuration only provides the leakage





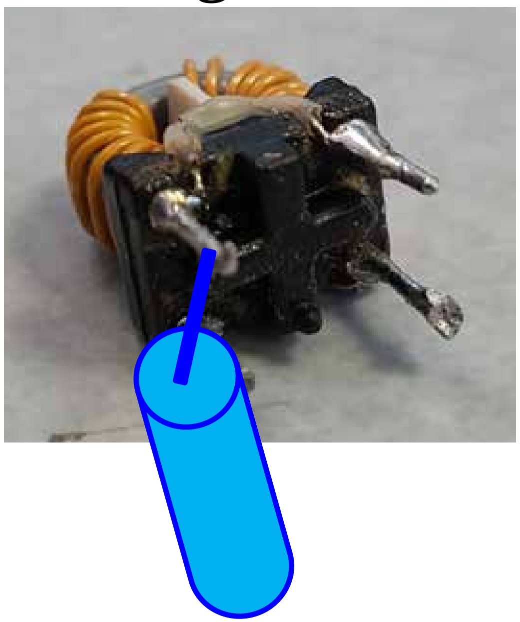


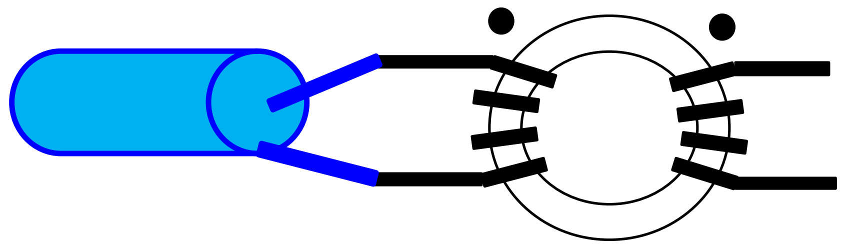
The extracted parameters:

$$R_{leak} = 3.67k\Omega$$
$$L_{leak} = 2.85\mu H$$
$$C_p = 3.8pF$$

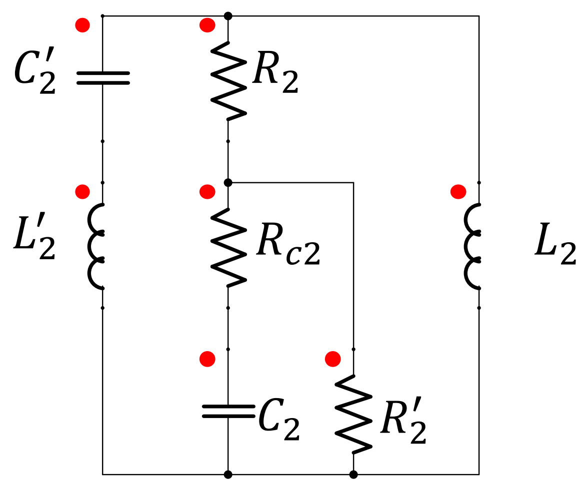
Characterization of EMI Chokes [1]

- Configuration T_4



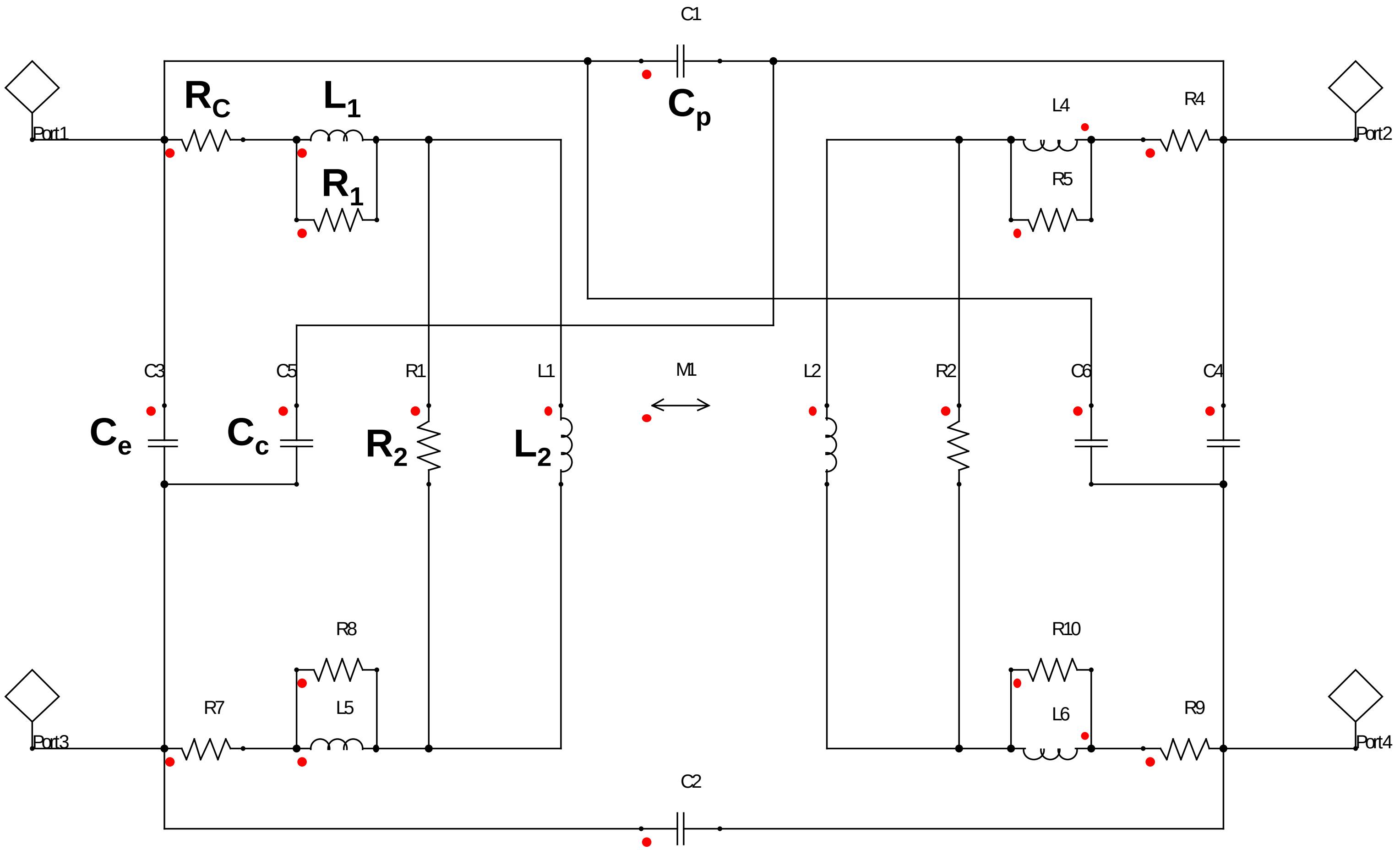


- Equivalent Circuit:



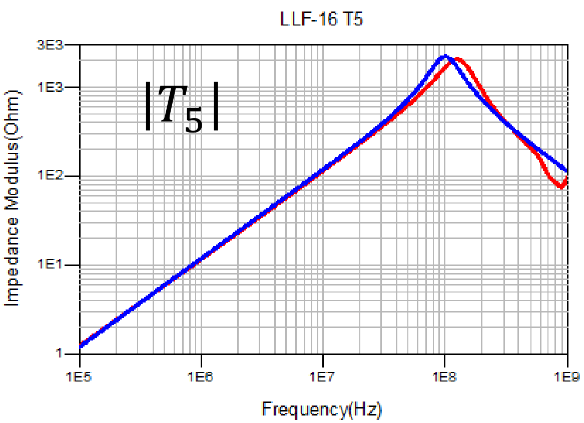
Characterization of EMI Chokes

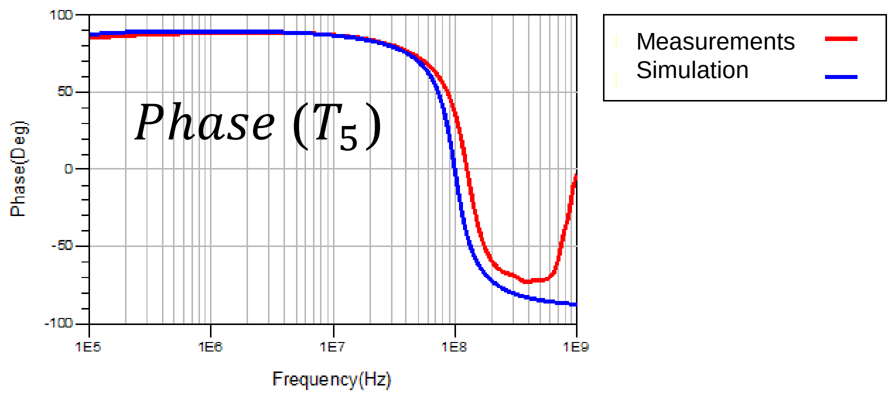
- Simplified Circuit



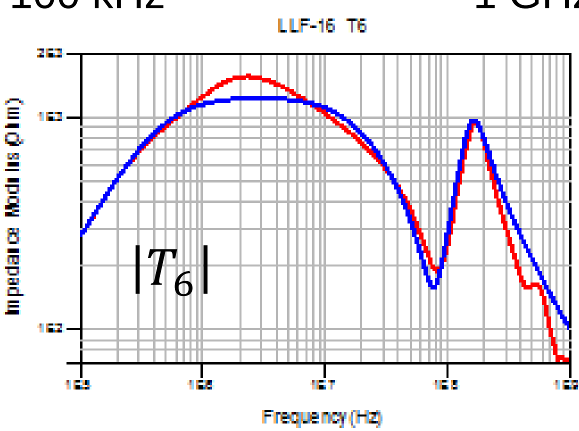
Extracted Circuit for LLF-16

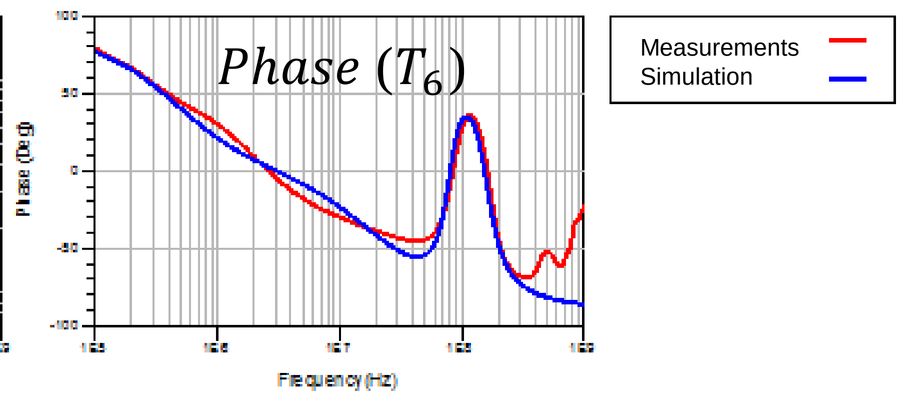
Magnetizing Impedance	Leakage Impedance	Parasitic Capacitances
L_2= 0.45 mH	L_1= 0.47 uH	C_c= 1.19 pF
R'_2= 2.453 kΩ	R_1= 937.2 Ω	C_e= 0.6 pF
C_2= 0 pF	R_c= 0.013 Ω	C_p= 0.45 pF





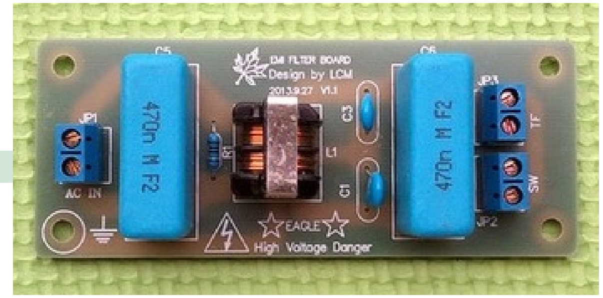
100 kHz 1 GHz 100 kHz 1 GHz



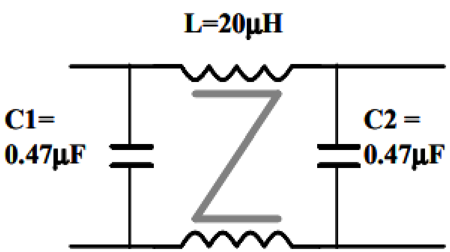


Real filter

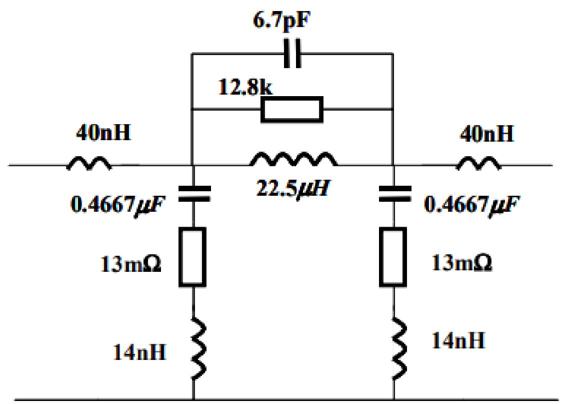
1st filter EMI filter



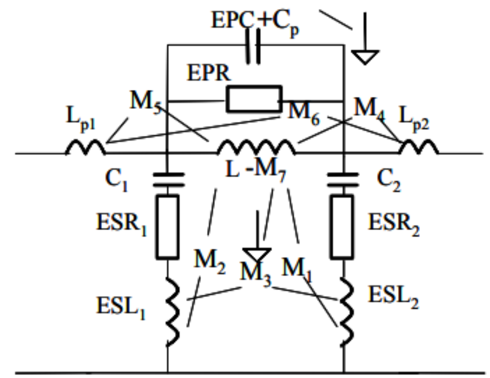
- EMI filter
  - Usually consists of film capacitors, ceramic capacitors and inductors.
  - The response of the filter can be degraded by the mutual parasitic parameters.



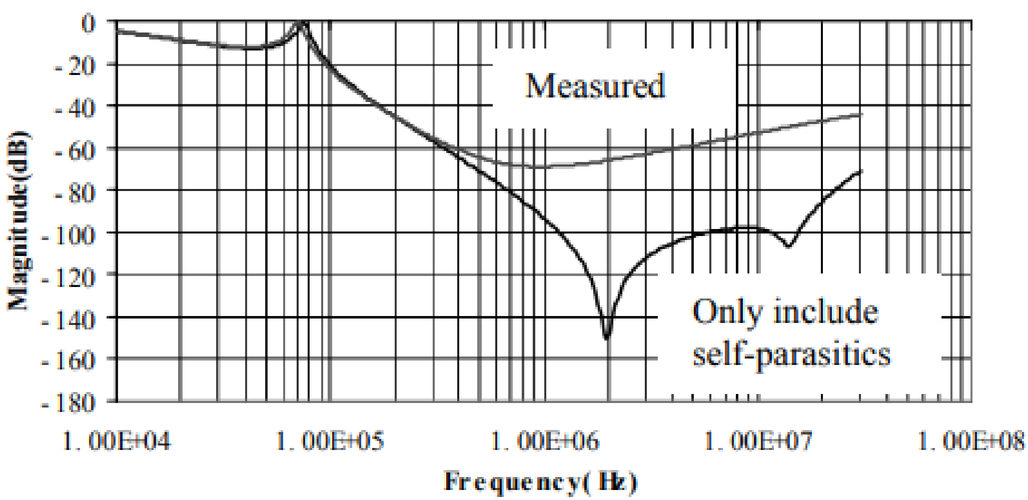
One-stage EMI filter



Circuit model including self parasitic



Parasitic coupling in an EMI filter [inductive]



[1] Shuo Wang, W. G. Odendaal and F. C. Lee, Extraction of Parasitic Parameters of EMI Filters Using Scattering Parameters . Pg2672, IAS 2004.

Inductive Coupling

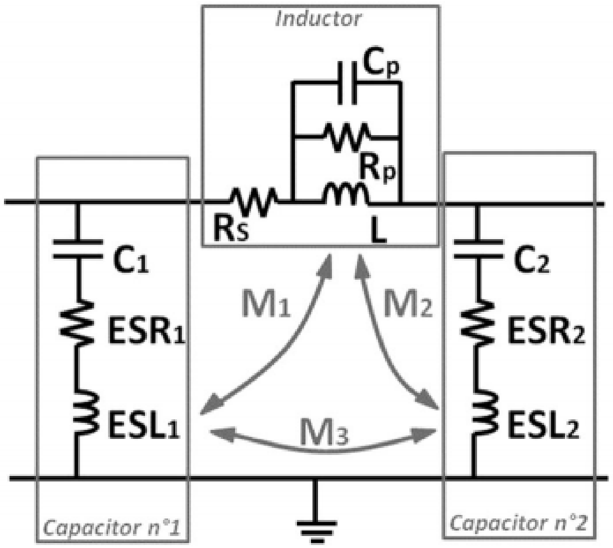


Fig. 1. Electrical model of a Pi filter by considering magnetic couplings between components.

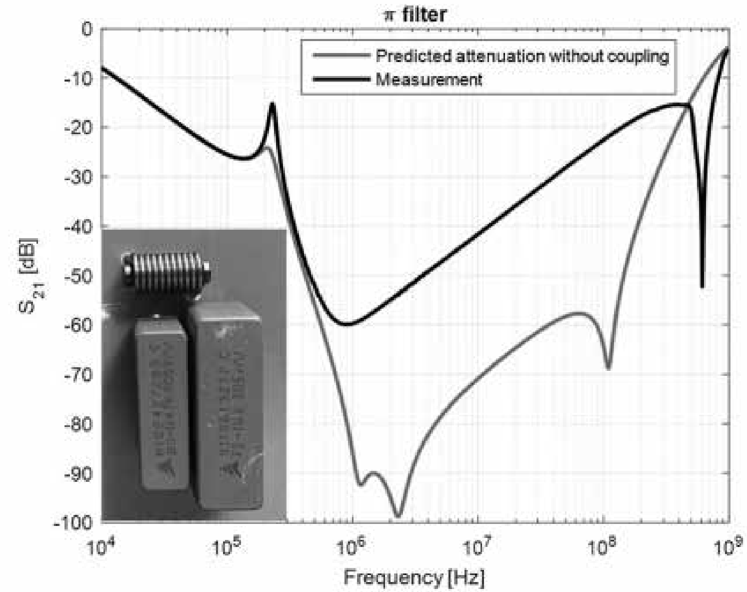
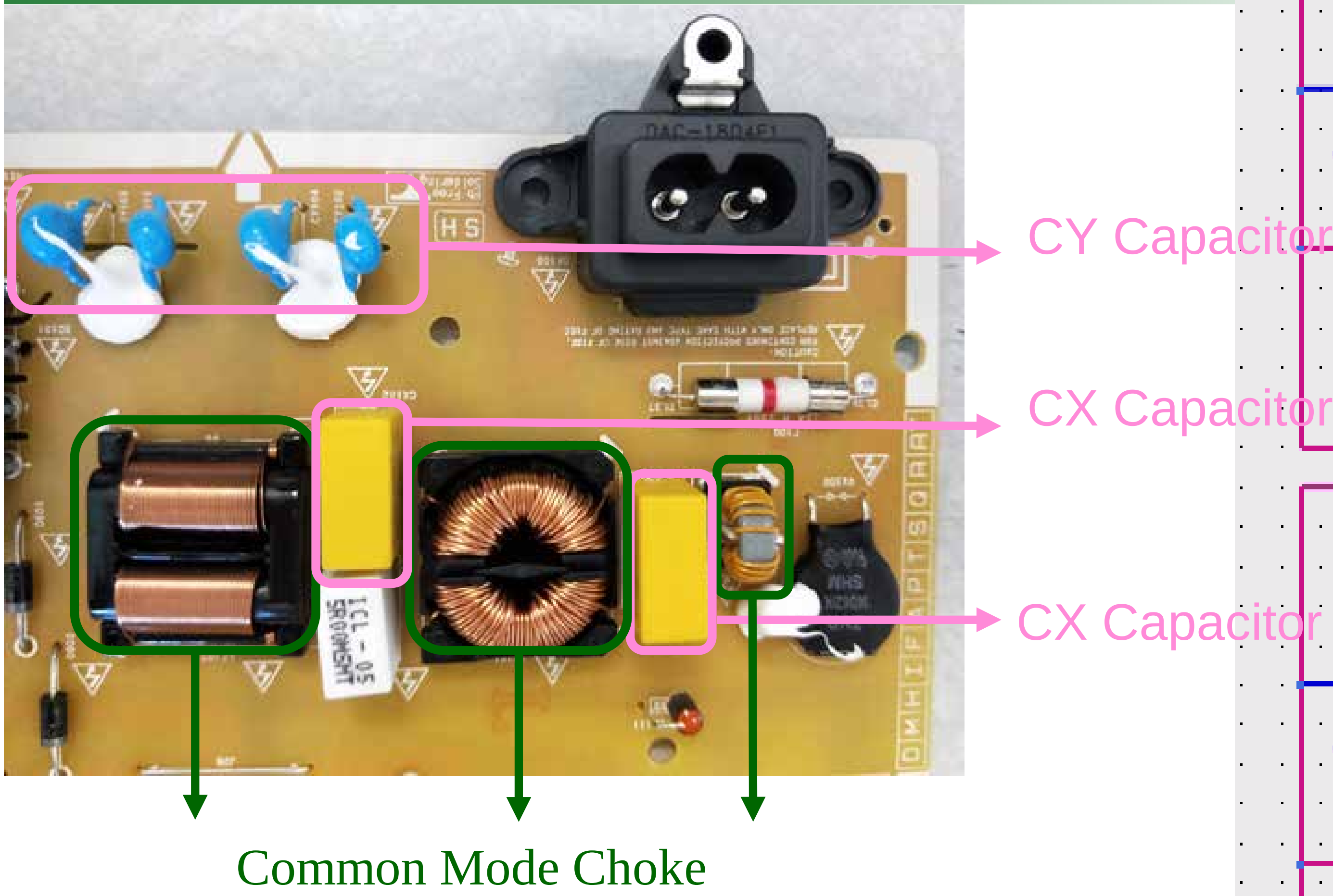
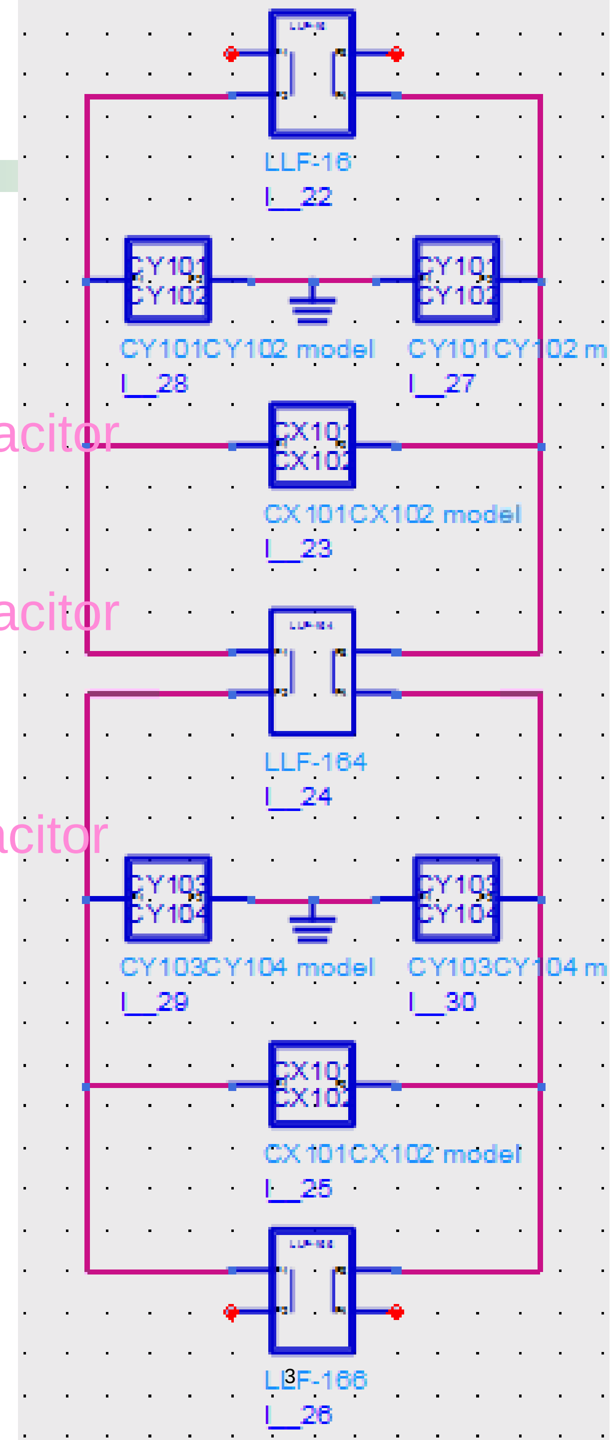


Fig. 2. Comparison between predicted and measured filter attenuations without placement information.

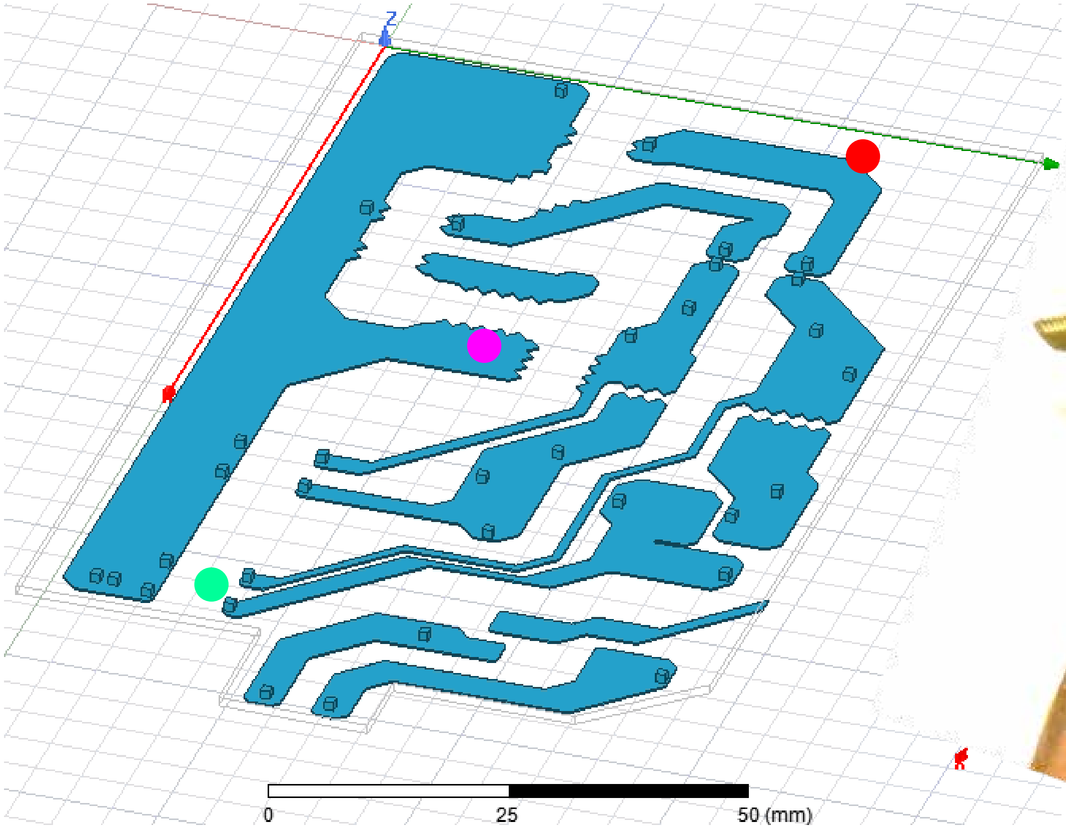
Accurate Analytical Prediction of EMI Filter Attenuation by Considering Intercomponent Coupling Phenomena
Marine Stojanovic ; Frédéric Lafon ; Richard Perdriau ; Mohamed Ramdani

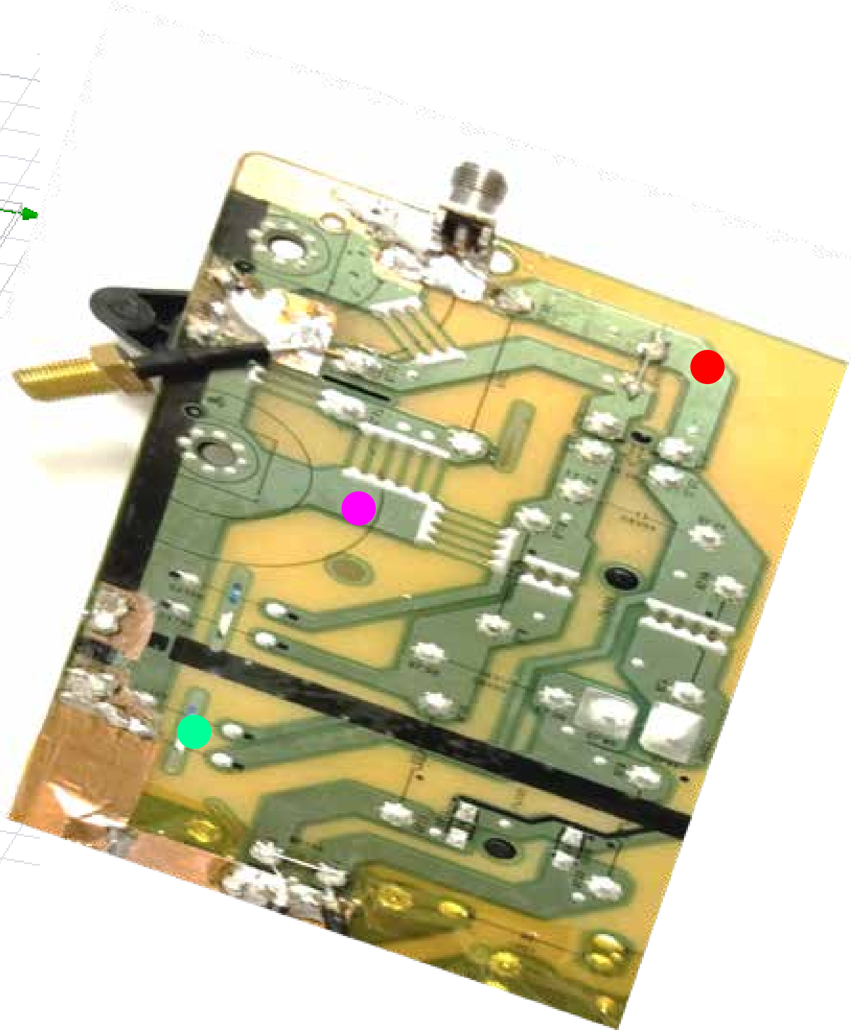
2nd filter EMI filter





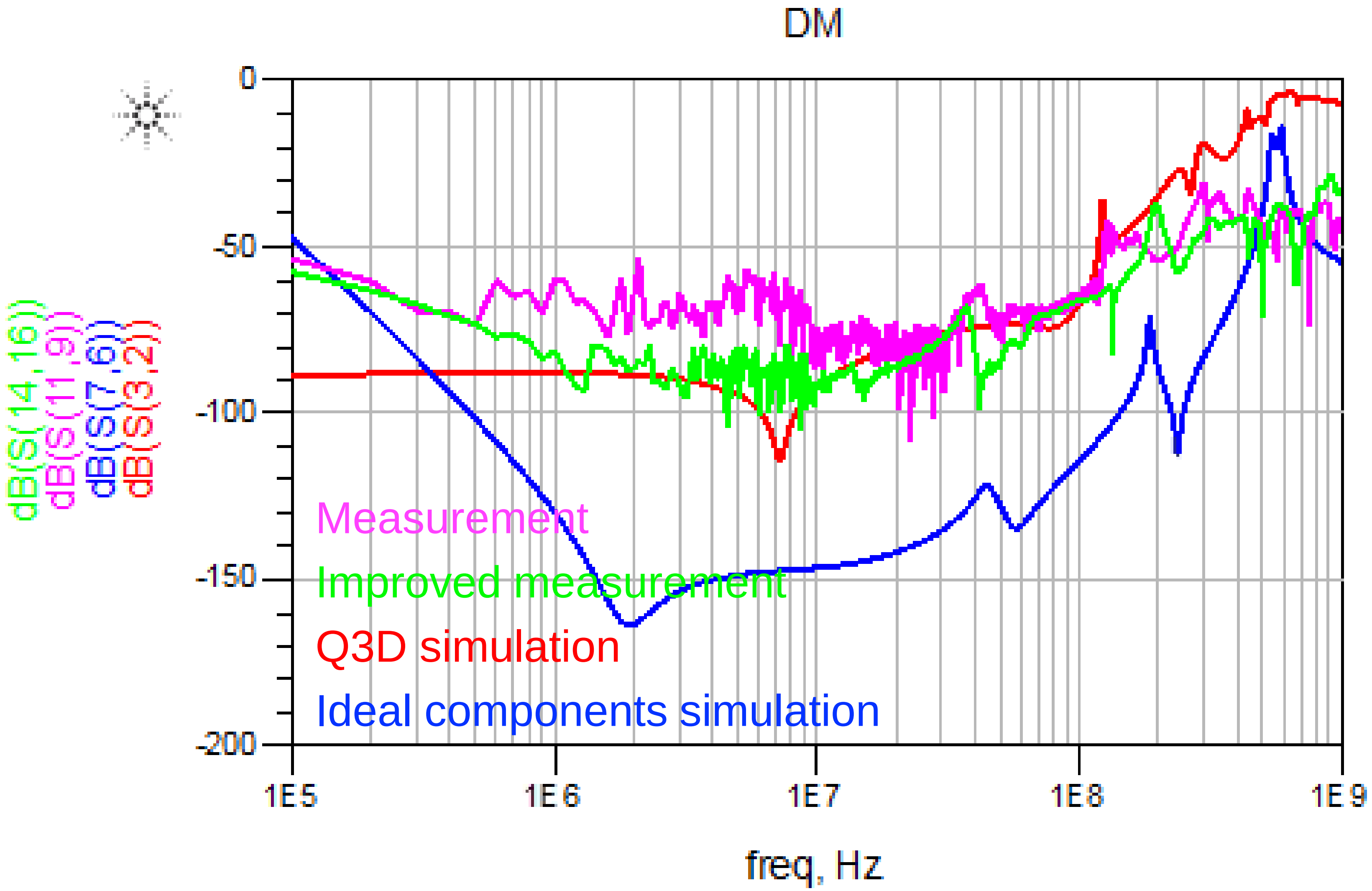
Parasitic associated with PCB layout





The layout introduces both capacitive and inductive coupling to components. The layout also introduces time delay, relevant at higher frequencies and loss which helps to attenuate resonances.

DM results of EMI Filter

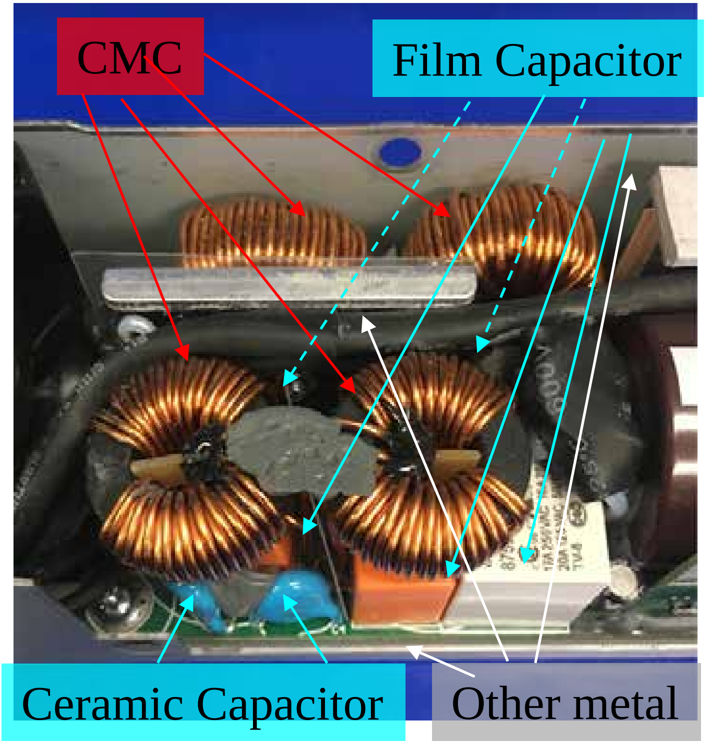


No method is easy!

3-D modelling

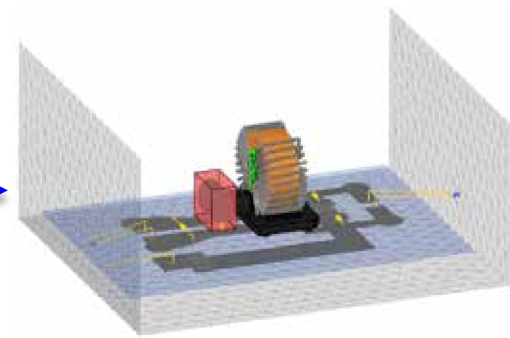
3D modelling

- Allows for dealing with more compact filter design.
- Allows for 3D placement of components.
- Take into account coupling, connectors, and wires

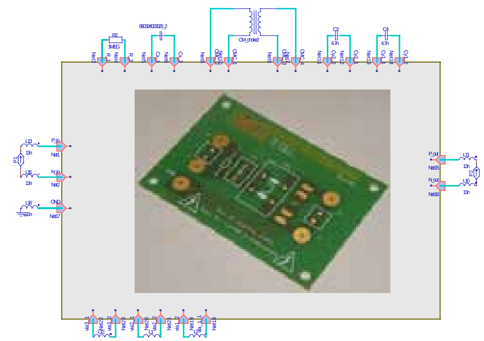


Methodologies for the Modeling of EMC Filters

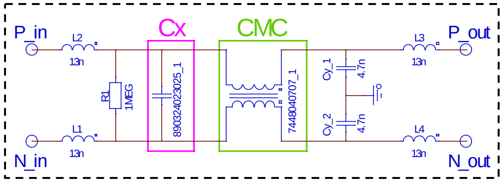
3D simulation



Stray RLC parameters of the PCB traces included to the circuit calculation with s-parameters



Circuit calculation of the filter with s-parameters of the components



EMCoS Consulting and Software

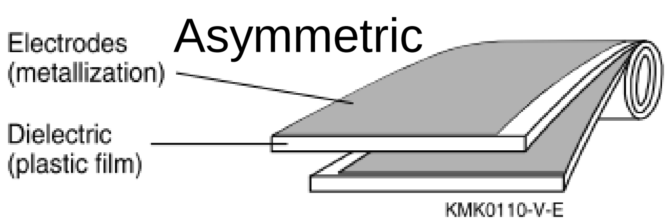
Example Film Capacitor

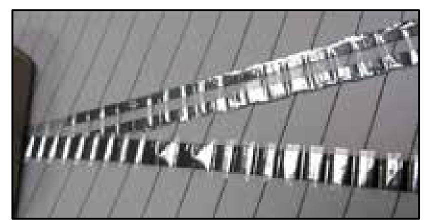
Film capacitor

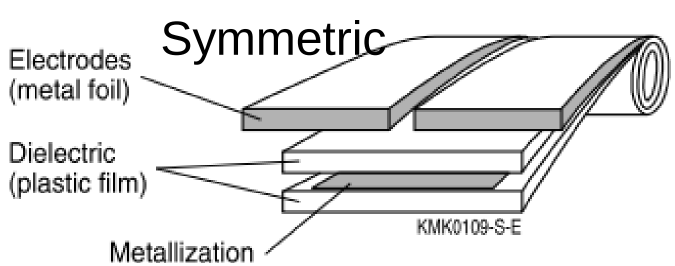
Film capacitor

- Used in EMI filter for the benefit of low ESR, high VAC ratings, capacitance stability.
- Symmetric/Asymmetric rolling

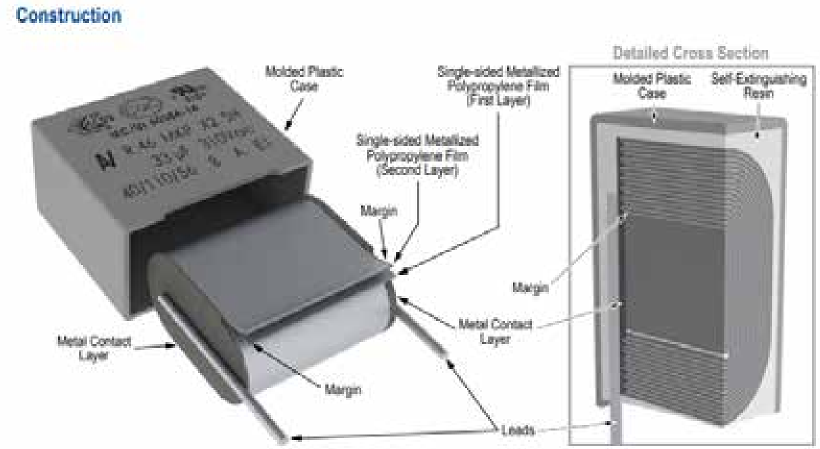
At least two methods to roll it





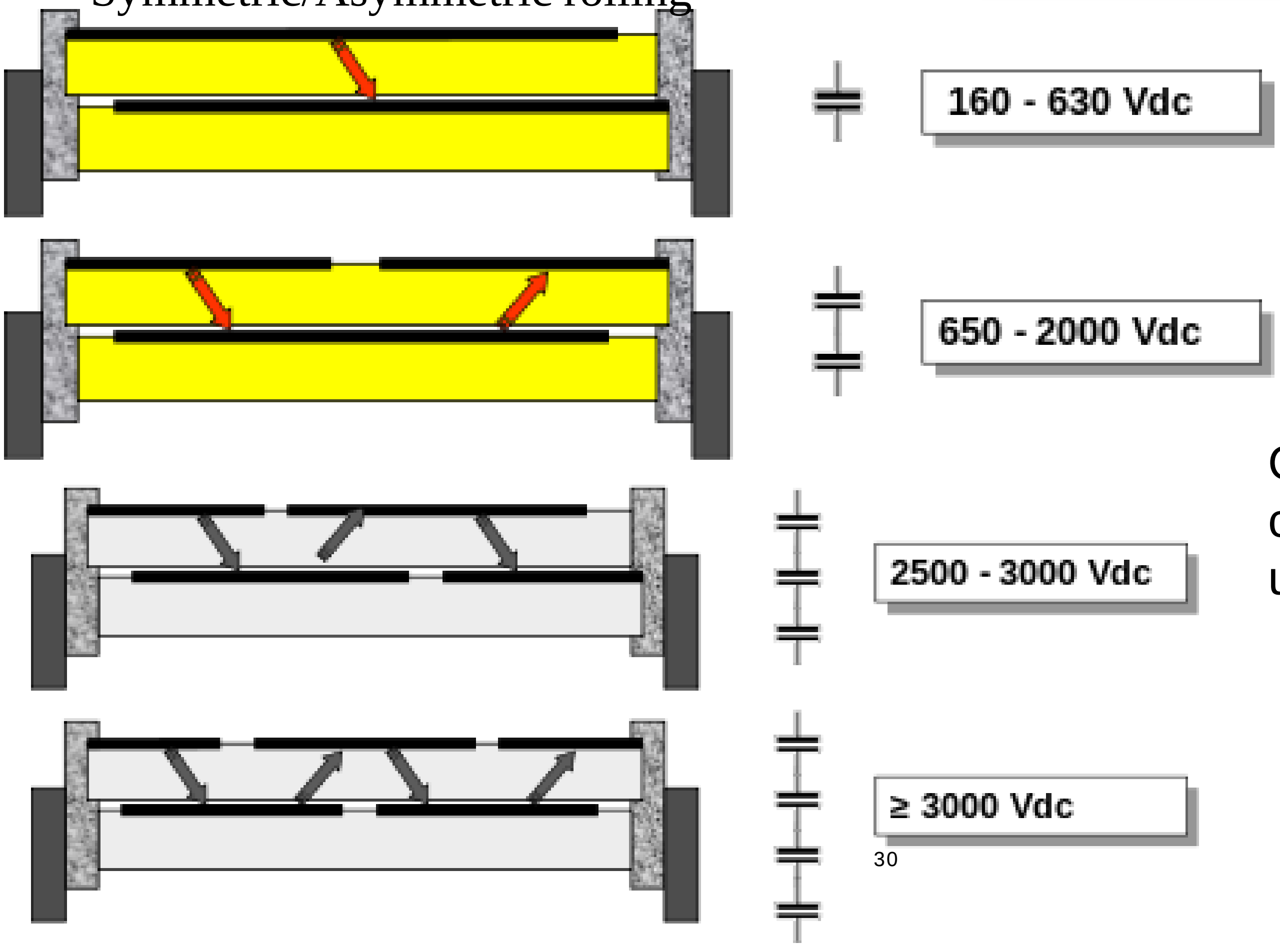


Film capacitor



Film capacitor

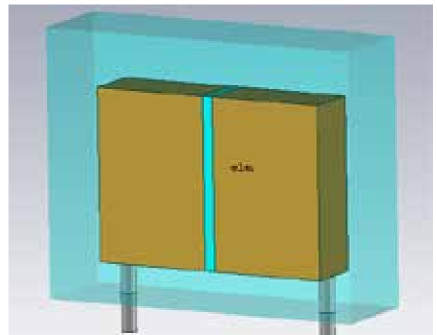
- Used in EMI filter for the benefit of low ESR, high VAC ratings, capacitance stability.
- Symmetric/Asymmetric rolling



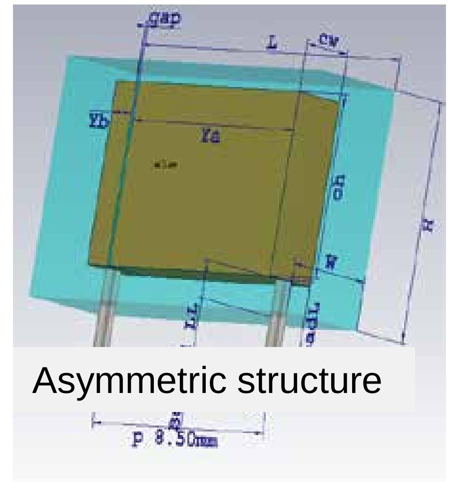
Other types of rolling can also be handled using similar strategy

Proposed modelling structure

Cutting the capacitor to obtain dimensions

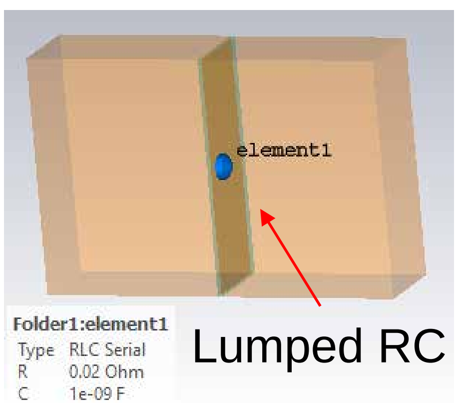


Symmetric structure



Asymmetric structure

The roll can be considered as centered inside the shell.



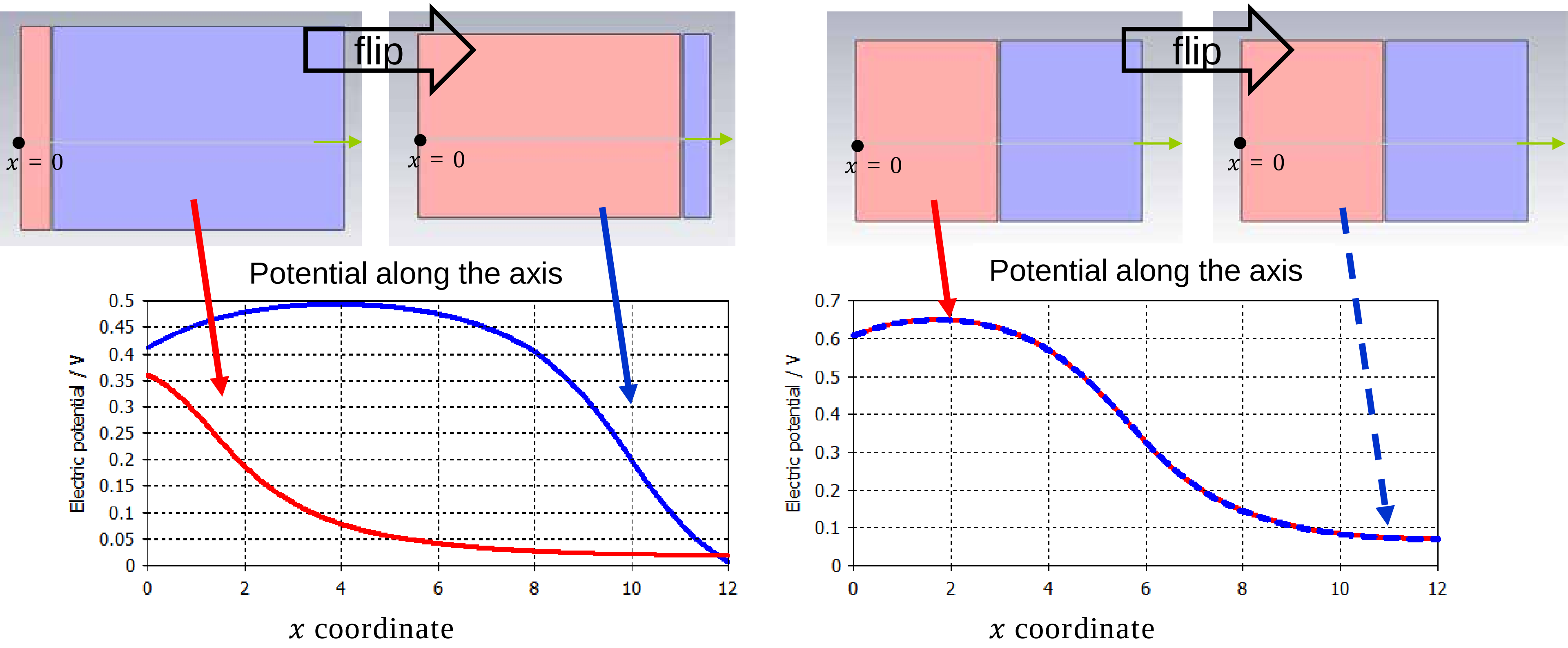
Lumped RC series

The structure is made up of

- Core A
- Core B
- Dielectric filling the gap
- Outer shell dielectric
- Leads
- [Lumped element: RC series]

Materials	Structure
Lossy dielectric	Dielectric in the gap
PEC	Lead of the capacitor
Lossy Metal	Core Bodies
Lossless Dielectric	Shell of the capacitor

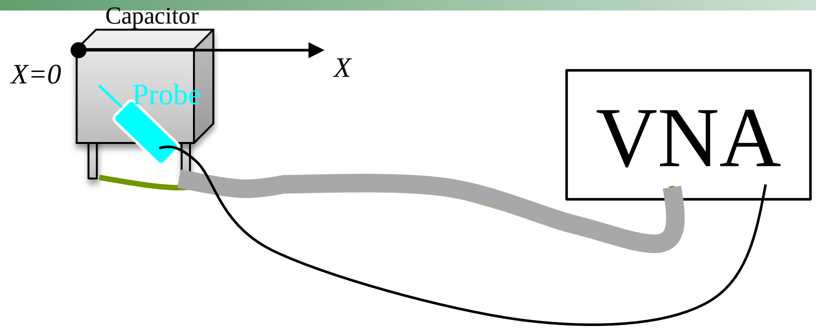
Approach for determining the inner structure

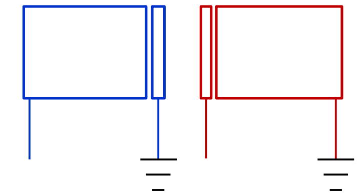


The coupling to other components depends on the symmetry of the construction of the capacitor:

- symmetric, then mounting is not relevant
- assymetric: mounting direction changes coupling

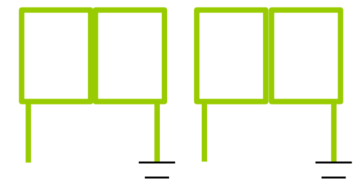
Determining the inner structure by measurement



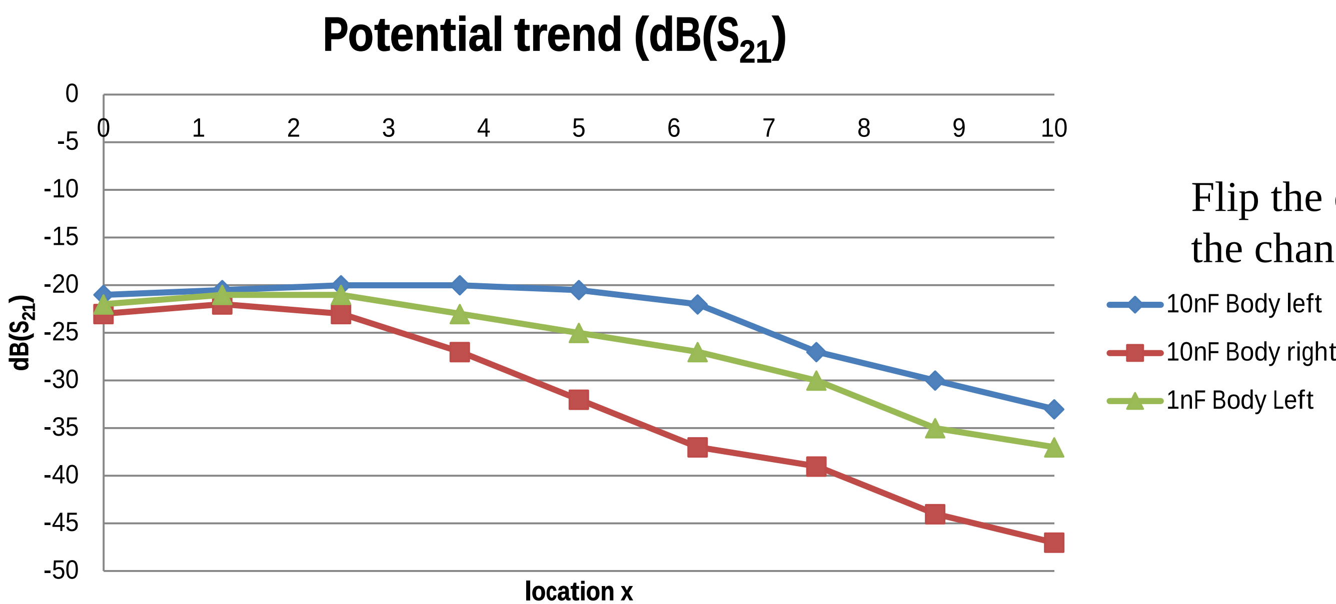


Asymmetric

Move an active, high impedance probe along the capacitor to obtain a measure of the surface potential



Symmetric

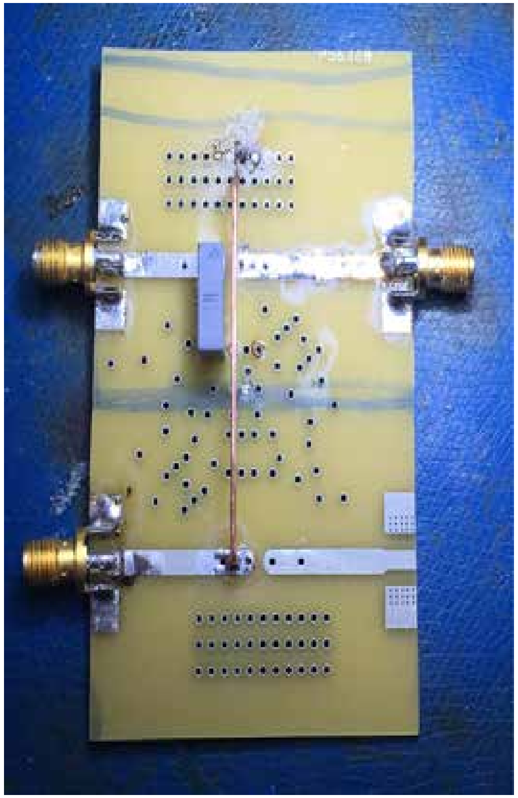


Flip the capacitor, monitor the change in the trend.

1nF curves are identical after flipping

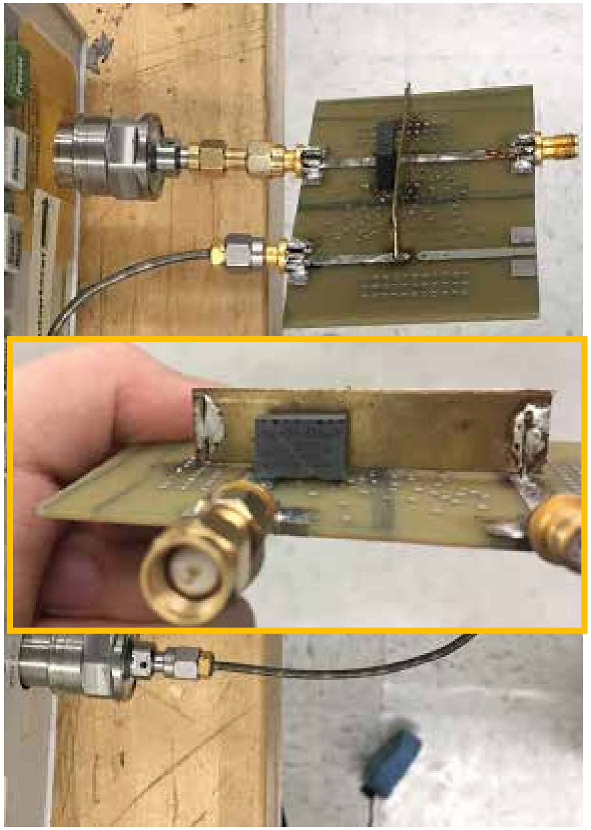
Three validation cases. Validation: S21 sim vs. meas.

capacitor to wire coupling



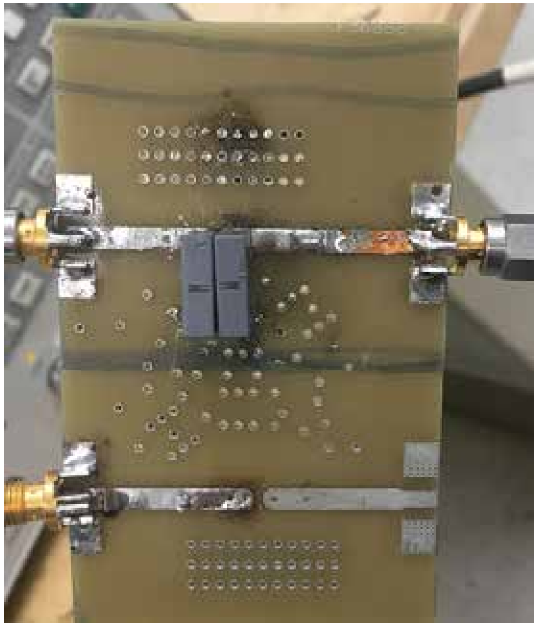
Copper Wire Diameter: 0.7 mm
Wire length: 46 mm
Wire height: 8.3 mm (from GND)
Distance to capacitor surface: 1.2 mm

capacitor to sheet coupling



The sheet has length of 46 mm; height 12 mm

capacitor to capacitor coupling

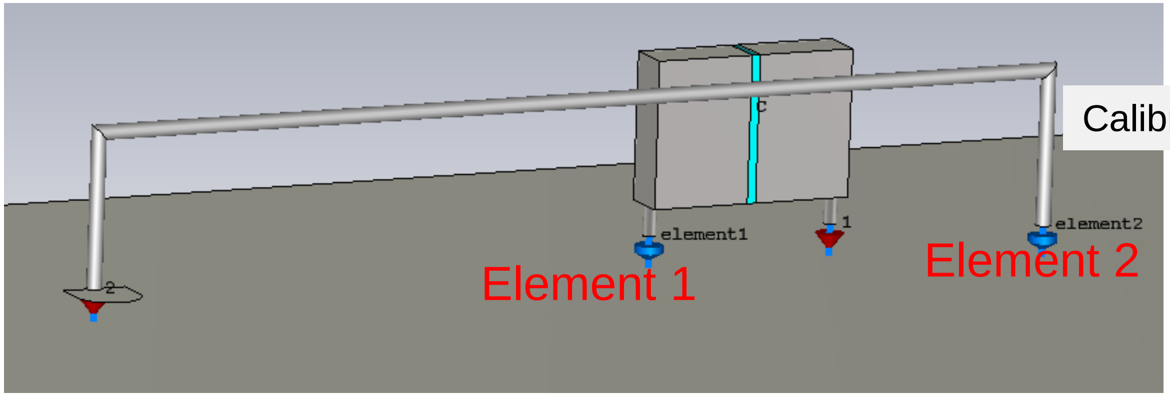


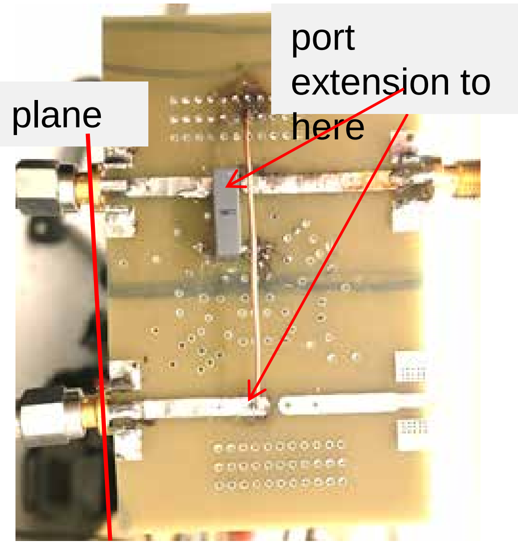
1 nF capacitors, placed as close as possible.

Measured: S_{21}

Parameter: Different loading combinations are tested

Capacitor to wire coupling (various loading combinations)

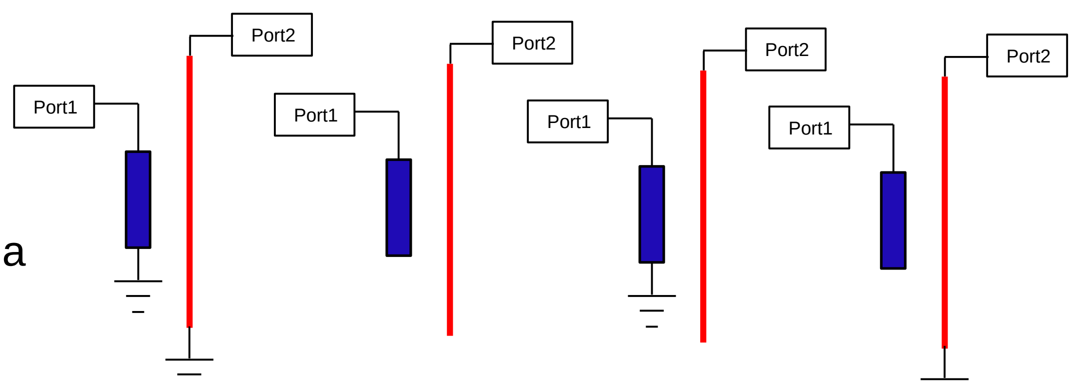




- Element 1,2 are used to adjust the termination condition
- FR4 is hidden

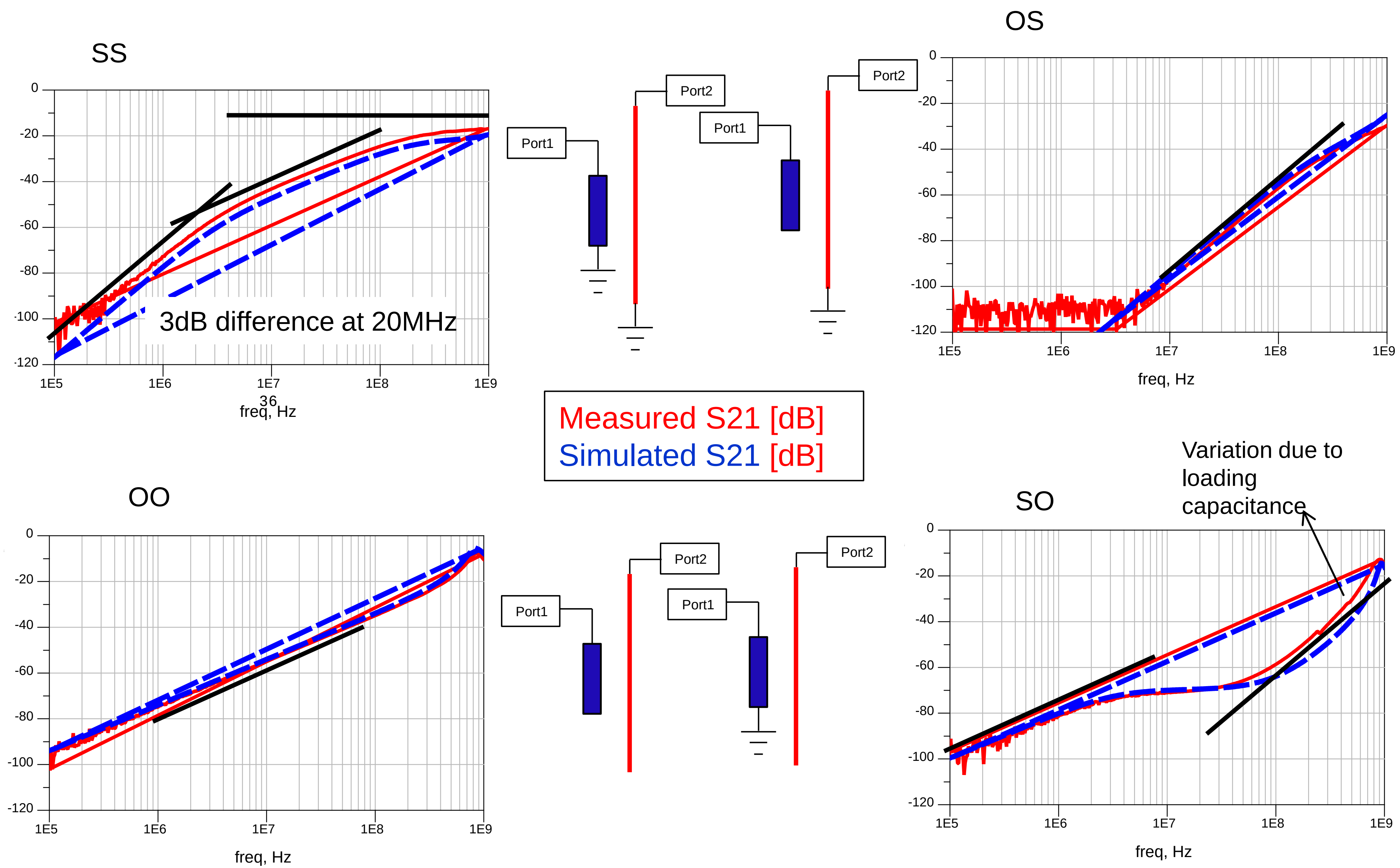
In open condition, element 1,2 are set as a small capacitor representing the via capacitance;

In shorted loading condition, the wire/pin are extended to make contact with ground.

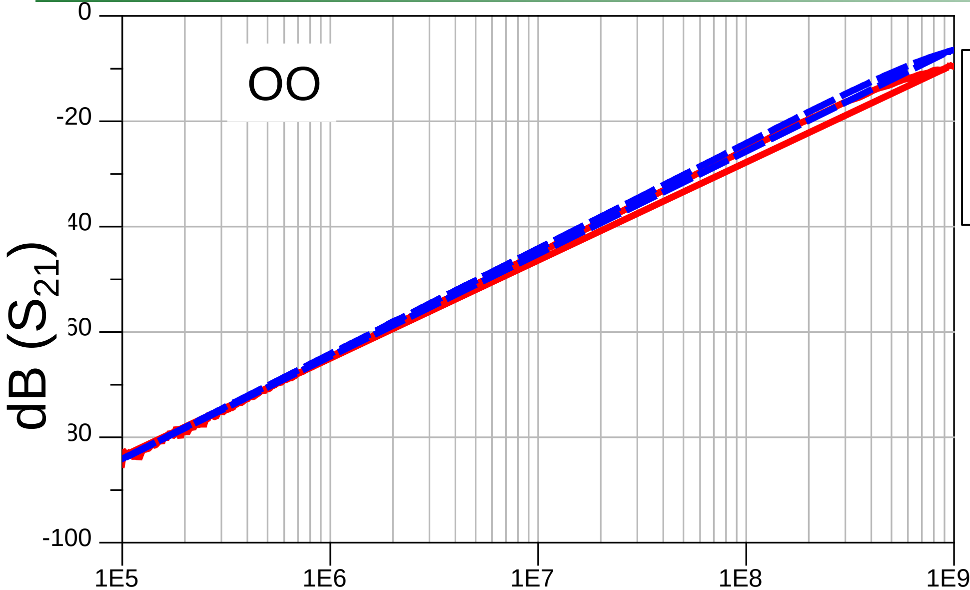


Short-Short SS | Open-Open OO | Short-Open SO | Open-Short OS

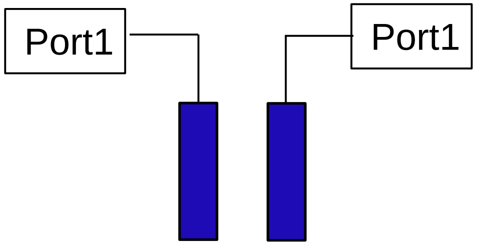
Capacitor to wire coupling: Numerical model is good

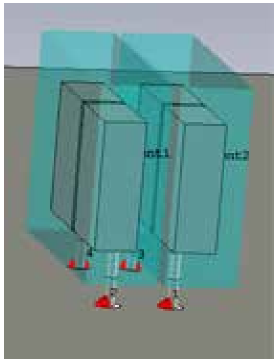


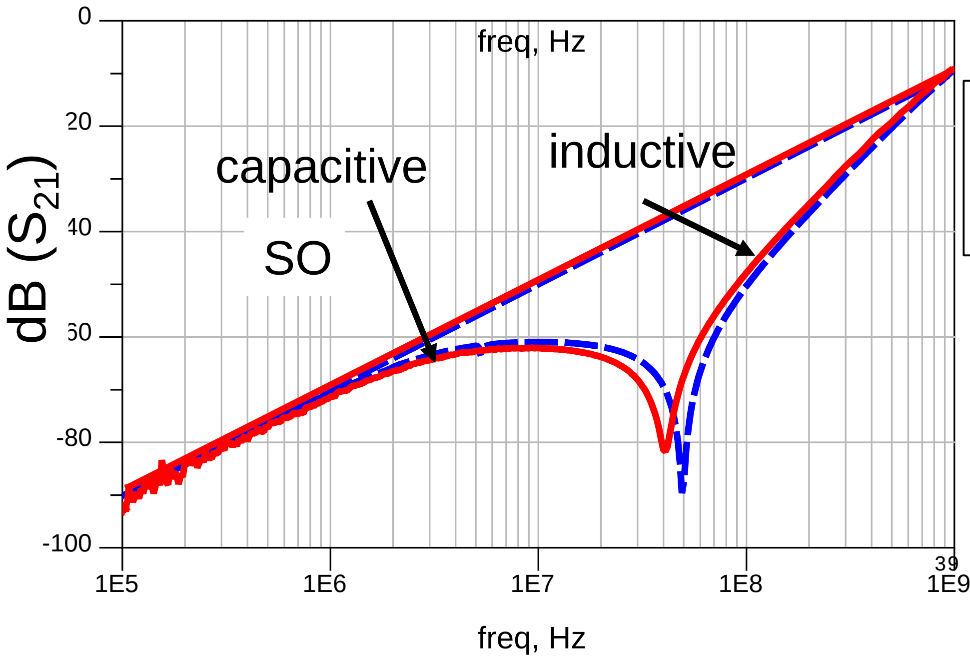
Capacitor to capacitor (symmetric) coupling



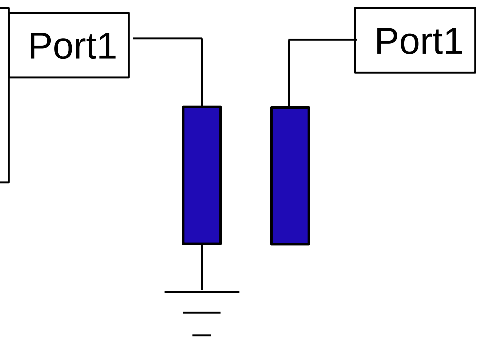
OO case
Measured S21
Simulated S21







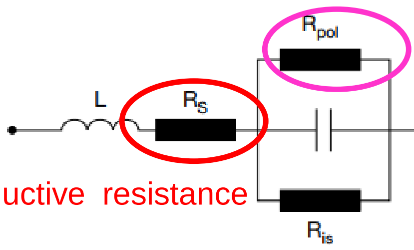
SO case
Measured S21
Simulated S21



ESR of film capacitor

EQUIVALENT SERIES RESISTANCE (ESR)

The ESR is the ohmic part of an equivalent series circuit. Its value assumes all losses to be represented by a single resistance in series with the idealized capacitor.



The ESR comprises the polarization losses of the dielectric material (R_{pol}), the losses caused by the resistance of the leads, termination and electrodes (R_s) and the insulation resistance (R_{is}).

https://www.vishay.com/docs/26033/gentechinfofilm.pdf

$$\text{ESR} = \frac{\tan\delta}{\omega \times C}$$

$$R_{d//is} = \frac{R_d * R_{is}}{R_d + R_{is}} \approx R_d = \frac{\tan\delta_d}{\omega C} \propto \frac{1}{f}$$

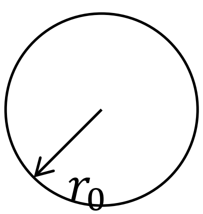
Dielectric dissipation angle, not skin depth

$$R_{d//C} = \frac{\boldsymbol{R_d}}{1 + \tan^2\delta_d}$$

$$R_S = R_S(R_{S,DC}, r_0, \delta)$$

$$\boldsymbol{ESR} = \boldsymbol{R_s} + \frac{\boldsymbol{R_d}}{1 + \tan^2\delta_d}$$

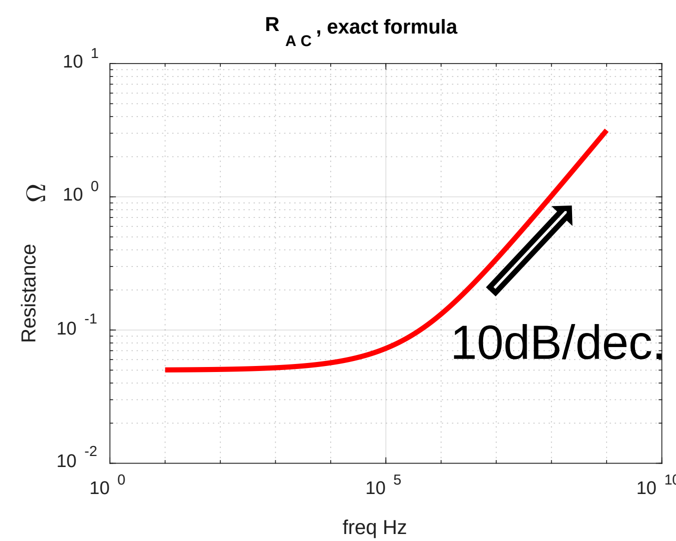
In a round wire having radius r_0 and skin depth δ:



$$\boldsymbol{R_{S,AC}} = \frac{\frac{r_0^2}{\delta^2} R_{S,DC}}{2\left(\frac{r_0}{\delta} - 1 + e^{-\frac{r_0}{\delta}}\right)}, \quad R_{DC} = \frac{\rho l}{\pi r_0^2}$$

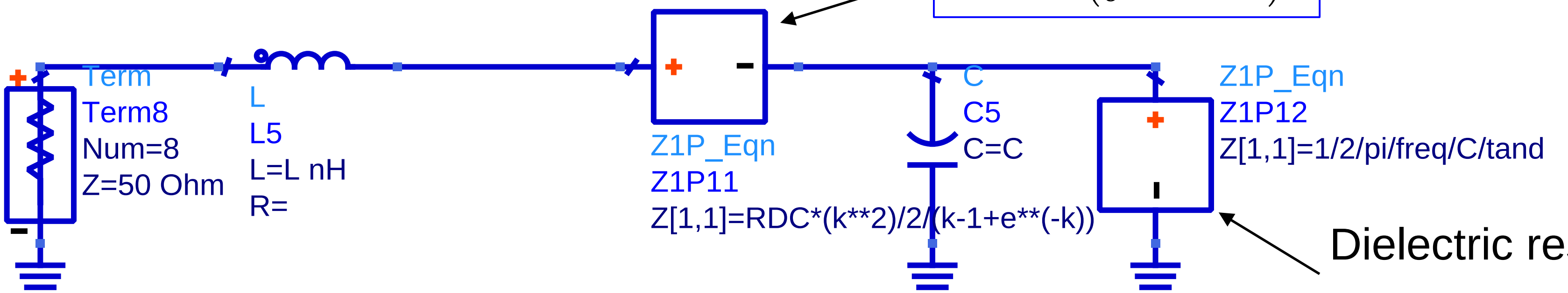
A high frequency approximation can be made as

$$\lim_{\frac{r_0}{\delta} \to \infty} R_{S,AC} = \frac{r_0}{2\delta} R_{S,DC} \propto \sqrt{f}$$



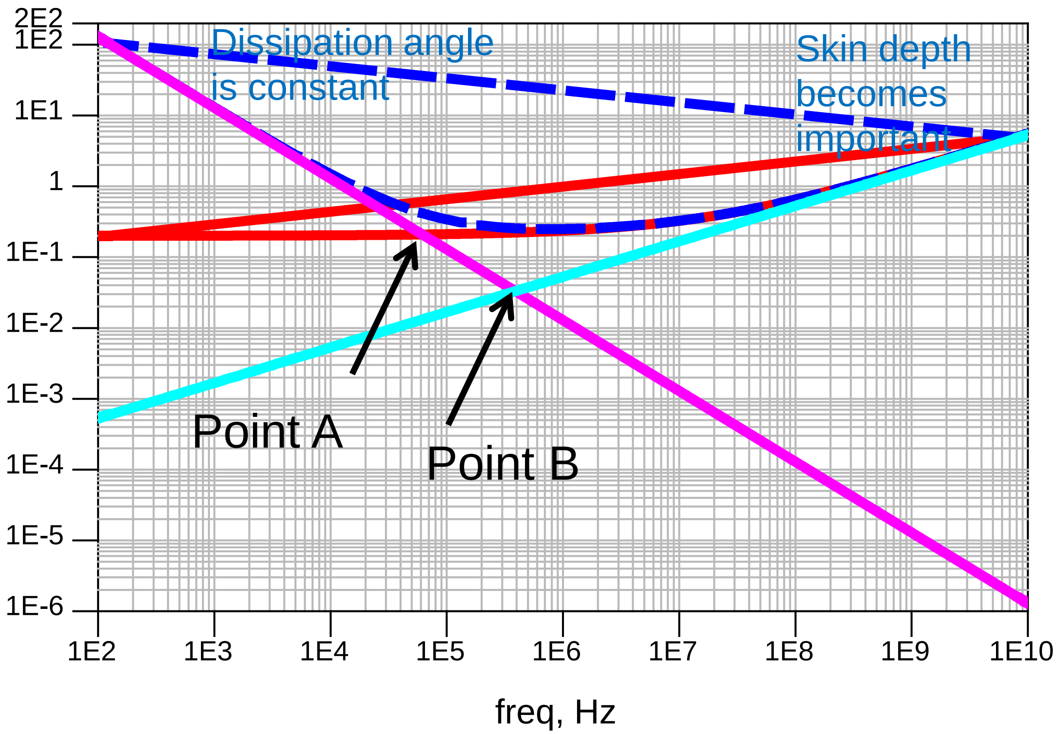
Components of ESR

$$R_{S,AC} = \frac{\frac{r_0^2}{\delta^2} R_{S,DC}}{2\left(\frac{r_0}{\delta} - 1 + e^{-\frac{r_0}{\delta}}\right)}$$



Dielectric resistance:

$$R_d = \frac{1}{\omega C \tan \delta_d}$$



R_d

R_{AC} **with high freq. approximatio**

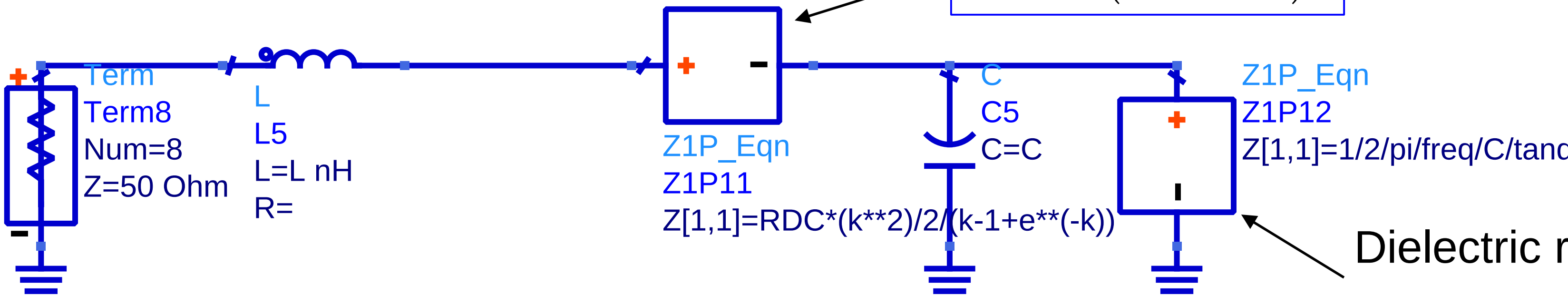
R_{AC} **exact formula**

$$ESR = R_s + \frac{R_d}{1+\tan^2 \delta_d}$$

If A is significantly higher than B, then a 'flat' region appears.

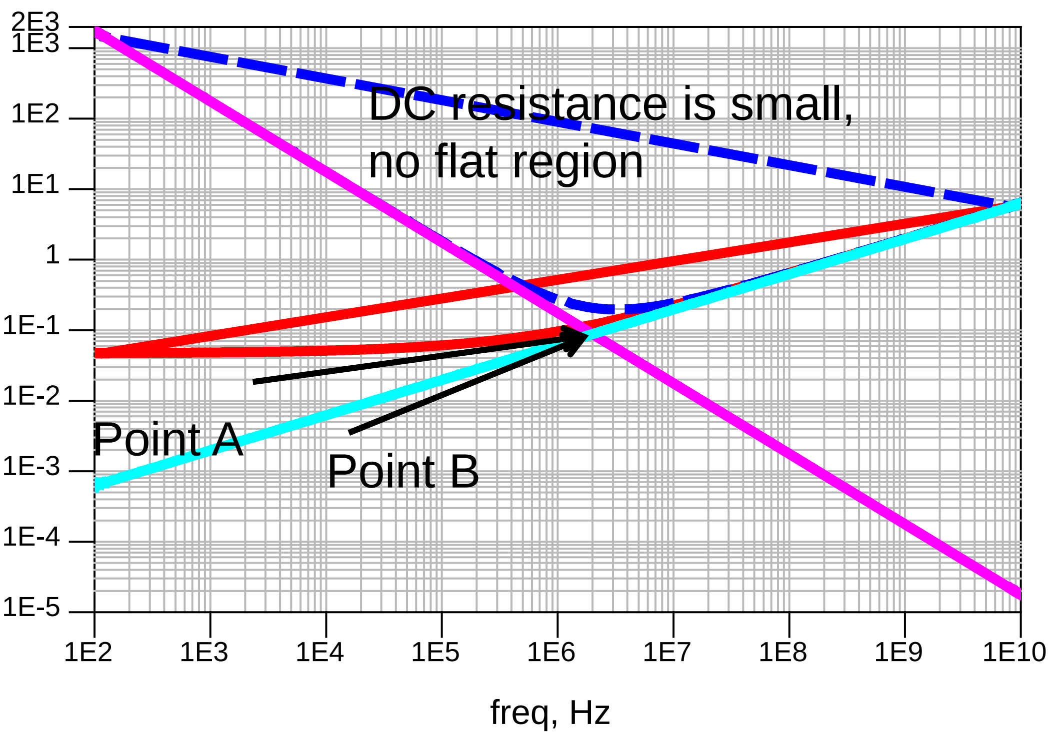
Components of ESR

$$R_{S,AC} = \frac{\frac{r_0^2}{\delta^2} R_{S,DC}}{2\left(\frac{r_0}{\delta} - 1 + e^{-\frac{r_0}{\delta}}\right)}$$



Dielectric resistance:

$$R_d = \frac{1}{\omega C \tan \delta_d}$$



R_d

R_{AC} **with high freq. approximation**

R_{AC} **exact formula**

$$ESR = R_s + \frac{R_d}{1+\tan^2 \delta_d}$$

If A is close to B (R_{DC} is small) , there won’t be a ‘flat’ region.

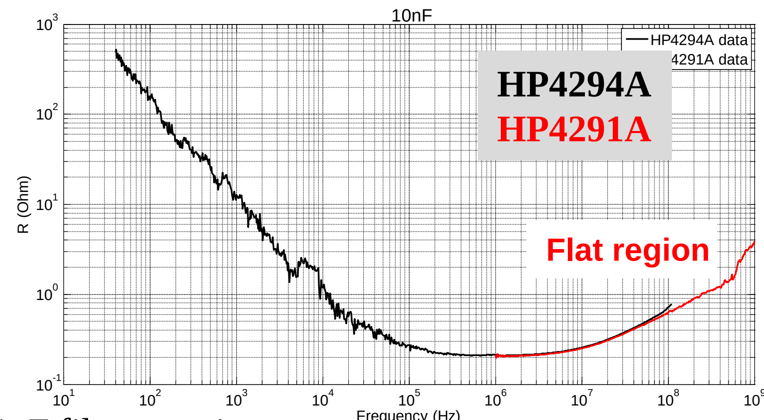
Measure ESR of the capacitor using Impedance Analyzer

HP4294A & HP4291A are used at MS&T

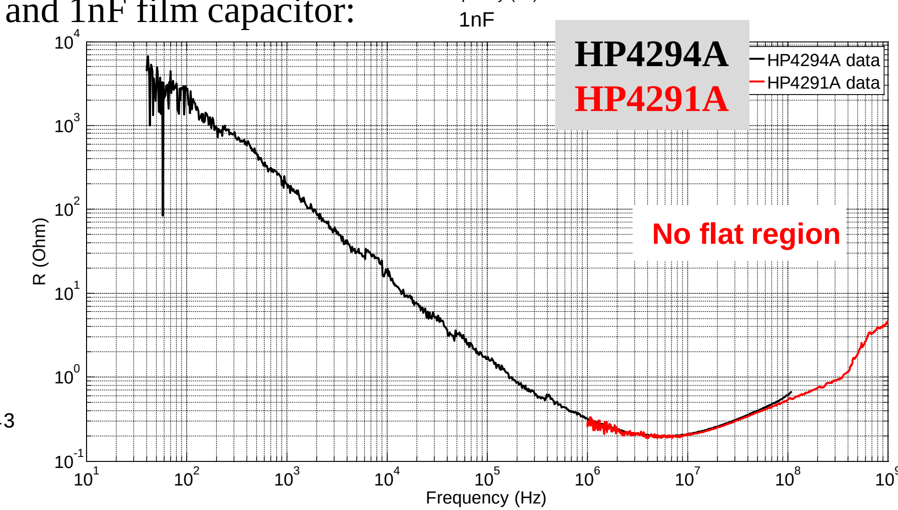
By combining their results we can obtain the ESR of a film capacitor from 40Hz to 1GHz

Calibration, port extension and standard validation ensures good data.

Measuring 0.1 Ohm SMD resistor for validation.



ESR of 10nF and 1nF film capacitor:



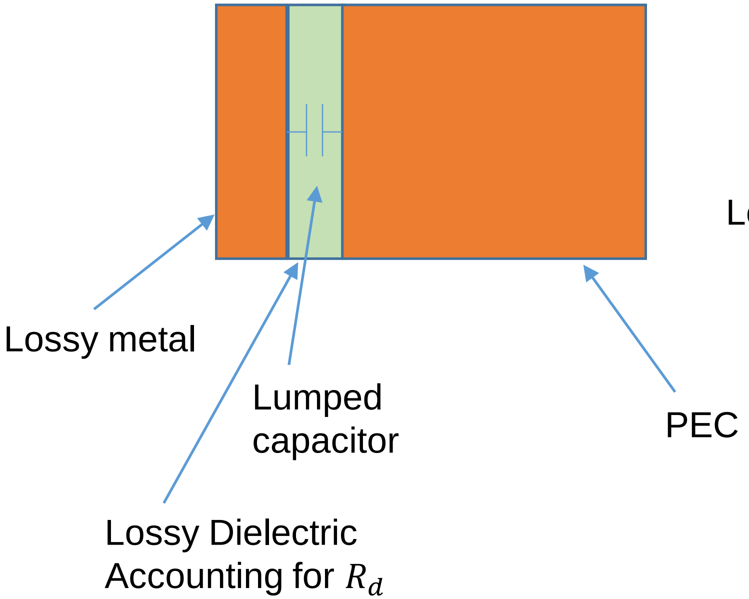
ESR can be modelled in two means

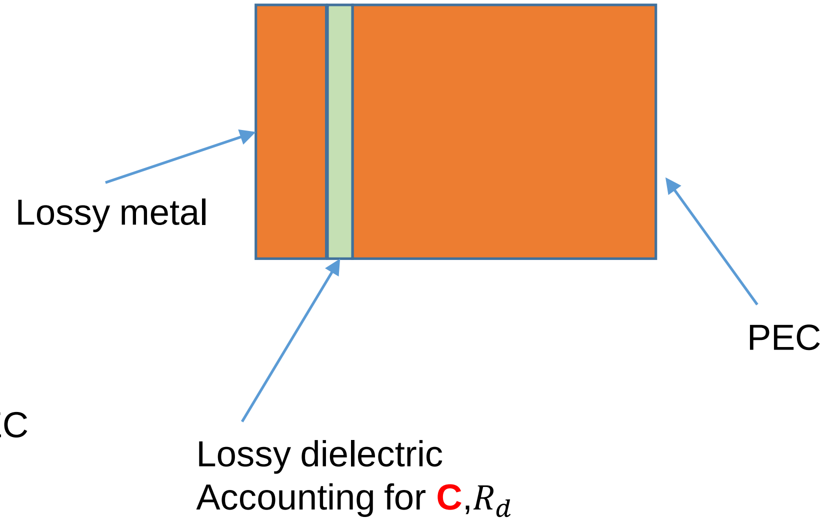
With lumped element

- Lumped element R_{DC}
- Lossy Dielctric R_d
- Lossy Metal R_{AC}

Without lumped element

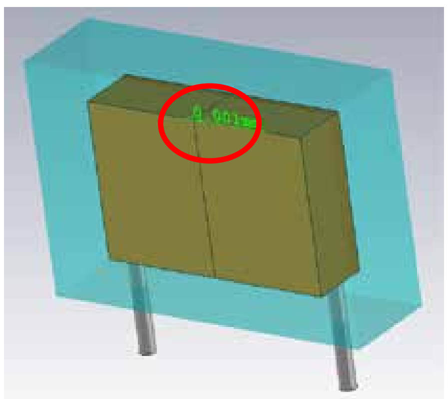
- Lossy Dielctric $\boldsymbol{C}$, R_d
- Lossy Metal R_{AC}

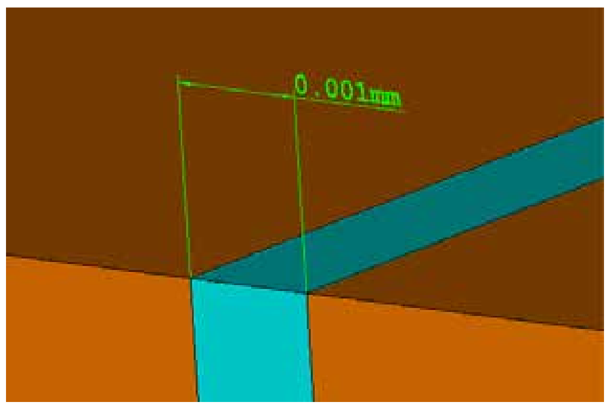




Model without lumped element

- Model without lumped element makes the tuning procedure easier.
- When the capacitance to is too large (>1uF), solver inaccuracy problems may occur.
- The time cost and mesh size is comparable with the model using lumped element.
- The mutual coupling is not affected when switching from lumped element to without lumped element.





The gap is set as $1\mu m$, to handle large capacitance case, and avoid solver accuracy issues.

$$C = \frac{\varepsilon_0 \varepsilon_r \cdot cw \cdot ch}{gap}$$

$$\tan\delta_d = \tan\delta = \frac{ESR}{\omega C}$$

The material inside the gap determines both the capacitance and low frequency ESR of the model.
Once the dimensions of the model are fixed:

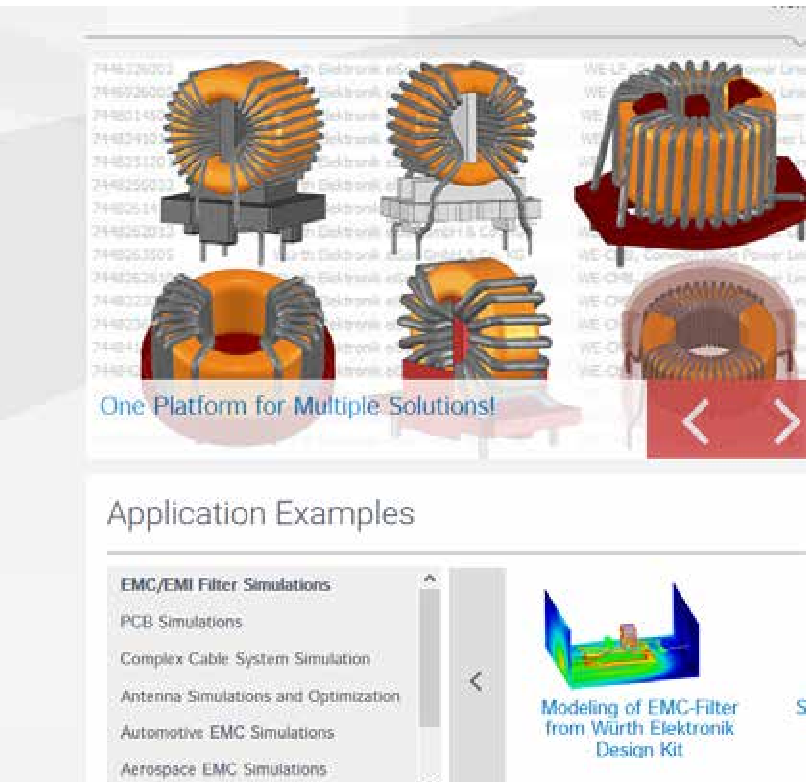
- The relative dielectric constant determines the capacitance
- The electrical loss tangent of the material $\tan\delta_d$ determines the $\tan\delta$ or ESR at low frequency.

Full wave simulation requirements

- For full wave simulation the inner structure needs to be know.
- It maybe not necessary to reproduce the inner structure.
- Material properties need to be known.
- The complexity needs to be acceptable from the memory demand and simulation time

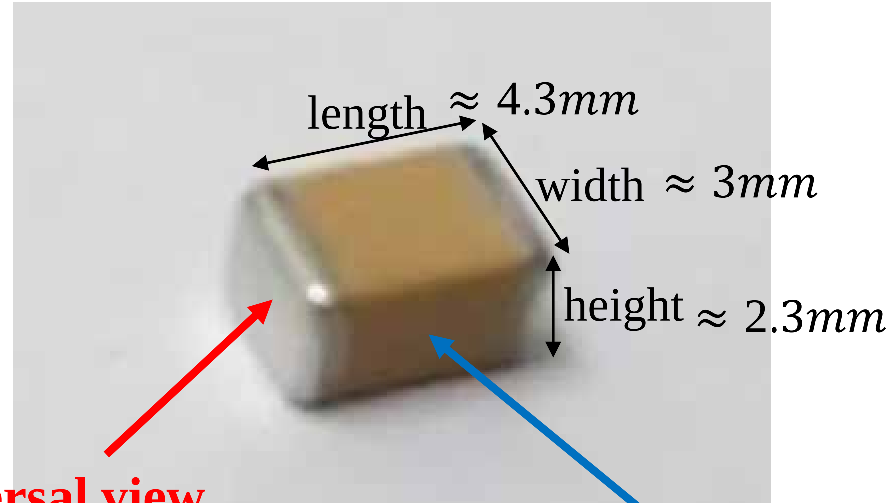
Simulation choices

- Due to the shape of the structure CST time domain solvers, FIT or TLM are not suitable
- HFSS
- CST frequency domain
- EMCOS MoM



SMT capacitor

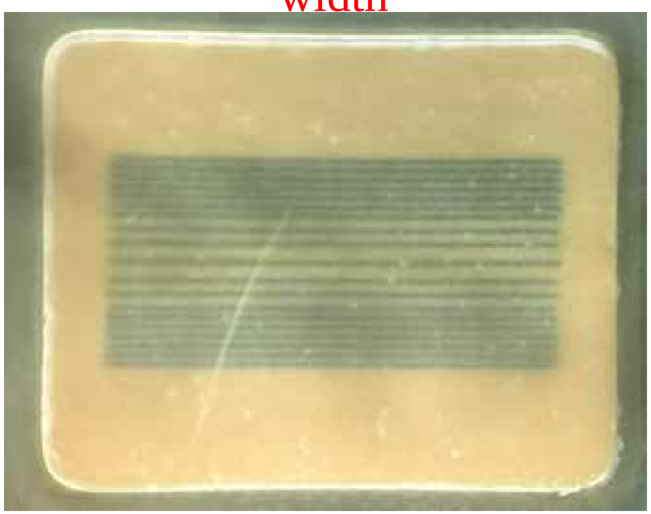
SMD capacitor



1nF capacitance

Transversal view

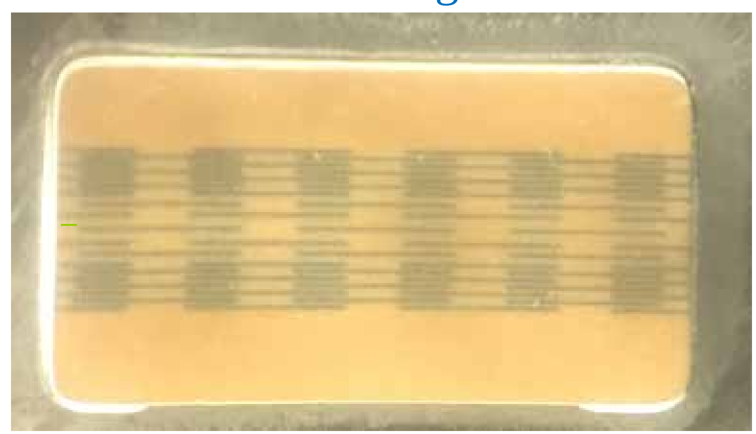
width



height

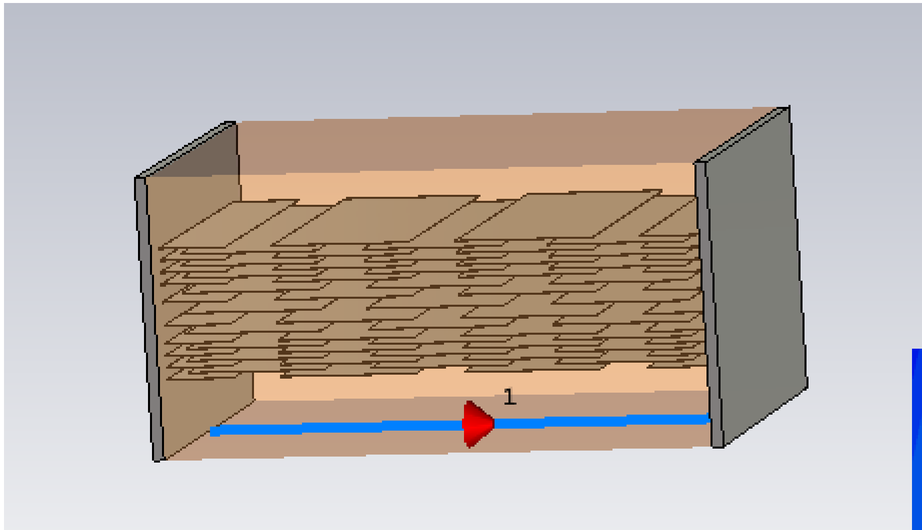
Lateral view:

length



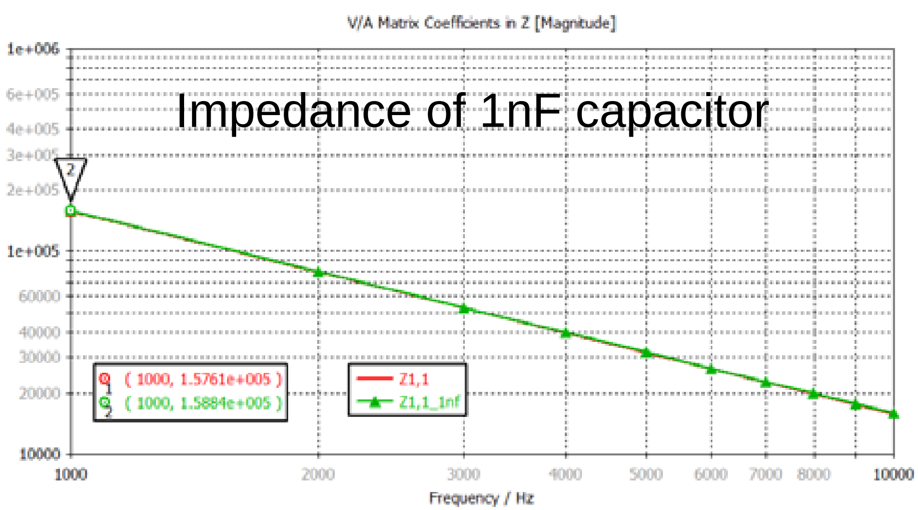
height

3D model for 1nF capacitor CST MW studio

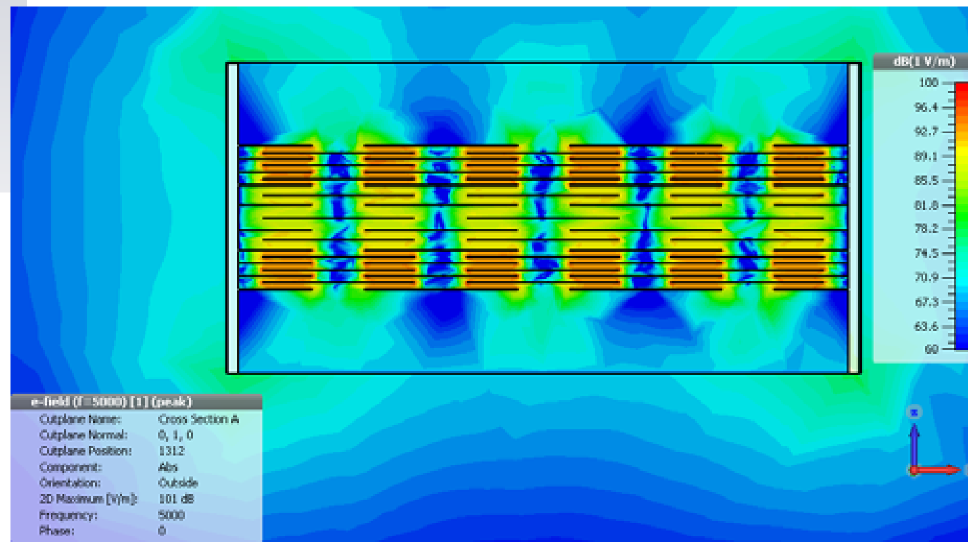


Created by a discrete port between two soldering terminals, adjusted ε_r to reach 1nF capacitance.

$\boldsymbol{\varepsilon_r = 1578}$

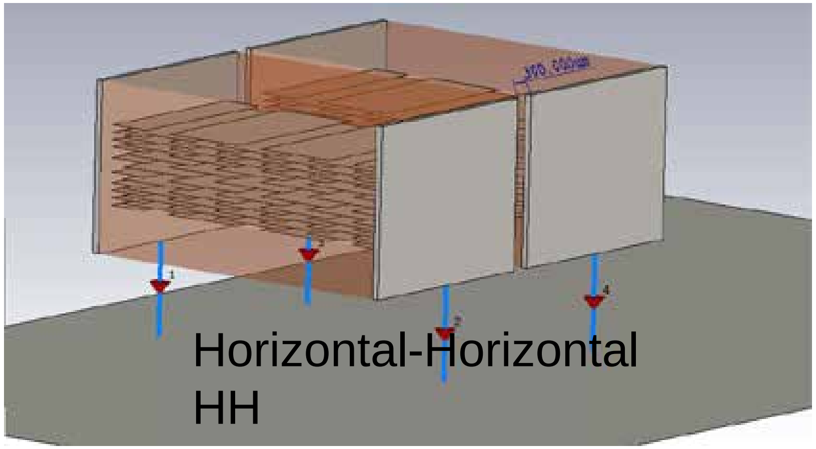


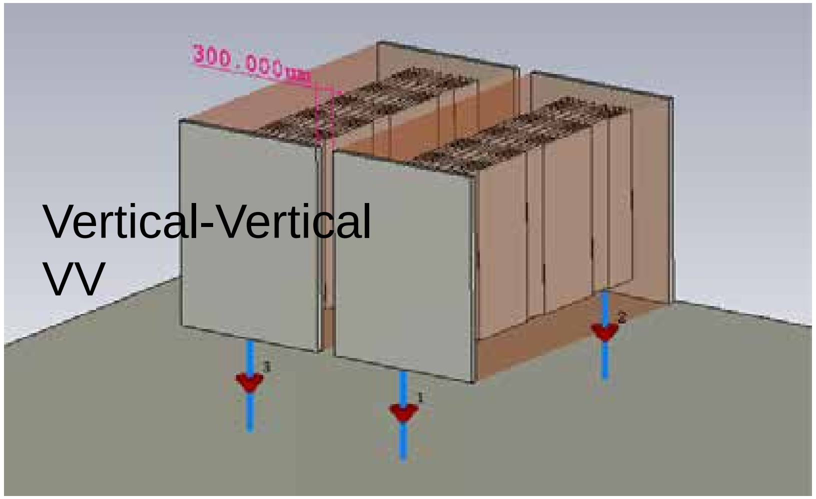
Impedance of 1nF capacitor



E-field distribution

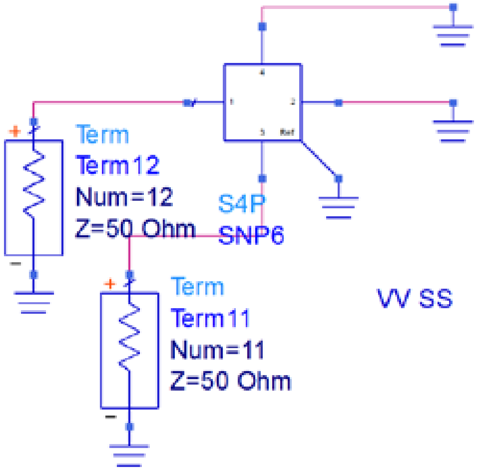
Coupling between two capacitors (HH, VV)



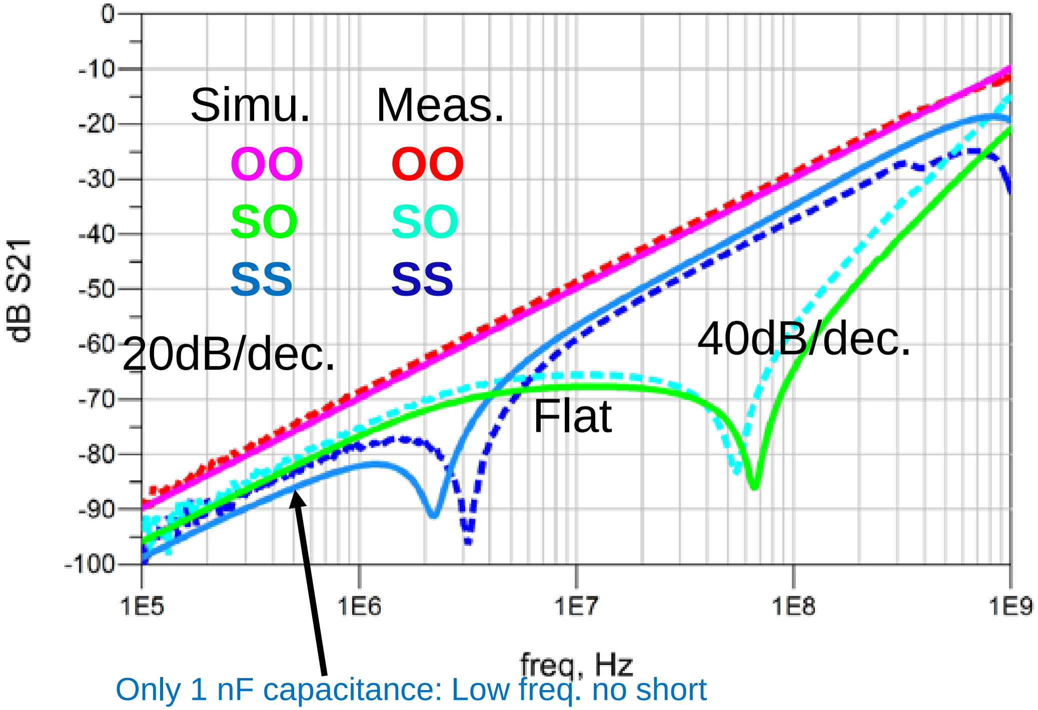


HH, VV, HV cases are all modeled in CST MW studio. Each terminal is assigned a port, the loading conditions can thus be easily altered in post processing.

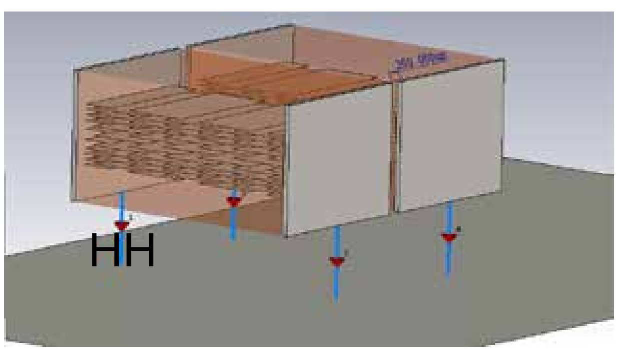
For example: vertically placed capacitor having loading combination short-short is denoted as VV SS



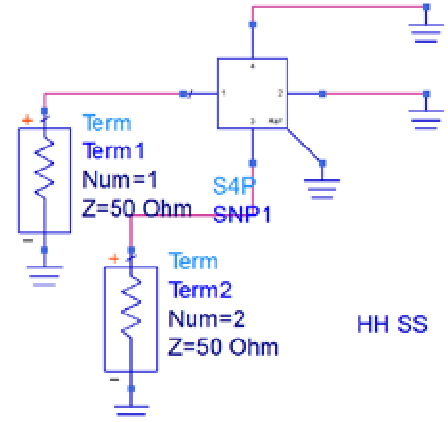
The HH case comparison

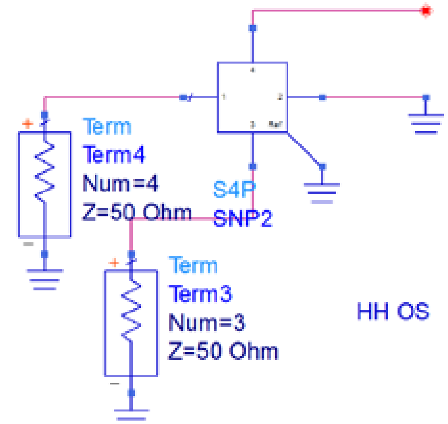


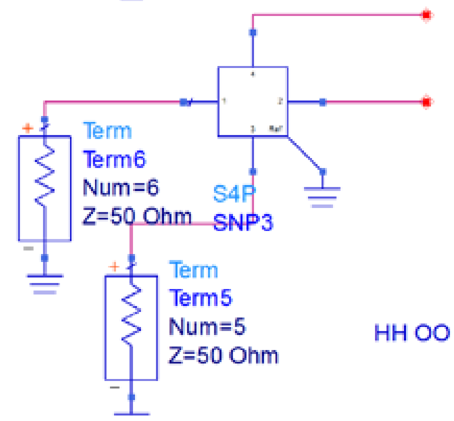
Time for the simulation: 8min 26s



The SS case has maximum 3dB difference between simulation and measurement in capacitive and inductive part of the coupling. Other two cases are well matched.







Summary of capacitor modeling

- 3D model is made explicitly following the measured dimensions of the MLCC.
  - In MW studio, the tuning yields $\boldsymbol{\varepsilon_r \approx 1.6E3}$ to reach a capacitance of 1nF.

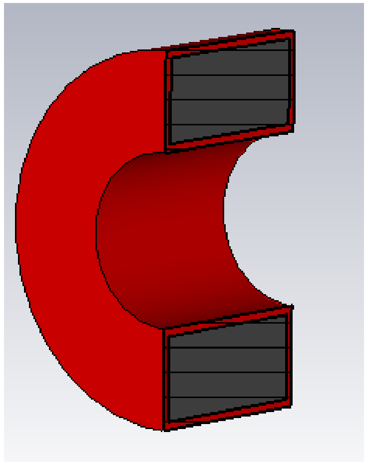
- The simulated coupling between two capacitors, in different orientation and loading condition combinations are compared with the measured result. Works!

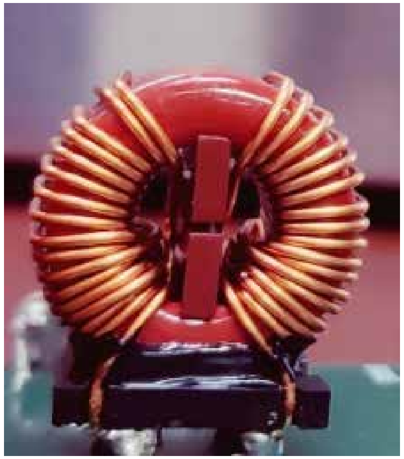
CMC

CMC

Common mode choke

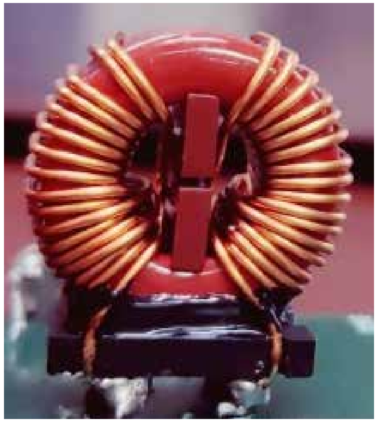
- Used in EMI filter to suppress common mode noise.
- Core come in different types: Mn-Zn, Ni-Zn, Nano Crystalline etc.
- The core and the wire are both coated with insulation layer.
- Wires can overlap in actual windings.





Coating layer is relevant!

3D model example

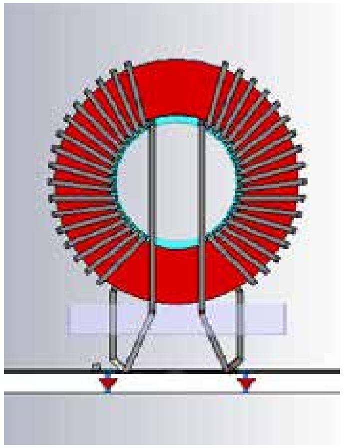


17 turn CMC
Inner Diameter 10mm
Outer Diameter 18.2mm
Width 10.7mm
[with paint]

The covered angle of each winding is about 130°

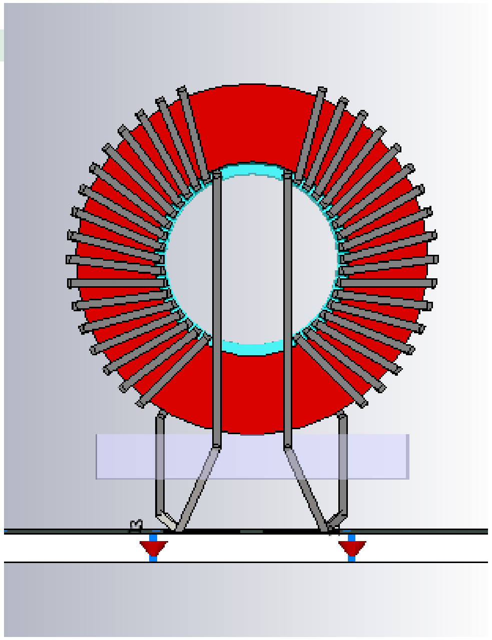
Inner Diameter 9mm
Outer Diameter 20mm
Width 9.8mm
[without paint]

The paint has thickness of around 0.4mm



A model is made using all measured dimensions.

Challenges during the modelling



1. Wire

   The wire has very thin insulation coating;

   The wires are squeezed together and often overlap in reality.

2. The Material properties

   $\mu'(f), \mu''(f)$

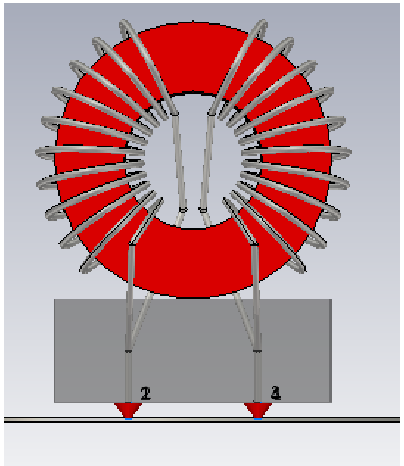
   $\varepsilon'(f), \varepsilon''(f)$

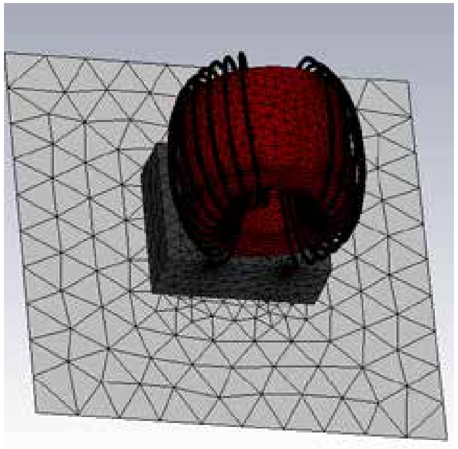
   σ

   – Frequency dependence of the material parameters is not easy to measure.

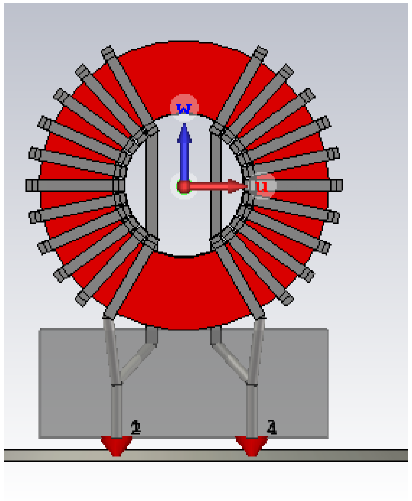
   – Materials may not be homogenous.

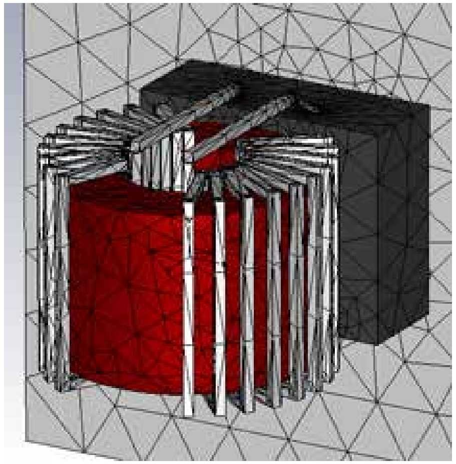
Modelling of the wire (wire shape)





Round wire:
Mesh Count 537k
Mesh time 27m
Solver Time **6h15m total frequency range**



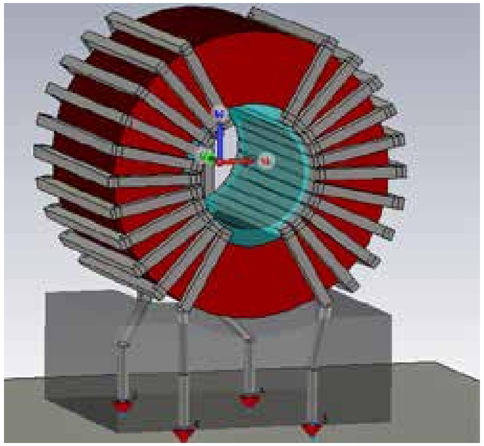


Square wire:
Mesh Count 59k
Mesh time 16s
Solver Time **20m**

Using square wires instead of round wires, reduces mesh count in the frequency domain solver.

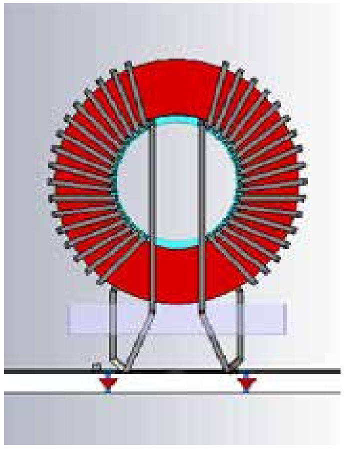
Coating of the wire

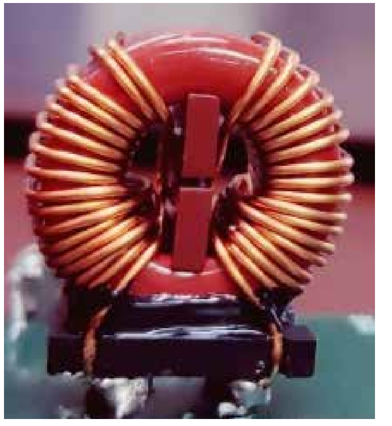
- In actual windings, the parasitic capacitance contributed by the adjacent wires can be large, due to the small distance between them.
- In simulation, many gaps of μm scale need be avoided.
- A solution to this problem will be published.



Assigning material properties

Material	Assigned parameter
Core	$\mu'(f), \mu''(f), \varepsilon'(f), \varepsilon''(f)$
Insulation layer	ε_r
Painting of core	$\varepsilon_r = 1$
Wire	PEC
Seat	$\varepsilon_r = 2$





- The base is not modelled, however, the wire lengths need to be exact, as they influence coupling and leakage inductance.

- PEC is used for the wires, because the DC resistance can be easily assigned using lumped element or be placed elsewhere to save solver time; besides, the skin effect is negligible in the frequency below 100MHz.

- The painting is at first not modelled.

Extract μ', μ'' one coil, the other left open

Extracted from measurement:

$$\mu' = \frac{2\pi X(f)}{\omega N^2 \mu_0 H_E \ln\left(\frac{D_E}{D_I}\right)}; \quad \mu'' = \frac{2\pi R(f)}{\omega N^2 \mu_0 H_E \ln\left(\frac{D_E}{D_I}\right)};$$

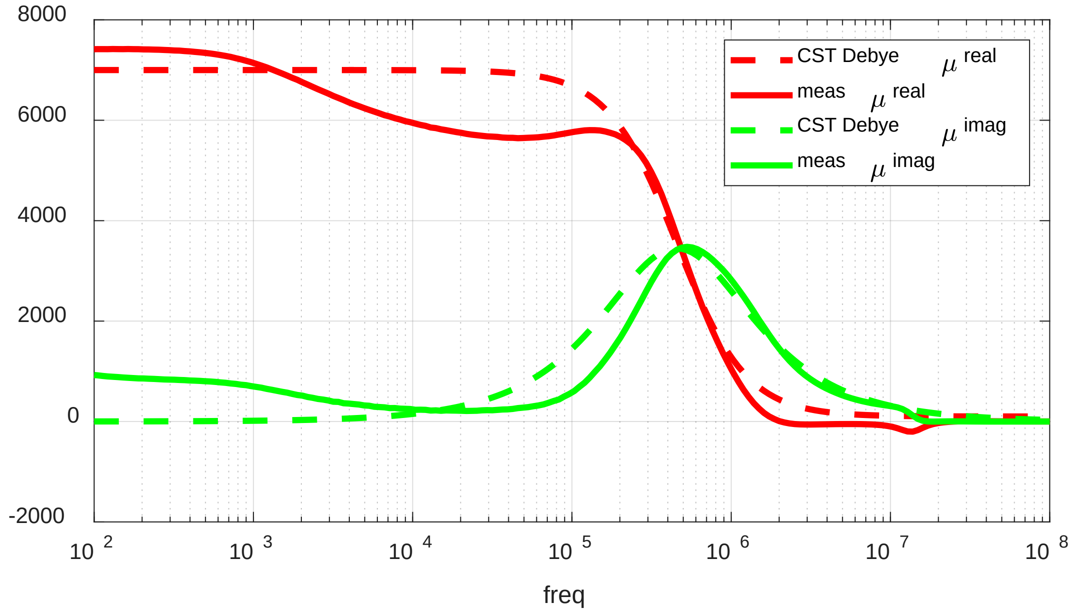
1st order Debye model:

$$\mu_r = \mu_\infty + \frac{\mu_{static} - \mu_\infty}{1 + j\omega\tau_{relaxation}}$$

$$\mu_{static} = 7000 \quad \mu_\infty = 100$$

$$\tau_{relaxation} = 3.5e-7s$$

An approximated value



The permeability of some cores can be approximated using 1st order Debye model.

Core Magnetic Material Properties - measurement

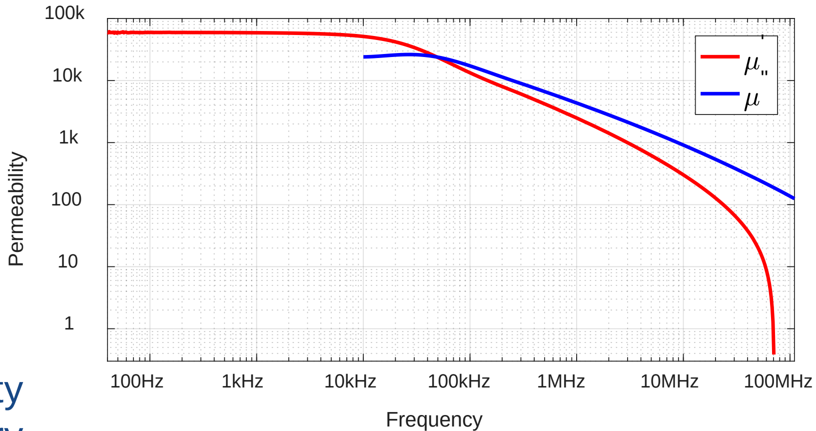
Measurements of the complex permeability

- Test fixture is used to measure magnetic parameters of toroidal cores
- Measurement of input impedance of the fixture with and without toroidal core is done
- Complex permeability is calculated from the formula (1)

$$\mu = 1 + \frac{2\pi(Zwi_{th\,core} - Zfi_{xture})}{j\omega\mu_0 h \ln\frac{D_{out}}{D_{in}}} \quad (1)$$

Reference: Agilent Solutions for Measuring Permittivity and Permeability with LCR Meters and Impedance Analyzers

Fig.6 EMCoS test fixture for the measurement of core permeability



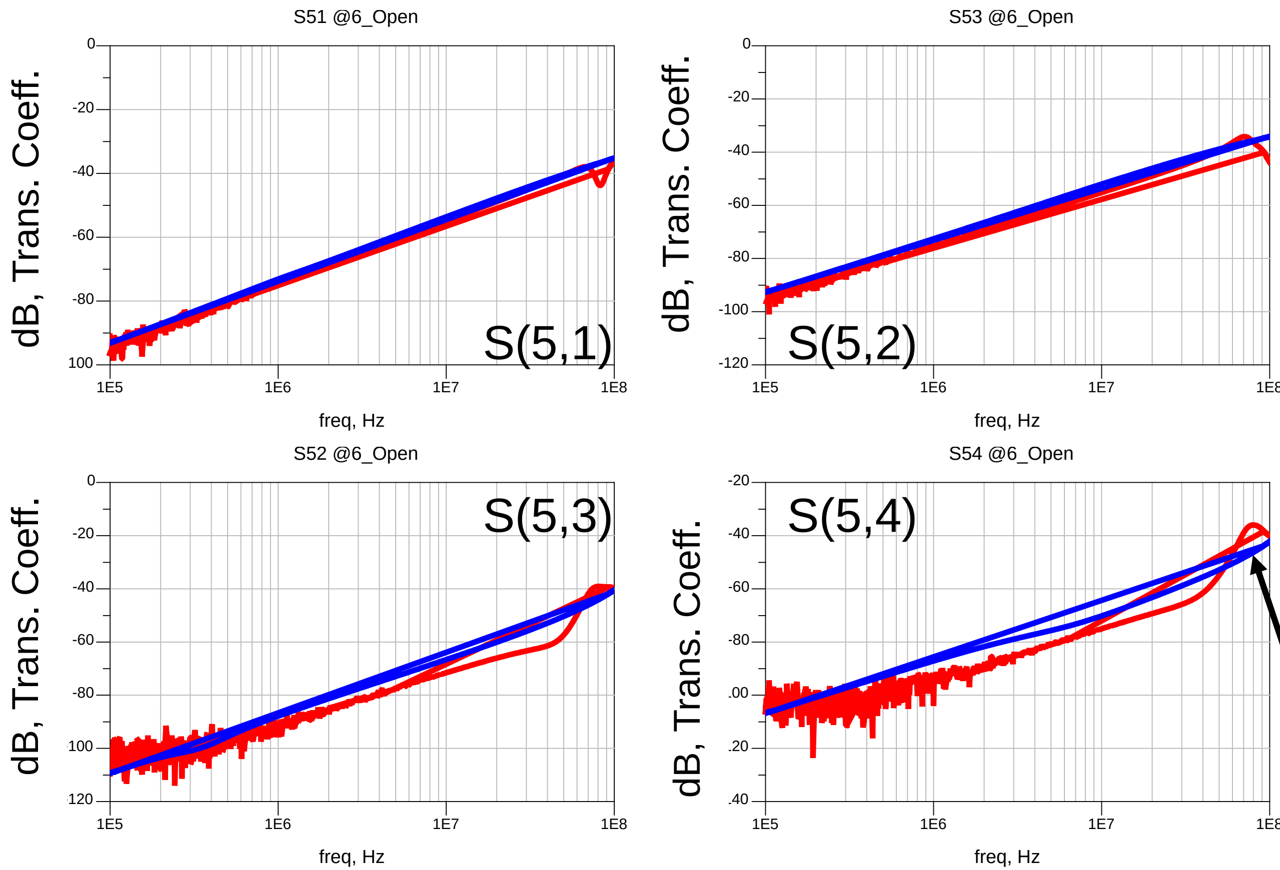
Measured complex permeability vs. frequency

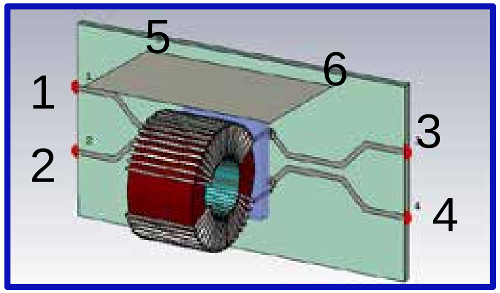
EMCoS Consulting and Software

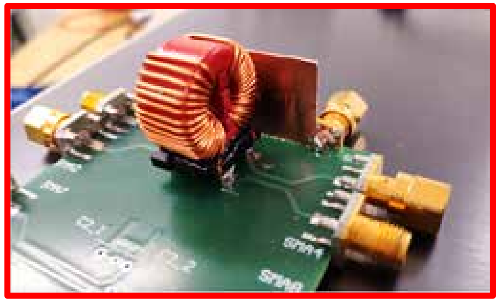
Measurements of complex permeability are performed in EMCoS laboratory using impedance analyzer in the frequency range from 40 Hz up to 110 MHz

Coil to wire coupling

Test case for mutual parasitic prediction [P6 open]







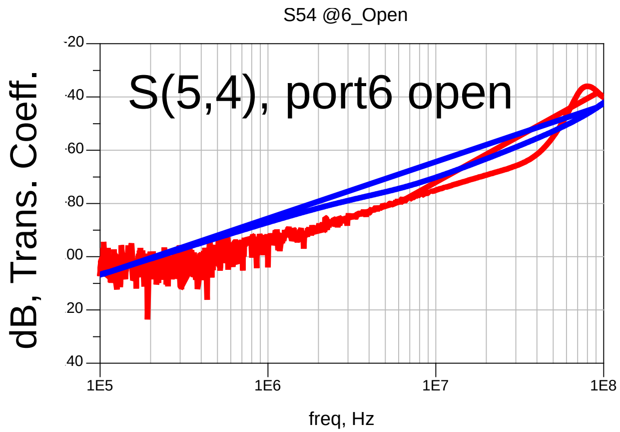
Measurement
Simulated

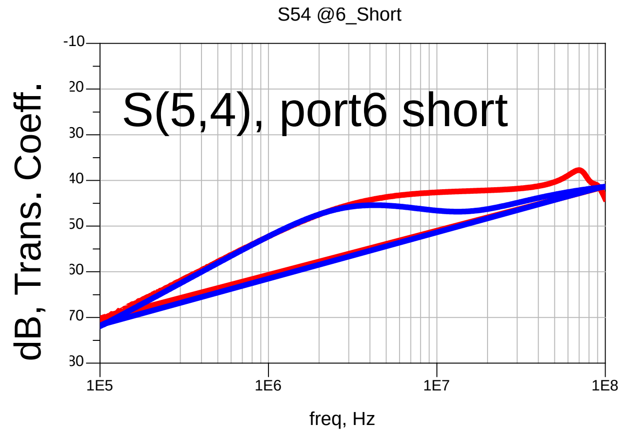
Core defined by
1st order Debye model
$\mu_{sta} = 7000; \mu_{\infty} = 1; \tau = 3.5e-7s$

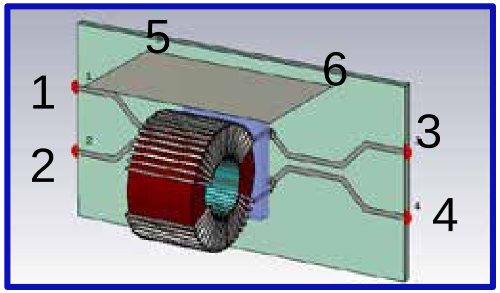
A resonance is missed, it is related to the core permittivity

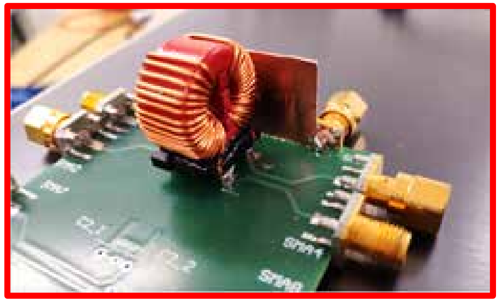
Mismatch between simulation and measurement

Take the far-end coupling S_{54} as example:





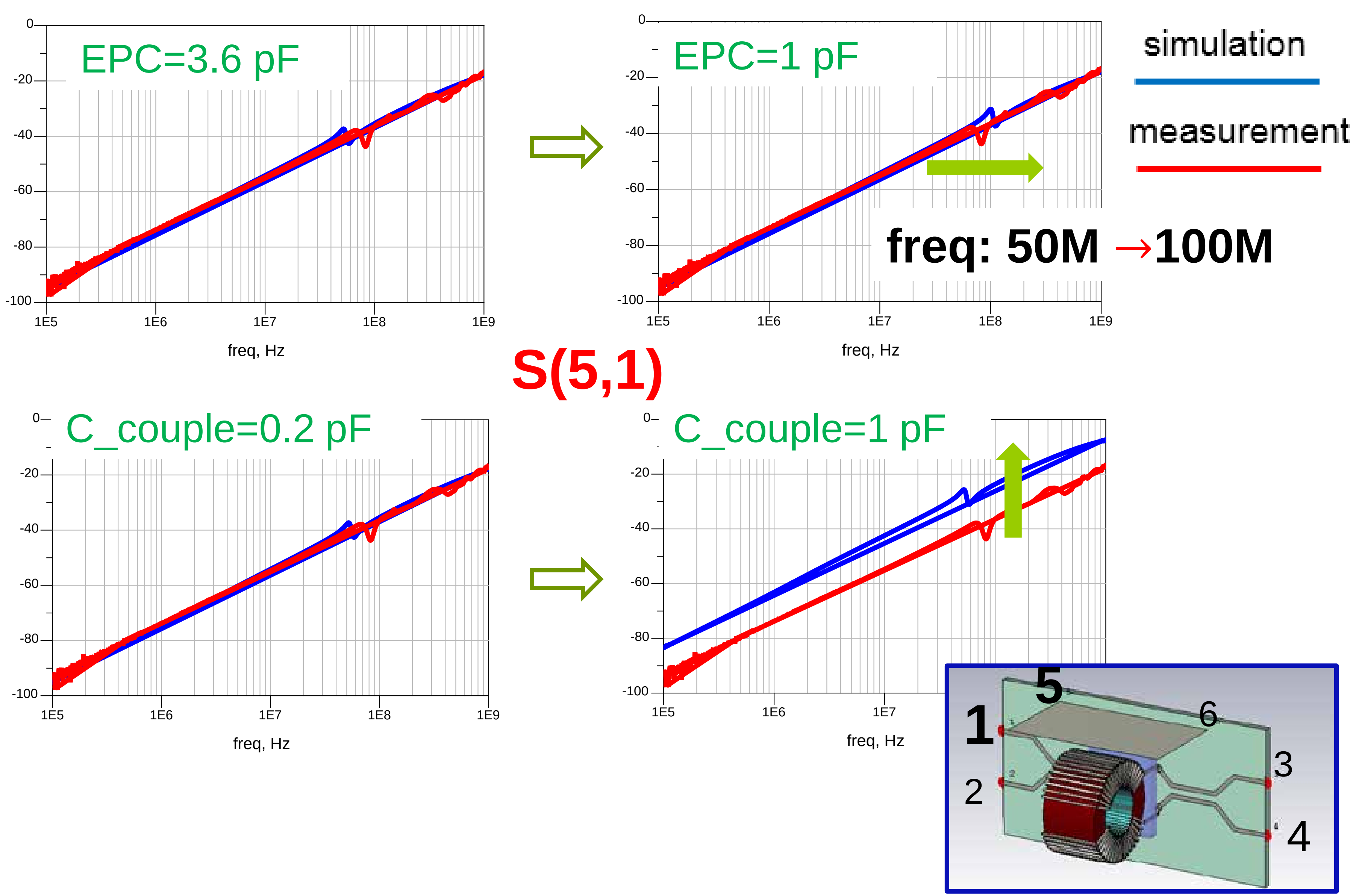




The major trend shows good match, while the resonance doesn’t show up in the simulation result.

Eps_r needs to be known.

Parameters' Impact on Coupling [P6 open]



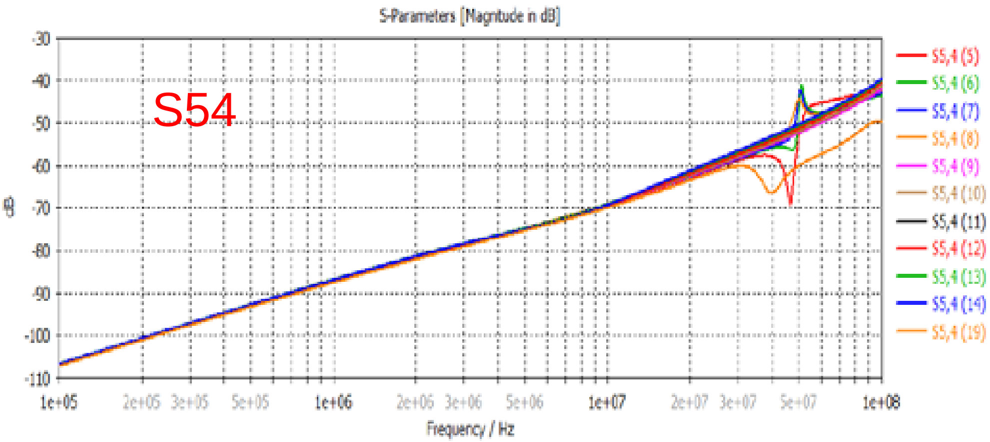
Parameters that affects the resonance

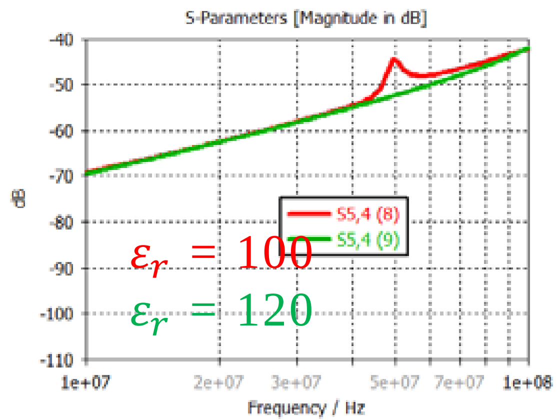
Parameters to tune	**Influence on resonance**
Leakage inductance	Increase the leakage inductance will lower the resonance frequency
EPC	Increase the value of EPC, will lower the resonance frequency
C_couple	Increase C_couple will increase the level of curves.

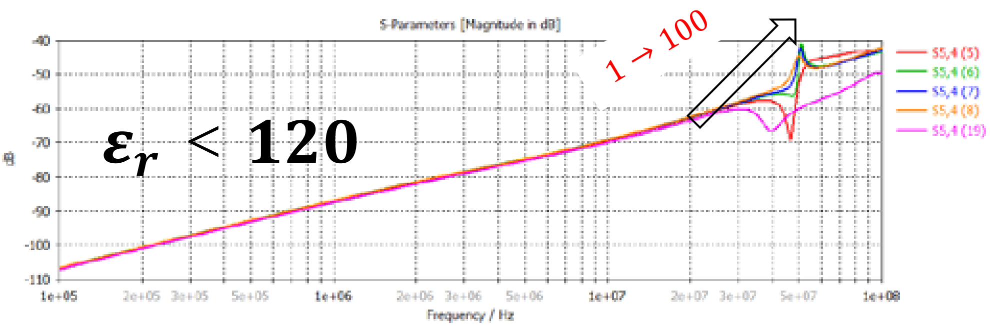
Important to determine ε_r (key parameter for EPC, inter coil coupling capacitor)

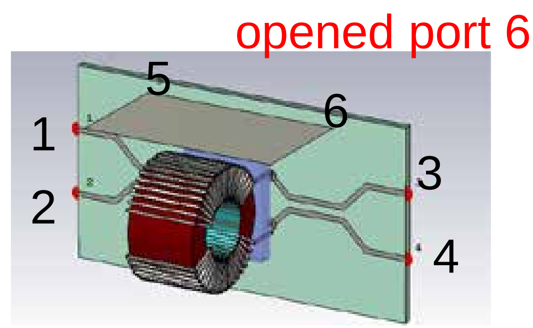
Use 3D model to investigate the impact of ε_r

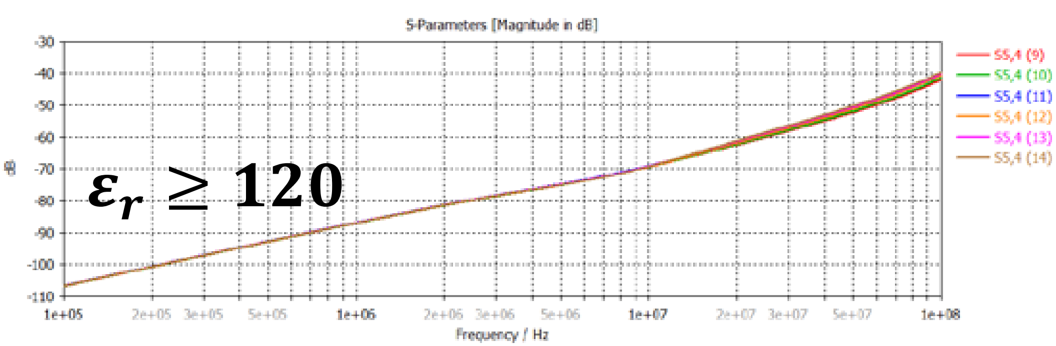
Investigate the impact of ε_r (open-ended plate)











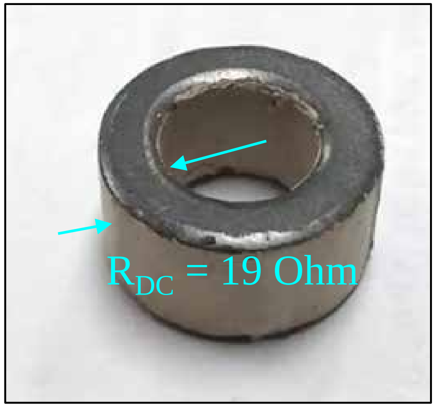
3D Run ID	PlateDepth	MuInf	PlateH	ferriteEr
5	2	100	20	30
6	2	100	20	70
7	2	100	20	50
8	2	100	20	100
9	2	100	20	150
10	2	100	20	180
11	2	100	20	120
12	2	100	20	210
13	2	100	20	250
14	2	100	20	300

Summary

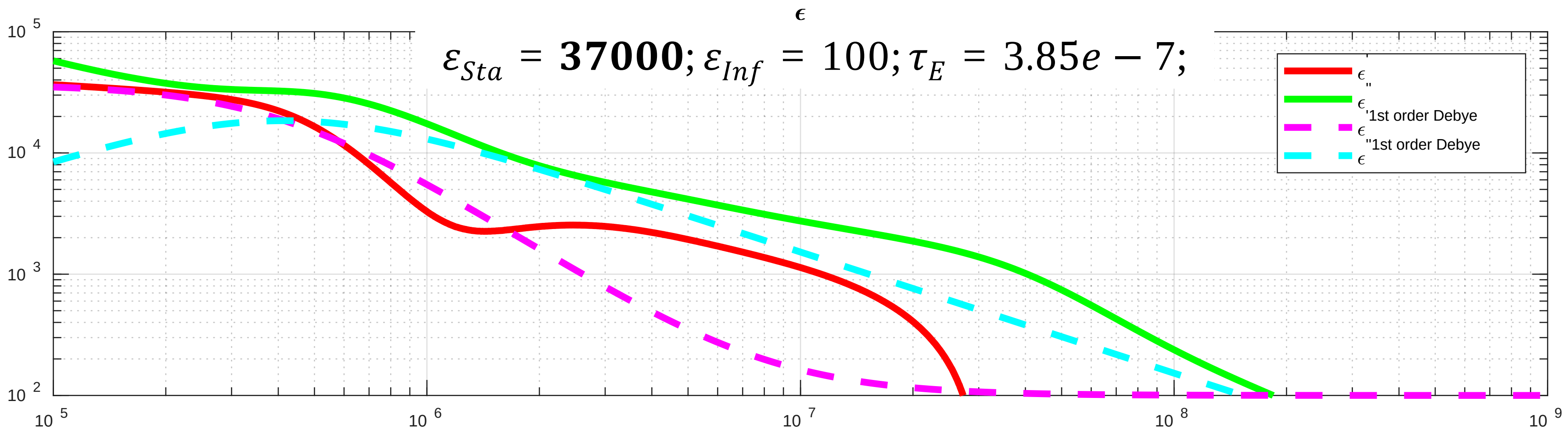
- The CMC model can represent the actual CMC and the coupling between the CMC and metal plate up to 10MHz.
- From the circuit analysis, the EPC and coupling capacitance affects the coupling between the CMC and the plate.
- By adjusting the ε_r and μ_∞, it's seen that the higher order resonance above 50MHz, is contributed by both the inductance and the capacitance associated with the core material.

Attempts on extracting ε and μ_∞

- Measure the core with silver paint on outer and inner surface.
- Extract the ε and μ of the core.
  - Implement in 3D simulation scenario first
  - Try extraction using measured data
    - Both inner and outer surface is completely covered by silver paint.
    - DC resistance measured using mustimeter (point to point) is around 19Ω
    - Copper tape at tip of the probe touches the surfaces of the core.
    - The contact is enhanced by inserting foam in the inner space and tape at the outer surface.



Extracting the ε



The 1st order Debye model is not enough to represent the rapid decrease of ε'

The ε' at above 10MHz remains unknown. But can be solved under another configuration

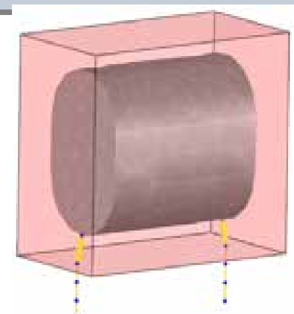
The misalignment with the Debye model indicates the static **conductivity** of the core, as well as the small DC resistance measured across the toroid.

Filter modeling at EMCOS

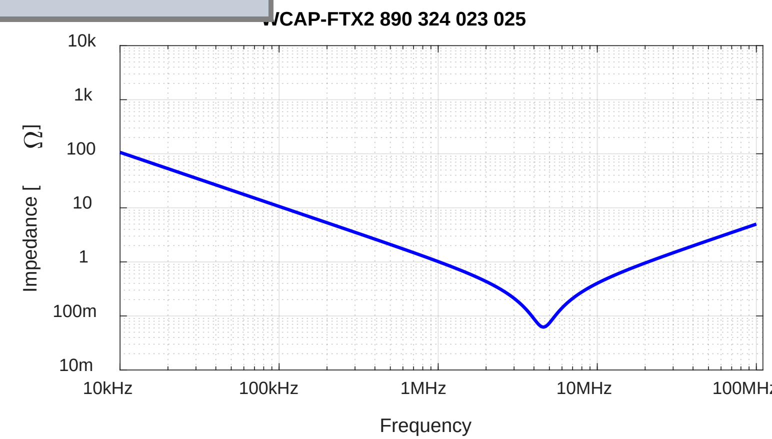
Modeling of the Filter Components EMCOS

WCAP-FTX2 MKP Film Capacitor 890324023025

Film capacitor



F3D model of film capacitor



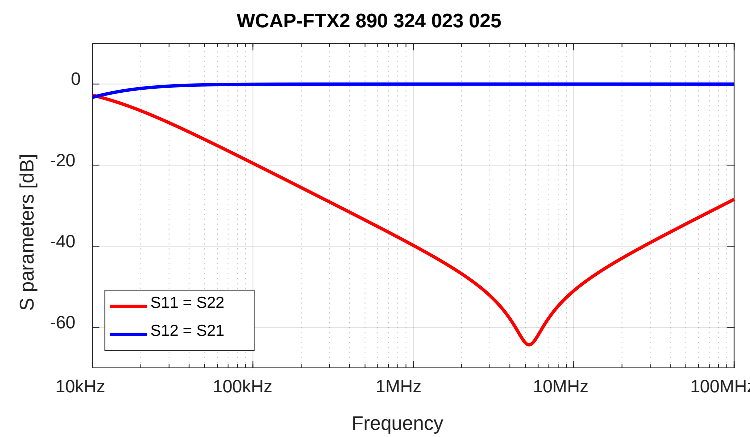
Calculated impedance (Pin length = 3mm)

Electrical parameters of film capacitor

Electrical parameters	
Nominal capacitance, C	0.15 µF
Equivalent series resistance, ESR	60 mΩ
Equivalent series inductance, ESL	8.0 nH
Rated voltage, V (AC)	275 V

Geometrical parameters of film capacitor

Geometrical parameters	
Max. dimensions, (L × W × H)	13 × 7 × 12 mm
Distance between pins	10 mm
Pins diameter	0.6 mm



Calculated S parameters (Pin length = 3mm)

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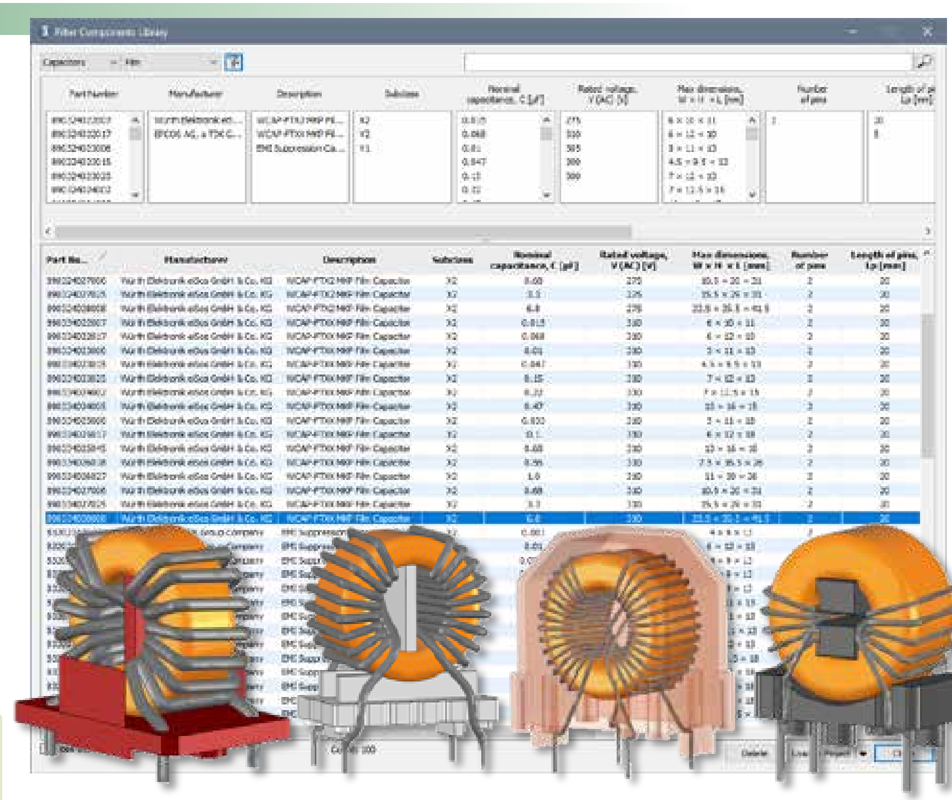
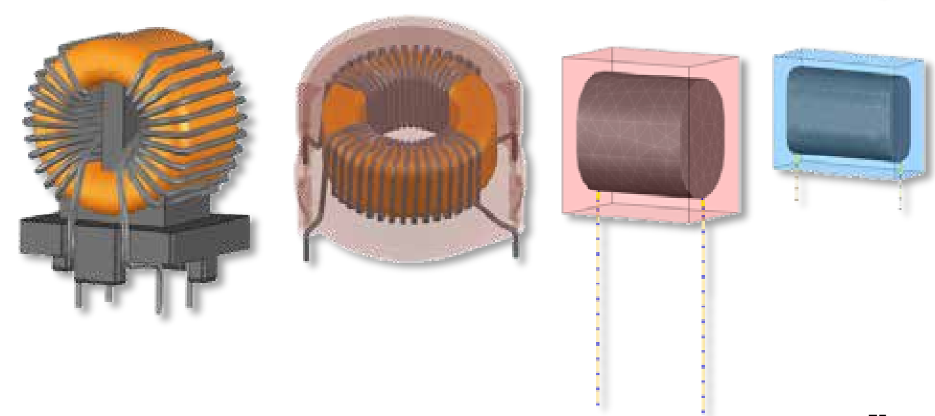
EMCoS Studio Filters Components Library

- Integrated library of pre-assembled standard filter components of different types provides possibility to easily add a desired component to 3D / Circuit filter layout
- The library is based on OEM datasheets and measurements of actual components
- The components are grouped by types and each component type has own library catalog



General Structure of Library Catalogs:

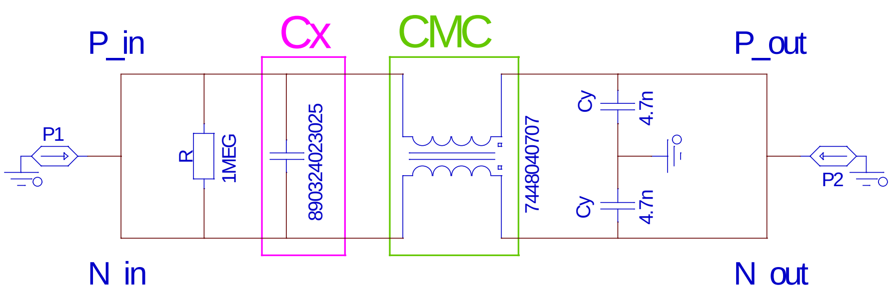
Cores:	***Capacitors:***	***Inductors:***
Rods	*Film*	*DM Choke*
Bars	*Feedthrough*	*CM Choke 1-phase*
Bobbins	*SMD*	*CM Choke 3-phase*
Toroids		
U&E Cores		
Suppressors		

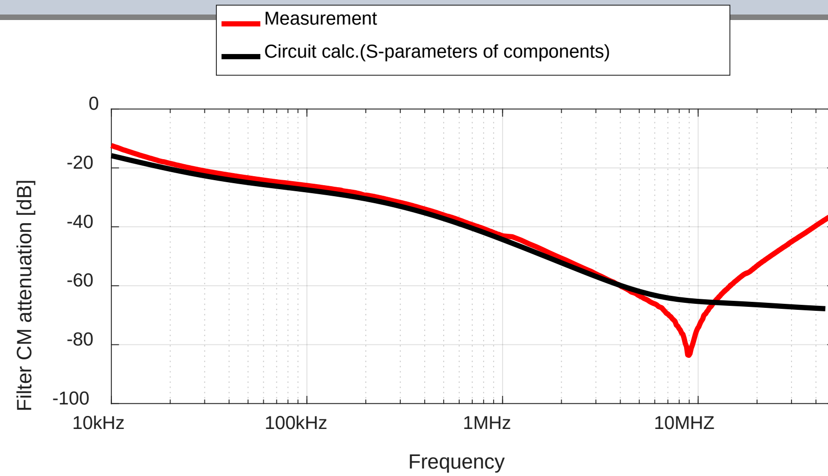


Simulation Models of EMC Filter in EMCoS Studio

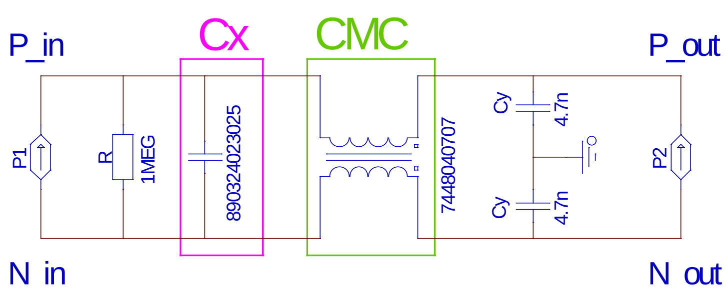
Circuit calculation of the filter with s-parameters of the components

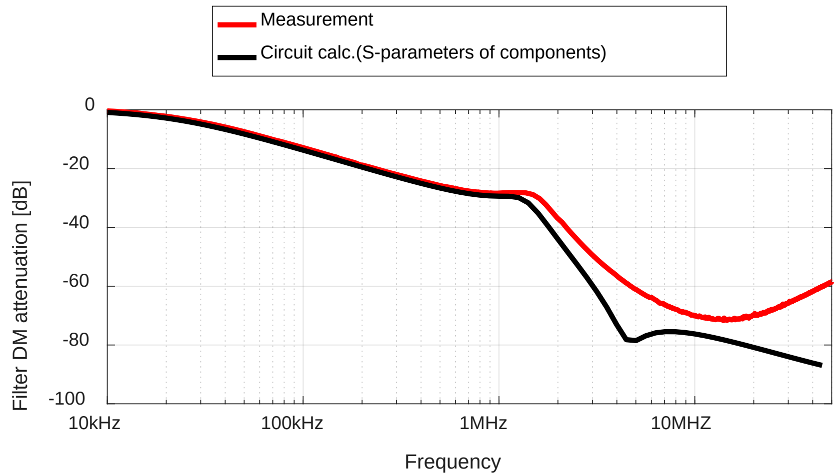
Common Mode





Differential Mode

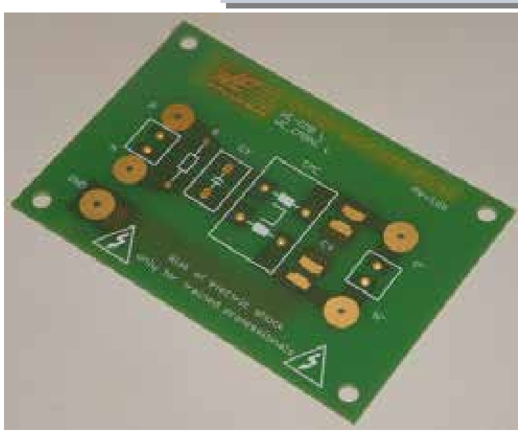




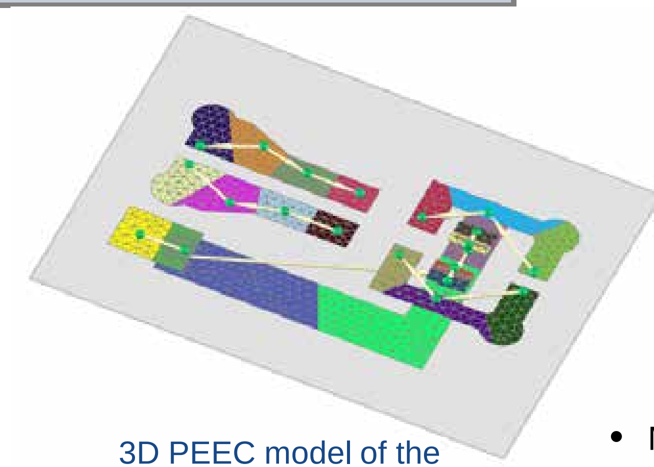
Speed-oriented EMCoS circuit solver **TSReady** with the modified nodal analysis (MNA) approach is used for circuit calculations

3D PEEC Solution of Stray RLC Parameters of the PCB

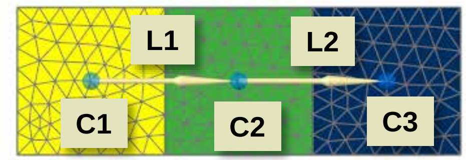
Equivalent Circuit Extraction



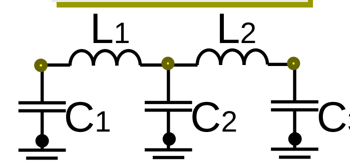
Evaluation board from Würth Elektronik design kit



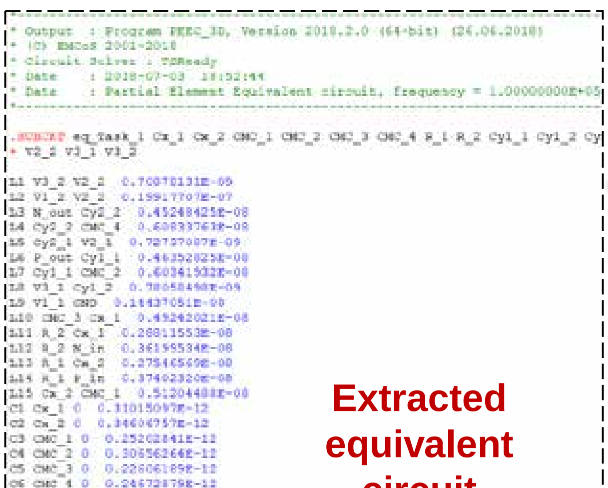
3D PEEC model of the evaluation board



Pi-scheme



- Model is divided into partial elements: surface geometry patch elements (for CG calculation) and branches (for RL calculation)
- Pins are corresponding to partial capacitance (C) and conductance (G) elements. Each pin has coordinate and corresponding surface geometry patch
- Branches are corresponding to partial inductance (L) and resistance (R) elements. Branches are based on pins
- Automatic partitioning is supported

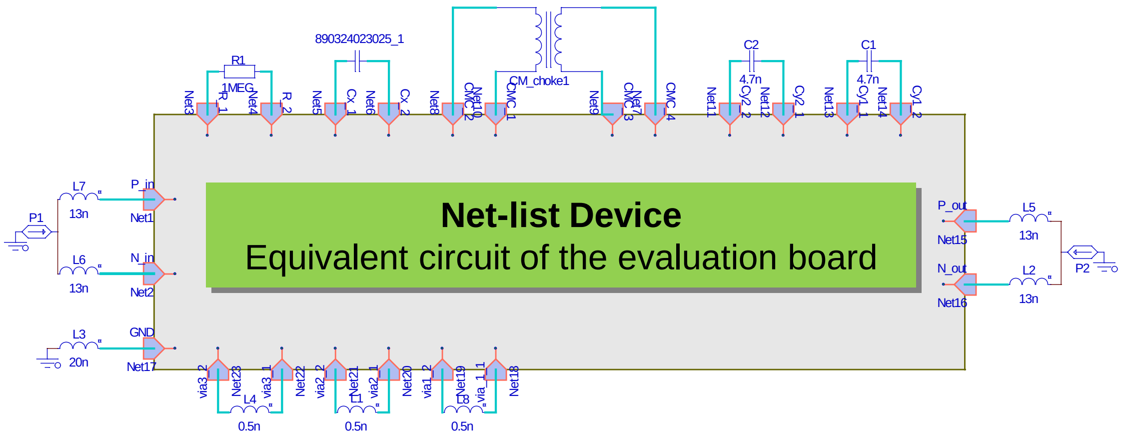


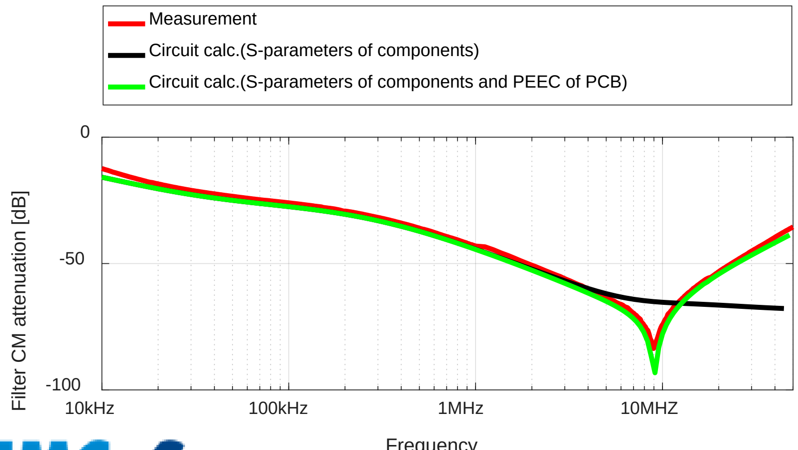
```
*------------------------------------------------------------------------
* Output   : Program PEEC_3D, Version 2018.2.0 (64-bit) (26.06.2018)
* (C) EMCoS 2001-2018
* Circuit Solver : TDReady
* Date     : 2018-07-03  18:52:44
* Data     : Partial Element Equivalent circuit, frequency = 1.00000000E+05
*------------------------------------------------------------------------

.SUBCKT eq_Task_1 Cx_1 Cx_2 CMC_1 CMC_2 CMC_3 CMC_4 R_1 R_2 Cy1_1 Cy1_2 Cy
+ V2_2 V1_1 V1_2

L1 V3_2 V2_2  0.70070131E-05
L2 V1_2 V2_2  0.19917707E-07
L3 N_out Cy2_2  0.45248425E-08
L4 Cy2_2 CMC_4  0.60833763E-08
L5 Cy2_1 V2_1  0.72727007E-09
L6 P_out Cy1_1  0.46352825E-08
L7 Cy1_1 CMC_2  0.60341532E-08
L8 V1_1 Cy1_2  0.78658490E-09
L9 V1_1 GND  0.11437051E-08
L10 CMC_3 Cx_1  0.49242021E-08
L11 R_2 Cx_1  0.28811553E-08
L12 R_2 N_in  0.36195534E-08
L13 R_1 Cx_2  0.27546560E-08
L14 R_1 P_in  0.37402320E-08
L15 Cx_2 CMC_1  0.51204408E-08
C1 Cx_1 0  0.31015097E-12
C2 Cx_2 0  0.34604757E-12
C3 CMC_1 0  0.25202841E-12
C4 CMC_2 0  0.30656264E-12
C5 CMC_3 0  0.22606185E-12
C6 CMC_4 0  0.24672879E-12
```

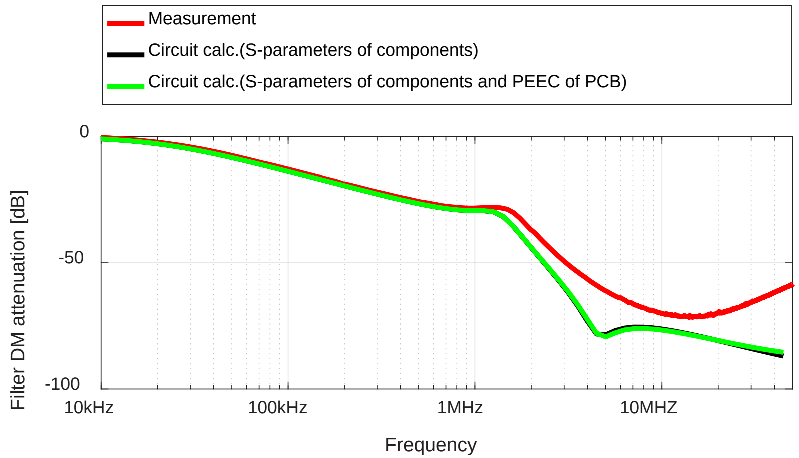
Extracted equivalent circuit

Simulation Models of EMC Filter in EMCoS Studio

Circuit Calculation of the Filter with S-Parameters of the Components and Stray RLC Parameters of the PCB Traces

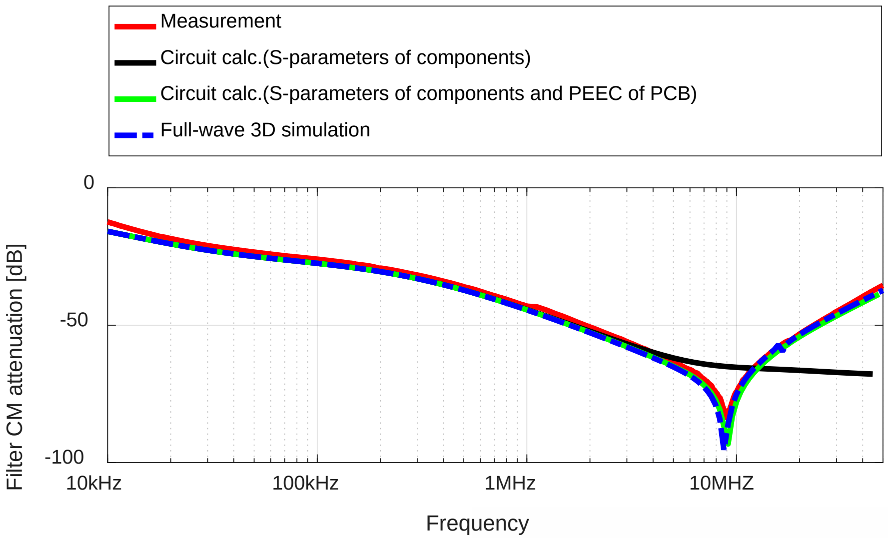


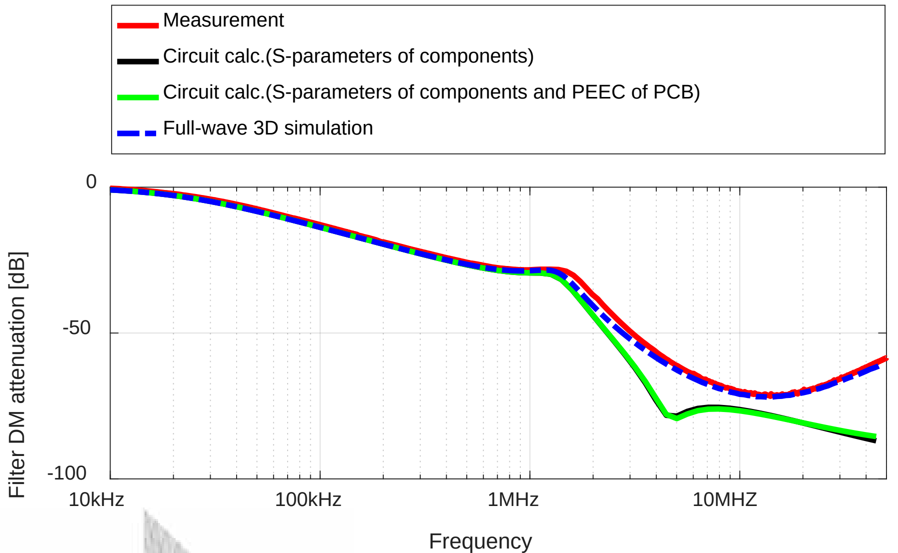


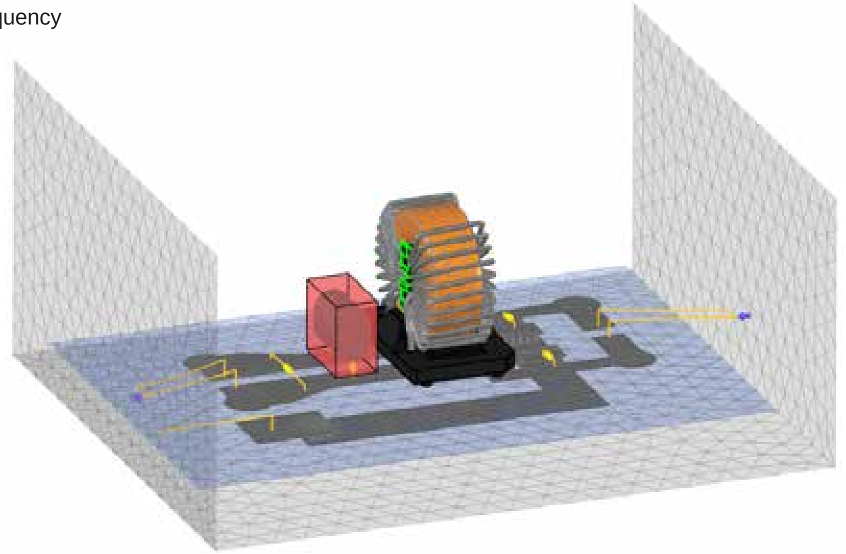


Simulation Models of EMC Filter in EMCoS Studio

3D simulation with full-wave MoM solver





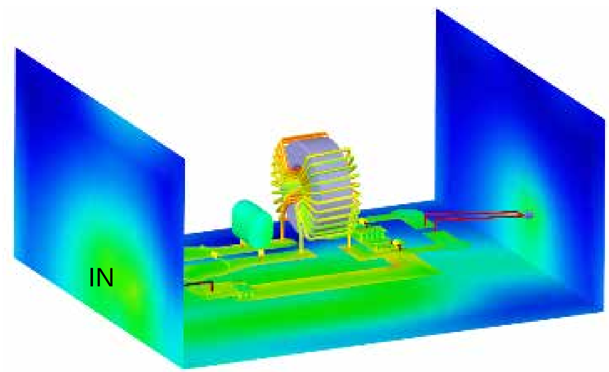


EMCoS
Consulting and Software

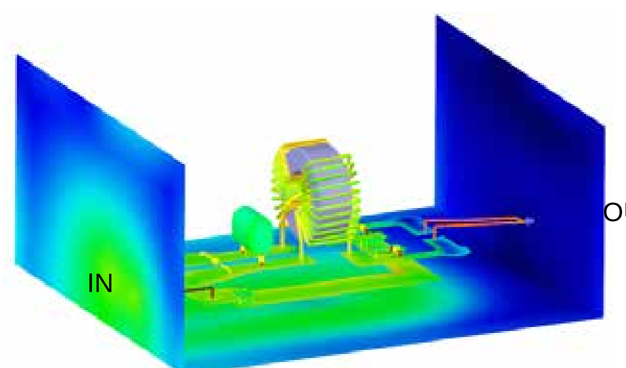
3D Current Distribution

3D simulation with full-wave MoM solver TriD

Common Mode

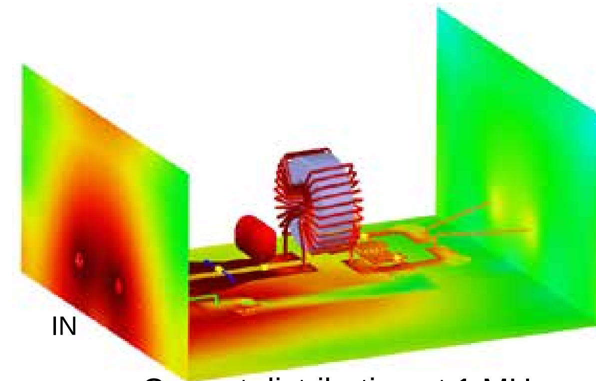


Current distribution at 1 MHz

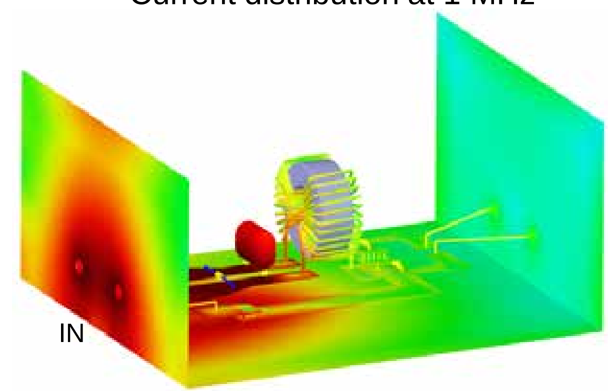


Current distribution at 9 MHz

Differential Mode



Current distribution at 1 MHz



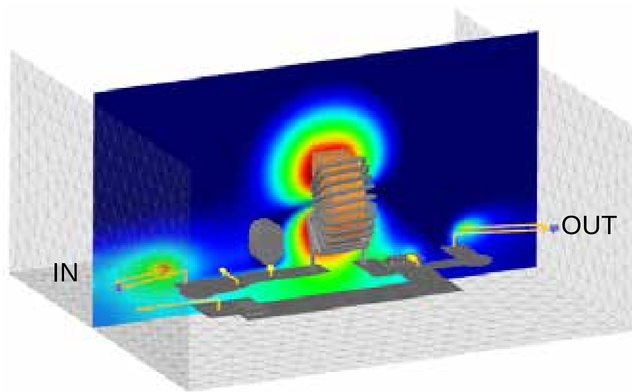
Current distribution at 9 MHz

EMCoS Consulting and Software

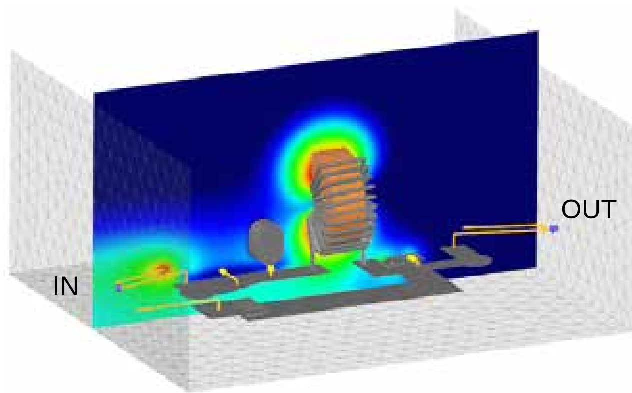
Magnetic Near Field Distribution

3D simulation with full-wave MoM solver TriD

Common Mode

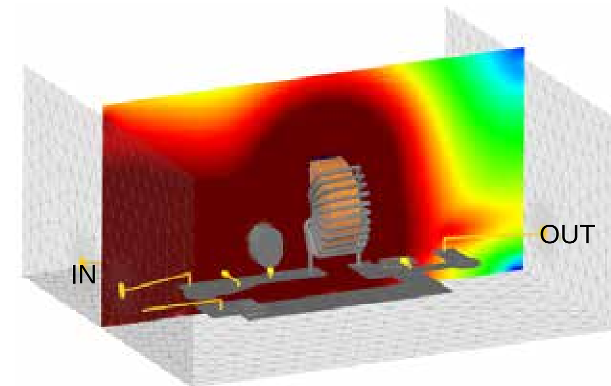


H-field distribution at 1 MHz

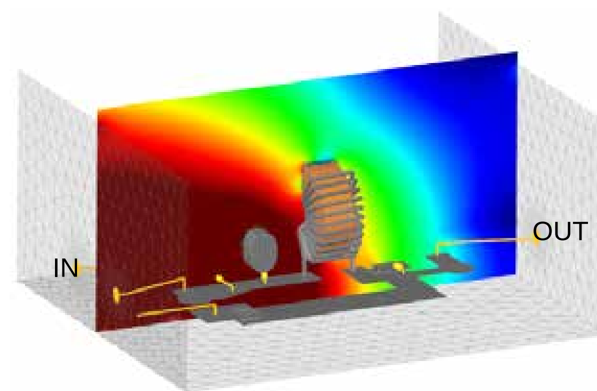


H-field distribution at 9 MHz

Differential Mode



H-field distribution at 1 MHz



H-field distribution at 9 MHz

EMCoS Consulting and Software

Conclusions – MoM modeling

- 3D models of the components as well as their circuit elements based on the S-parameters can be used for filter simulations
- Different simulation levels for the modeling and validation of EMC filter models are presented and show good matching with measurements
- Comparison of the simulation results with measurements is performed in the frequency range from 10 kHz up to 50 MHz and up
- 3D PEEC solution helps to reproduce effects caused by interaction and conductive coupling between PCB traces. FEM solutions are also suitable.
- 3D full-wave MoM solution takes into account conductive coupling as well as EM field interaction between components
- Demonstrated techniques can be used for the investigations and improvement of the EMC filters performance

EMCoS Consulting and Software

Measurement of core parameters

- 7 mm air line
- Using turns
- 16454A magnetic material test fixture

Solutions for measuring ε*, μ*

III. Permeability Evaluation

Inductance measurement method

Relative permeability of magnetic material derived from the self- inductance of a cored inductor that has a closed loop (such as the toroidal core) is often called effective permeability. The conventional method of measuring effective permeability is to wind some wire around the core and evaluate the inductance with respect to the ends of the wire. Effective permeability is derived from the inductance measurement result using the following equations:

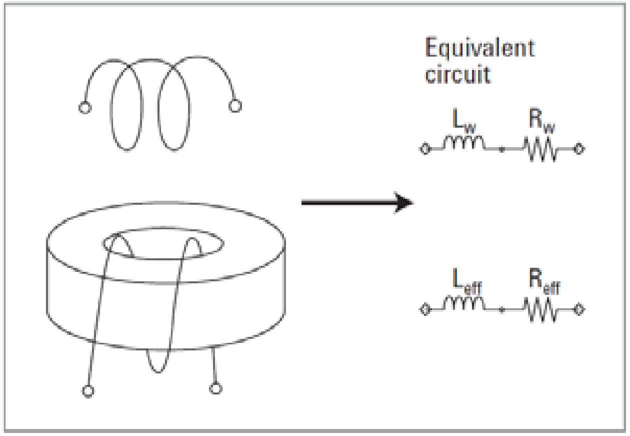


Figure 25. Method of measuring effective permeability

$$\mu'_e = \frac{\ell L_{eff}}{\mu_0 N^2 A}$$

$$\mu''_e = \frac{\ell (R_{eff} - R_w)}{\mu_0 N^2 \omega A}$$

R_{eff}: Equivalent resistance of magnetic core loss including wire resistance

L_{eff}: Inductance of toroidal coil

R_w: Resistance of wire only

L_w: Inductance of air-core coil inductance

N: Turns

ℓ: Average magnetic path length of toroidal core [m]

A: Cross-sectional area of toroidal core [m²]

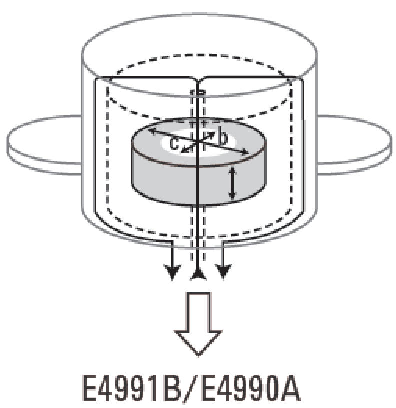
ω: 2π f (frequency)

μ_0: 4π x 10^{-7} [H/m]

Solutions for measuring ε*, μ*

III. Permeability Evaluation

Measurement system using the 16454A magnetic material test fixture



$$\dot{\mu} = \frac{(\dot{Z}m - \dot{Z}sm)\ 2\pi}{j\omega\mu_0 \quad h \ln\frac{c}{b}} + 1$$

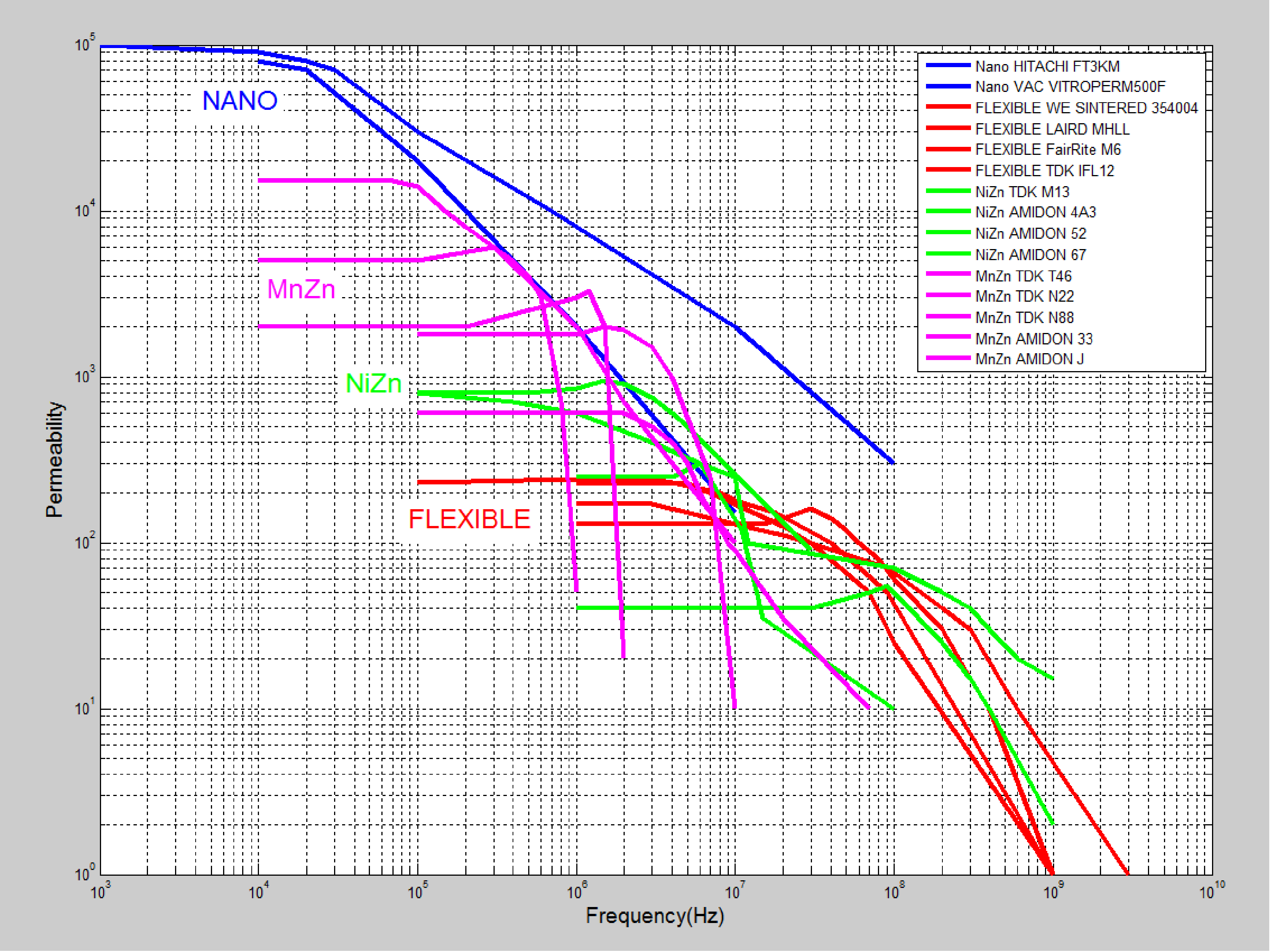
$\dot{\mu}$	Relative permeability
$\dot{Z}m$	Measured impedance with toroidal core
$\dot{Z}sm$	Measured impedance without toroidal core
μ_0	Permeability of free space
h	Height of MUT (material under test)
c	Outer diameter of MUT
b	Inner diameter of MUT

Figure 27. Structure of the 16454A and measurement concept

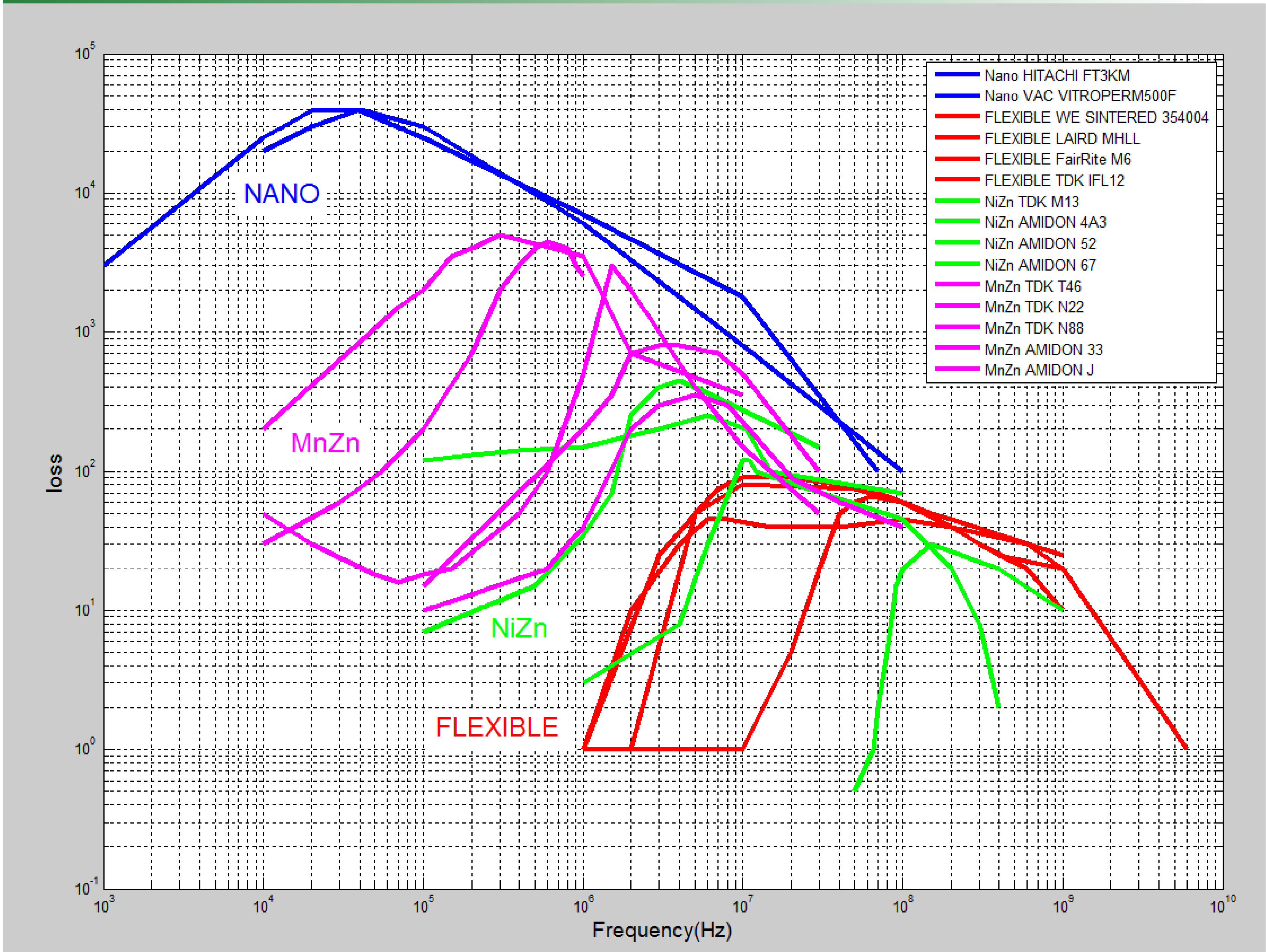
Material properties comparison

- Mn-Zn ferrites
- Nanocrystalline
- Flexible Material

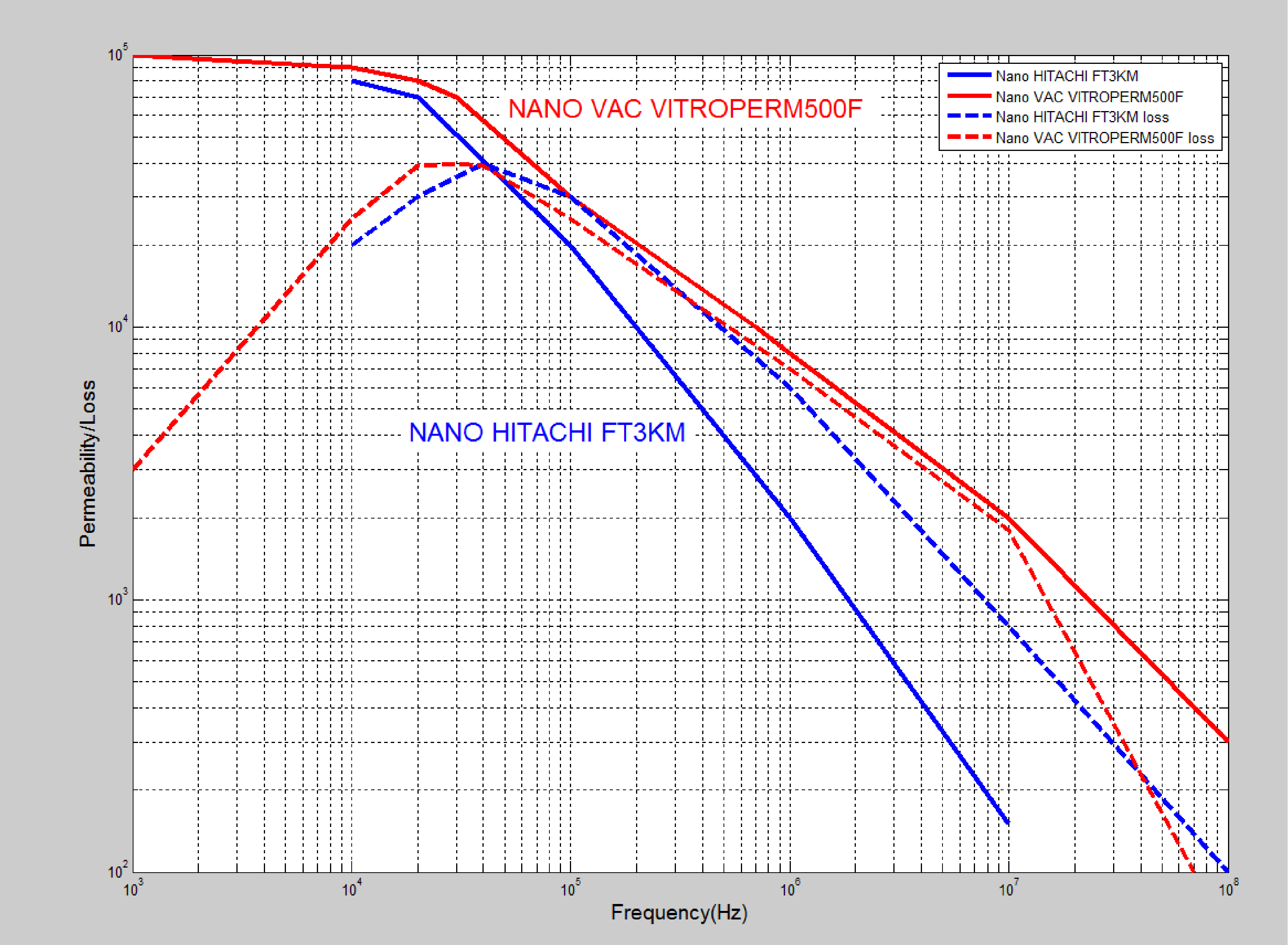
Overview on μ' vs. frequency



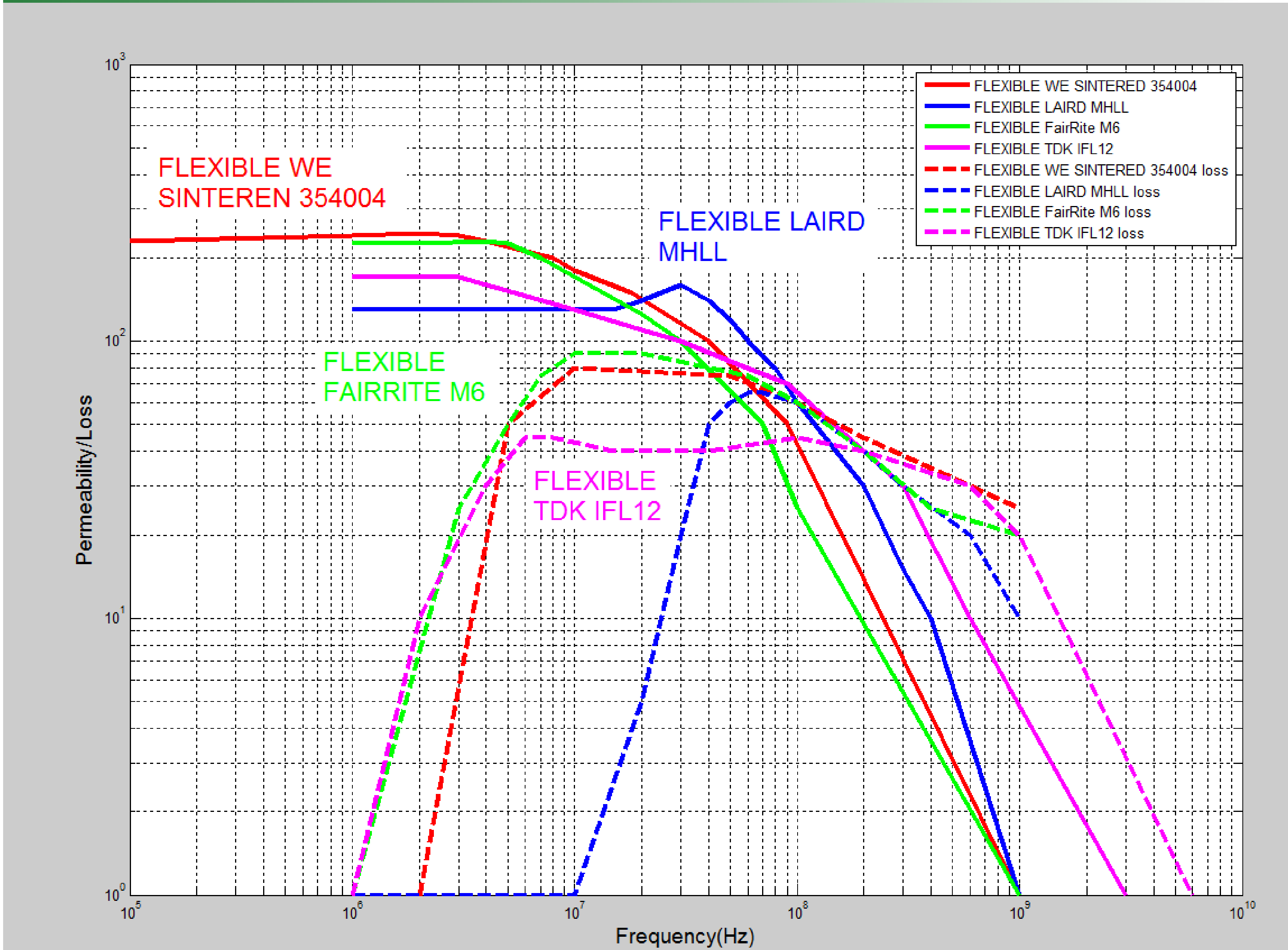
Overview on μ'' vs. frequency



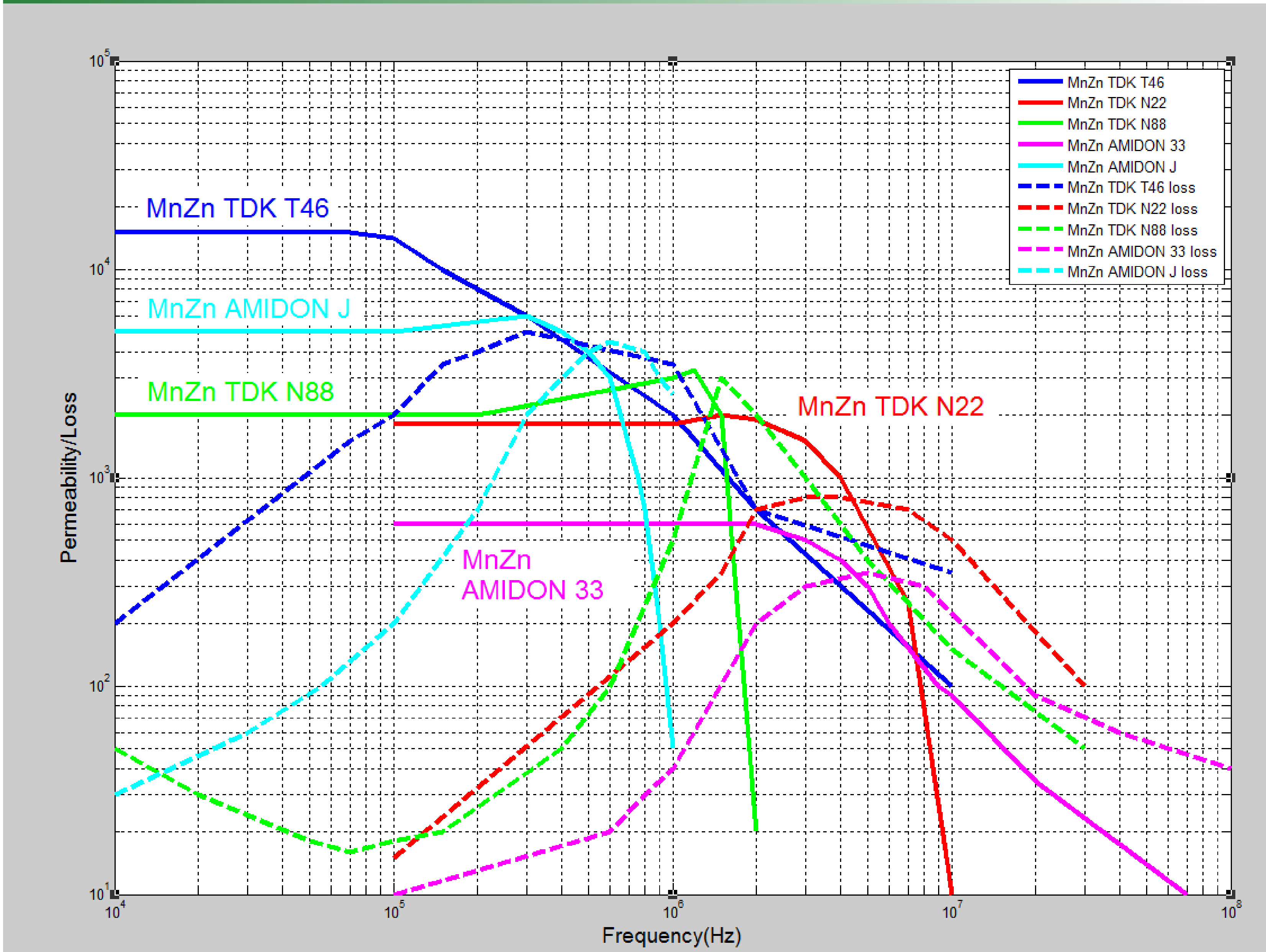
Nanocrystalline ----- μ', μ'' vs. frequency



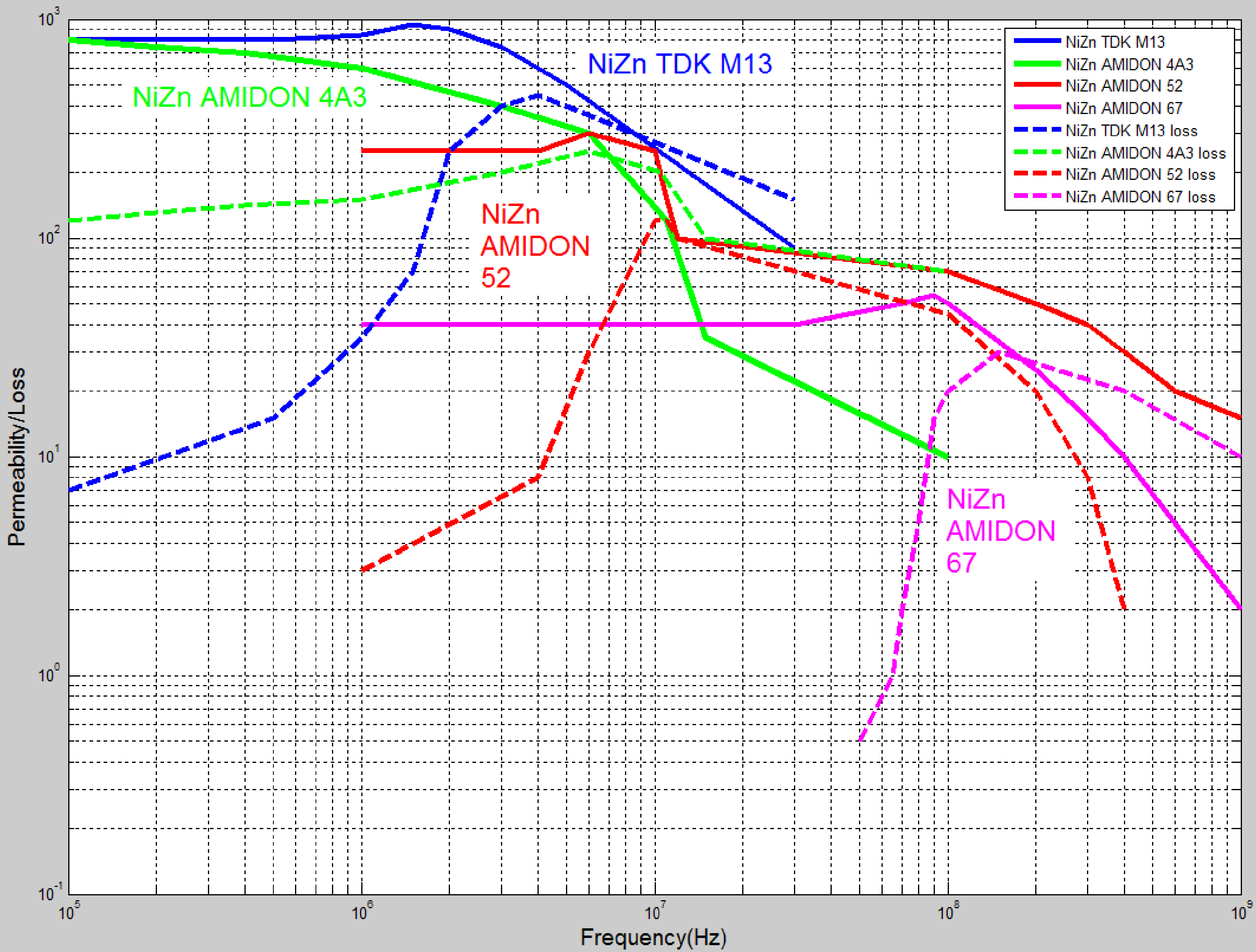
Flexible Material ----- μ', μ'' vs. frequency



MnZn ----- μ', μ'' vs. frequency



NiZn ----- μ', μ'' vs. frequency



Thank you