EMC WITH EMC

ELECTROMAGNETIC COMPATIBILITY WITH ELECTROMECHANICAL CONNECTIONS

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Ingénieur d'application

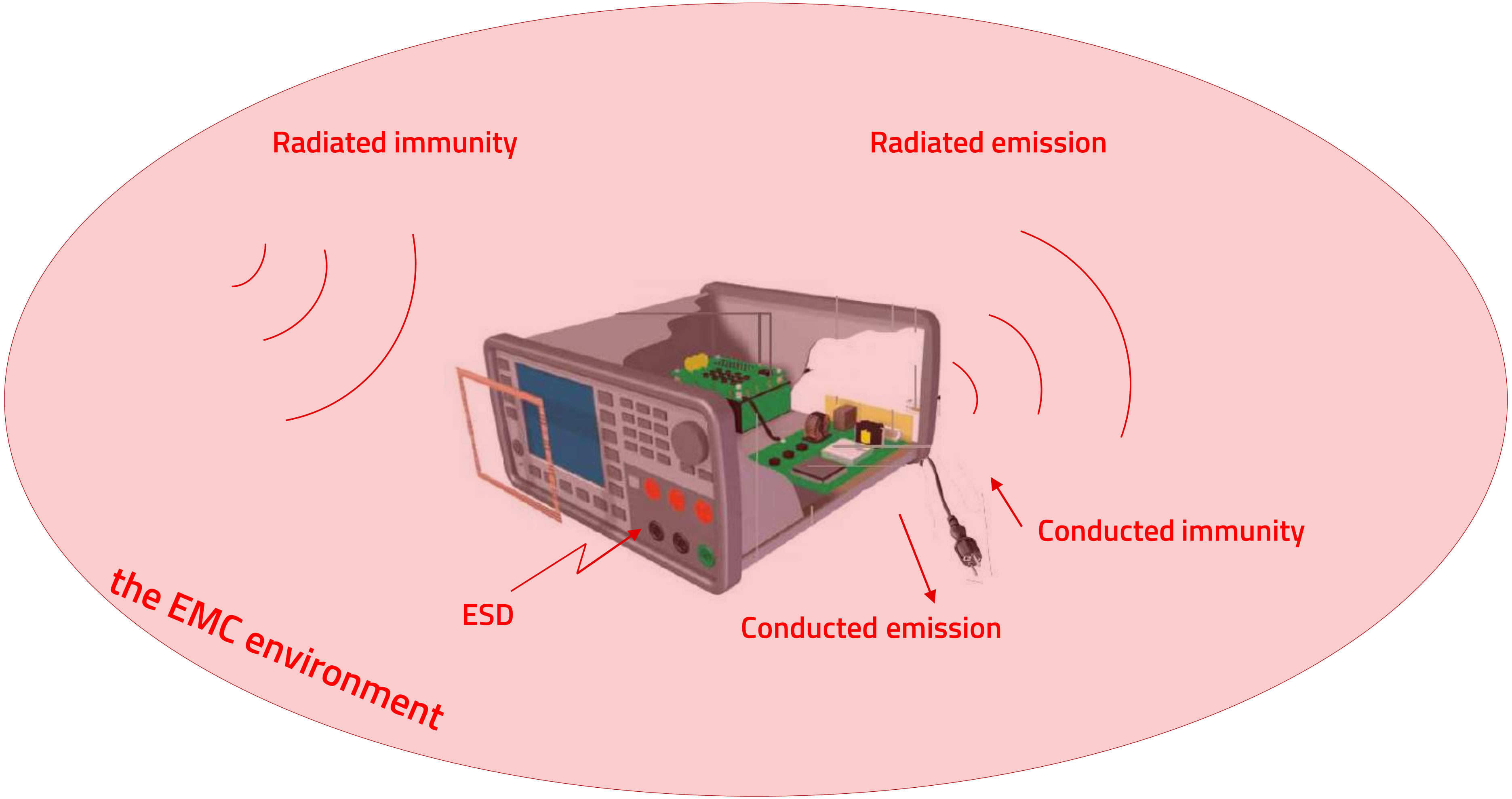
PUBLIC

Agenda

- Introduction
- Ground concepts
- Ground connections
- Coupling effects
- Shielding
- Interconnecting cable and shielding
- Wire to board connections
- Board to board connections
- Flat ribbon and FFC cables
- ZIF connector
- Tact switches

Introduction

Legal requirements



Introduction

Standards

In Austria: EMC-Guideline 2014/30/EU

international:

IEC 61000-1 - Allgemeines, Definitionen und Interpreta

IEC 61000-2 - Umgebungsbedingungen

IEC 61000-3 - Grenzwerte und Oberschwingungen

IEC 61000-4 - Prüf- und Messverfahren

IEC 61000-5 - Installationsrichtlinien und Abhilfemaßna

IEC 61000-6 - Fachgrundnormen Störaussendung/Stör

europäisch:

Informationstechnische Einrichtungen

Industrielle, wissenschaftliche und medizinische HF-Ger

Signalübertragung auf Niederspannungsnetzen

Rundfunkempfänger

Haushaltsgeräte

29.3.2014 DE Amtsblatt der Europäischen Union L 96/79

RICHTLINIE 2014/30/EU DES EUROPÄISCHEN PARLAMENTS UND DES RATES

vom 26. Februar 2014

zur Harmonisierung der Rechtsvorschriften der Mitgliedstaaten über die elektromagnetische Verträglichkeit (Neufassung)

(Text von Bedeutung für den EWR)

DAS EUROPÄISCHE PARLAMENT UND DER RAT DER EUROPÄISCHEN UNION —

gestützt auf den Vertrag über die Arbeitsweise der Europäischen Union, insbesondere auf Artikel 114,

auf Vorschlag der Europäischen Kommission,

nach Zuleitung des Entwurfs des Gesetzgebungsakts an die nationalen Parlamente,

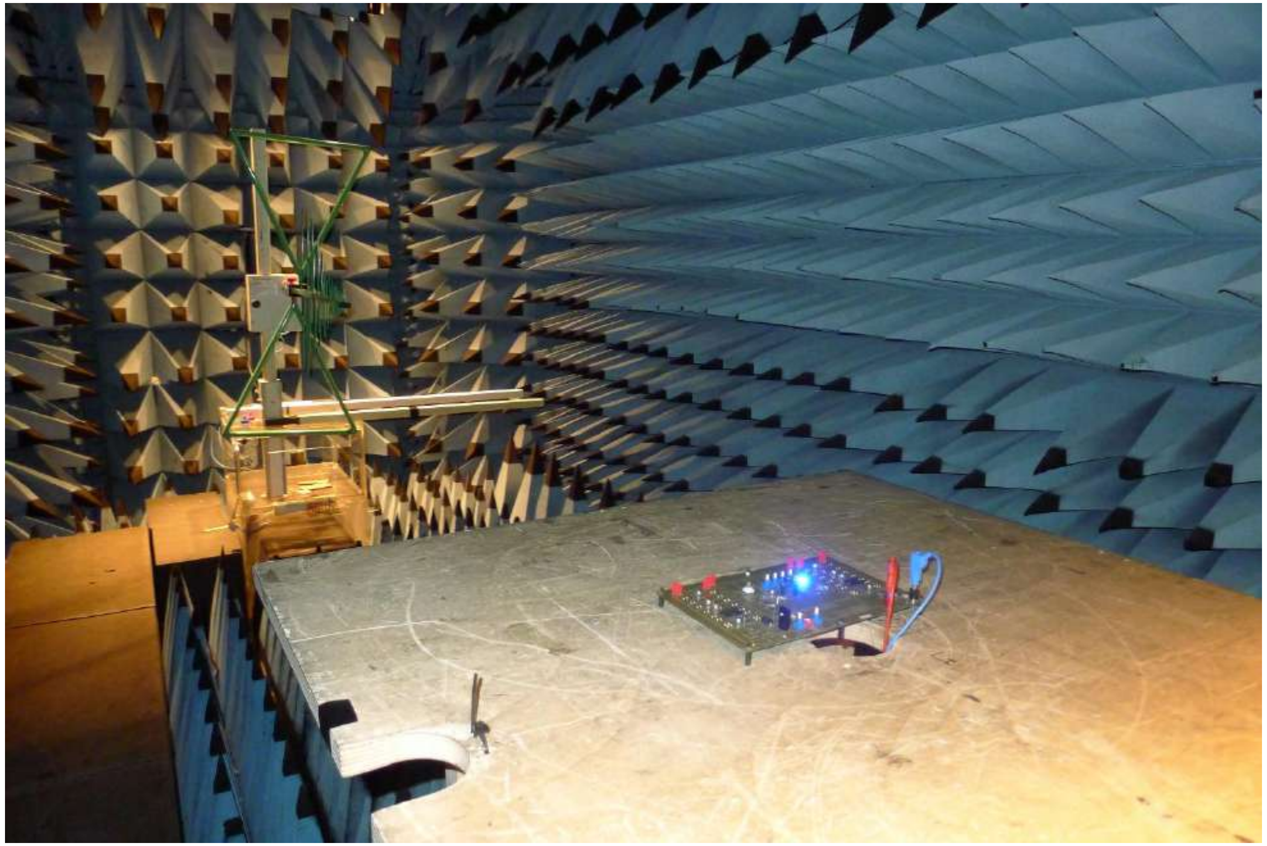
Rechtsvorschriften angewandt werden sollen, um eine einheitliche Grundlage für die Überarbeitung oder Neufassung dieser Rechtsvorschriften zu bieten. Die Richtlinie 2004/108/EG sollte an diesen Beschluss angepasst werden.

(4) Die Mitgliedstaaten sollten gewährleisten, dass Funkdienstnetze, einschließlich Rundfunkempfang und Amateurfunkdienst, die gemäß der Vollzugsordnung für den Funkdienst der Internationalen Fernmeldeunion (ITU) betrieben werden, Stromversorgungs- und Telekommunikationsnetze sowie die an diese Netze angeschlossene Geräte gegen elektromagnetische Störungen geschützt wer-

Introduction

The EMC lab

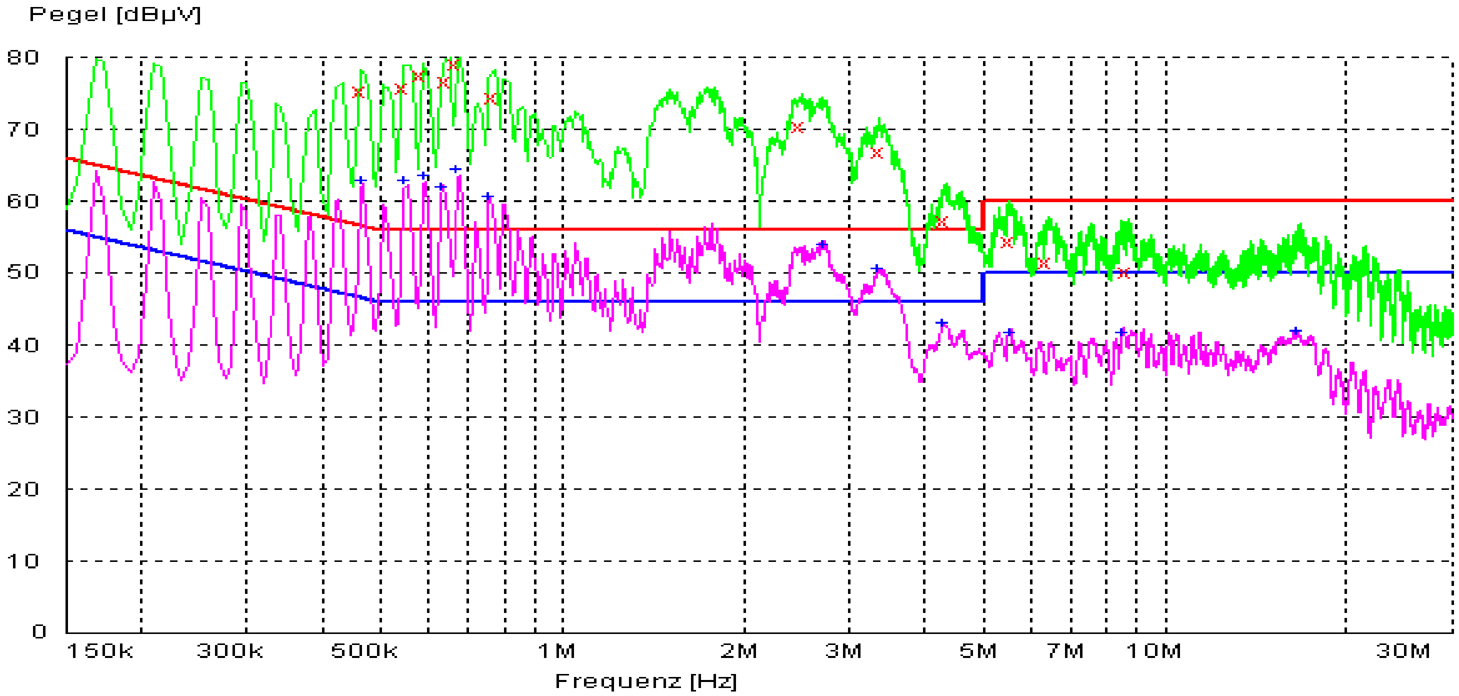
SEIBERSDORF LABORATORIES



Introduction

Conducted Emission

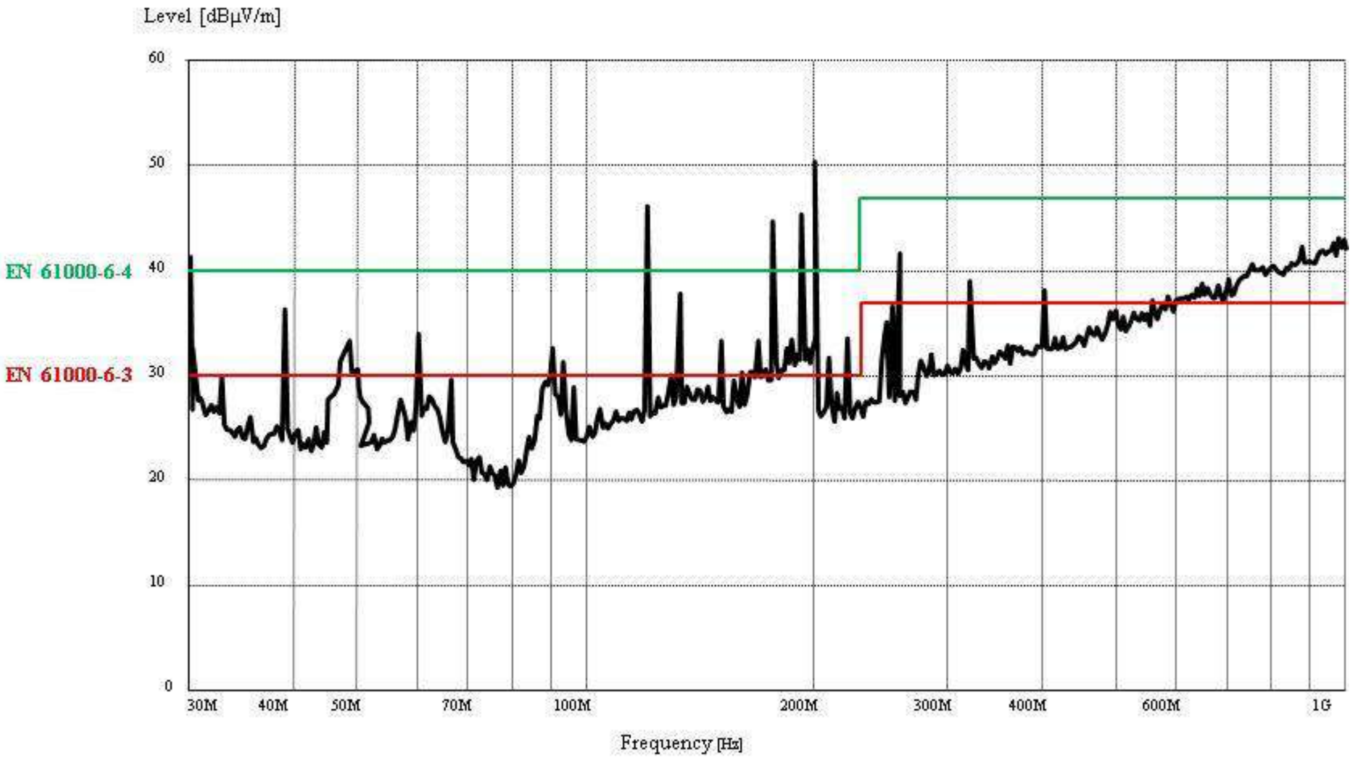
- Conducted emission over a broad frequency range
- Induced by ripple current on the input side (Common mode ; Differential mode)
- EMC requirements for
  „Conducted Emission“
  in accordance with
  ETSI, CEN, CENELEC



Introduction

Radiated Emission

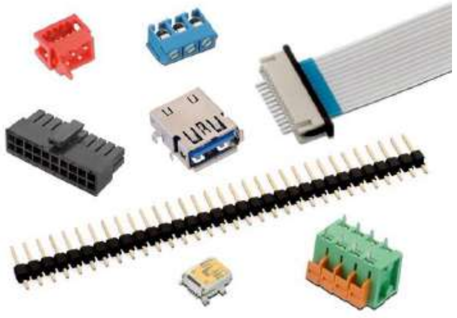
- Radiated Emission over a broad frequency range caused by:
  - Power path on the circuit board
  - Inductors and DC/DC converter
  - other unintentional sources
- EMC requirements for „Radiated Emission“ in accordance with ETSI, CEN, CENELEC
- e.g..: EN 61000-6-4 (**Industry**) QP
- e.g..: EN 61000-6-3 (**Consumer**) QP



Introduction

Overview

Connectors



Tact switches

Assembly

Ground concepts

Definition of Ground

En électrotechnique, la terre est le point de référence d'un circuit électrique à partir duquel les tensions sont mesurées, une voie de retour commune pour le courant électrique ou une connexion physique directe à la terre.

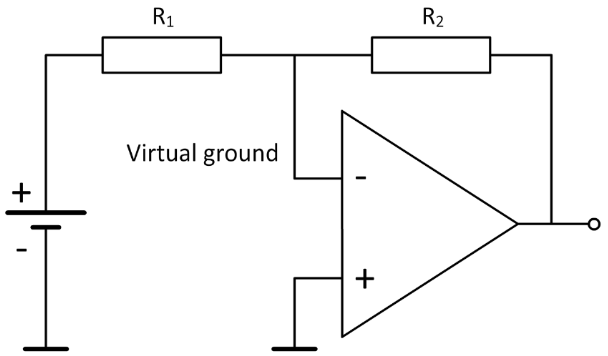
Wikipedia

Ground concepts

Types of ground

There are different types of grounds

- Floating grounds
  - Reference points in an isolated system. Battery or the patient side of a medical device
- Virtual grounds
  - These nodes can be found in a negative feedback circuit at the inverting terminal of an operational amplifier

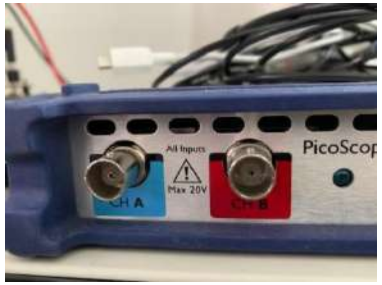


Ground concepts

Types of ground

There are different types of grounds

- AC grounds
  - These nodes have low-impedance DC values. Due to this fact they cannot be used as a ground but as a reference point.
- Earth grounds
  - In large systems this is literally connected to the ground
- Housing ground
  - Similar purpose as earth ground, however the device is not connected locally to the ground

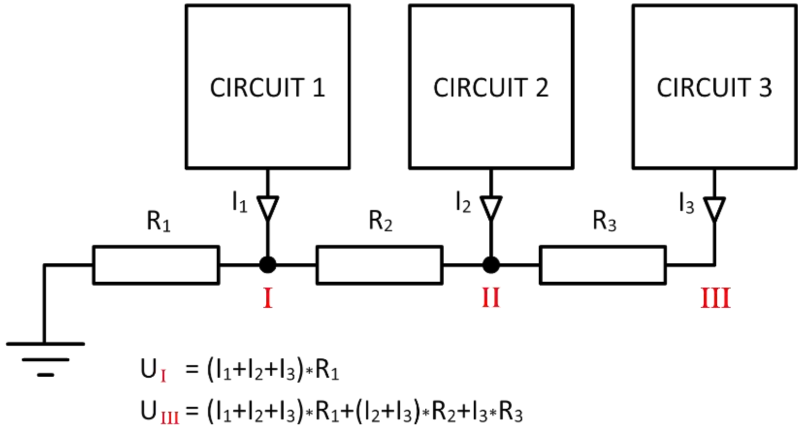


Ground concepts

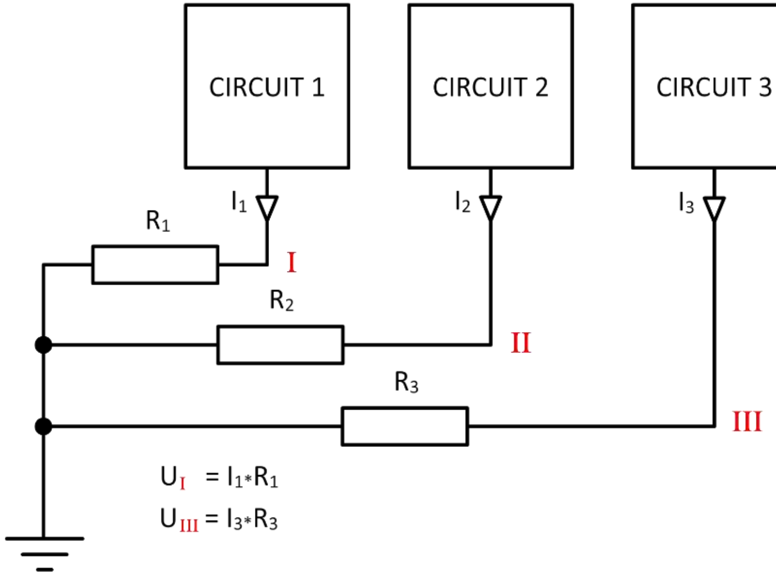
Ground structures

There are different ground structures

- Single Point Ground



Serial single point ground



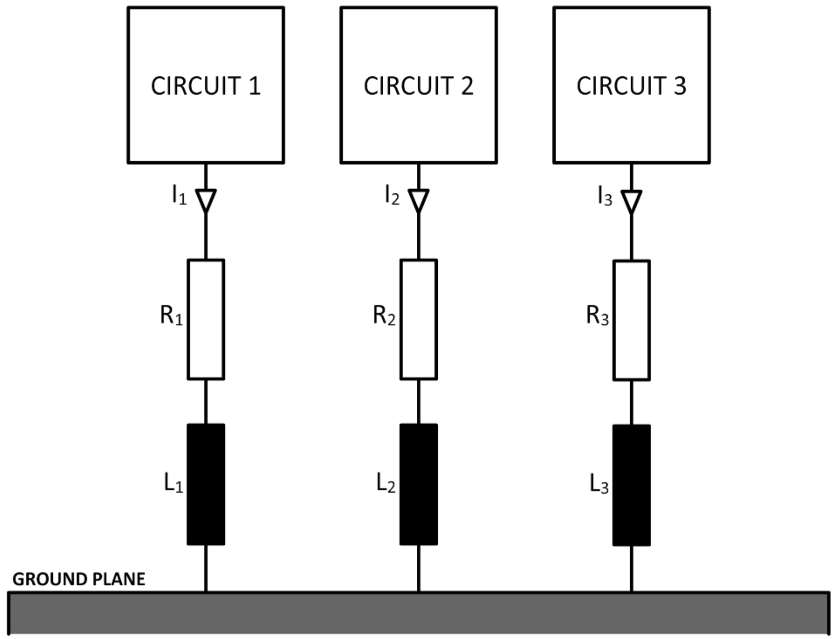
Parallel single point ground

Ground concepts

Ground structures

There are different ground structures

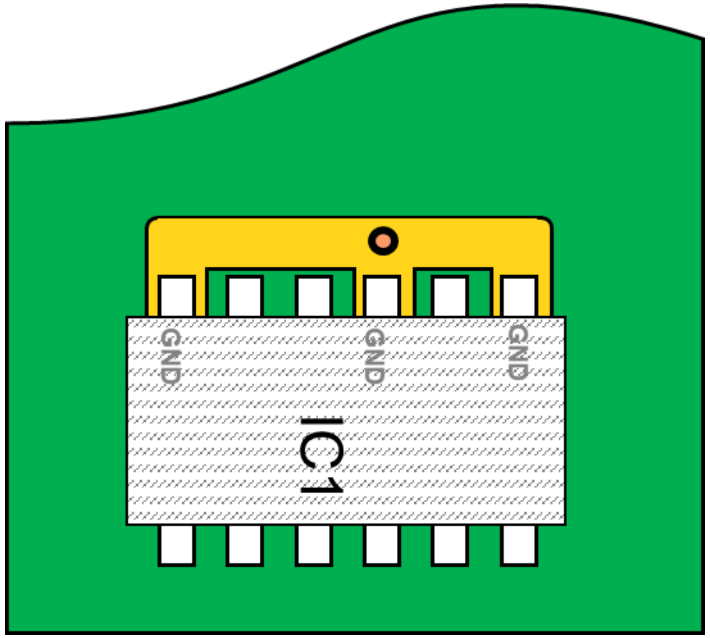
- Multi Point Ground



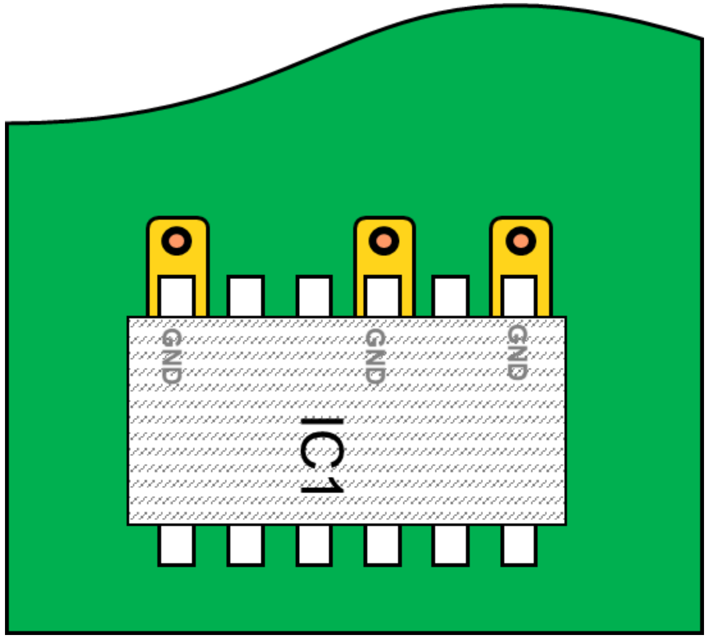
Ground concepts

Ground structures

High impedance connection



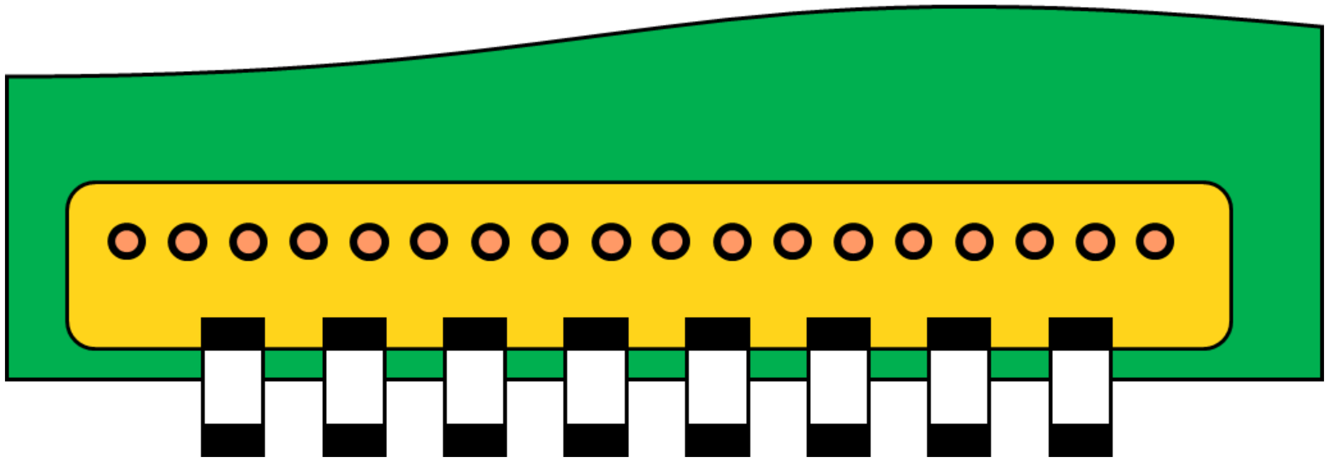
Low impedance connection



Ground concepts

Ground structures

GND island → Low impedant connection to GND

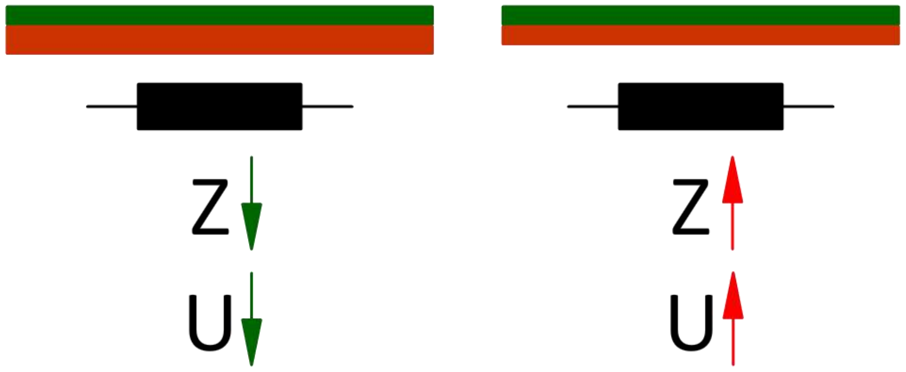


Ground concepts

Summary

A good ground is a low-impedance ground

- No or little interferences
  - Smaller voltage difference
- Higher signal purity
  - Filter will work better
- Decreased oscillation tendency related to amplifiers
  - Lower feedback
- Power, signal and analog parts should be separated and embedded in a good ground concept

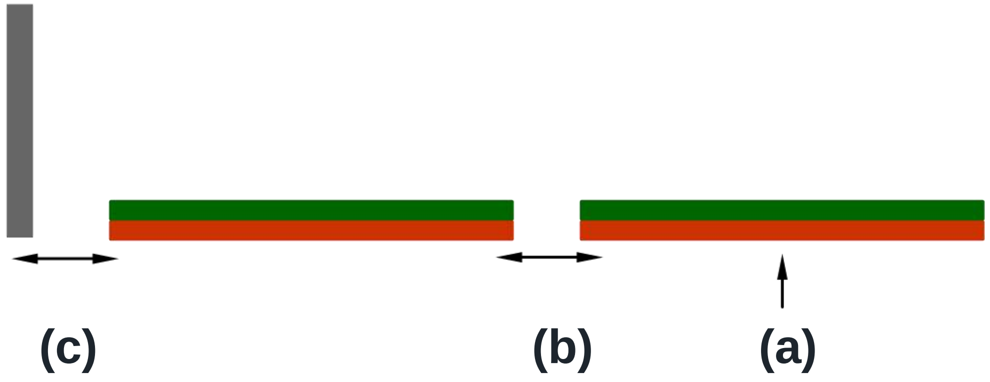


Ground concepts

Ground variations

There are three ground variations

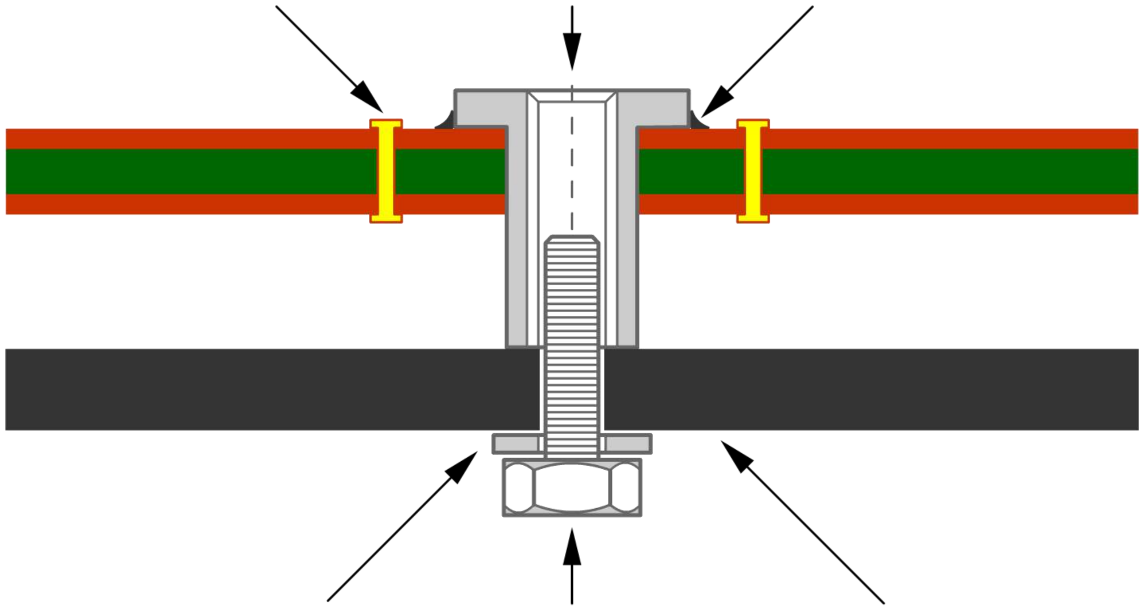
- (a) Ground planes on a circuit board
  - Separate eiSos layout recommendation presentation
- (b) Ground planes between circuit boards
  - Spacers
  - BTB or WTB connections
- (c) Ground planes between circuit boards and the housing
  - Spacers
  - Conductive glass fiber woven, conductive shielding gaskets, earthing metal clips, shielding tapes



Ground concepts

SMD Spacer for ground connections

- Tin plated SMD spacers
- Solid solder pad and a big surface area
- Large contact transitions area



Ground concepts

SMD Spacer for ground connections

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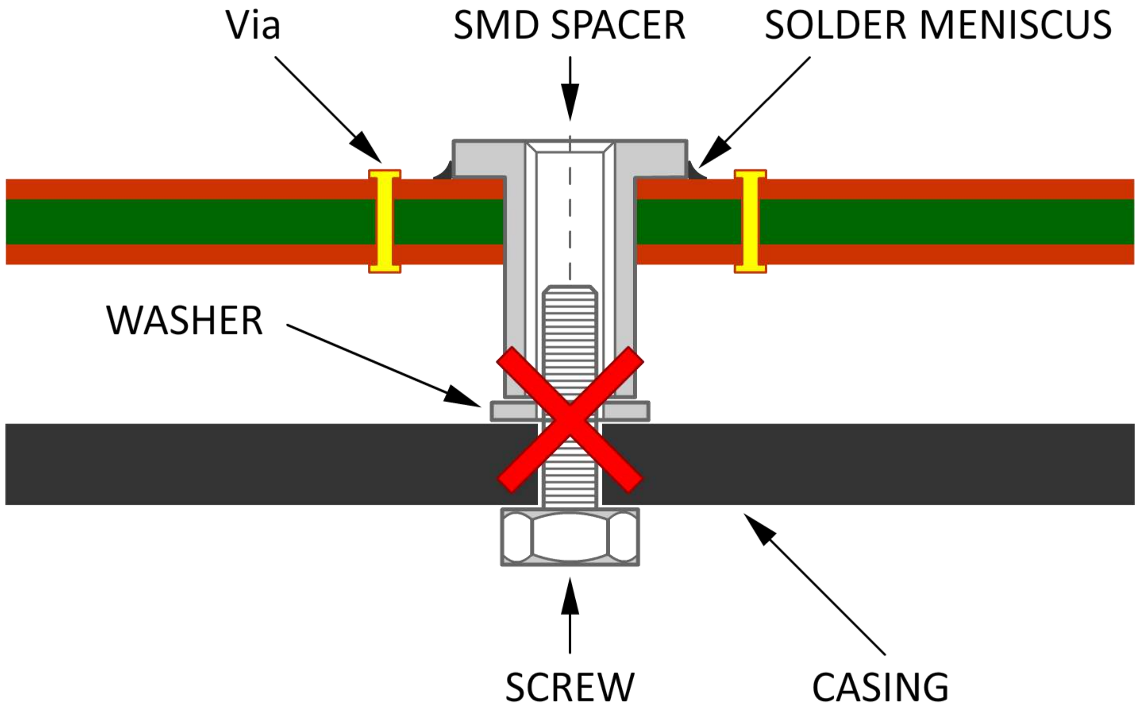
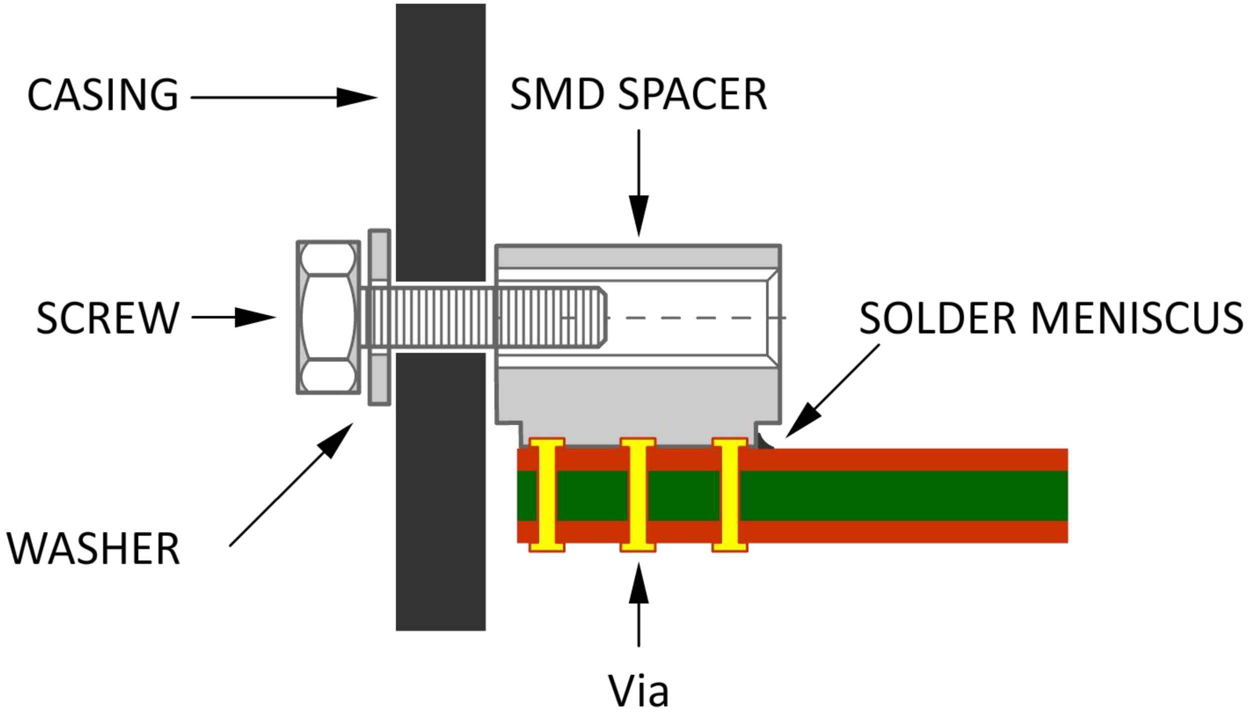


Ground concepts

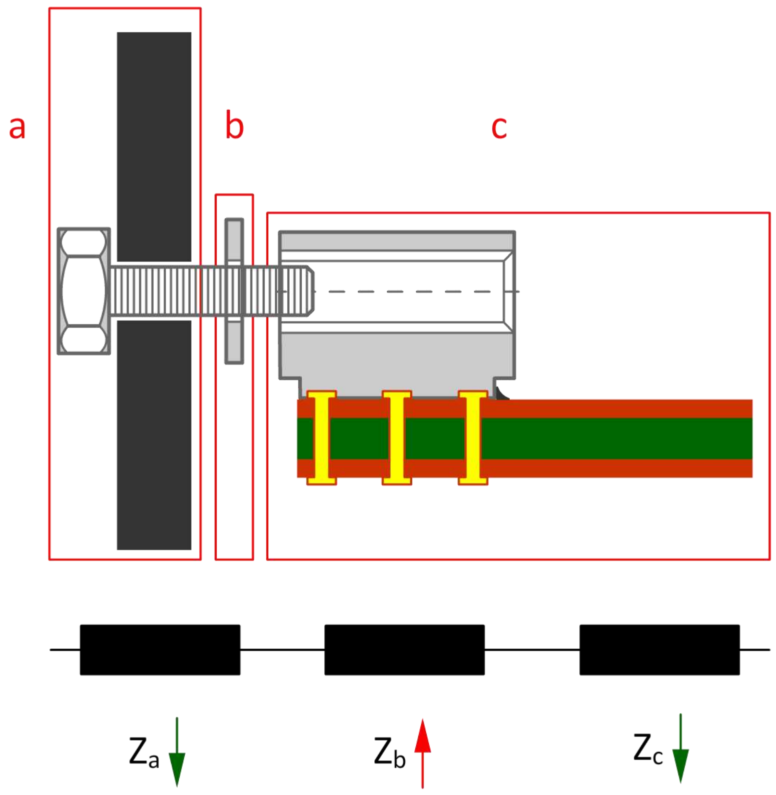
SMD Spacer for ground connections



Ground concepts

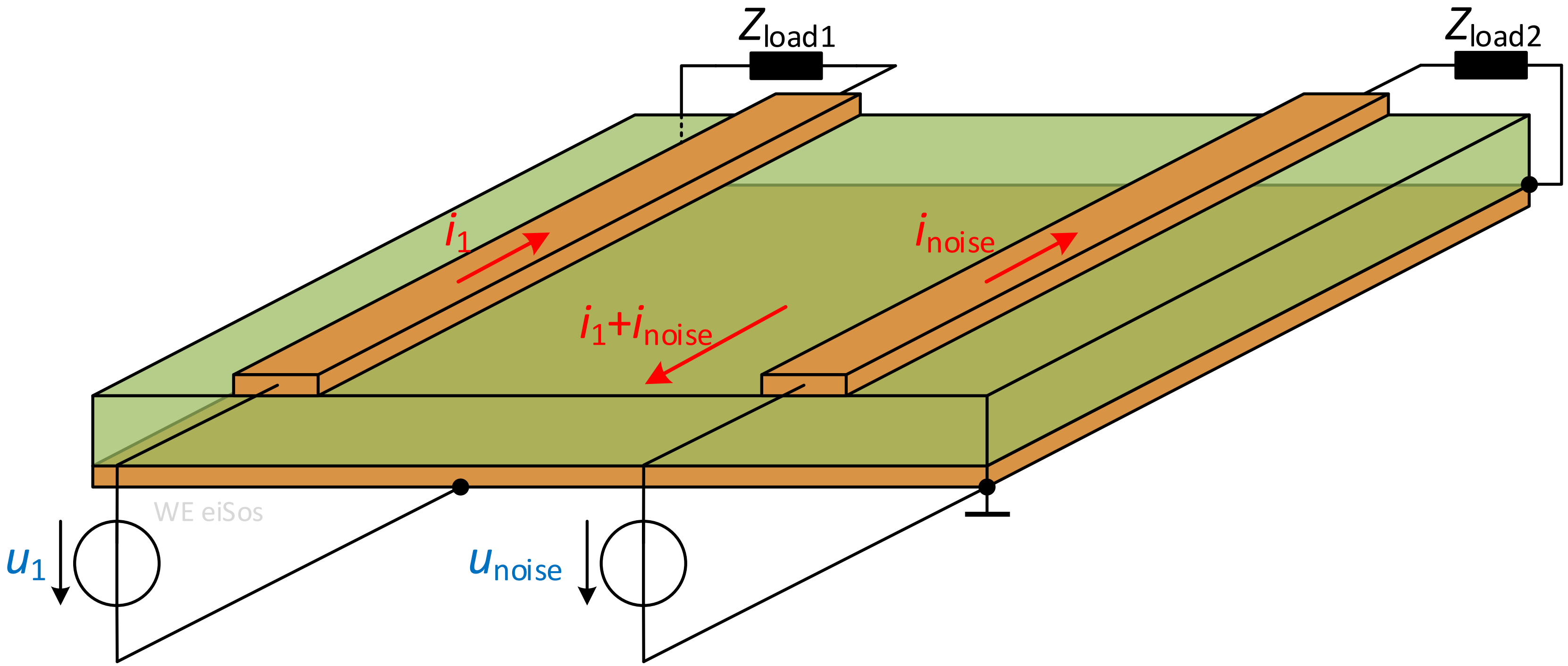
SMD Spacer for ground connections

- Washer placement is important
- High impedance objects react as RF filter



Coupling effects

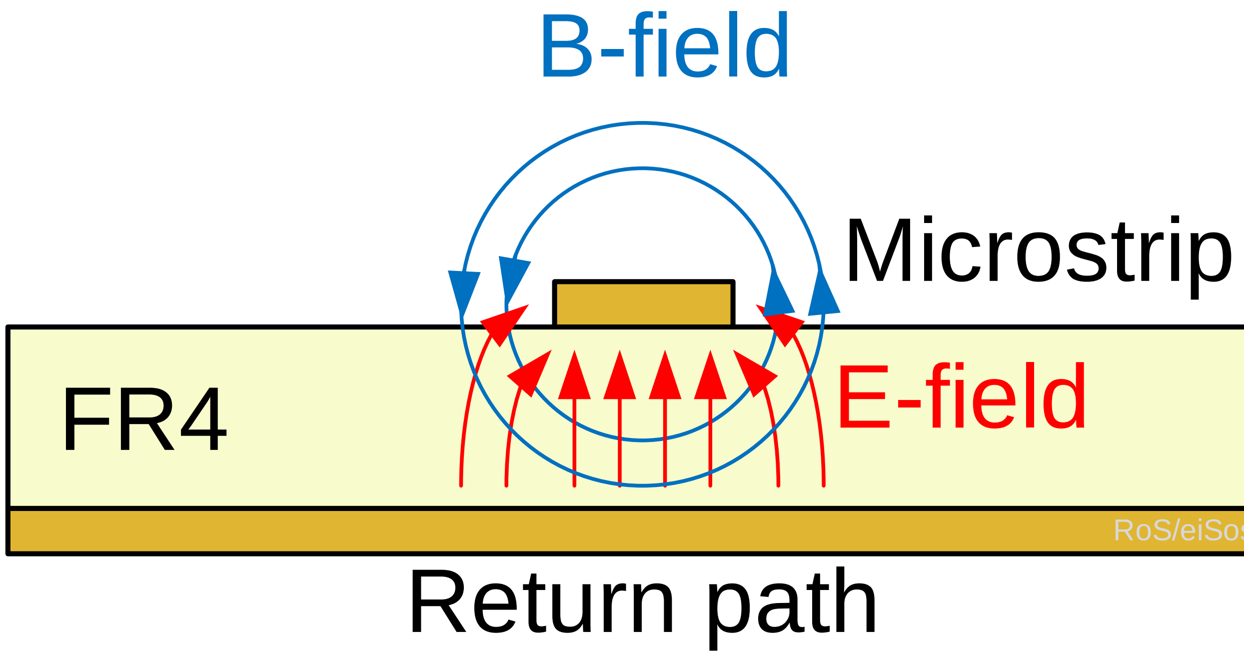
Overview



- Dominant **capacitive** coupling when $Z_{\mathrm{load},2} \rightarrow \infty$
- Dominant **inductive** coupling when $Z_{\mathrm{load},2} \rightarrow 0$
- **Impedance coupling** when they have the same common return (Ground plane)

Coupling effects

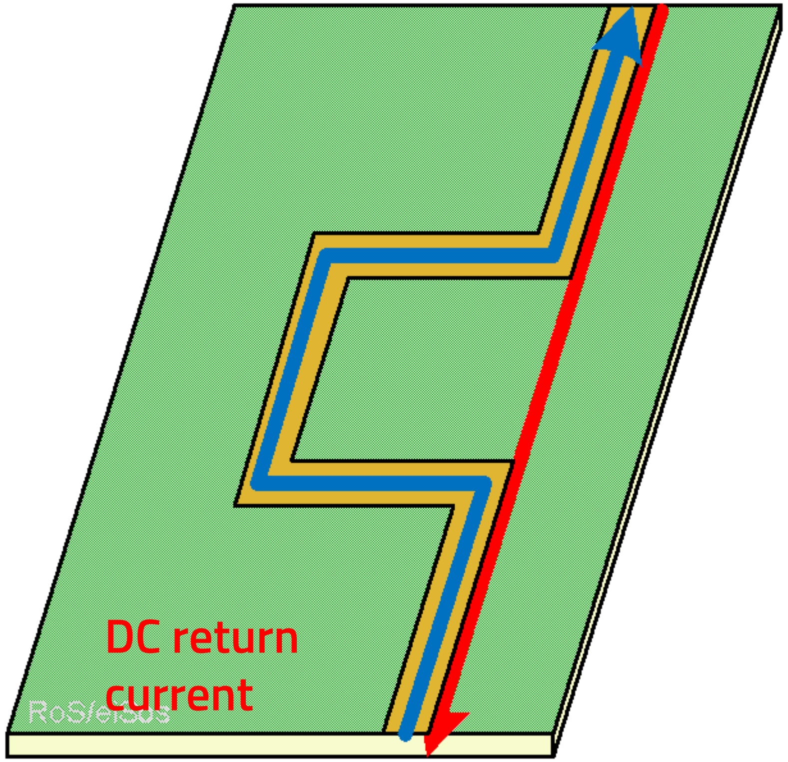
RF energy transmission



Coupling effects

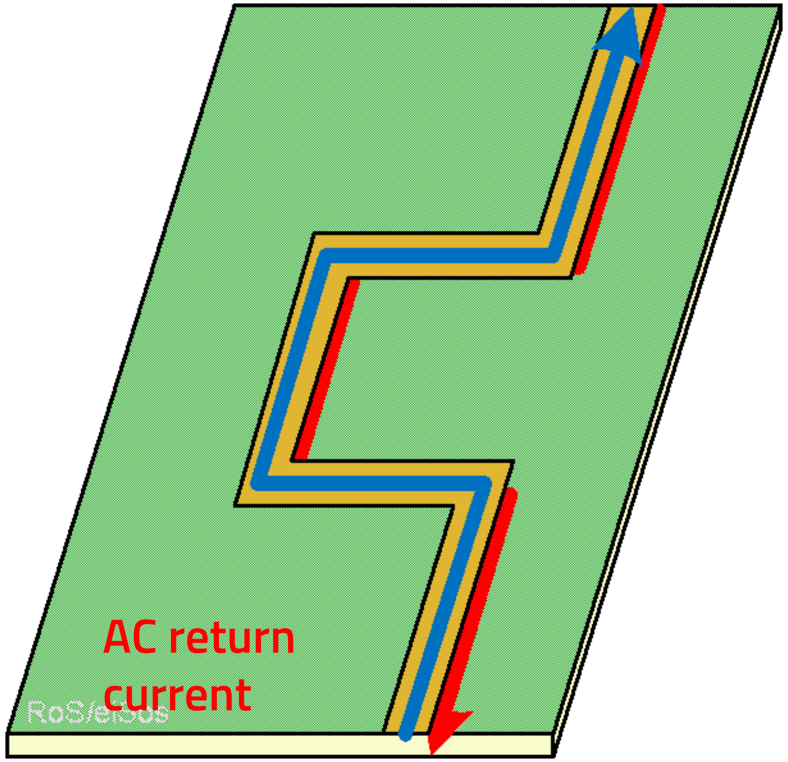
Path of least impedance

Microstrip



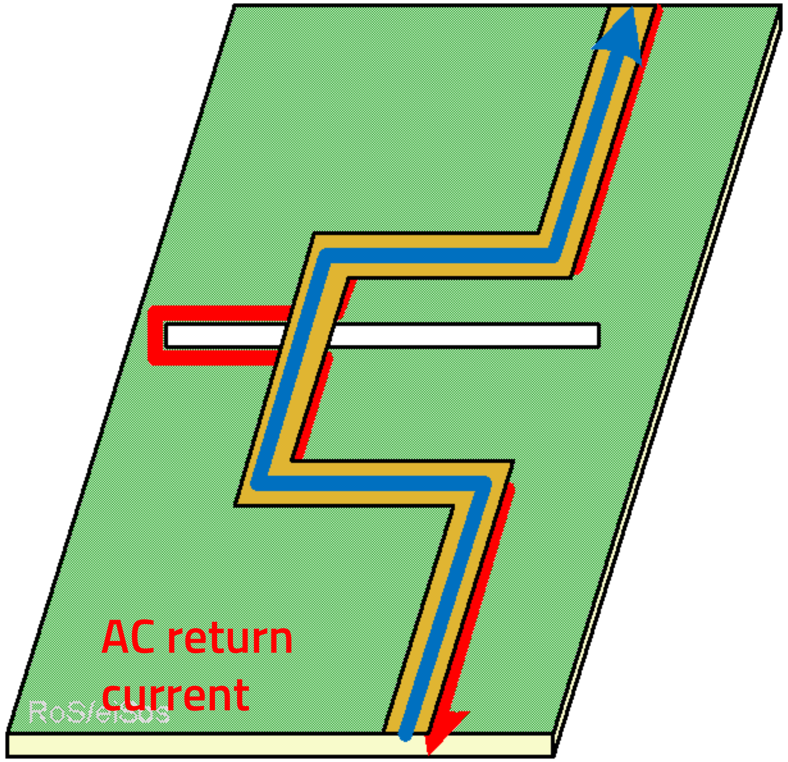
- Return path

Microstrip



- Return path

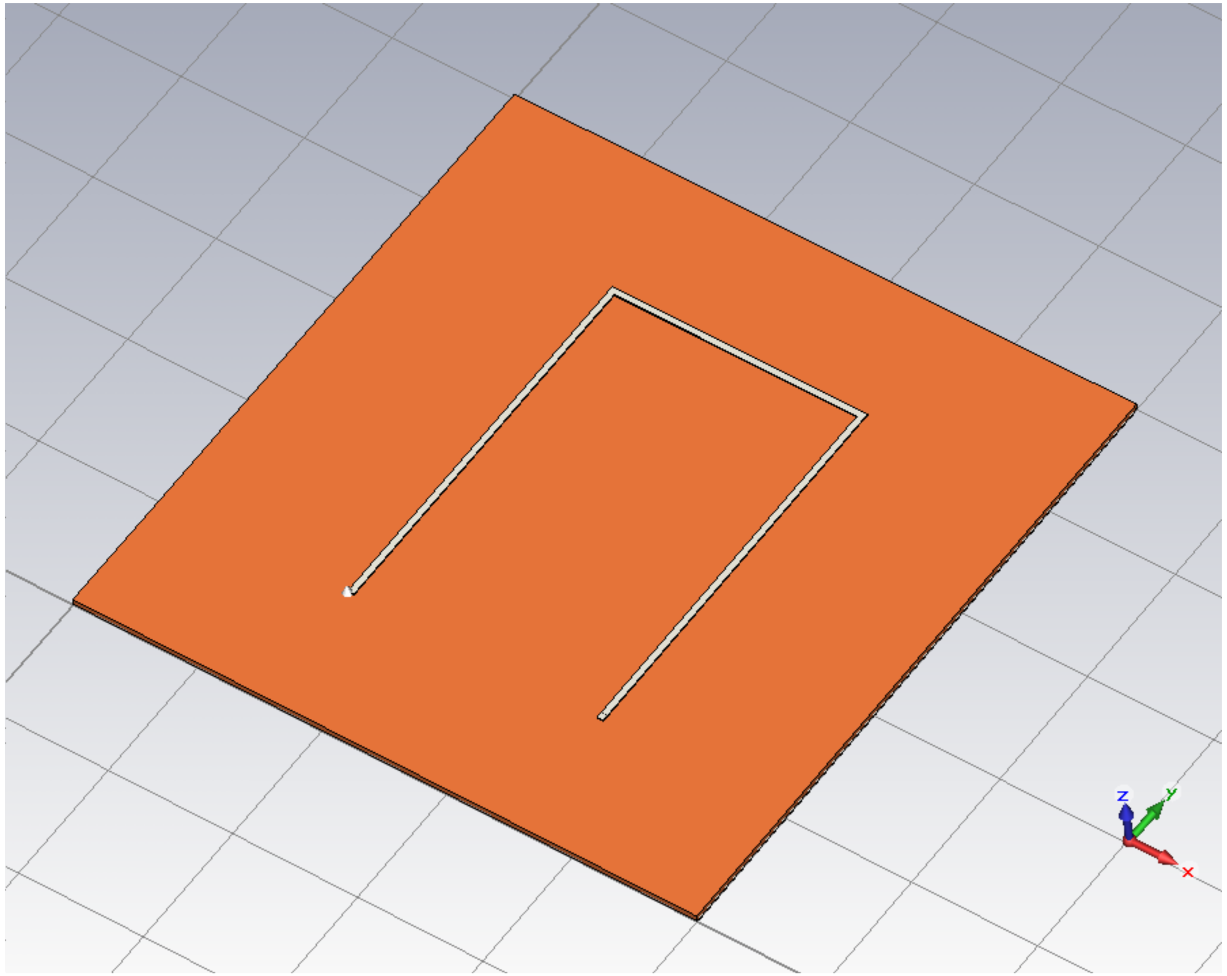
Microstrip

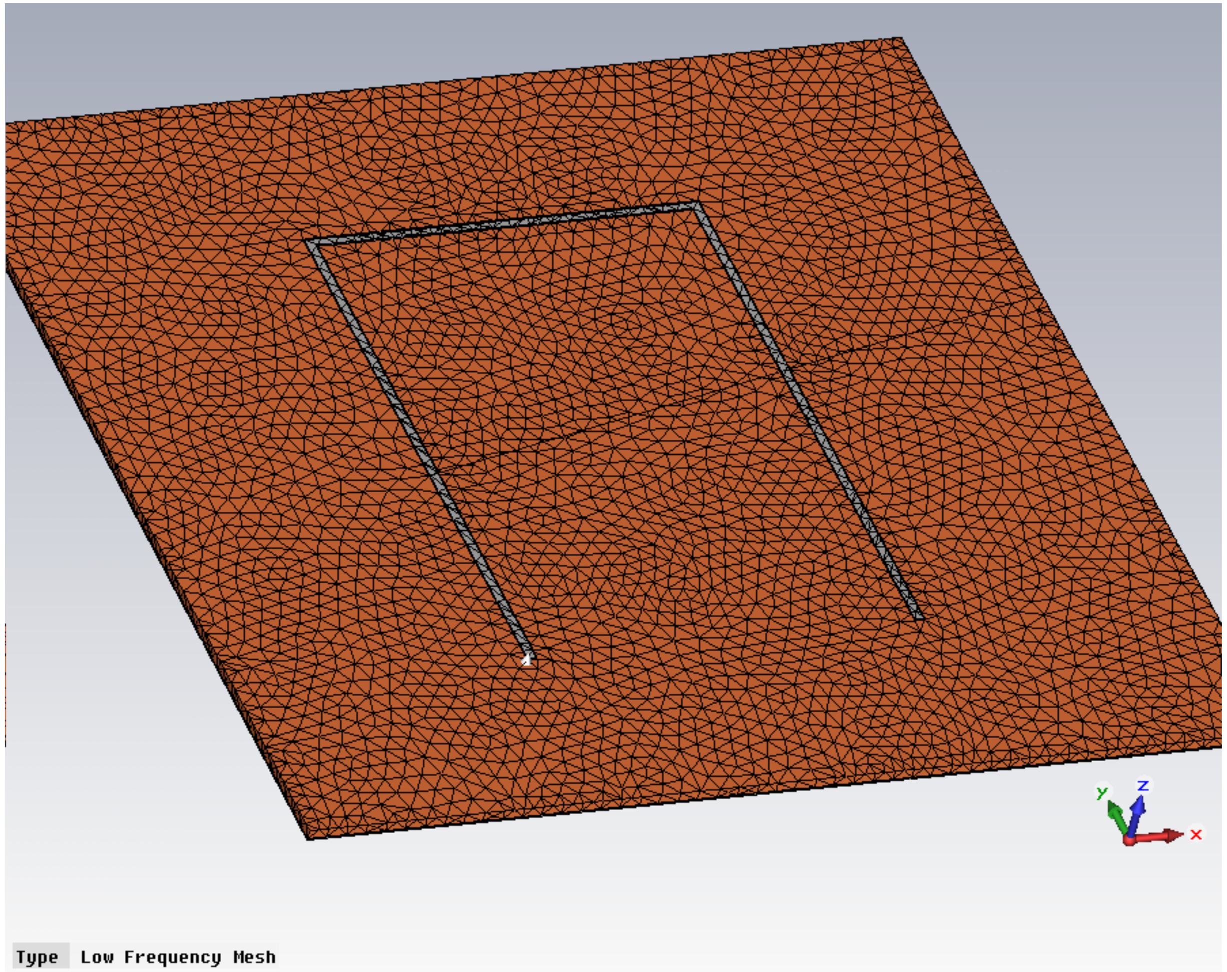


- Slotted return path

Coupling effects

Simulation in CST EMS





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Coupling effects

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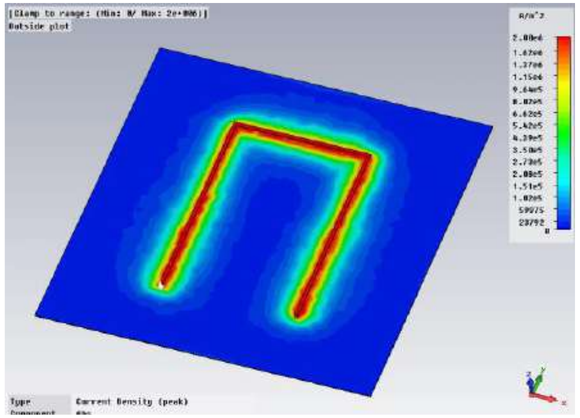
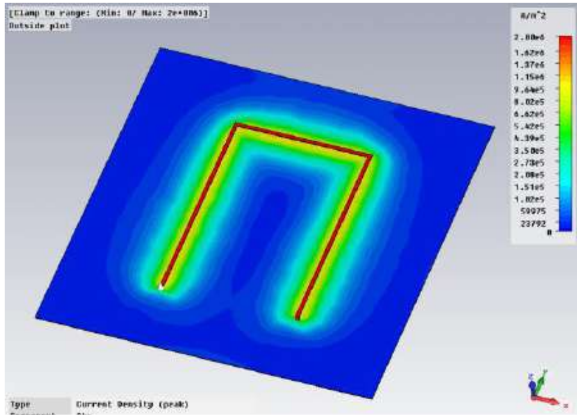
Current path with a u shaped conductor simulated in CST EMS

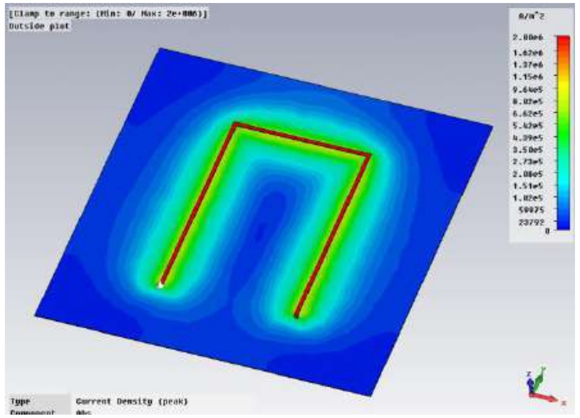
100kHz



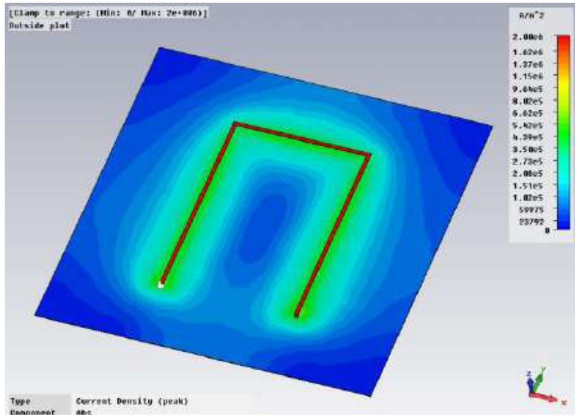
10kHz



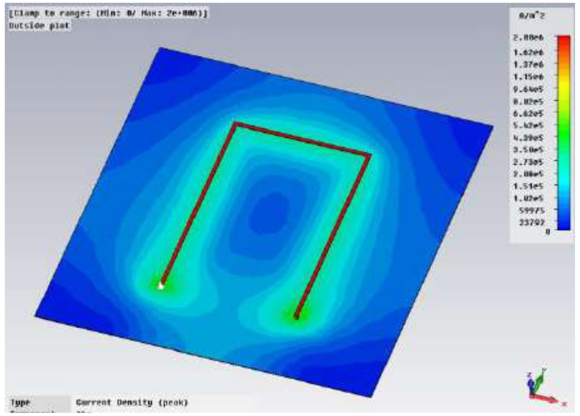
5kHz



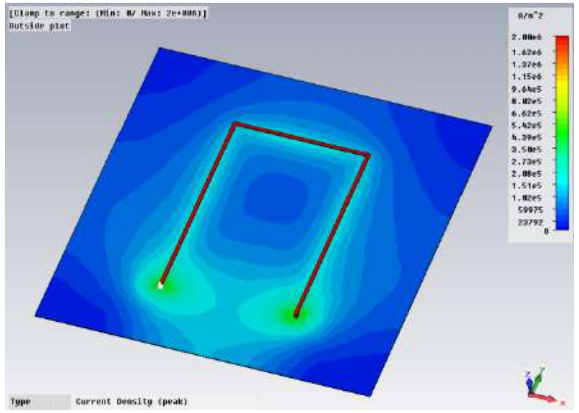
2kHz



1kHz



500Hz



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Coupling effects

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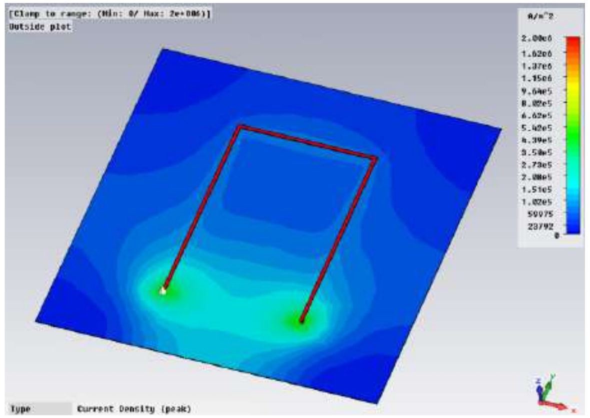
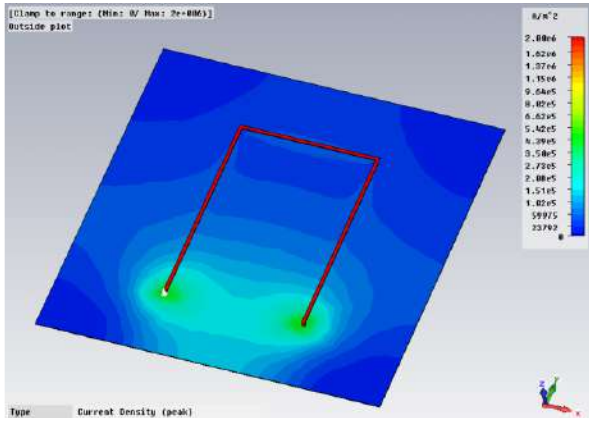
Current path with a u shaped conductor simulated in CST EMS

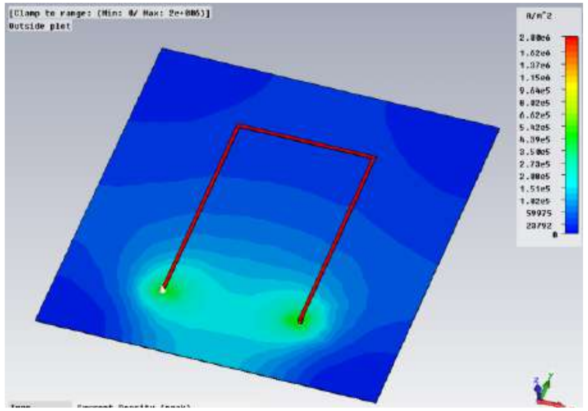
200Hz



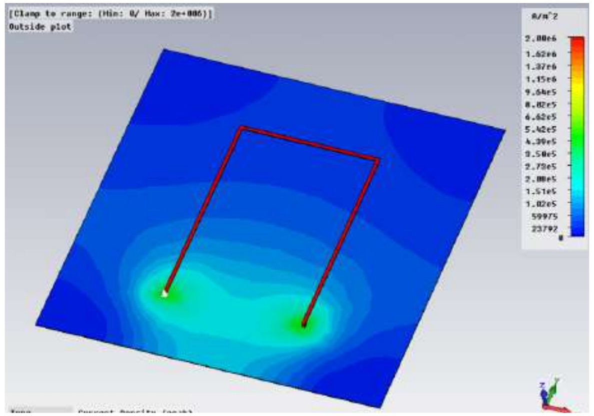
100Hz



50Hz



10Hz



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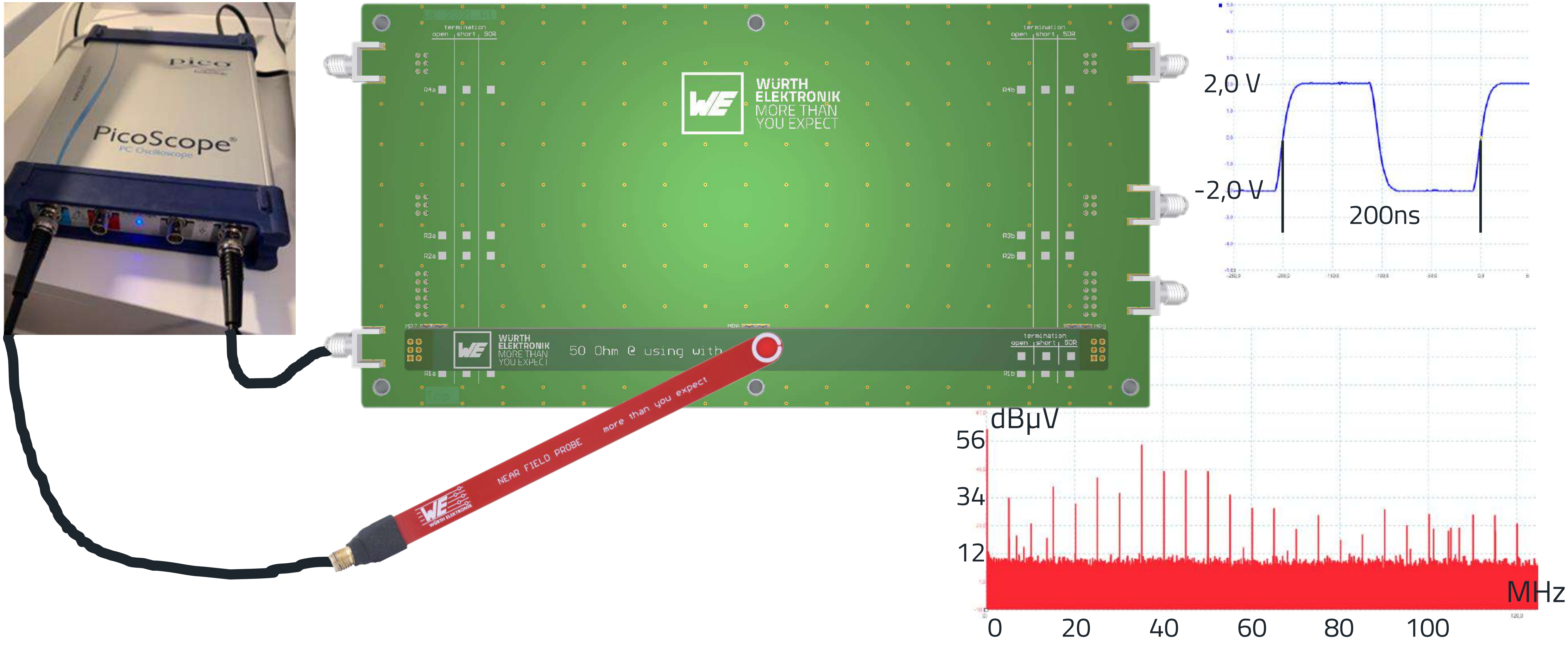
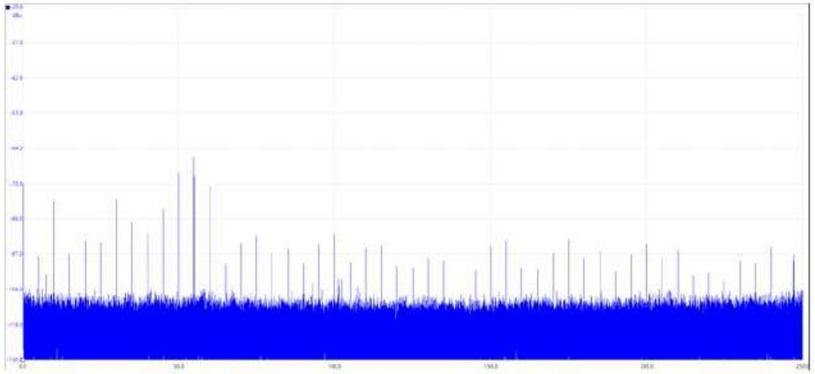
Coupling effects

Return path of high frequency current

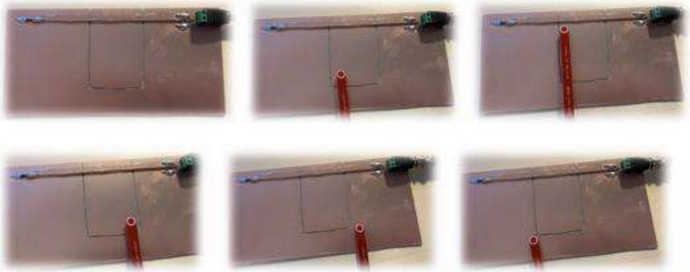


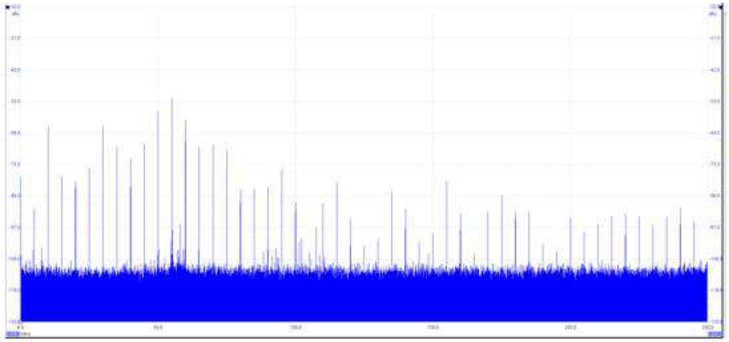
Coupling effects

Return path of high frequency current



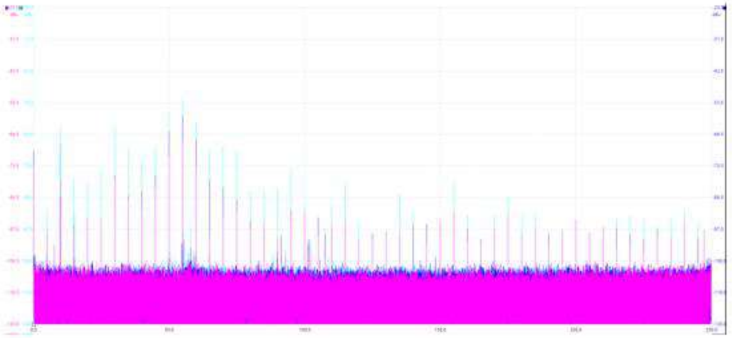
... ca. -67dB





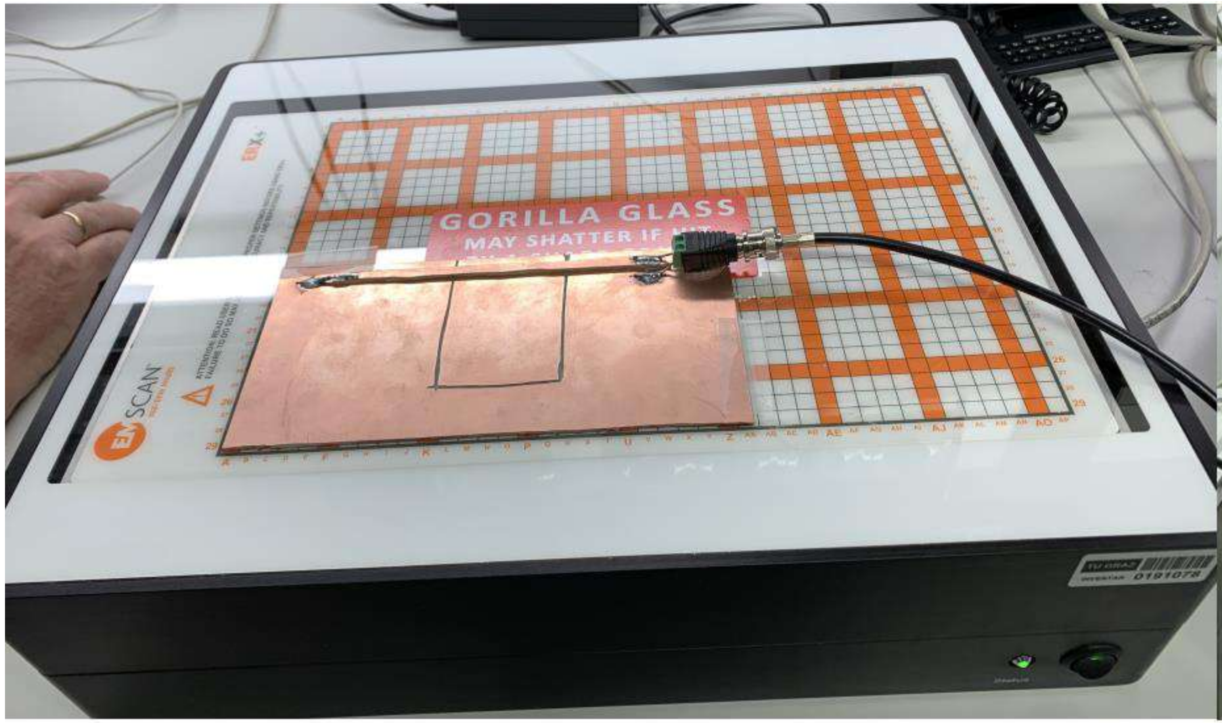
Ca. 52dB. ... Verschlechterung um ca. 15dB, im gesamten Bereich der Freistellung

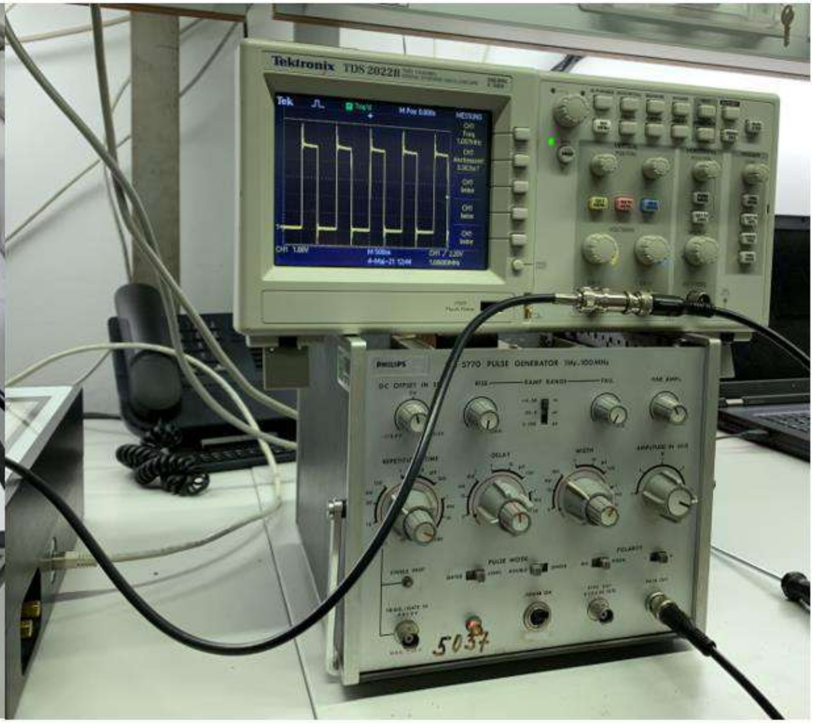
Vergleich



Coupling effects

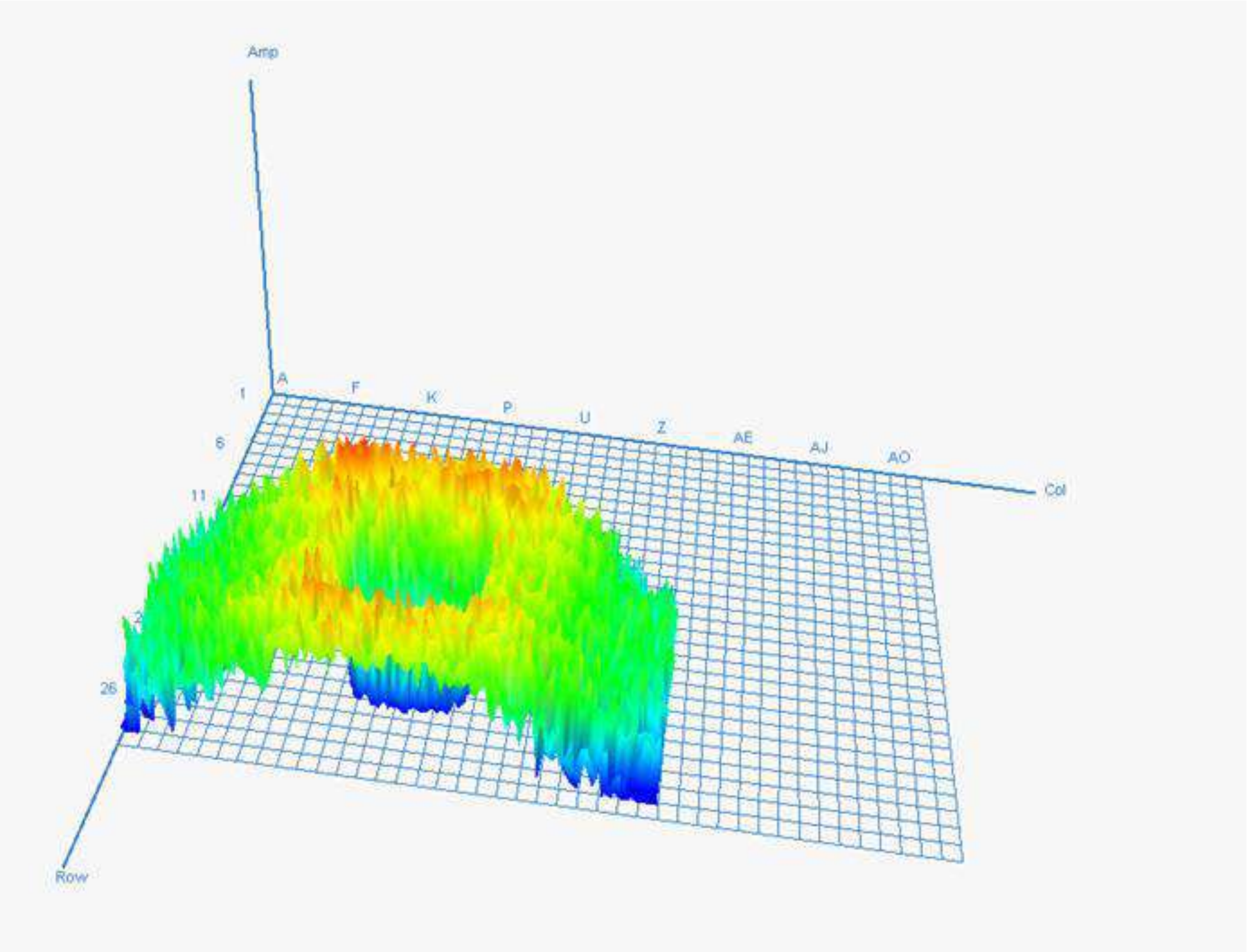
Return path of high frequency current





Coupling effects

Near field measurement

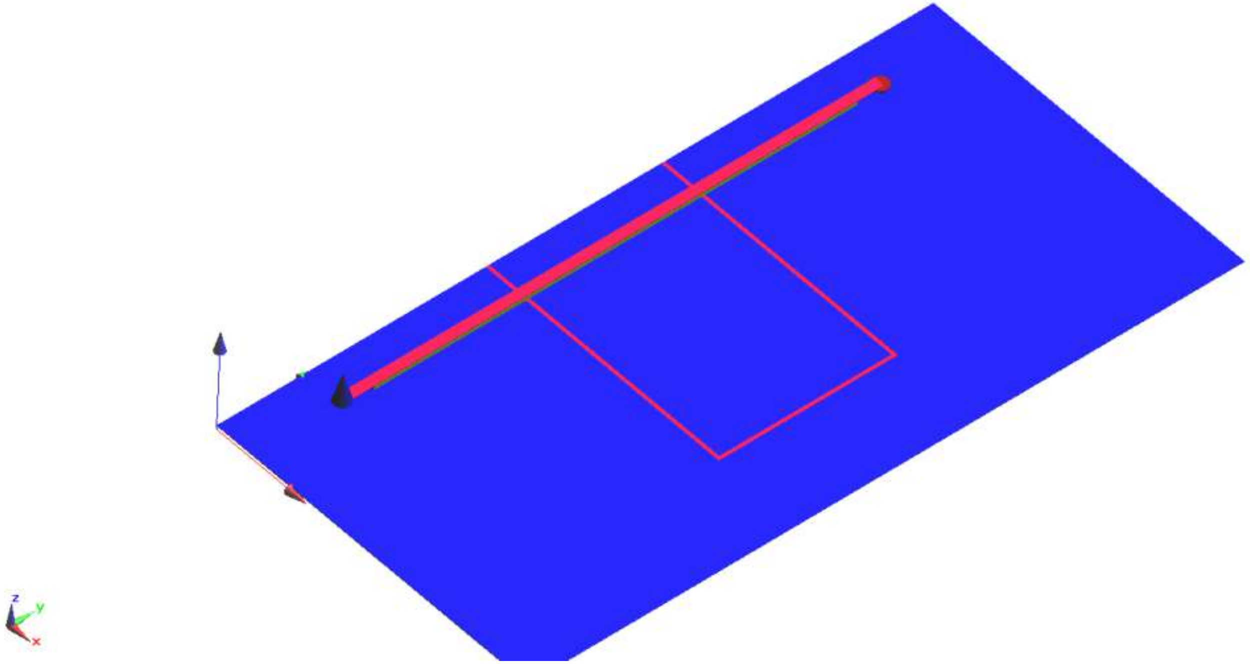


Coupling effects

Simulation

Simulationsoftware:
Sim4Life = FDTD-Simulationstool (FDTD=Finite Differences in Time Domain)
Swiss company ZMT (= Zurich Med tech)

Model:

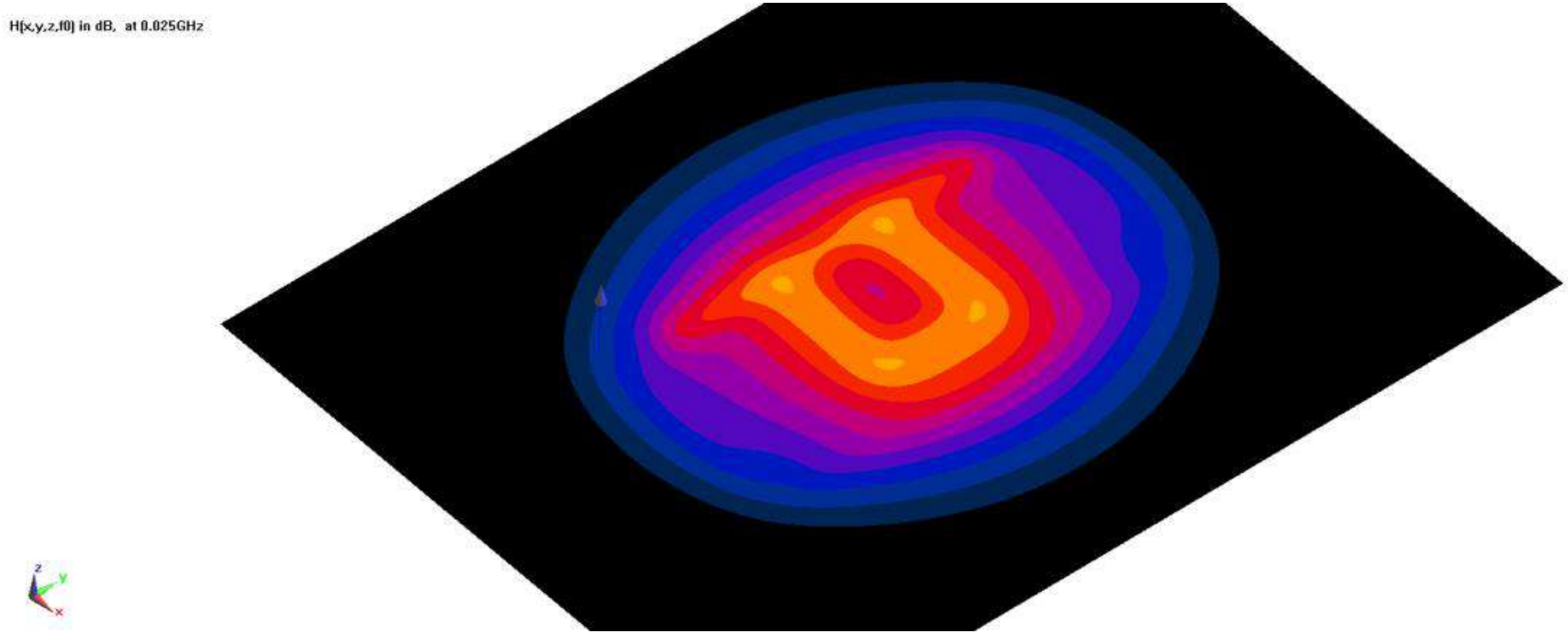


Coupling effects

Simulation

Magnetic-field simulation:

1cm under the prin (identical to the near field measurement with the EMScan)

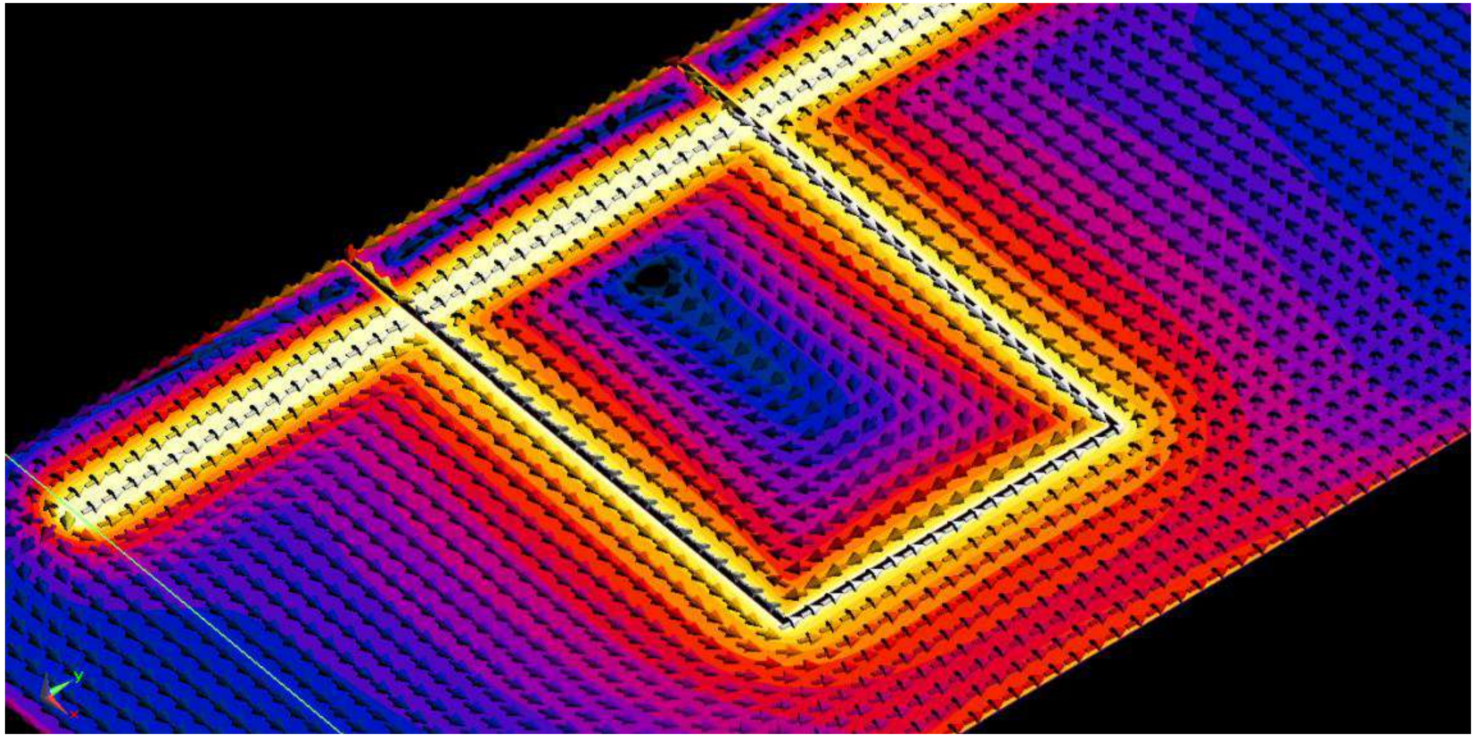


Coupling effects

Simulation

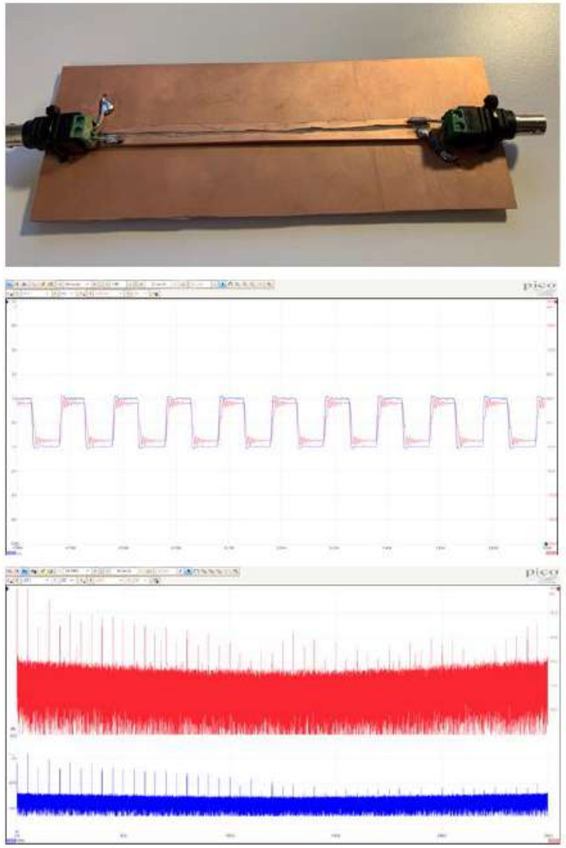
Current path:

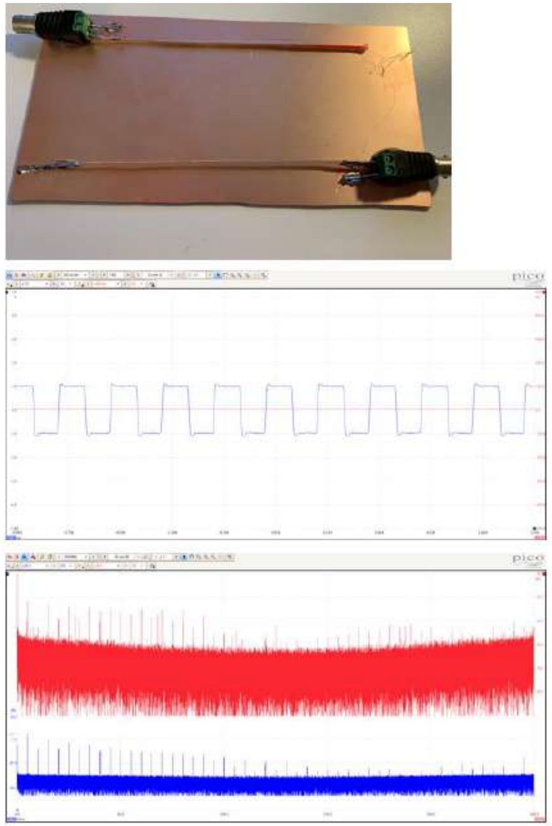
On the GND layer

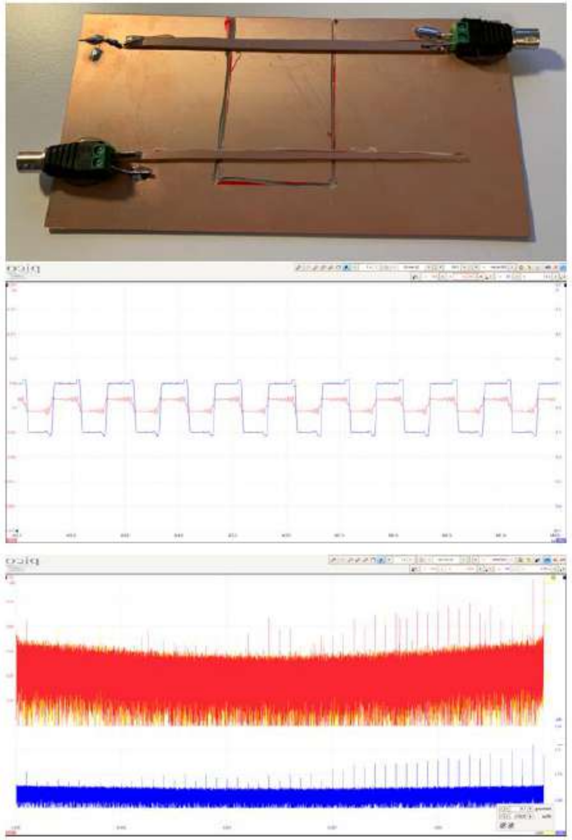


Coupling effects

Coupling

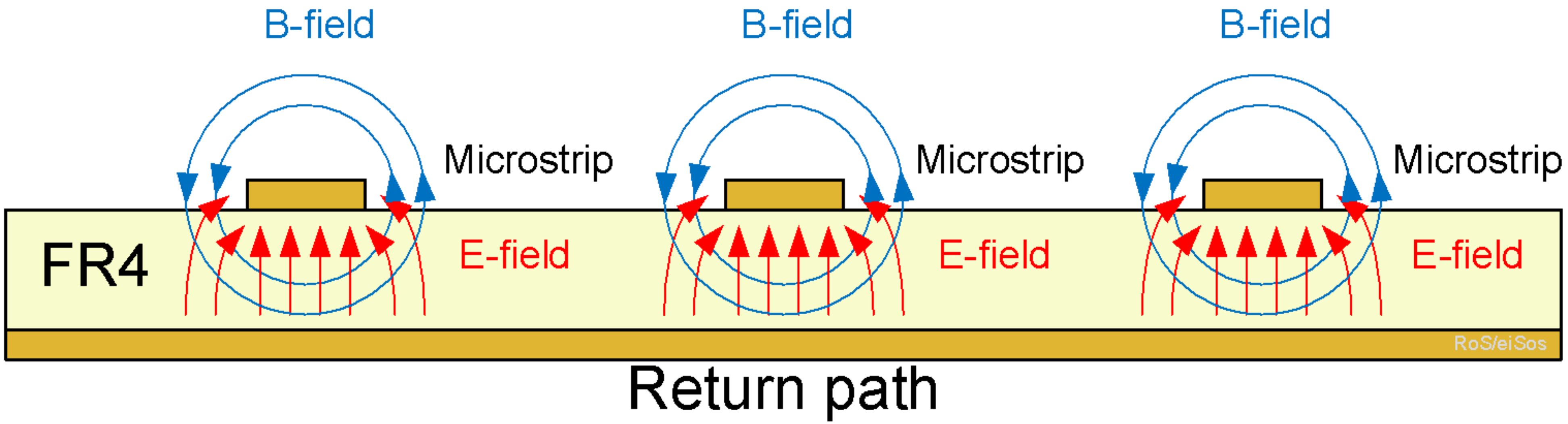






Coupling effects

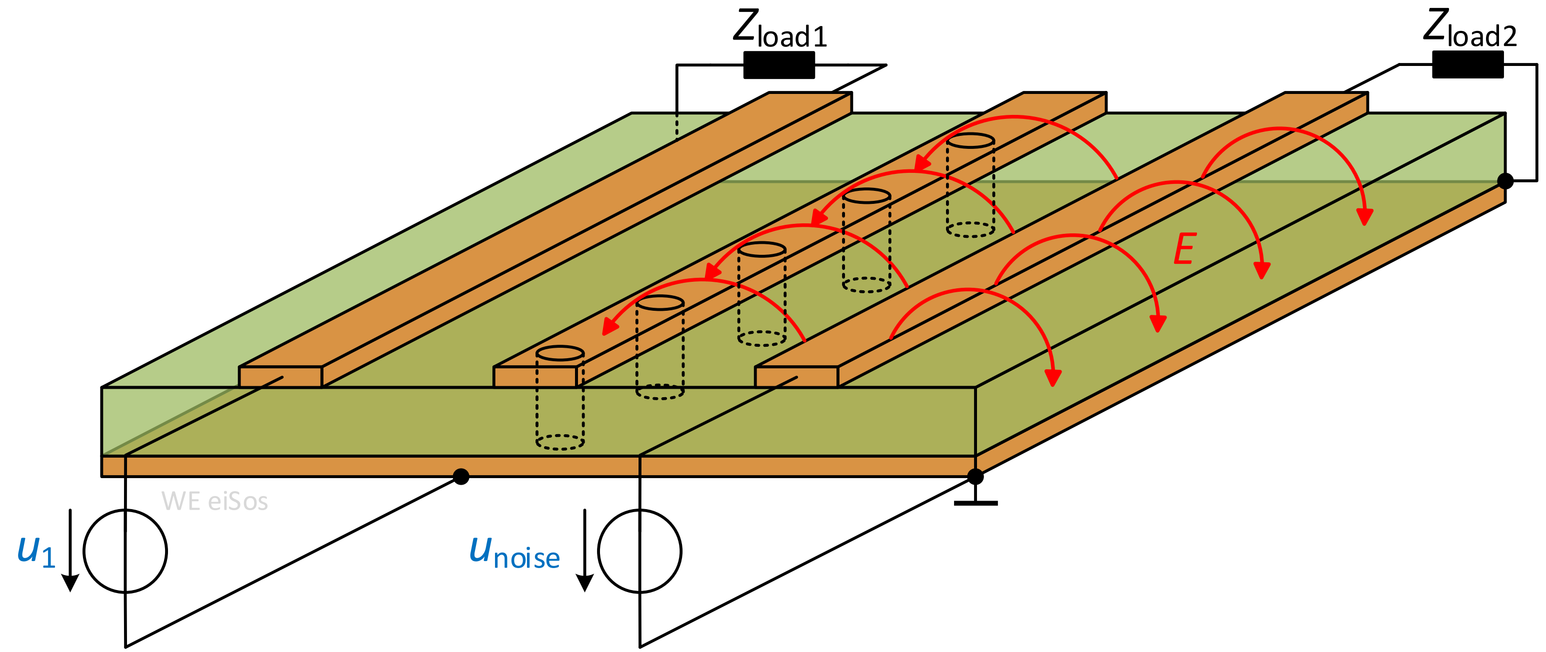
Minimize crosstalk



If the distance between two lines is arround tree times the thickness of the substrate, the crosstalk will go down to appoximately 1%

Coupling effects

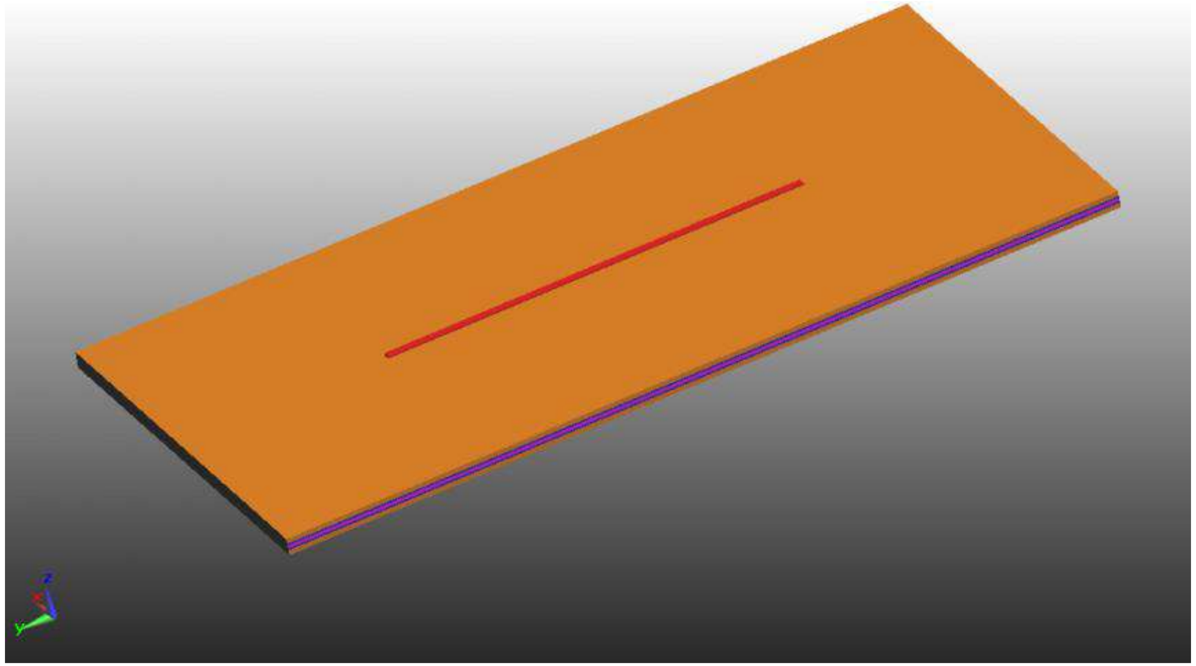
Minimize crosstalk



- Insert a track or area between the lines which is connected to GND by vias like a shield between the tracks
- Space between vias: smaller than λ/10 of the highest noise frequency

Coupling effects

What happens if the current has to change layer?



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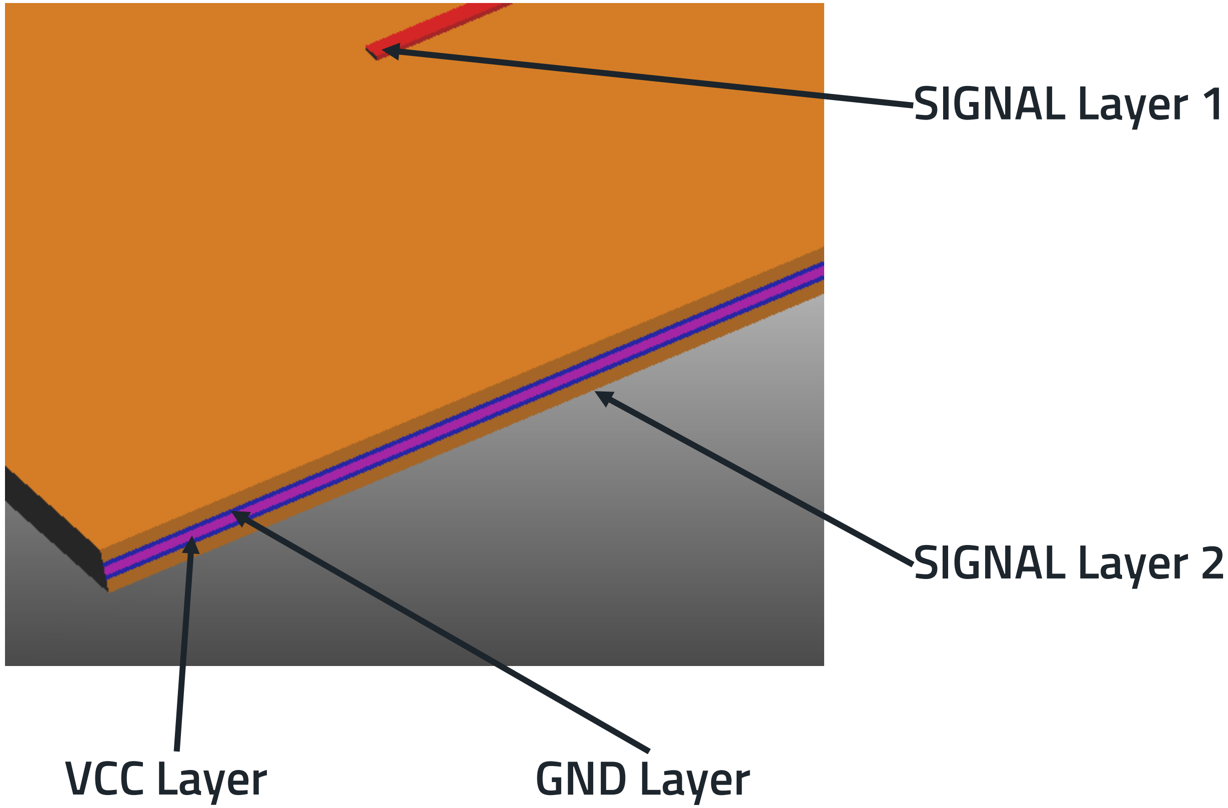
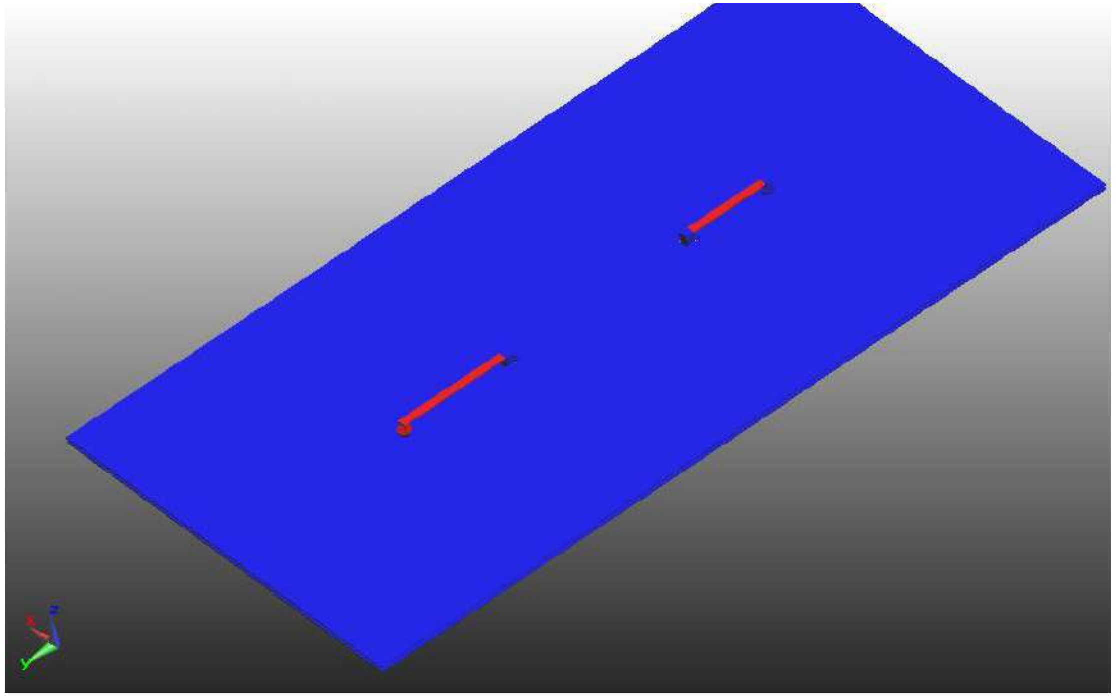
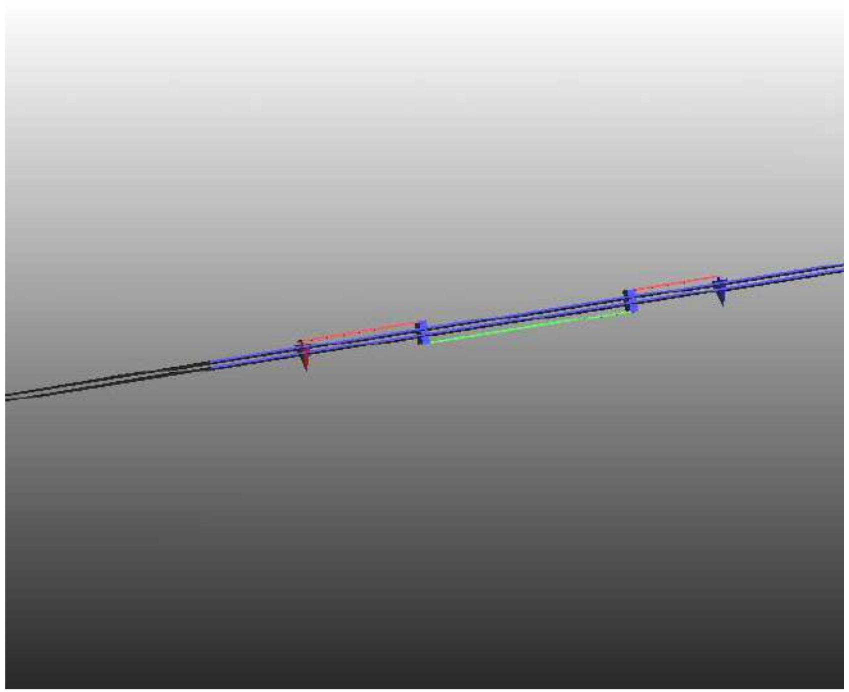
Print with 2 layers(Vcc, GND)
withouth a layer change of the signal line
f=1GHz



Coupling effects

What happens if the current has to change layer?





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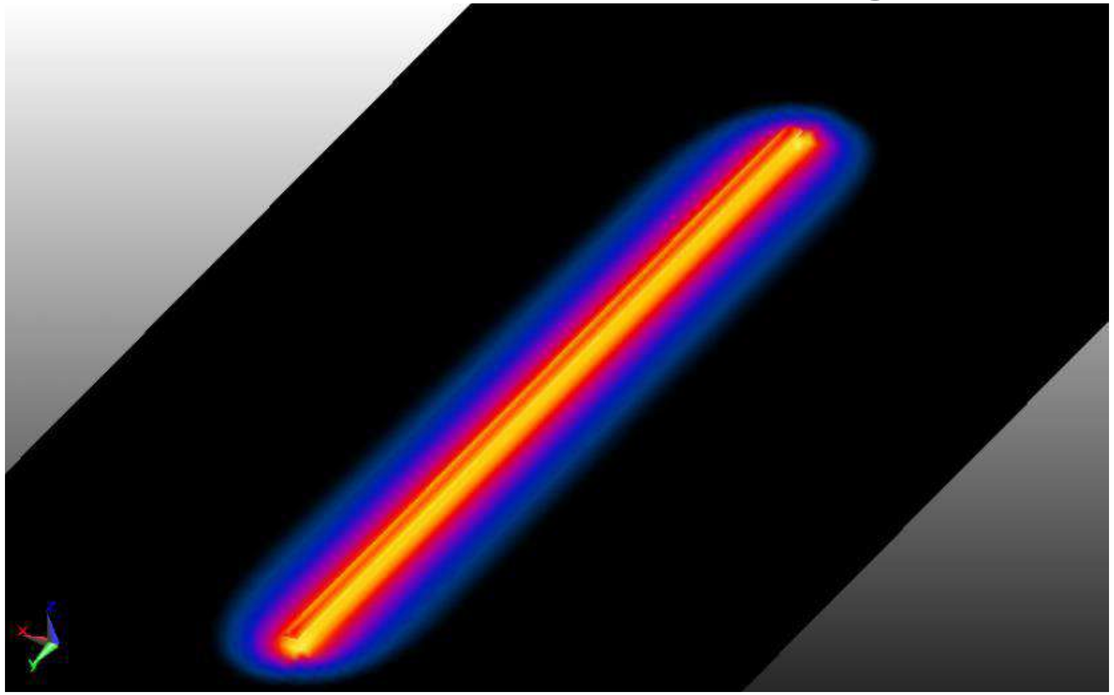
Print with 2 layers(Vcc, GND)
with a layer change of the signal line
f=1GHz

Coupling effects

Path of the return current simulated in CST EMS

Return current without layer change



Ground plane

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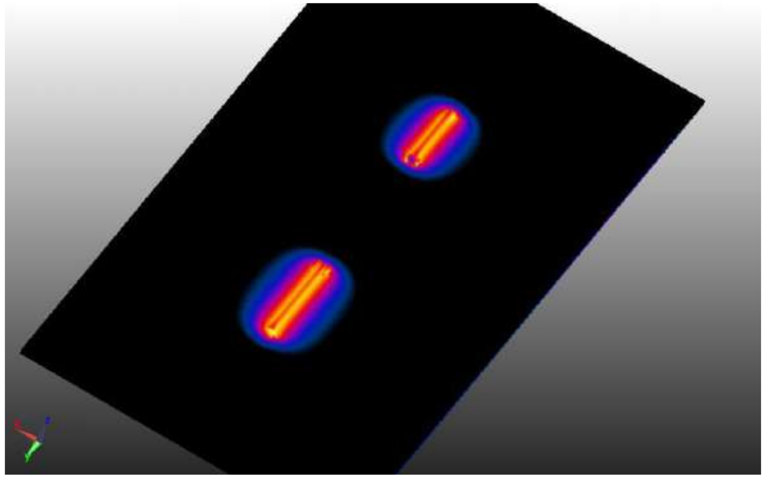
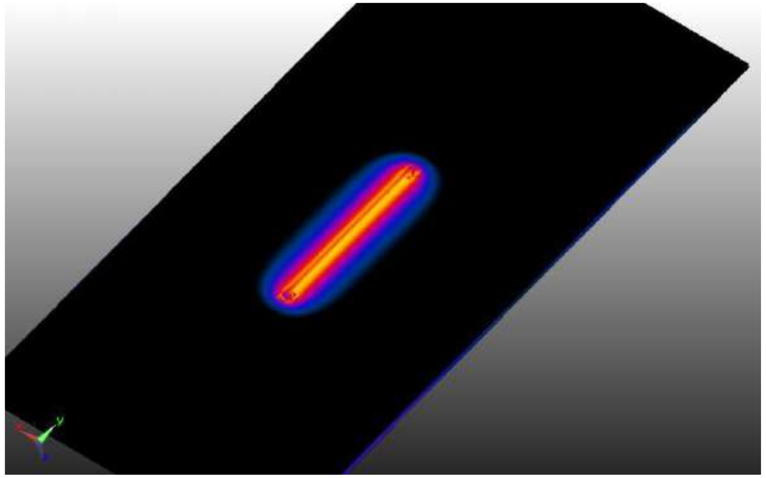
Reverse current also flows across the Vcc surface!

Return current with layer change



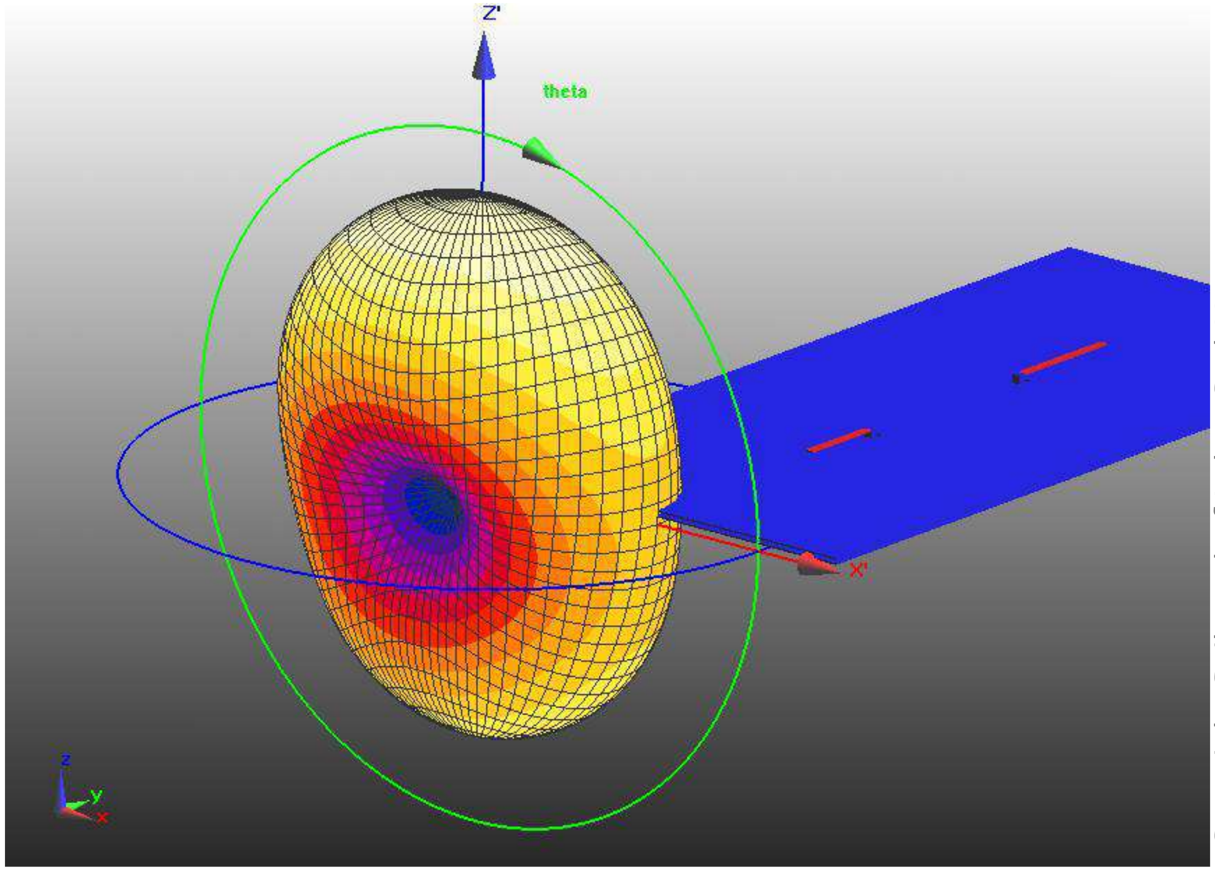
Ground plane



VCC plane

Coupling effects

Radiated power of the transmission line simulated in CST EMS



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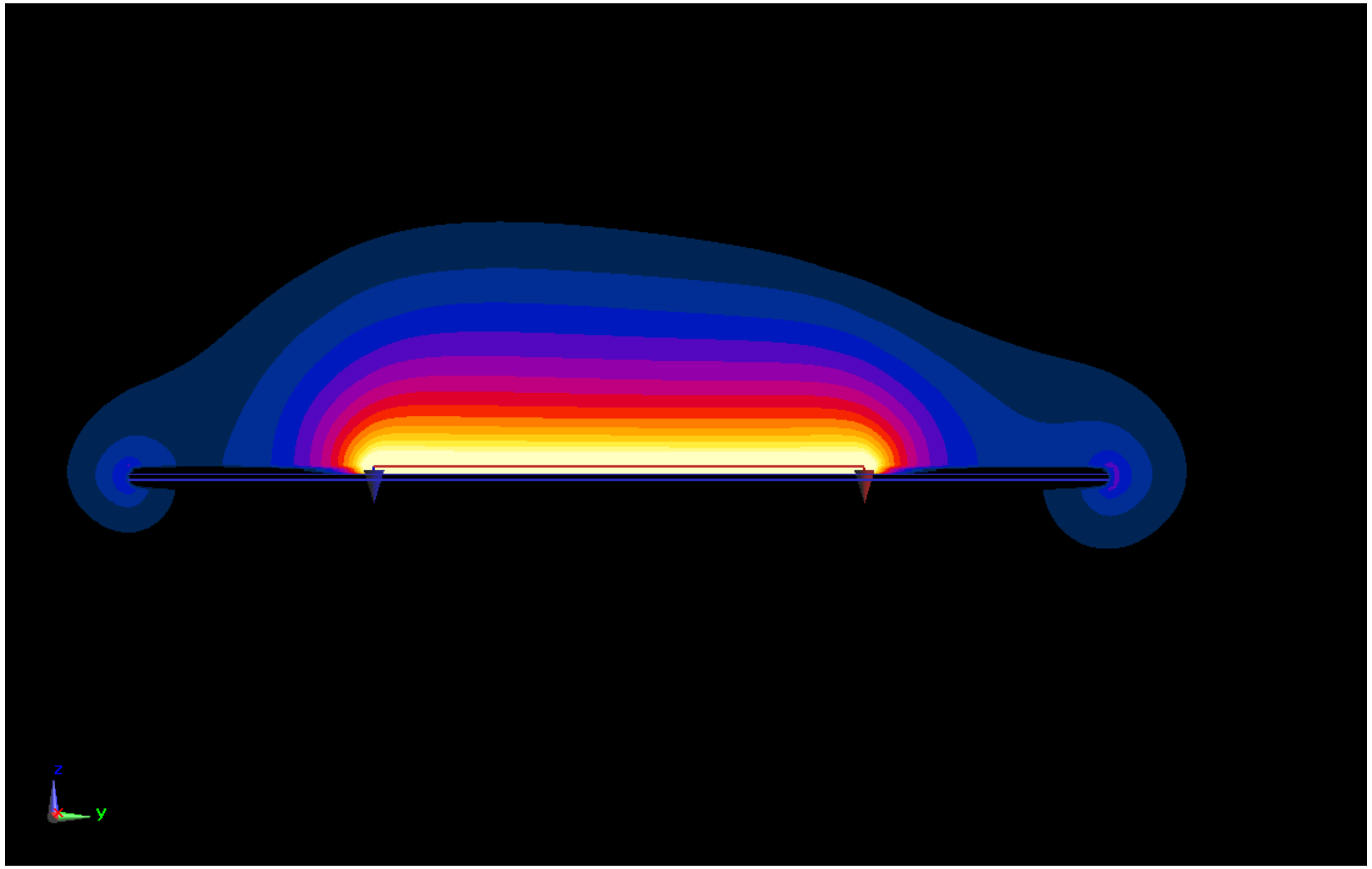
If the signal has to switch layers, the radiated power will doubled!

Coupling effects

E-field without layer change



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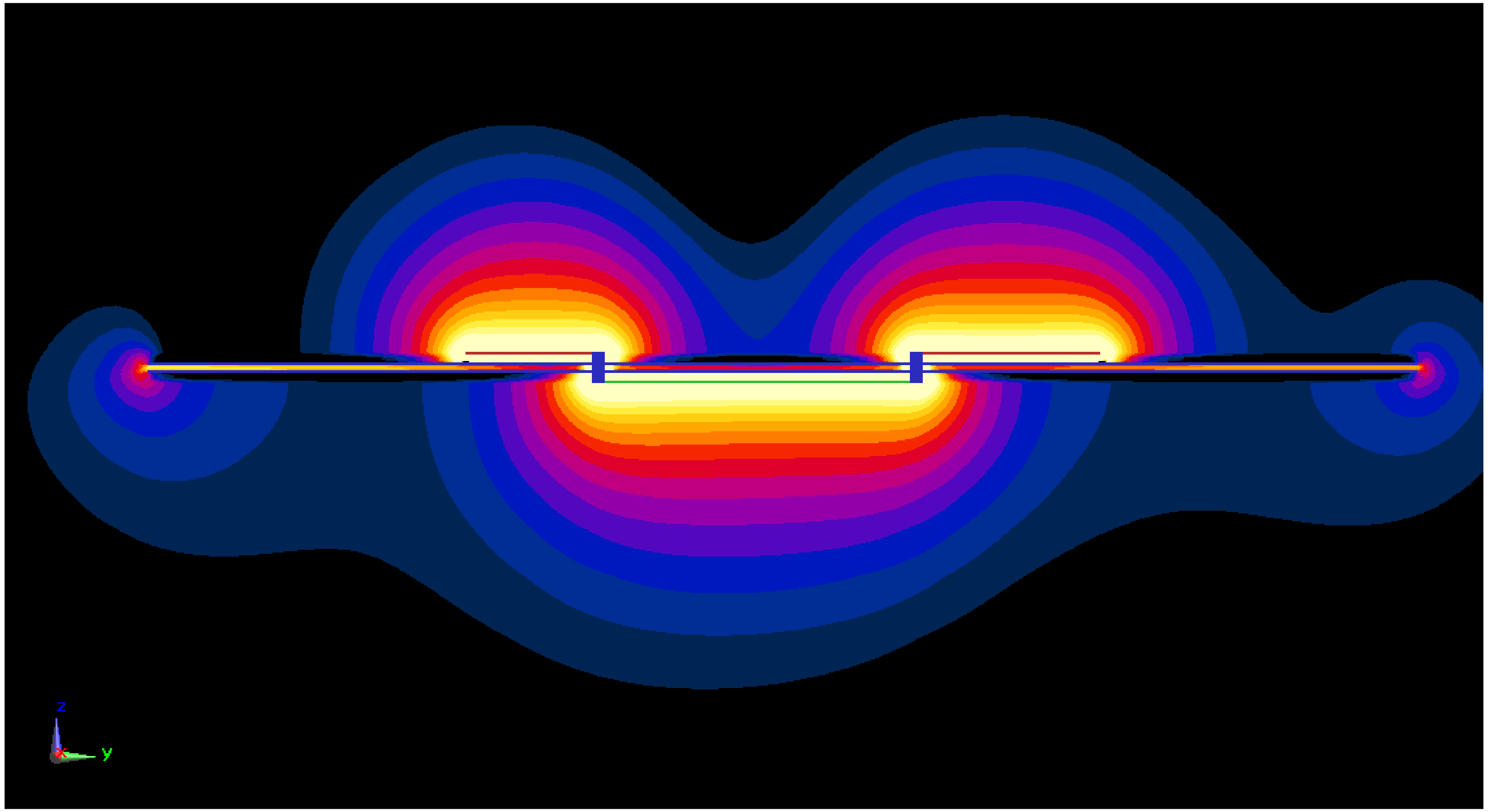
If the signal has to switch layers, the radiated power will doubled!

Coupling effects

E-field with layer change



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An electromagnetic wave propagates between the ground plane and the Vcc layer!

Shielding

Theoretical aspects of shielding

- Global shielding efficency
- Shielding efficiency SE_{dB} by Schelkunoff
- Absorption
- Reflection
- Apertures

Shielding

The cage of Faraday

Protection of external electromagnetic disturbances

Global shielding efficency in dB:

- 2 kinds of losses:
  1. Reflection
  2. Absorption

$$SE_{dB} = 20\log\left(\frac{Ei}{Et}\right)$$

$$SE_{dB} = 20\,log\left(\frac{Hi}{Ht}\right)$$

Shielding

The cage of Faraday

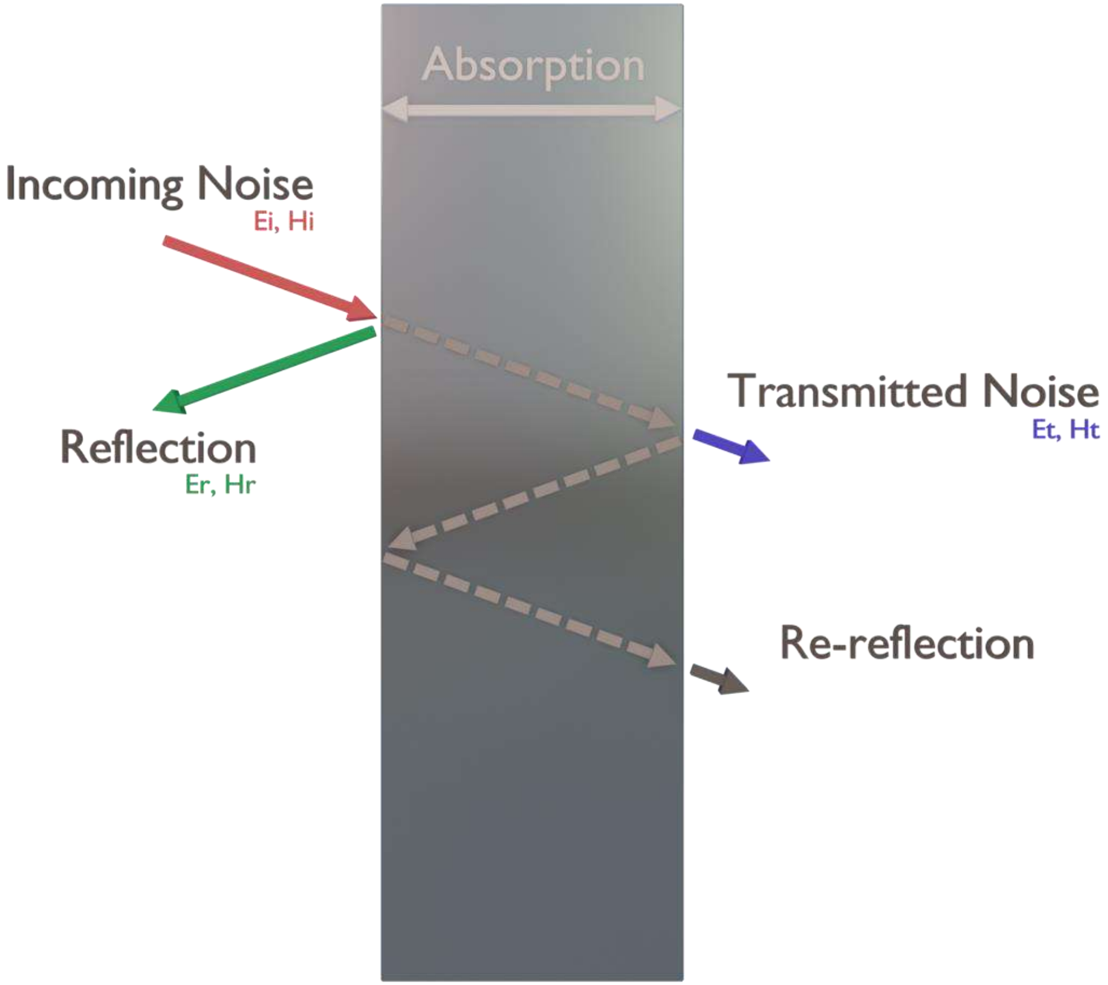
Protection of external electromagnetic disturbances

Global shielding efficency in dB:

- 2 kinds of losses:
  1. Reflection
  2. Absorption

$$SE_{dB} = 20\log(\frac{Ei}{Et})$$

$$SE_{dB} = 20\,log(\frac{Hi}{Ht})$$



Shielding efficiency SE_{dB} by Sergey Alexandrovich Schelkunov

Formula

- A_{dB} : Absorption
- R_{dB} : Reflection
- B_{dB} : Rereflection

$$SE_{dB} = A_{dB} + R_{dB} + B_{dB}$$

Rereflection

- Negligible, when the shielding material has a sufficient thickness

Absorption

Formula

- **Absorption loss**
- in dB:

$$A_{dB} = 1314 * t_{cm} * \sqrt{(f_{MHz} * \sigma r * \mu r)}$$

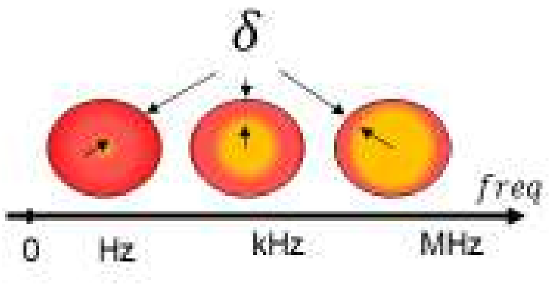
- t : Material thickness (cm)
- f : Frequency (MHz)
- σr : Relative conductivity
- μr : Relative permeability

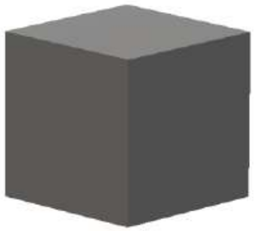
Absorption

Absorption diagram

Skin effect δ

Formula





Example

$3\delta_{100MHz} = 0{,}002556169\text{m}$

$5\delta_{100MHz} = 0{,}00426028\text{m}$

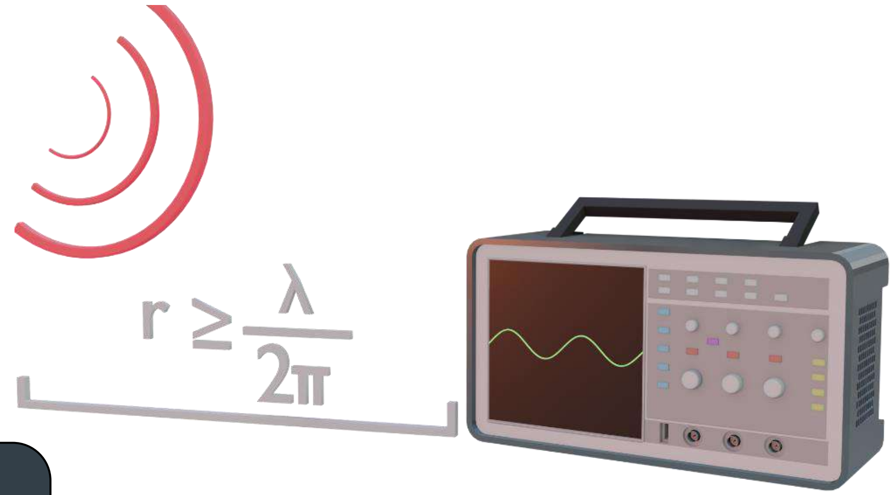
Aluminium foil 0,005 bis 0,02 m

- f : Frequency (MHz)
- σr : Relative conductivity
- μr : Relative permeability

$$\delta = \frac{0{,}0066}{\sqrt{\mu_r \sigma_r f_{MHz}}}$$

Reflection – Far field

Formula



Reflection loss

for the far field

- **Intrinsic impedance of a material:**

$$Z_m = 369\sqrt{\frac{\mu_r f_{MHz}}{\sigma_r}} * 10^{-6}$$

$$t > 3\delta$$

- **Reflection loss in dB:**

$$R_{dB} = 20\log\left(\frac{Z_w}{4Z_m}\right)$$

$$R_{dB} = 168 + 10\log\left(\frac{\sigma_r}{f * \mu_r}\right)$$

$$Z_w = \sqrt{\frac{\mu}{\varepsilon}} = 377\,\Omega$$

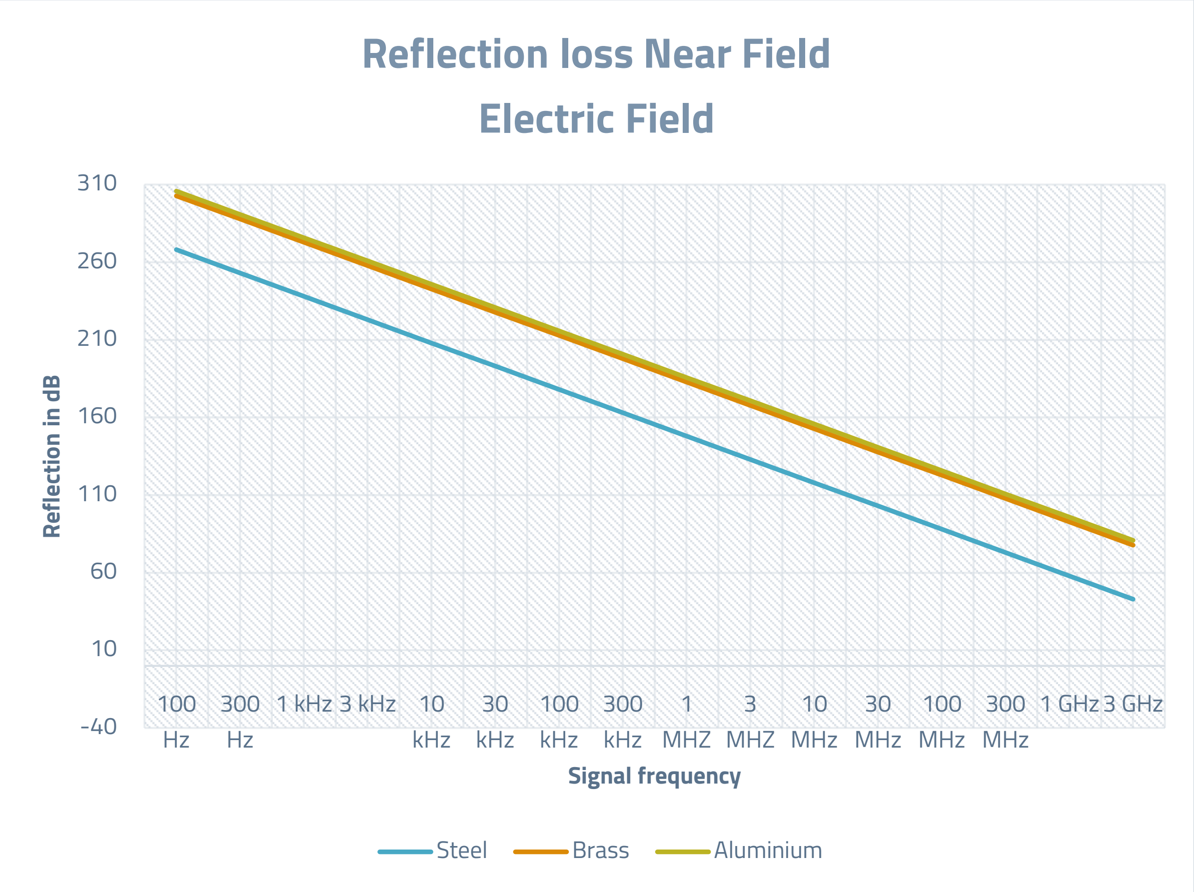
Disturbance source $r \geq \frac{\lambda}{2\pi}$

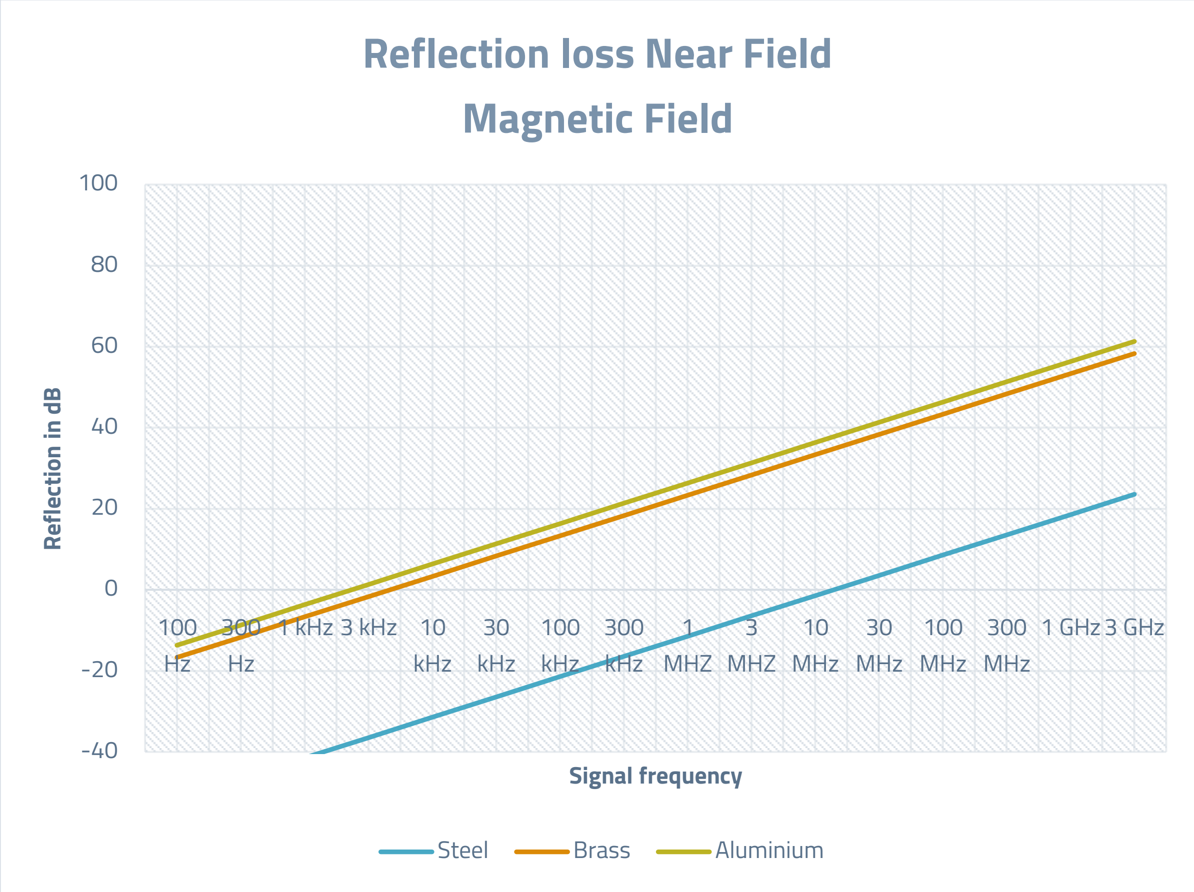
Reflection – Far field

Reflection diagram

Reflection – Near Field

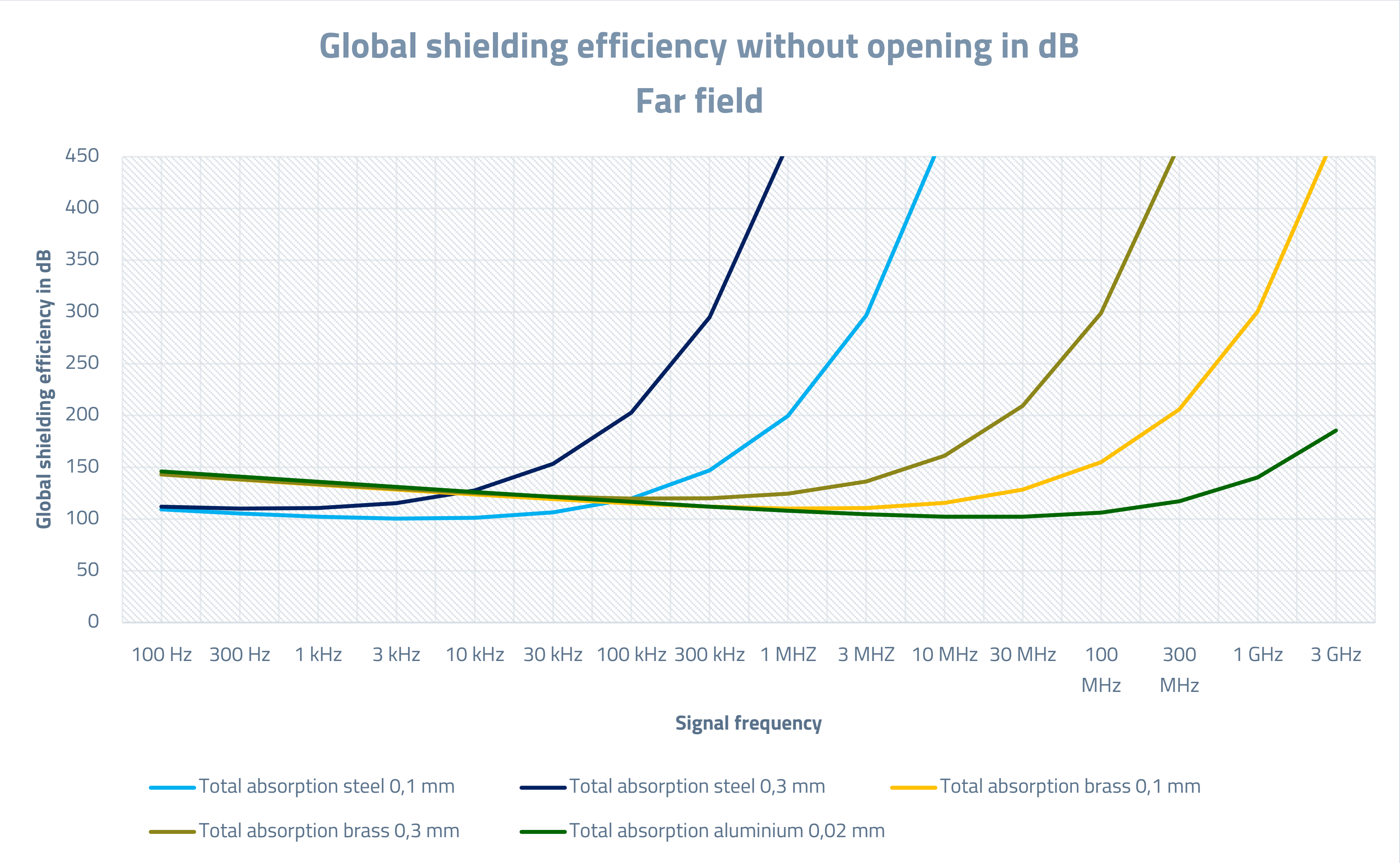
Difference between electric and magnetic field





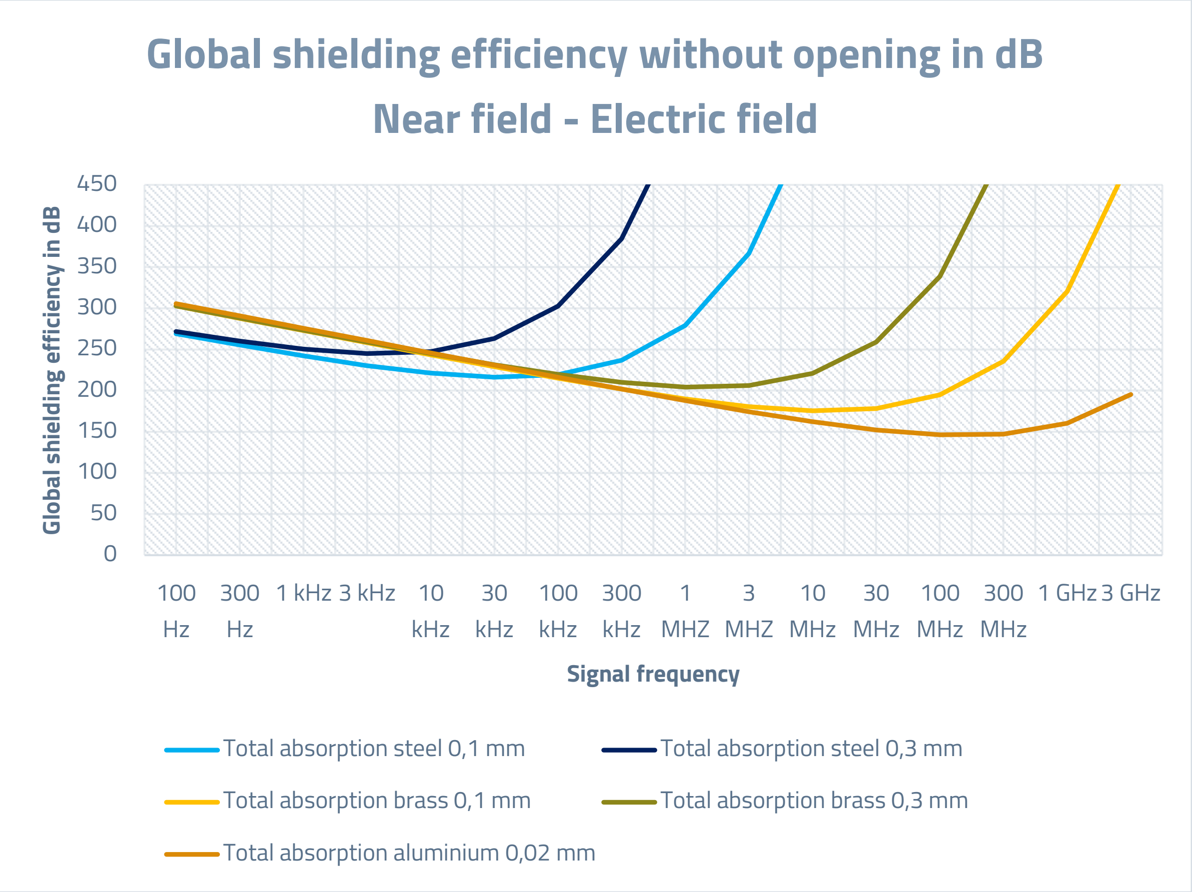
Shielding efficiency SE_{dB} by Sergey Alexandrovich Schelkunov

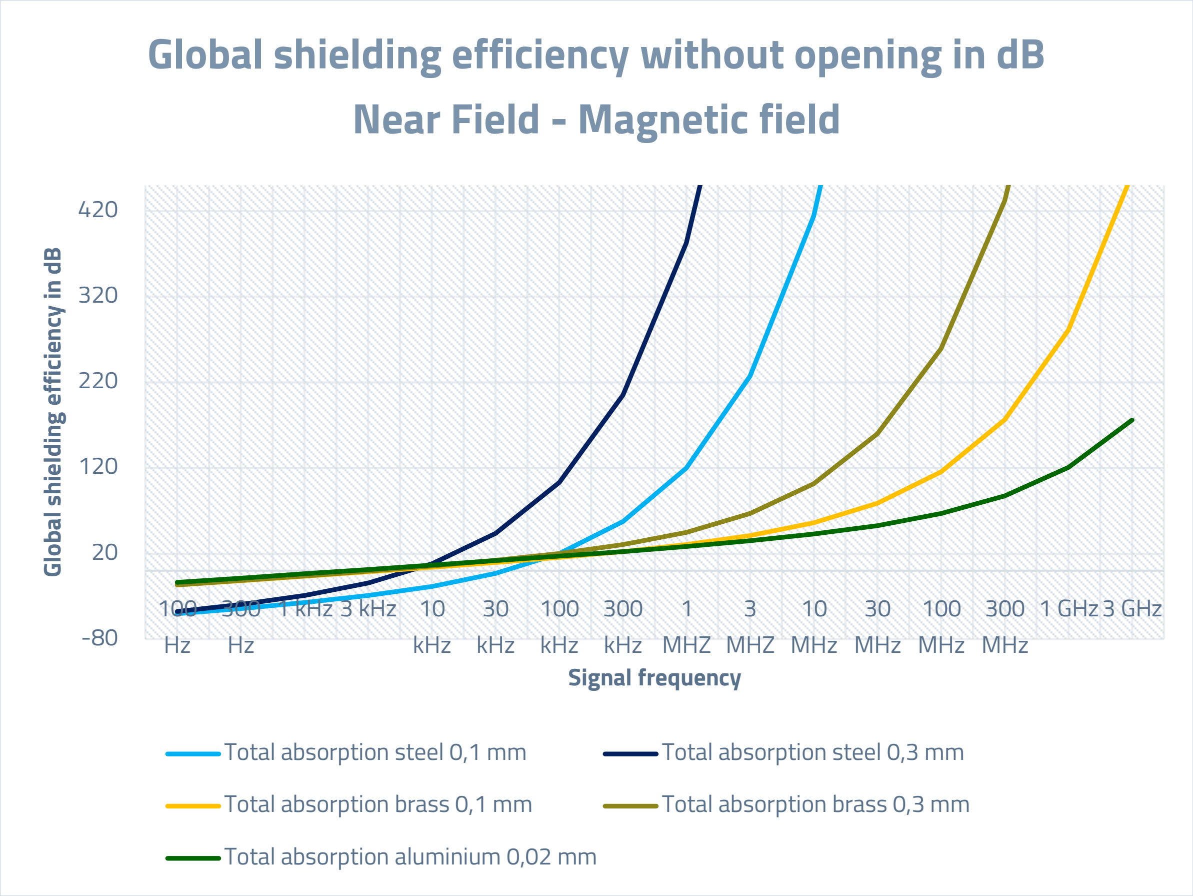
Far field shielding efficiency



Shielding efficiency SE_{dB} by Sergey Alexandrovich Schelkunov

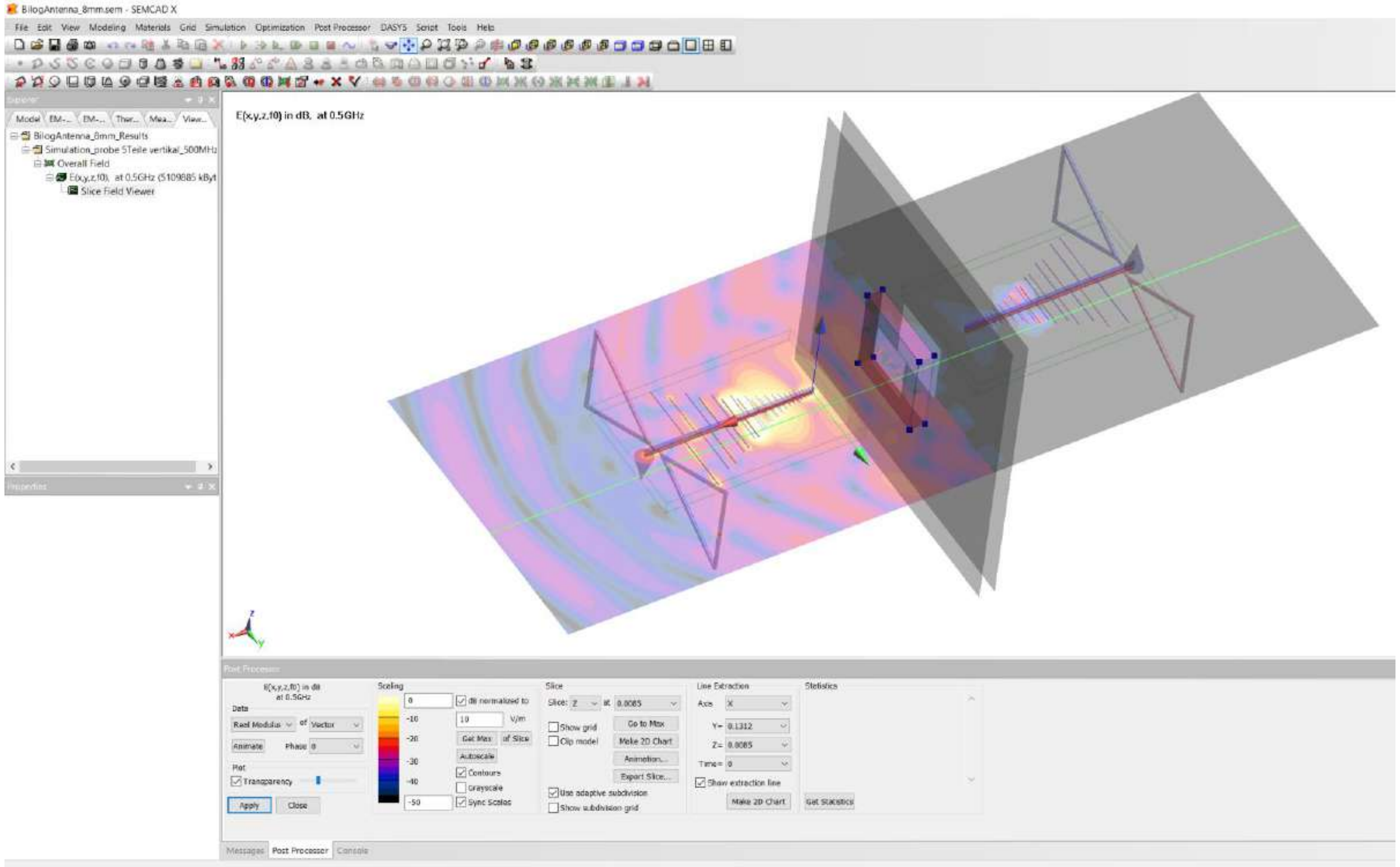
Near field shielding efficiency





Shielding efficiency

Simulation in Sim4Life



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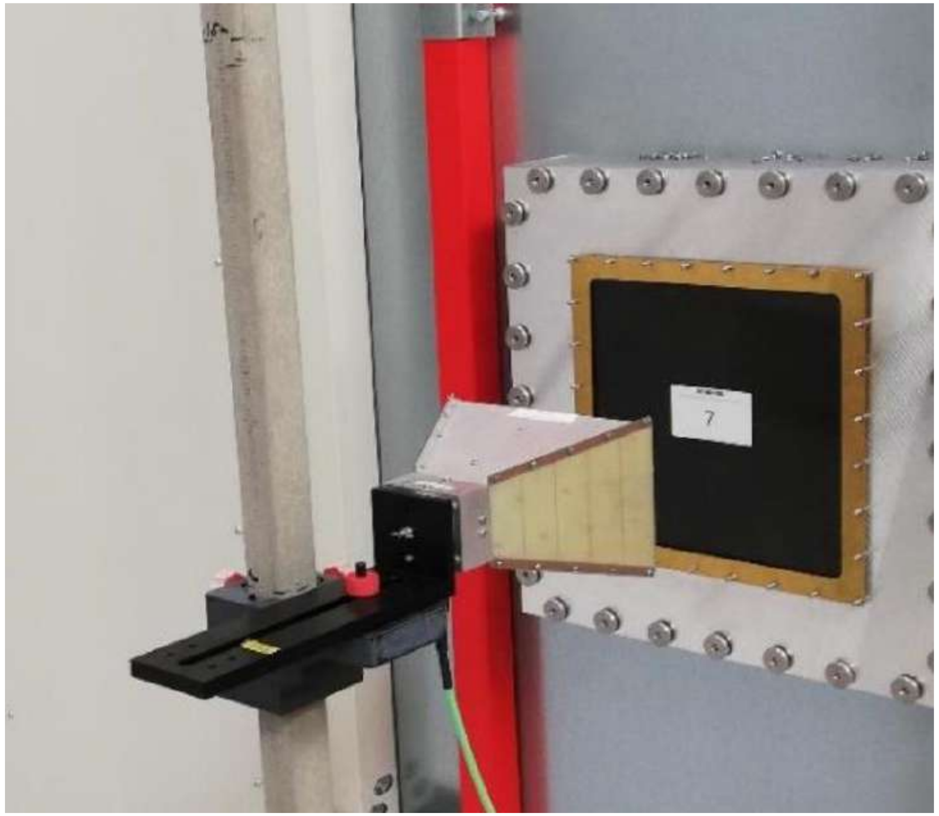
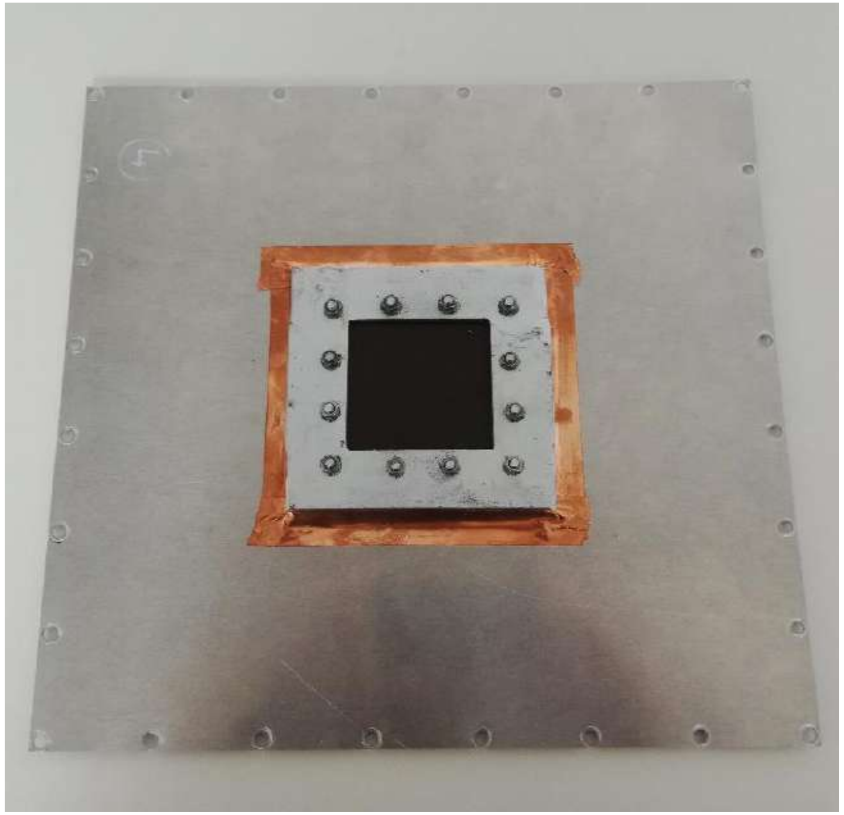
Shielding efficiency

Simulation in Sim4Life



Material sample 343mm



Material sample 80mm

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Shielding efficiency

Simulation in Sim4Life

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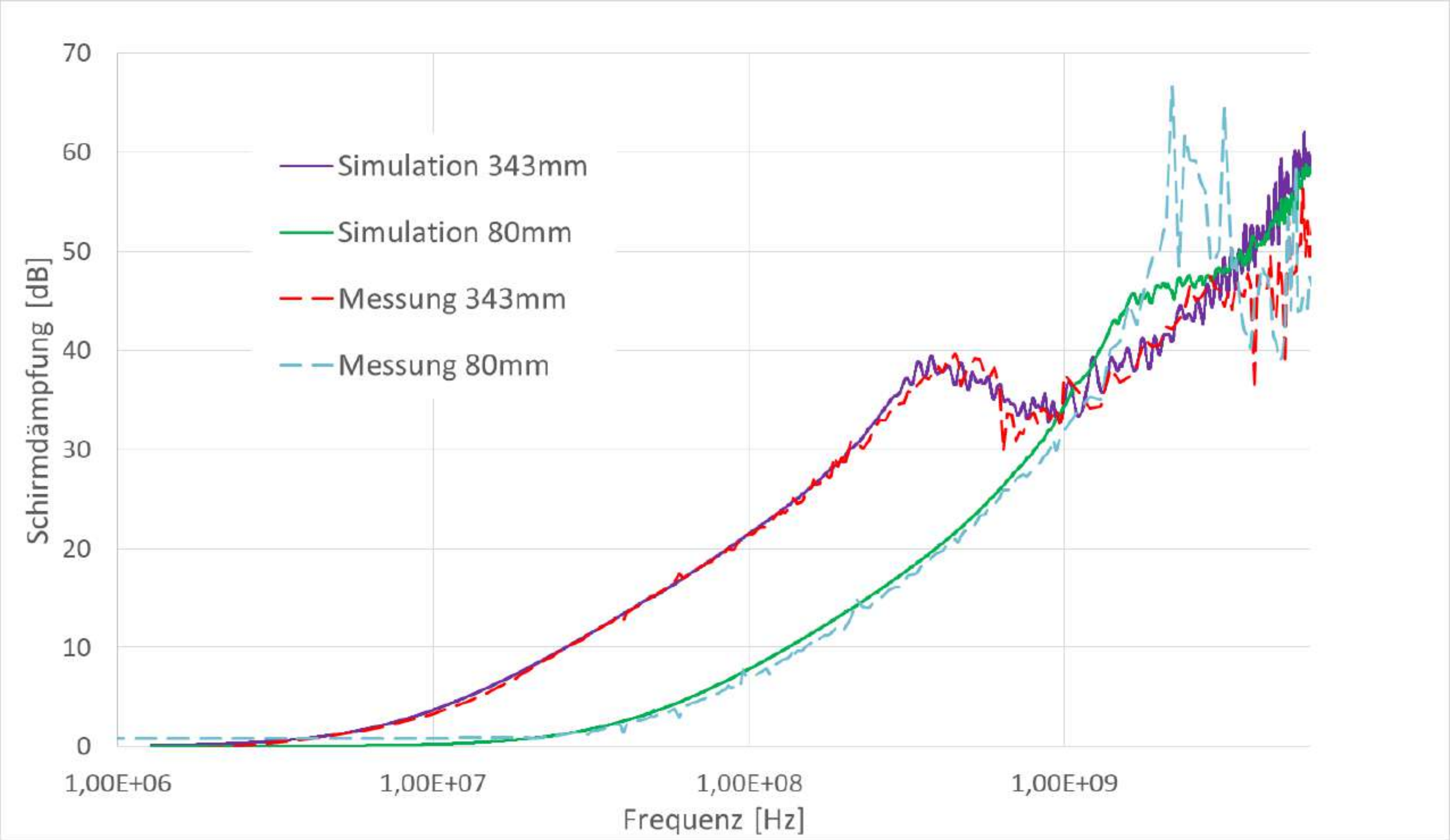

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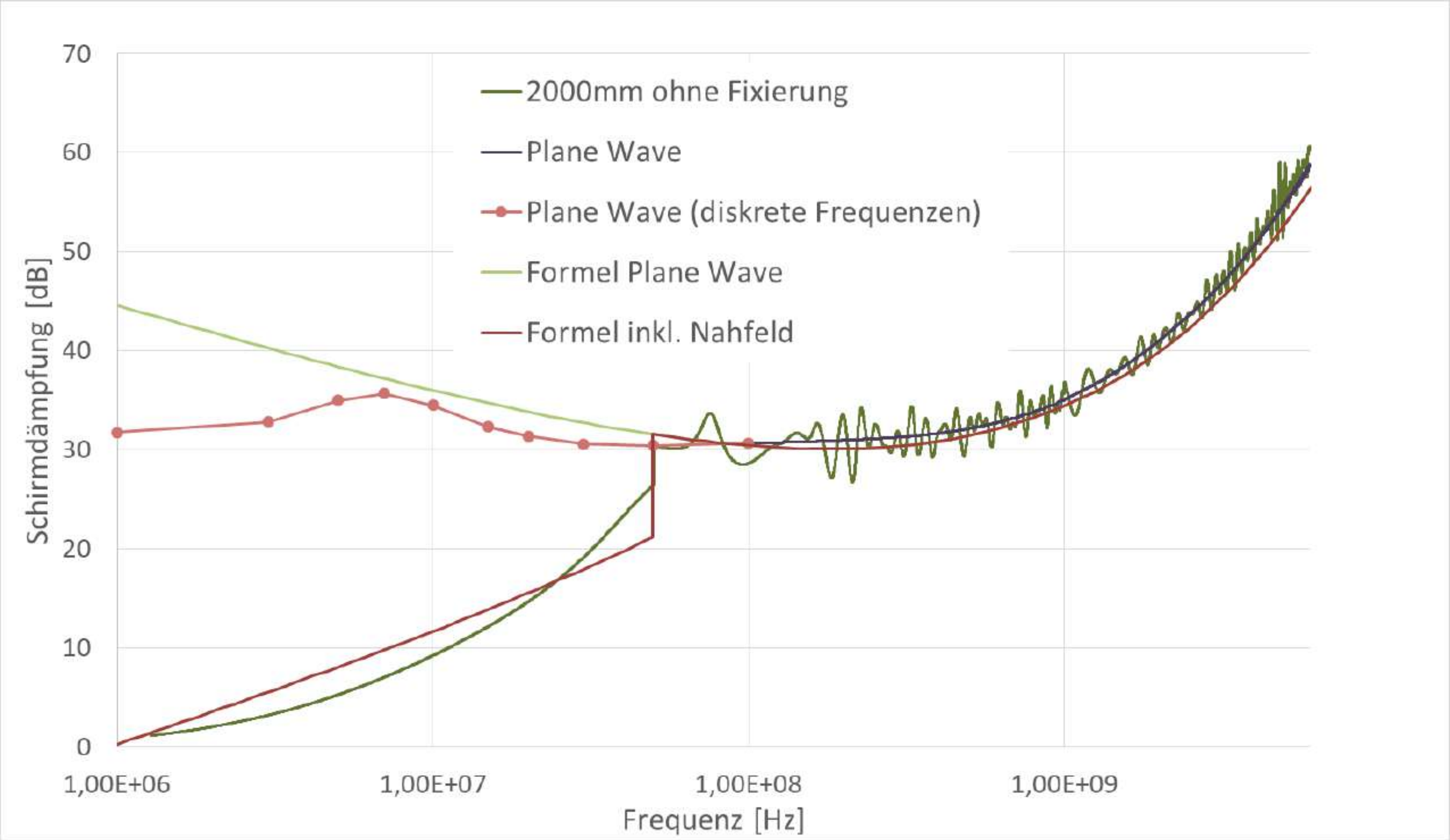
Shielding efficiency

Simulation in Sim4Life



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Shielding

WE shielding materials

Produkt	Shielding Material
USB 2.0	Bronze + Sn Bronze + Ni
USB 3.0	Bronze + Sn Stainless steel + Ni
USB3.1	Steel + Ni
USB3.1 type C	Steel + Ni
HDMI	Bronze + Sn
MJ	Bronze + Ni
DSUB	Steel + Sn Steel + Ni
DC power jack	Bronze + Ni

Shielding

Apertures

The maximal length of an apertures is defined by the frequency

Rule of thumb for critical length of apertures:

Industrial applications: $l < \frac{\lambda min}{20}$

Military applications: $l < \frac{\lambda min}{50}$

If $l \geq \frac{\lambda}{2}$ then your shielding is useless

Shielding

Shielding efficiency when using different long apertures

$$SE_{dB} = 20\log(\frac{\lambda}{2L})$$

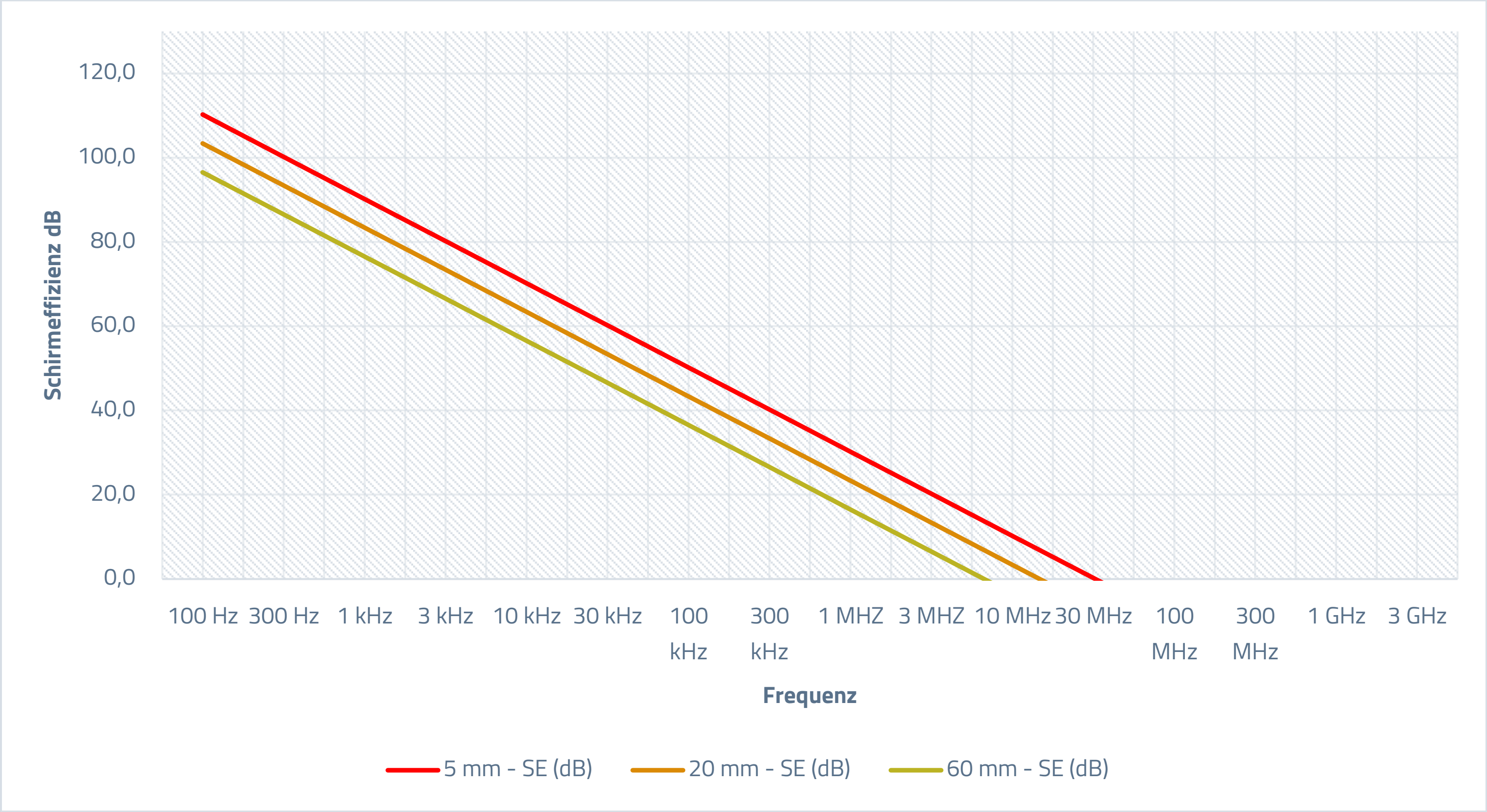
$$SE_{dB} = 20\log(\frac{\lambda}{20L})$$

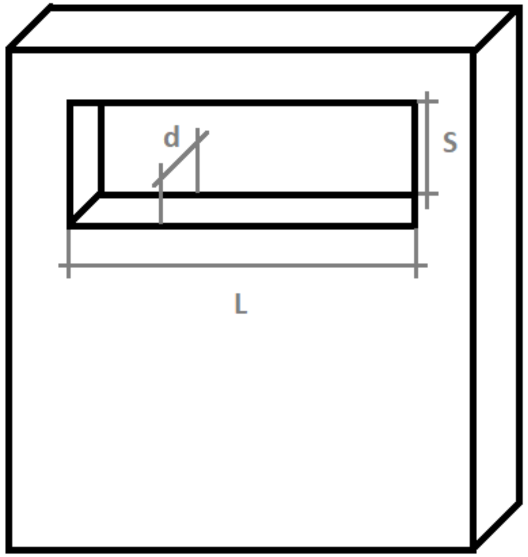
Shielding

Shielding efficiency when using different long apertures

$$SE_{dB} = 97 - 20\log(Lf_{MHz}) + 20\log\left(1 + \ln\left(\frac{L_{mm}}{S_{mm}}\right)\right) + SE_{shad} + 30 * \left(\frac{d_{mm}}{L_{mm}}\right)$$

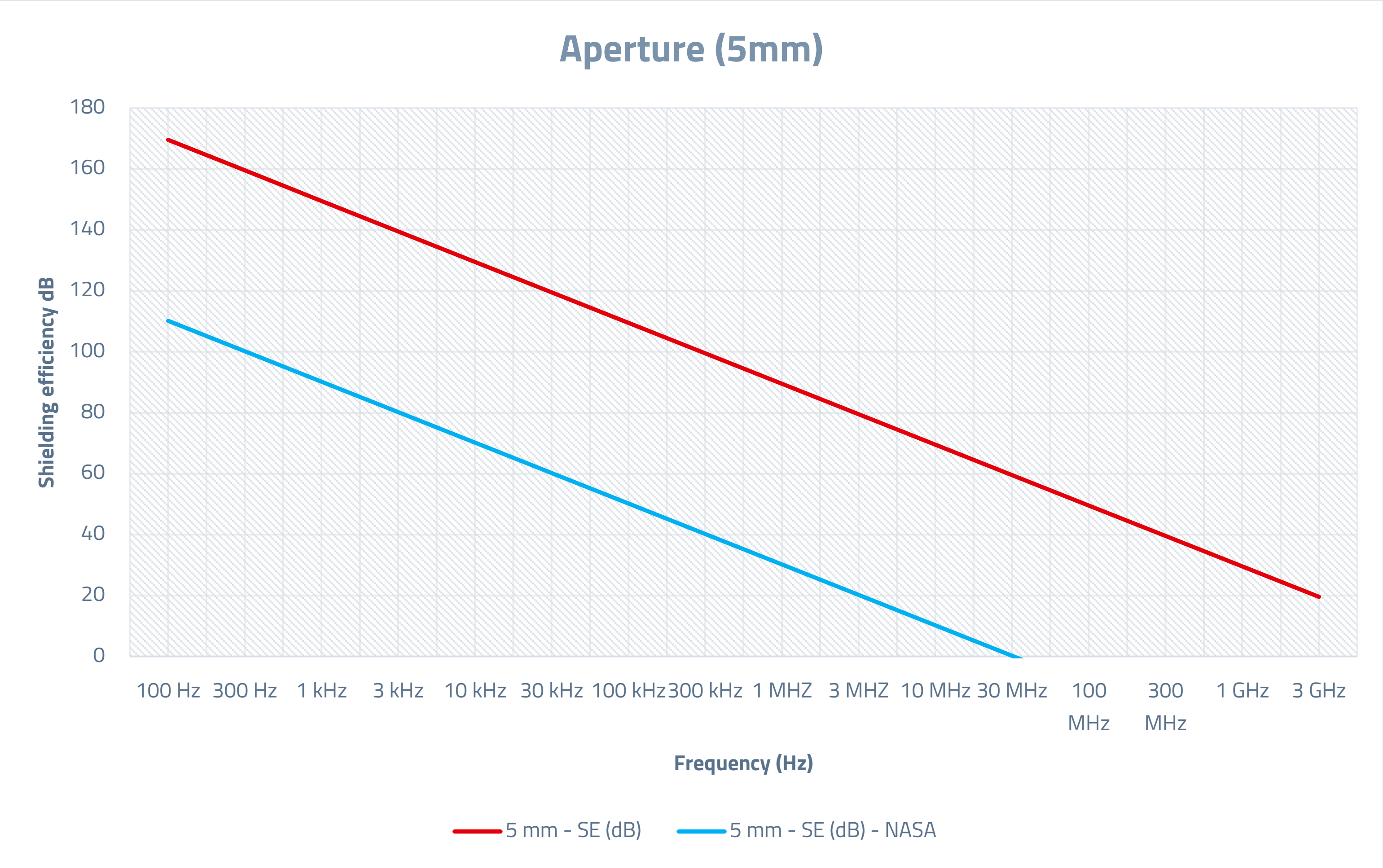
NASA - Design Guidelines for Shielding Effectiveness, Current Carrying Capability, and the Enhancement of Conductivity of Composite Materials





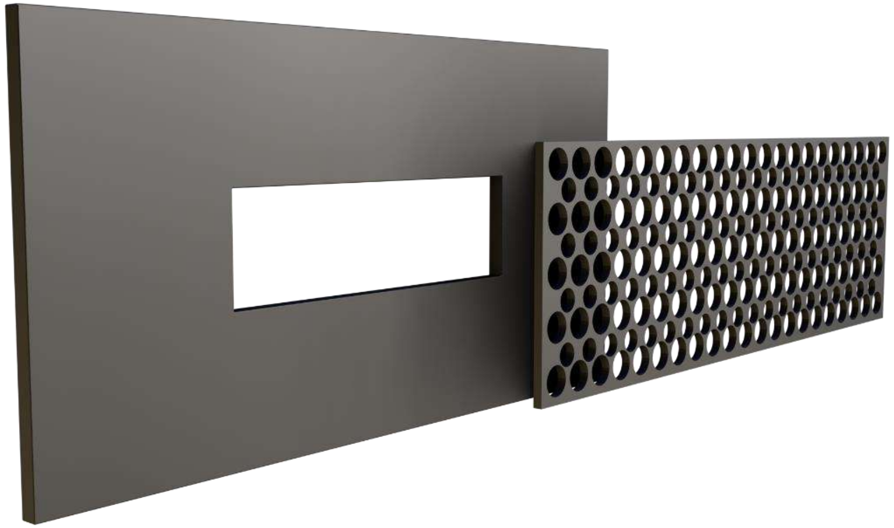
Shielding

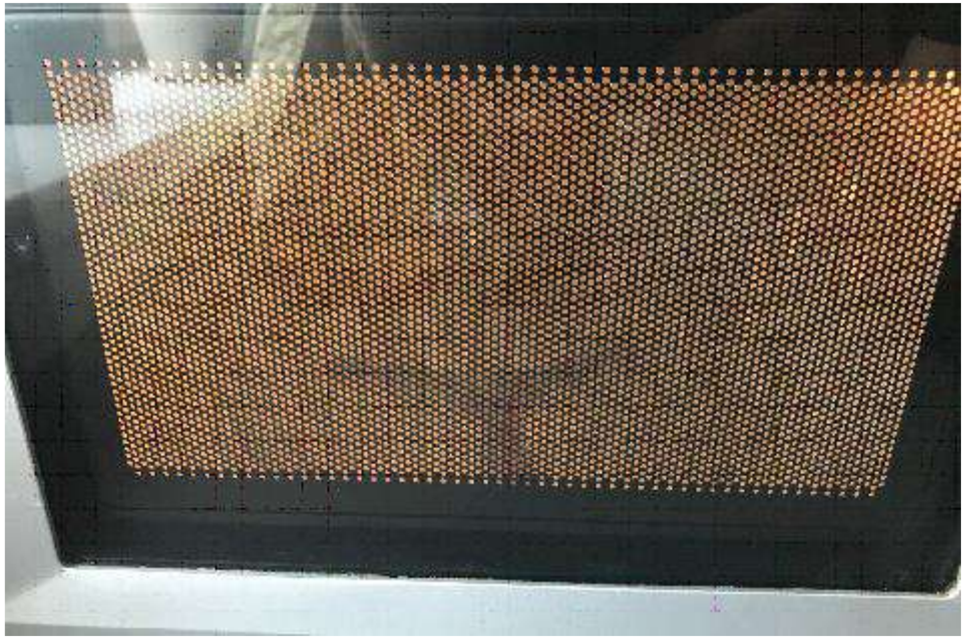
Comparing both formulas



Shielding

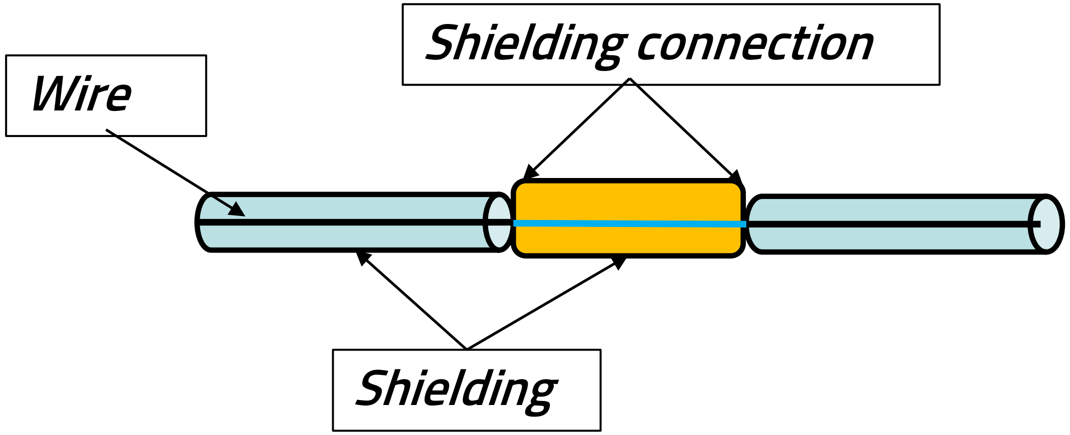
How can we increase the aperture size?





Shielding

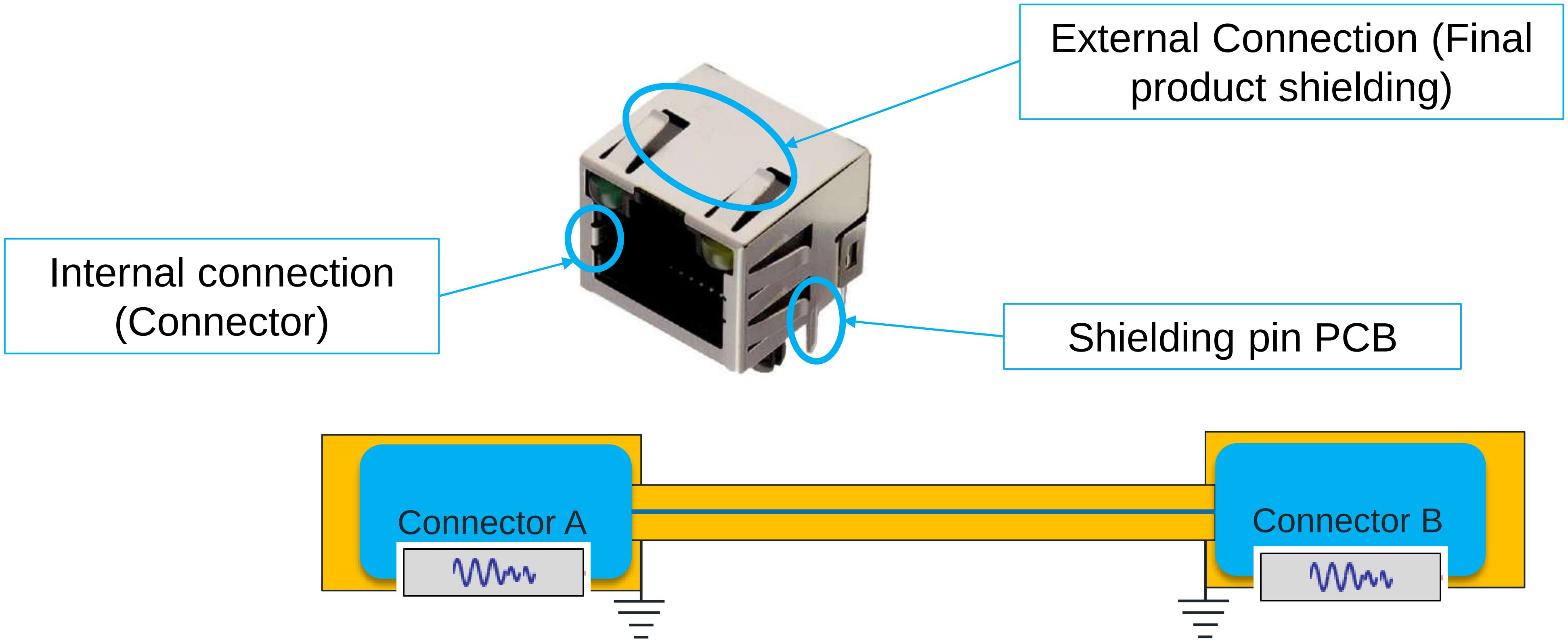
The usage of shielding in a connector



Shielding

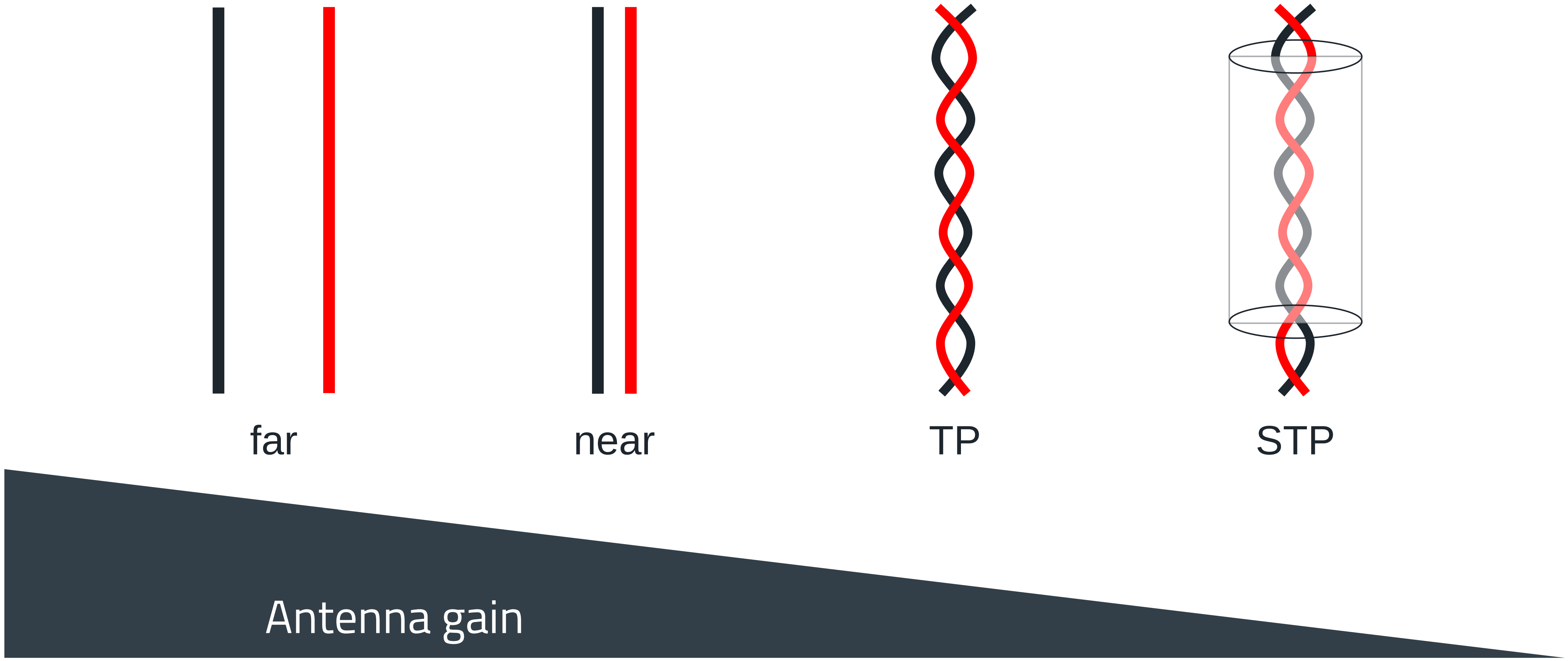
Return path of high frequency current

Shielding continuity (Electrical connection)



Shielding

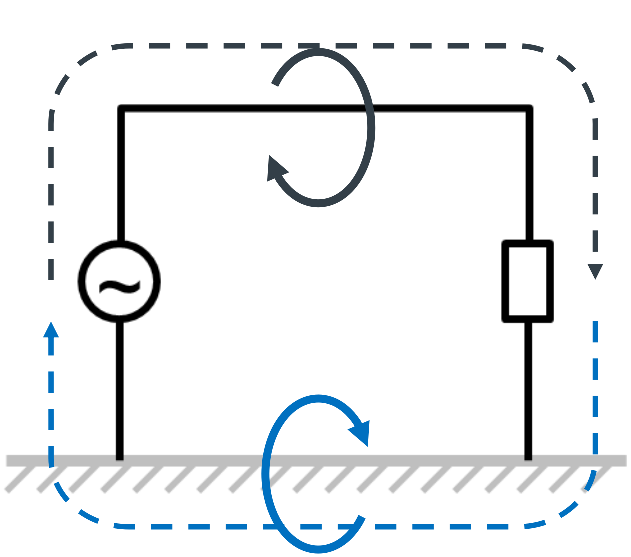
Cable as antenna



Shielding

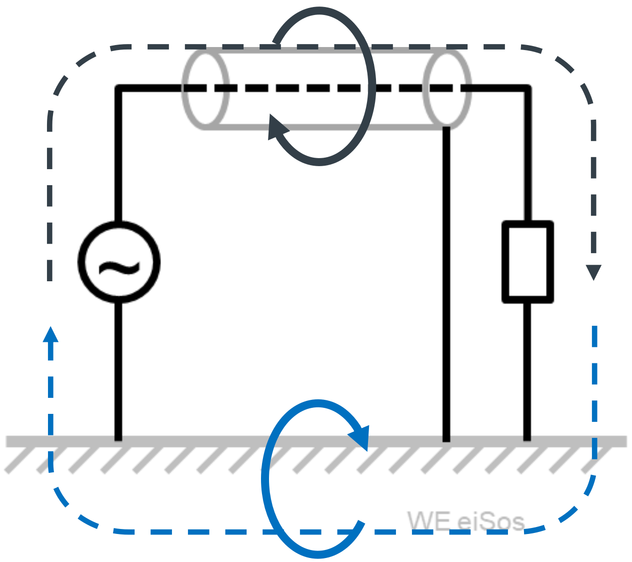
Cable shielding

RADIATED NOISE



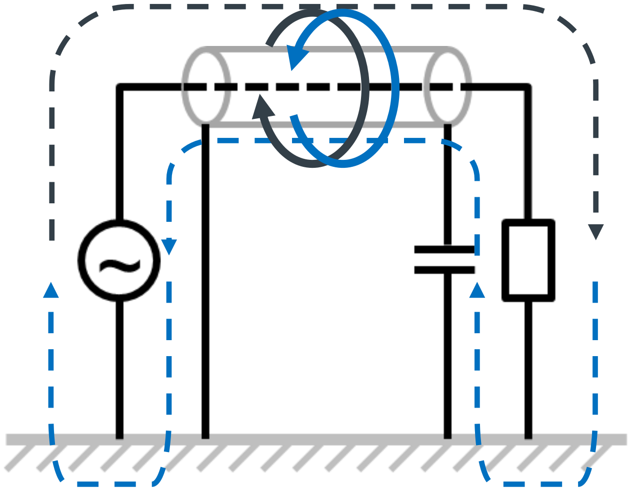
Without shielding, big enclosed current loop surface

Shielded E-field
uncompensated H-field



Added shielding,**one** end grounded, big current loop surface

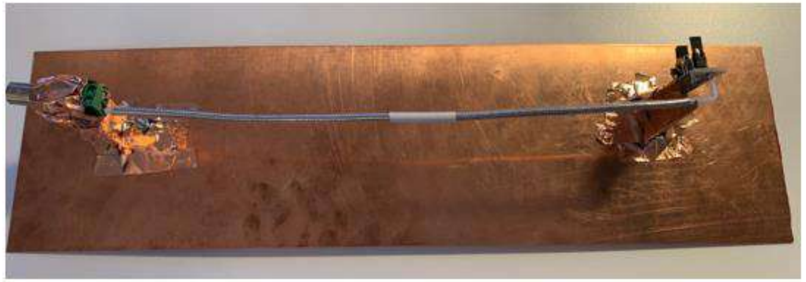
Shielded E-field
compensated H-field

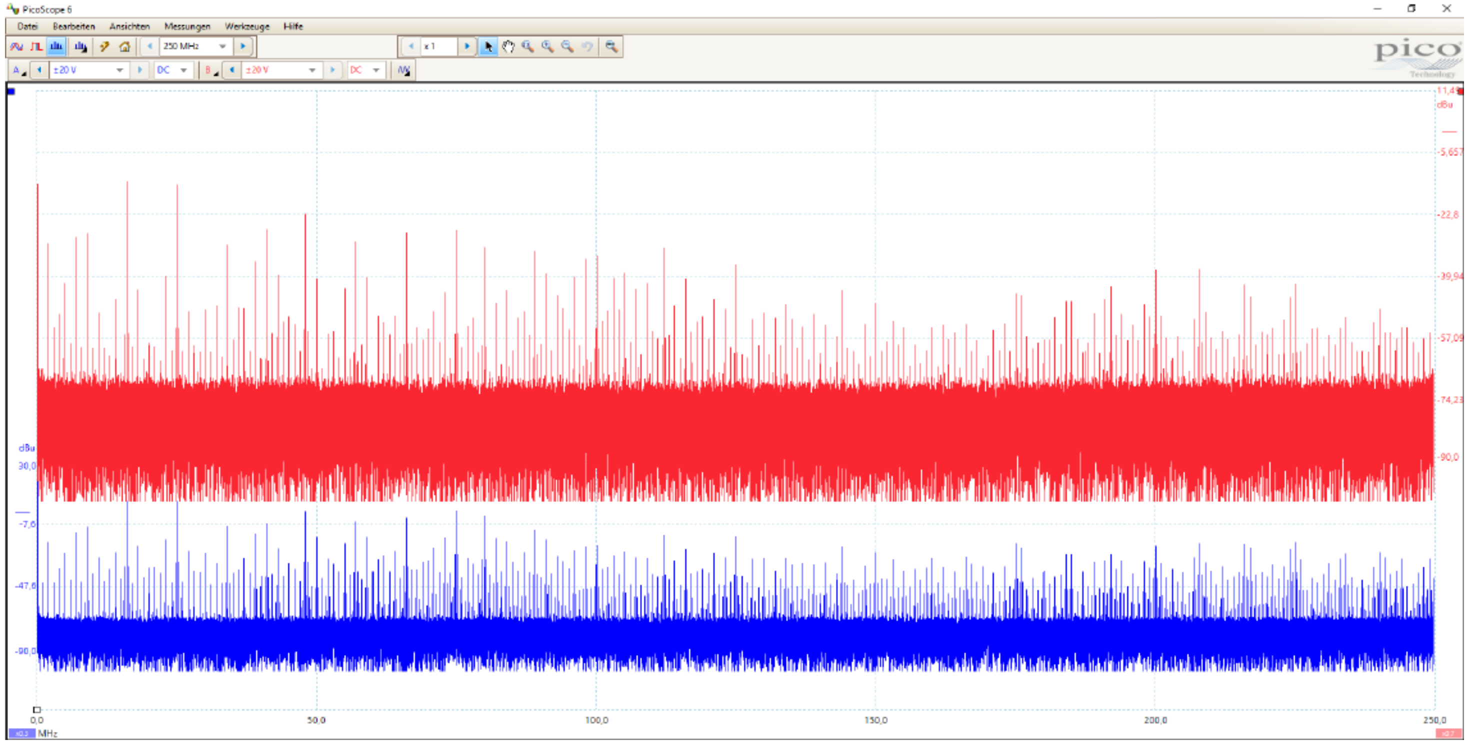


Added shielding,**both** ends grounded, **reduced** current loop surface

Shielding

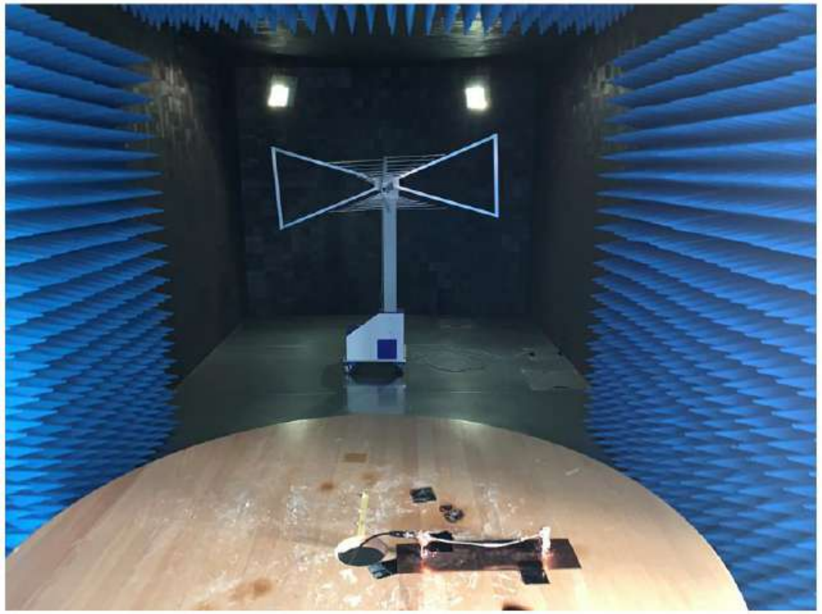
How should you attach the shielding?

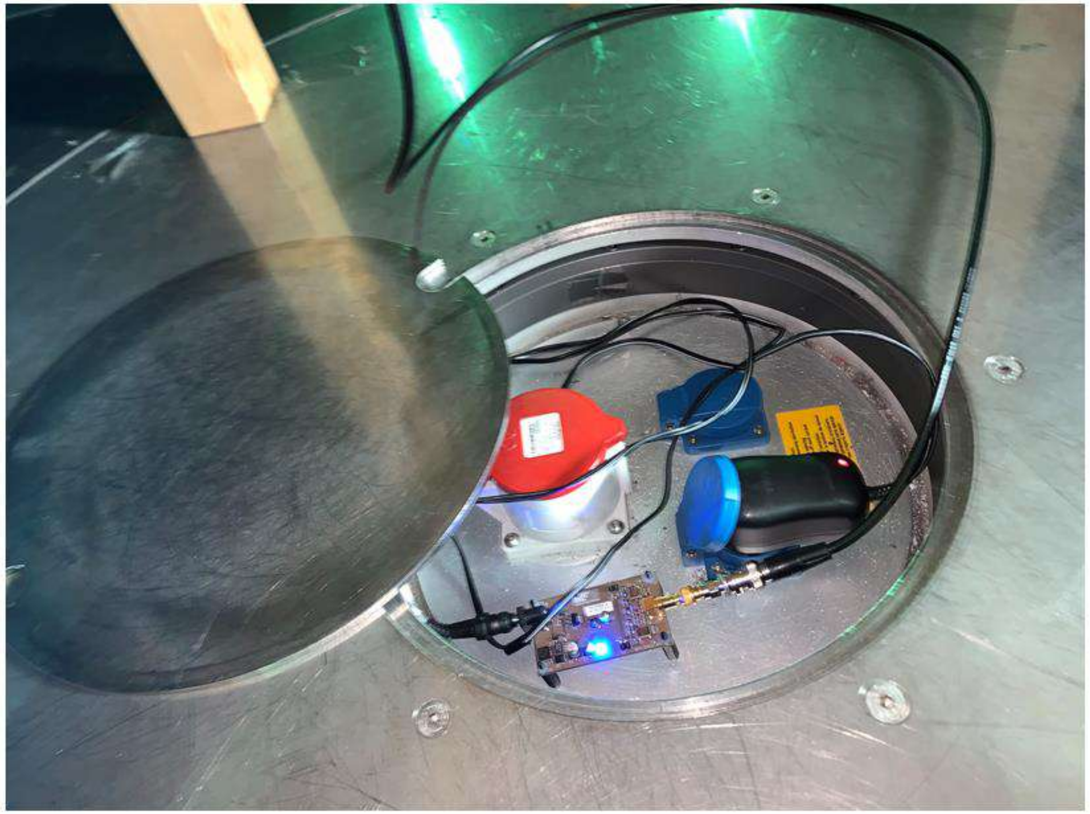




Shielding

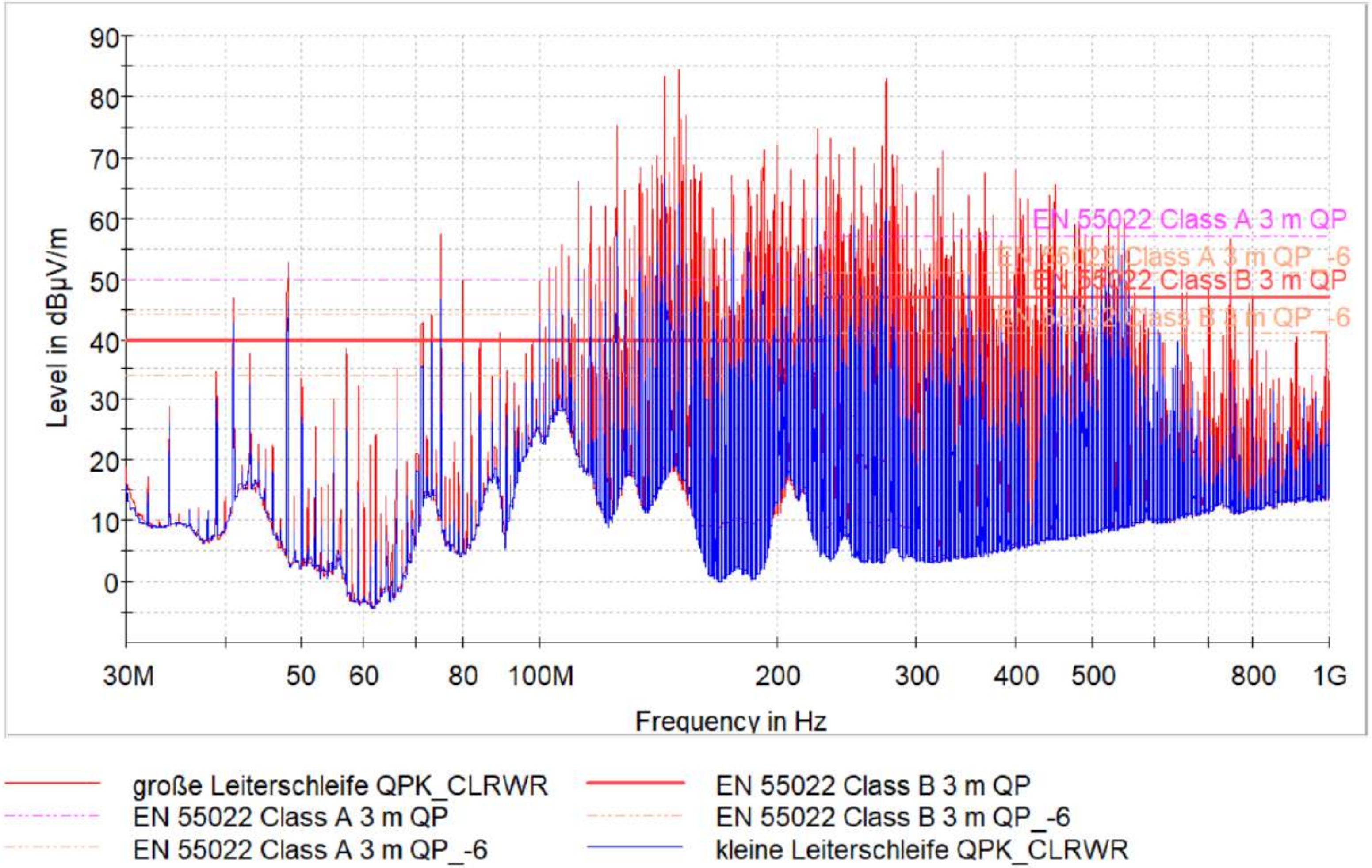
E – field measurements in the emc chamber





Shielding

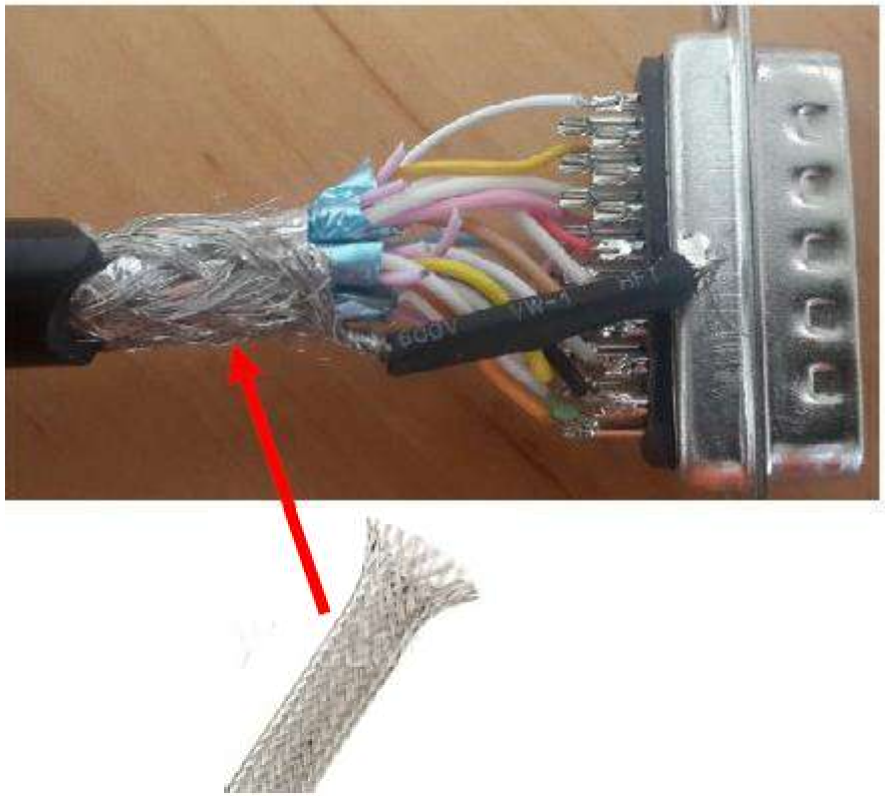
E – field measurements in the emc chamber



Shielding

Cable shielding examples

Area coverage of the braided shielding > 85%

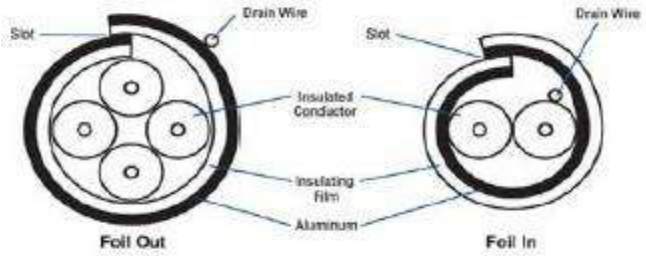


Every twisted pair should be shielded seperatly

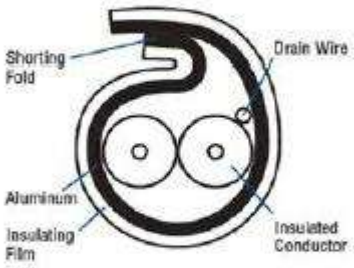
Shielding

Cable shielding examples

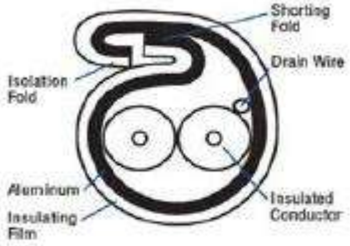
Don't



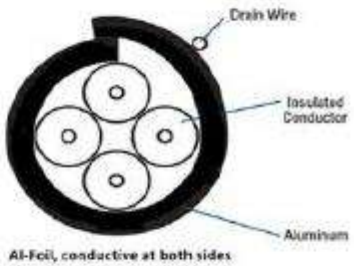
Good



Better



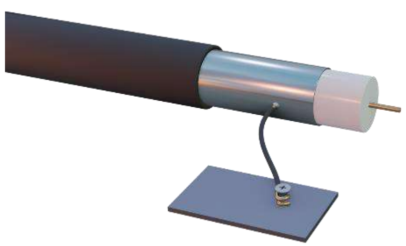
Best



Shielding

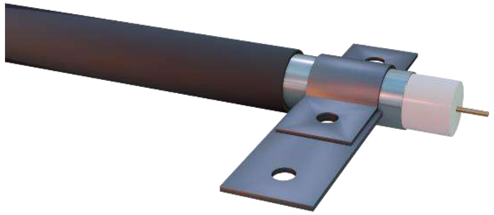
Cable shielding mounting tips

Avoid



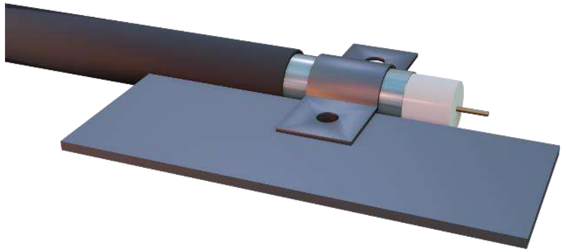
Soldered wire line

Acceptable



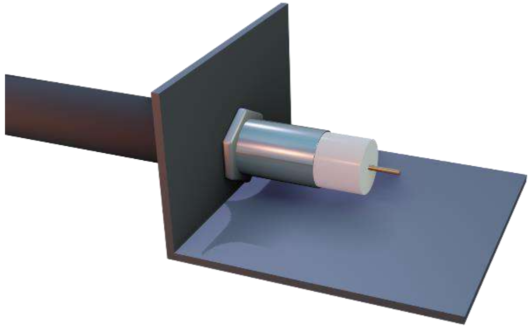
Metal sheet linked to ground panel

OK



Directly linked to ground panel

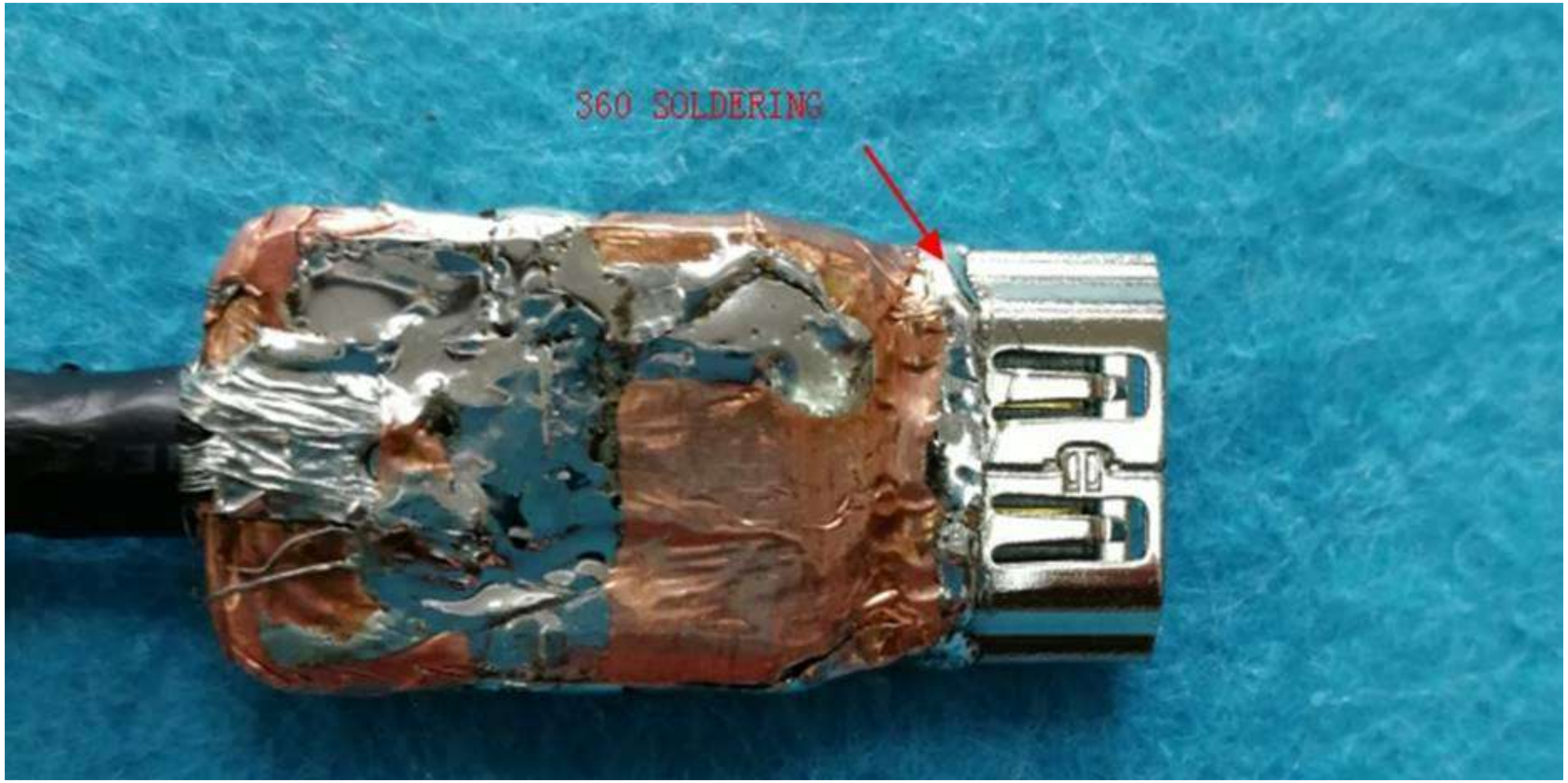
Optimal



Peripheral contact on the ground panel

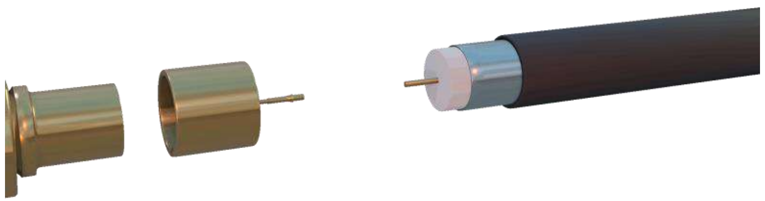
Shielding

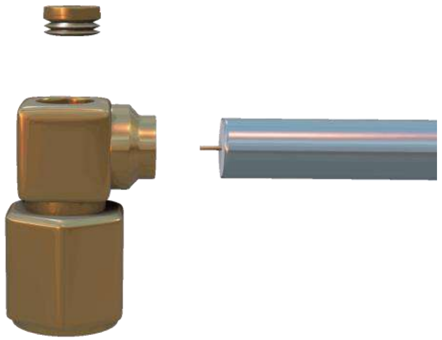
Cable shielding - HDMI shielding



Shielding

Cable shielding - Coaxial cable shielding





Shielding

Aperture

The maximal length of an apertures is defined by the frequency

If $l \geq \frac{\lambda}{2}$ then your shielding is useless

Shielding

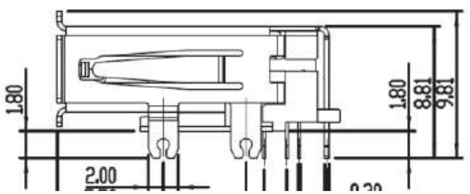
Example USB 3.1

100MHz and a aperture length of 5mm
1GHz and a aperture length of 5mm
5GHz and a aperture length of 5mm

$$SE_{@100MHz} = 20\log\left(\frac{\lambda}{2L}\right) = 49{,}5\ dB$$

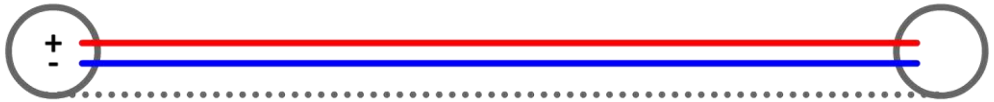
$$SE_{@1GHz} = 20\log\left(\frac{\lambda}{2L}\right) = 29{,}5\ \text{dB}$$

$$SE_{@5GHz} = 20\log\left(\frac{\lambda}{2L}\right) = 15{,}5\ \text{dB}$$



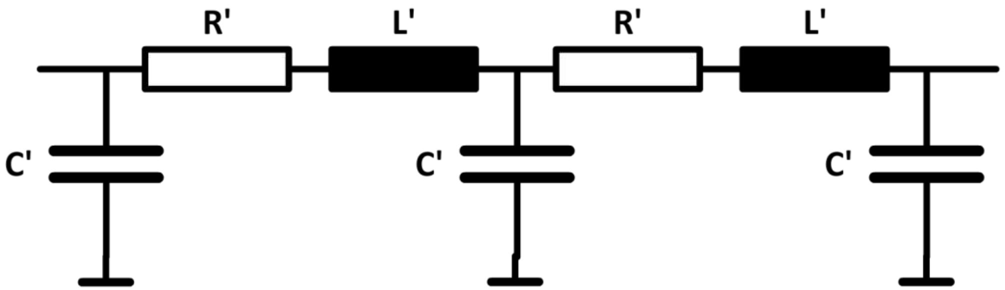
Shielding

Interconnecting cable and shielding



Interconnecting cable

R ↓ C ↓ L ↑ → $Z_{Conductor}$ 50 … 100Ω



Shielding

R ↑ C ↑ L ↓ → $Z_{Shielding}$ 1 … 5Ω

$$Z_0 = \sqrt{\frac{R' + j\omega L'}{G' + j\omega C'}}$$

f → 0: $Z_0 = \sqrt{\frac{R'}{G'}}$

f → ∞: $Z_0 = \sqrt{\frac{L'}{C'}}$

$\omega = 2\pi f$

Shielding

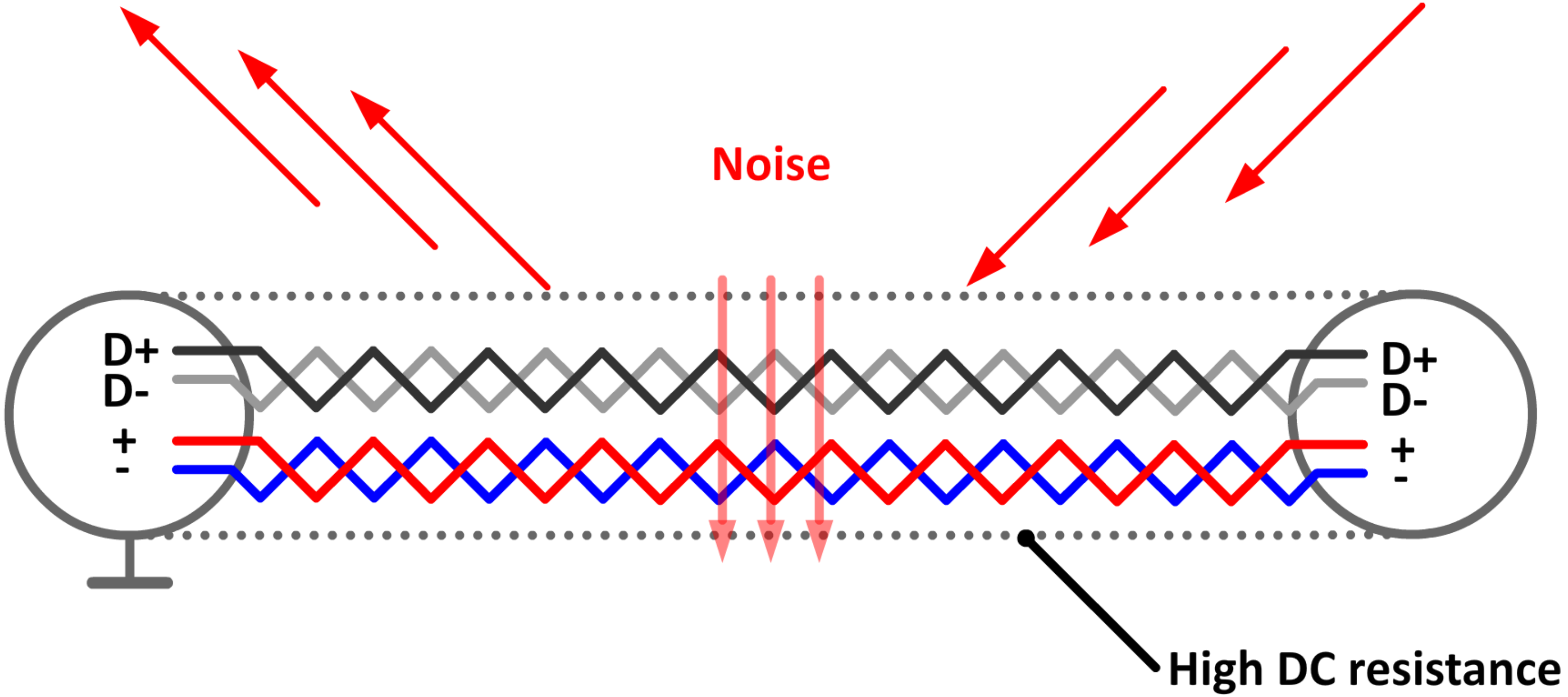
Interconnecting cable and shielding USB cable

Shielding

R ↑

C ↑

L ↓

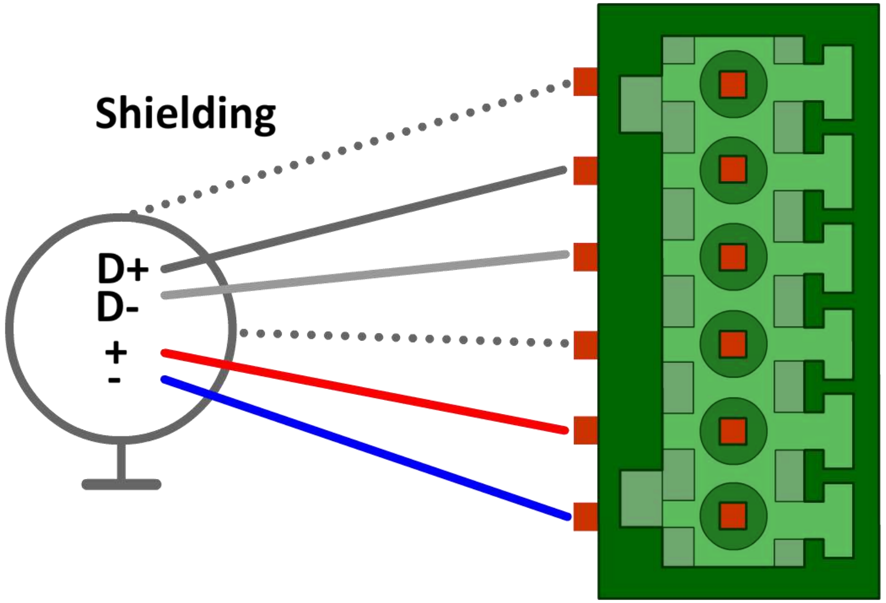


Shielding

USB signals on a Terminal Block

3 types of connections

- Current - as low resistance as possible
- Signals - impedance compliant
- Shielding - as low impedance as possible

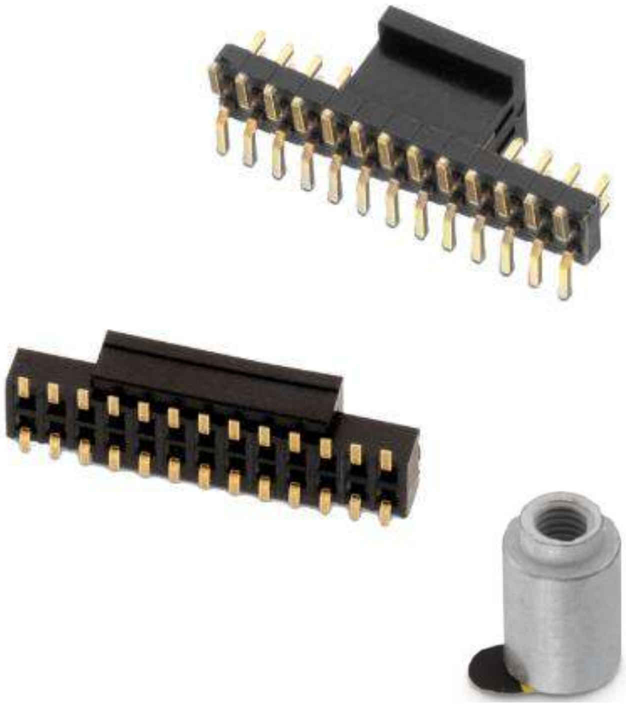


Board to board connection

Stacked boards

3 types of connections

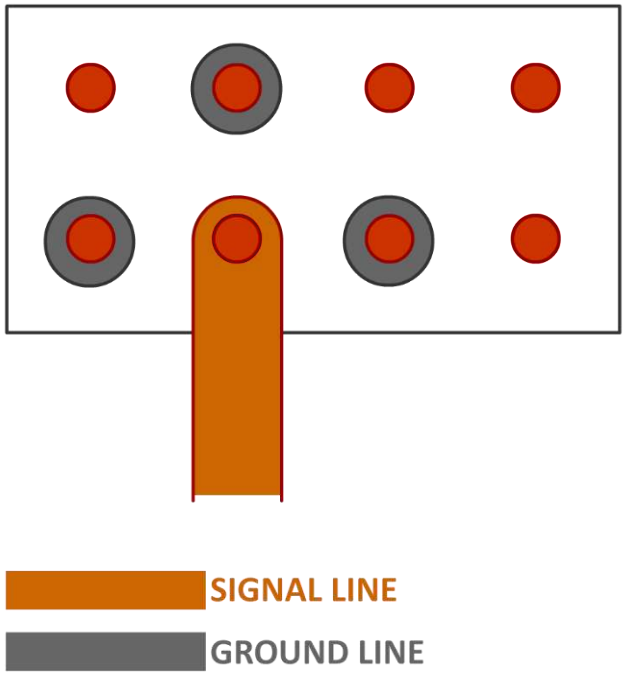
- Current - as low resistance as possible
- Signals - impedance compliant
- Shielding - as low impedance as possible

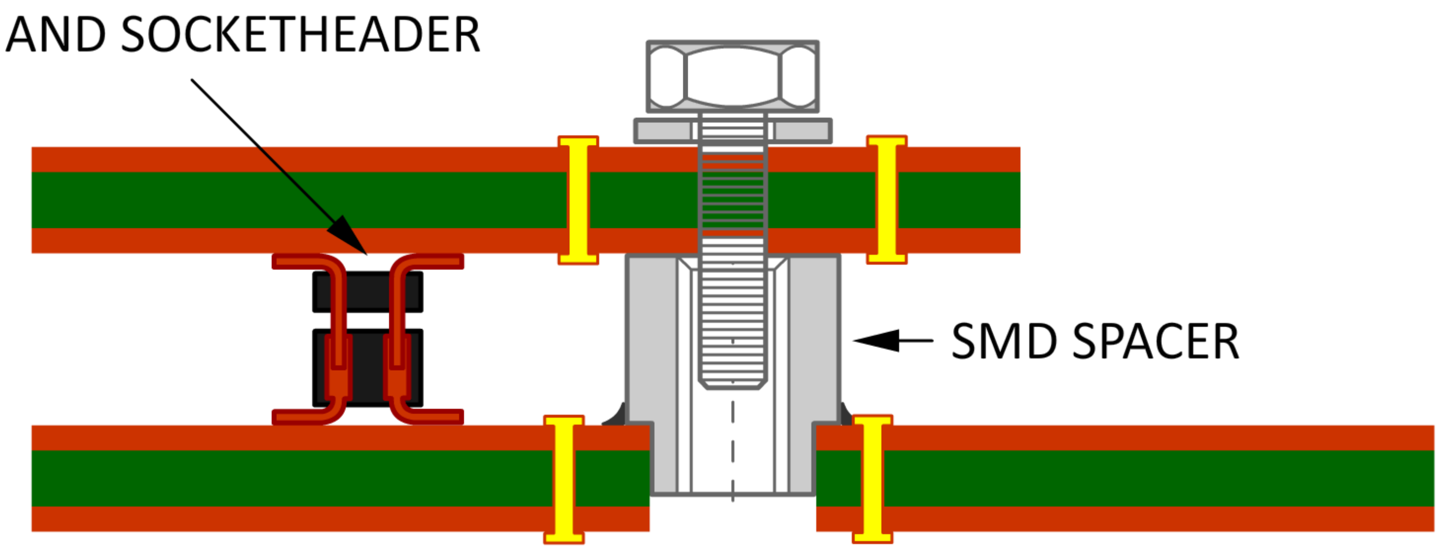


Board to board connection

Stacked boards

Transmitting a coaxial line

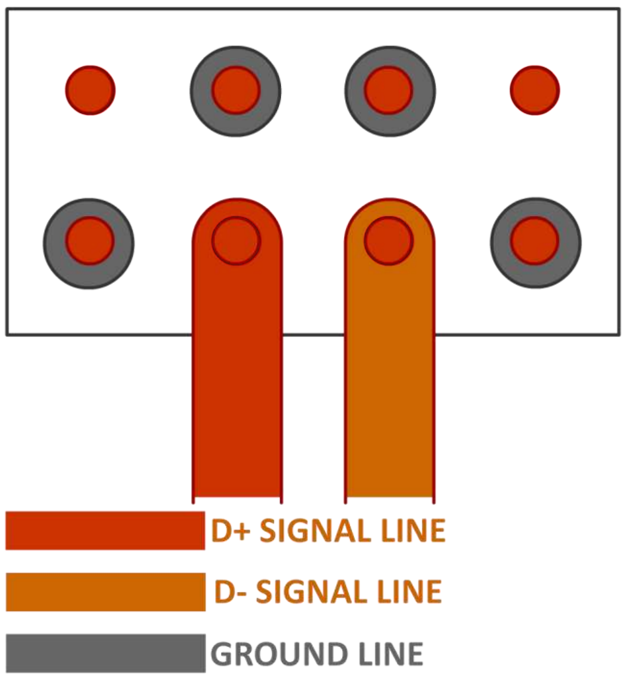


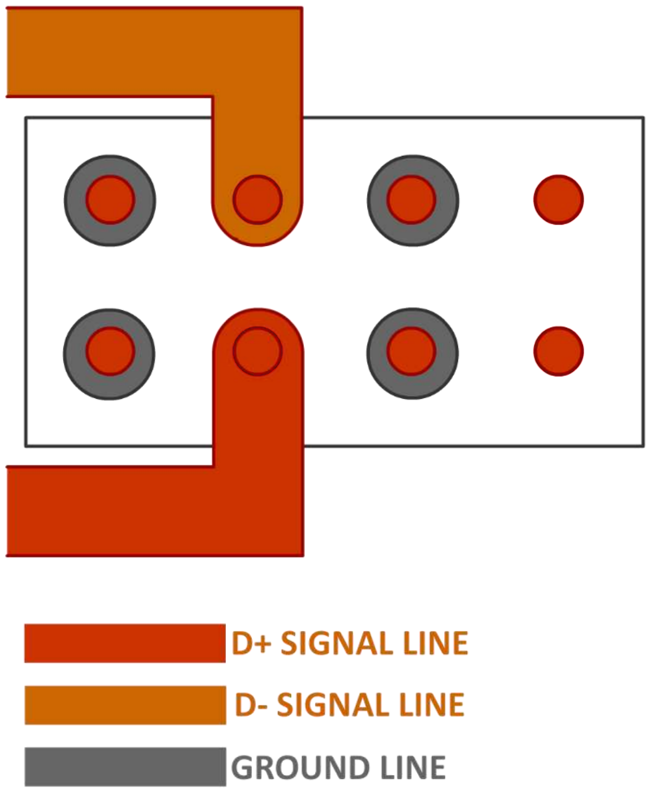


Board to board connection

Stacked boards

Transmitting a differential line





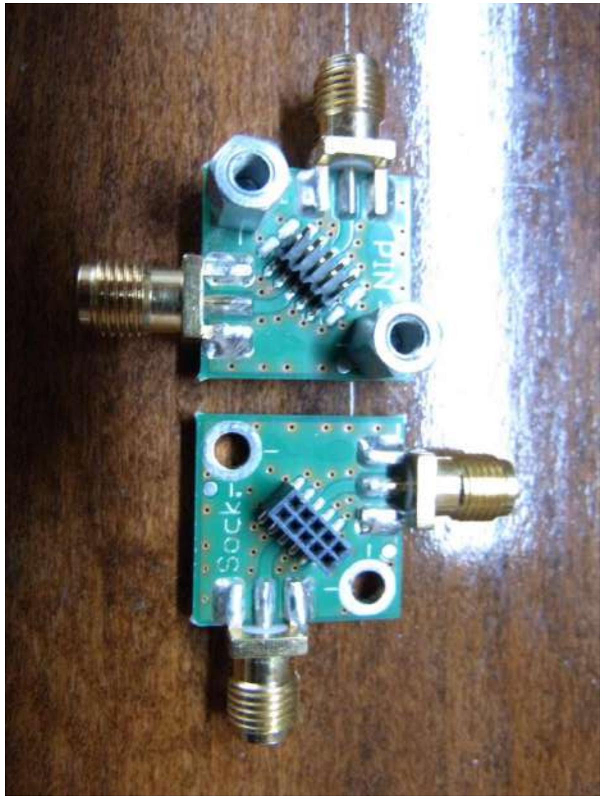
Board to board connection

RF behaviour of pin and socket header - Results

Insertion loss		
Circuit Board 1	Circuit Board 2	Circuit Board 3
@ 1GHz ca. 0,15dB	@ 1GHz ca. 0,15dB	@ 1GHz ca. 0,15dB
@ 2GHz ca. 0,26dB	@ 2GHz ca. 0,26dB	@ 2GHz ca. 0,26dB

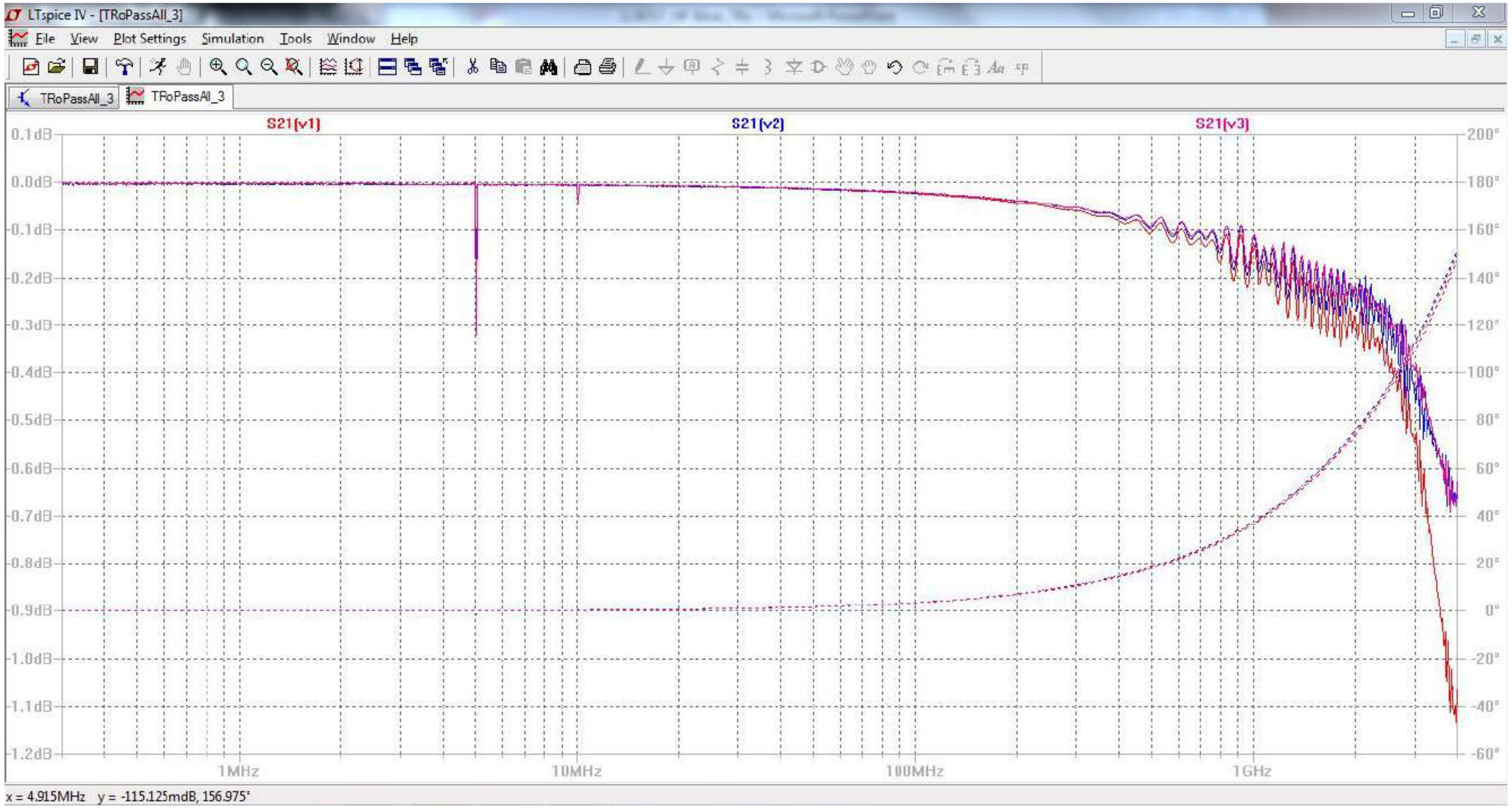
Matching		
Circuit Board 1	Circuit Board 2	Circuit Board 3
@ 1GHz ca. -25,27dB	@ 1GHz ca. -23,9dB	@ 1GHz ca. -21,35dB
@ 2GHz ca. -27,03dB	@ 2GHz ca. -23,7dB	@ 2GHz ca. -21,55dB

Cross talk		
Circuit Board 1	Circuit Board 2	Circuit Board 3
@ 1GHz ca. -27,22dB	@ 1GHz ca. -38,97dB	@ 1GHz ca. -61,48dB
@ 2GHz ca. -21,35dB	@ 2GHz ca. -33,29 dB	@ 2GHz ca. -57,37dB



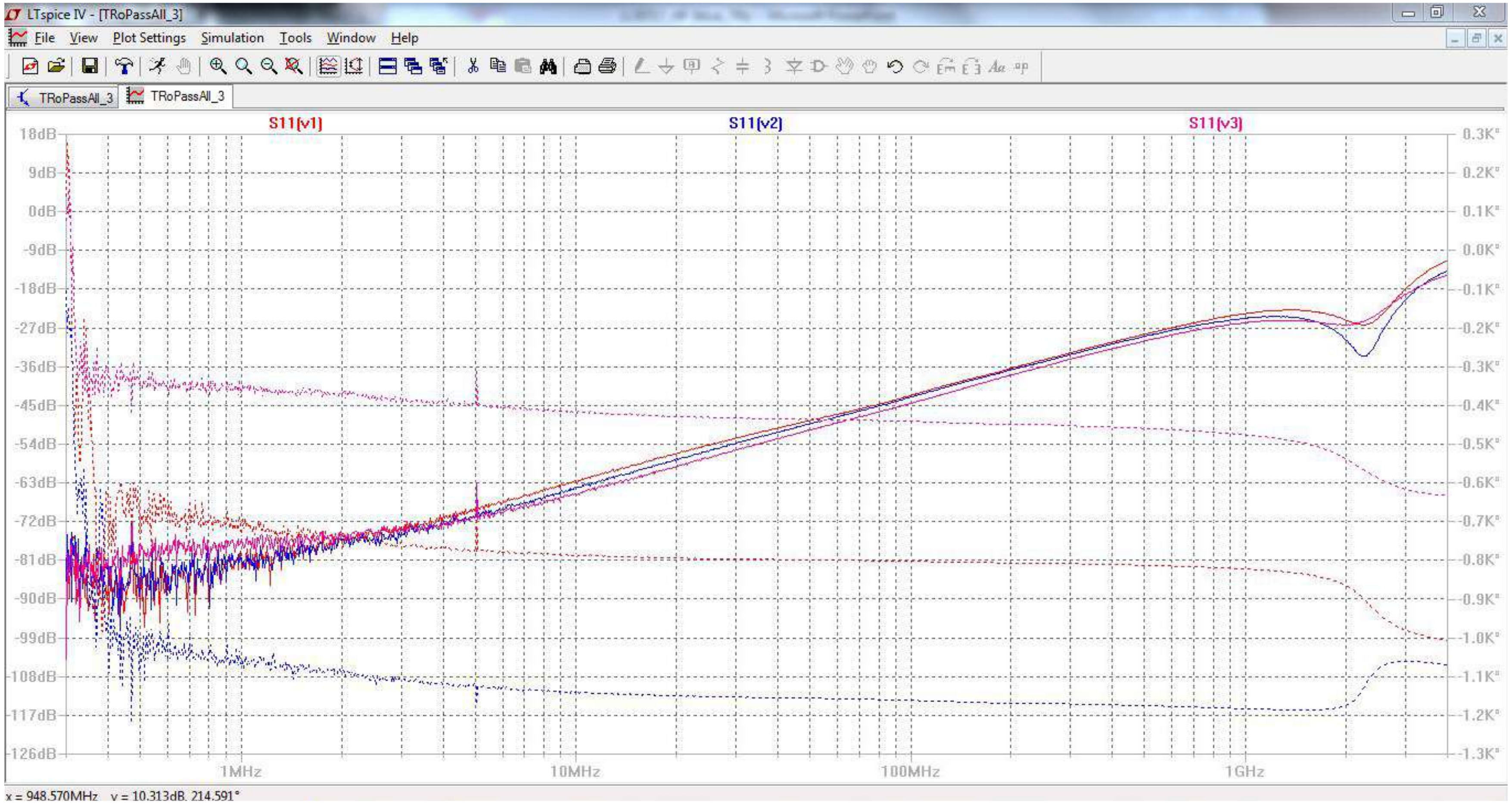
Board to board connection

Insertion loss



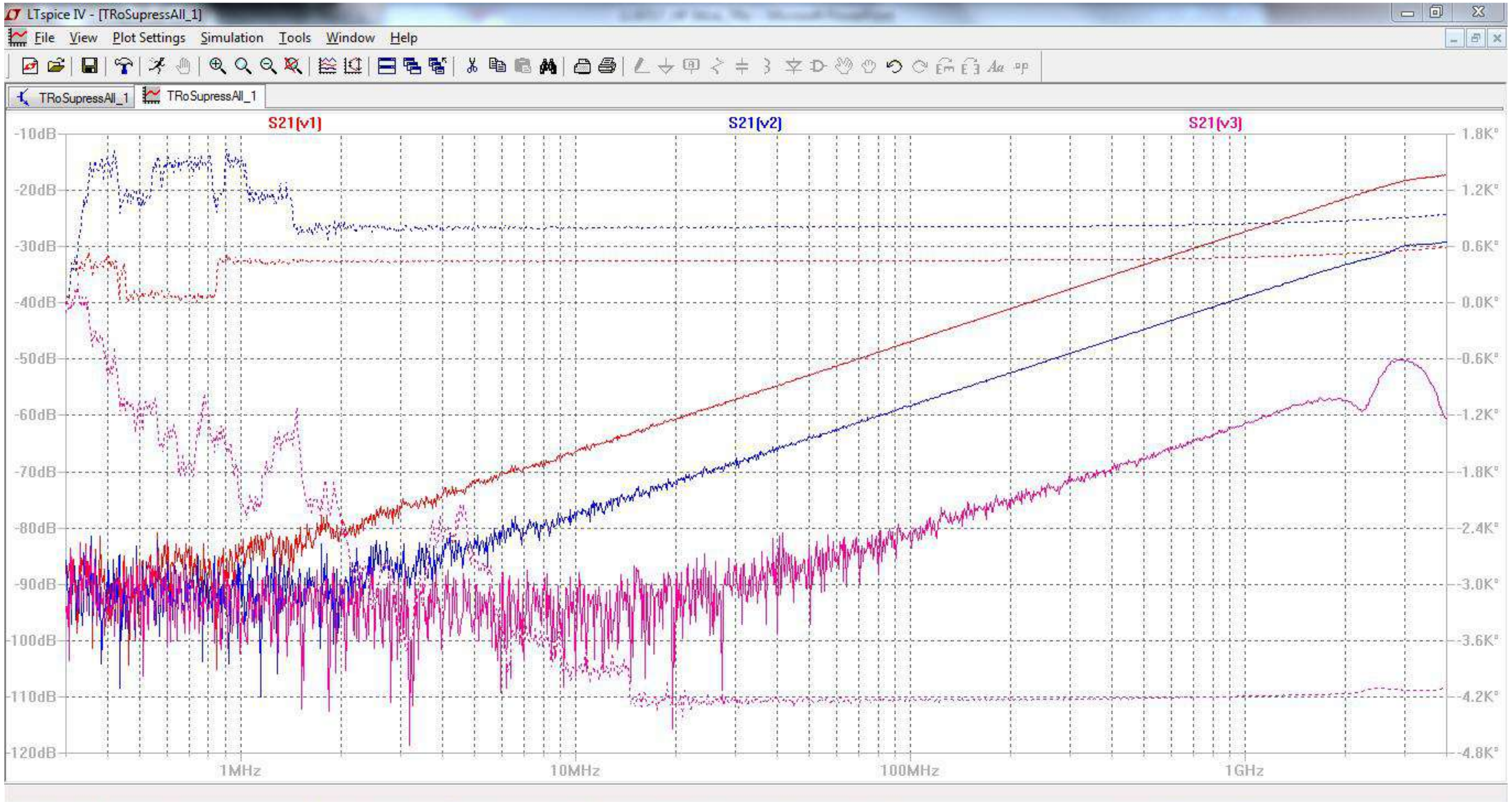
Board to board connection

Matching



Board to board connection

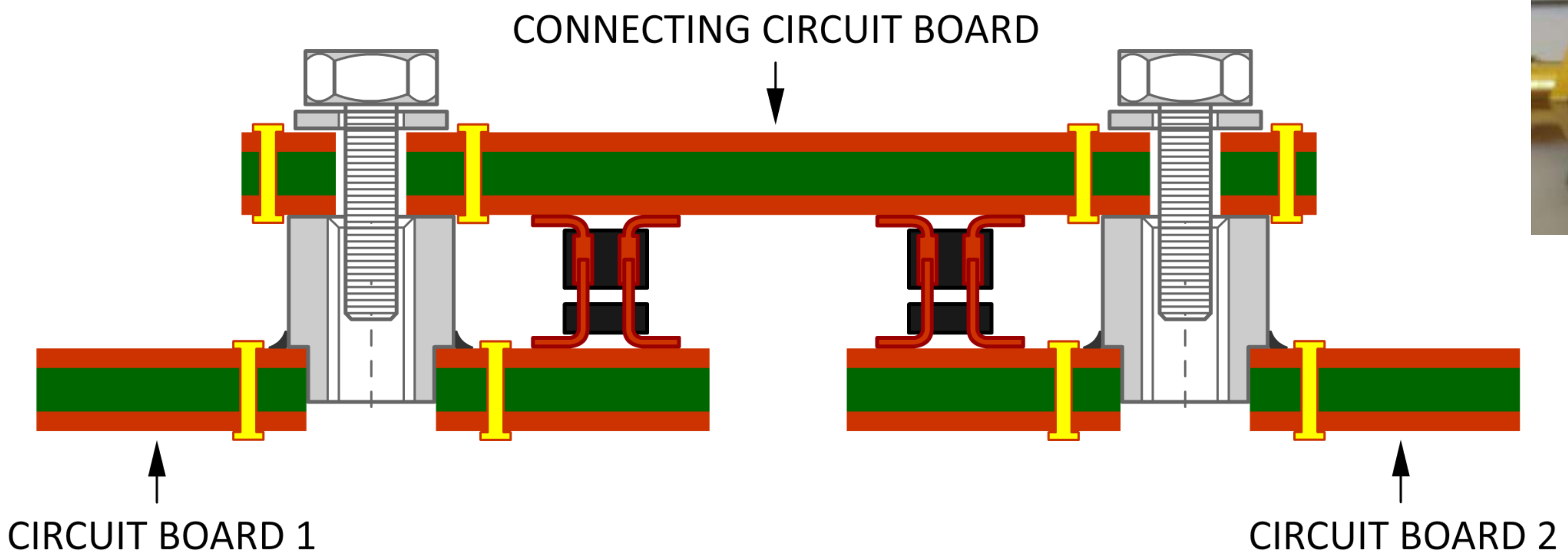
Cross talk

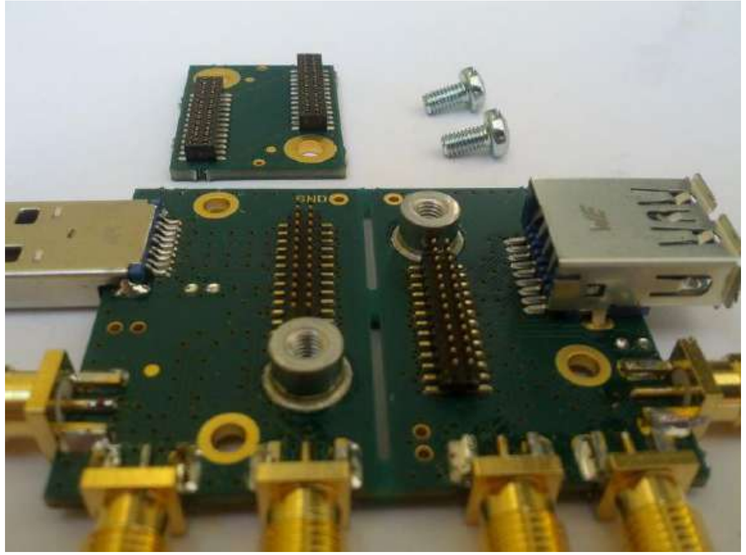


Board to board connection

Horizontal boards

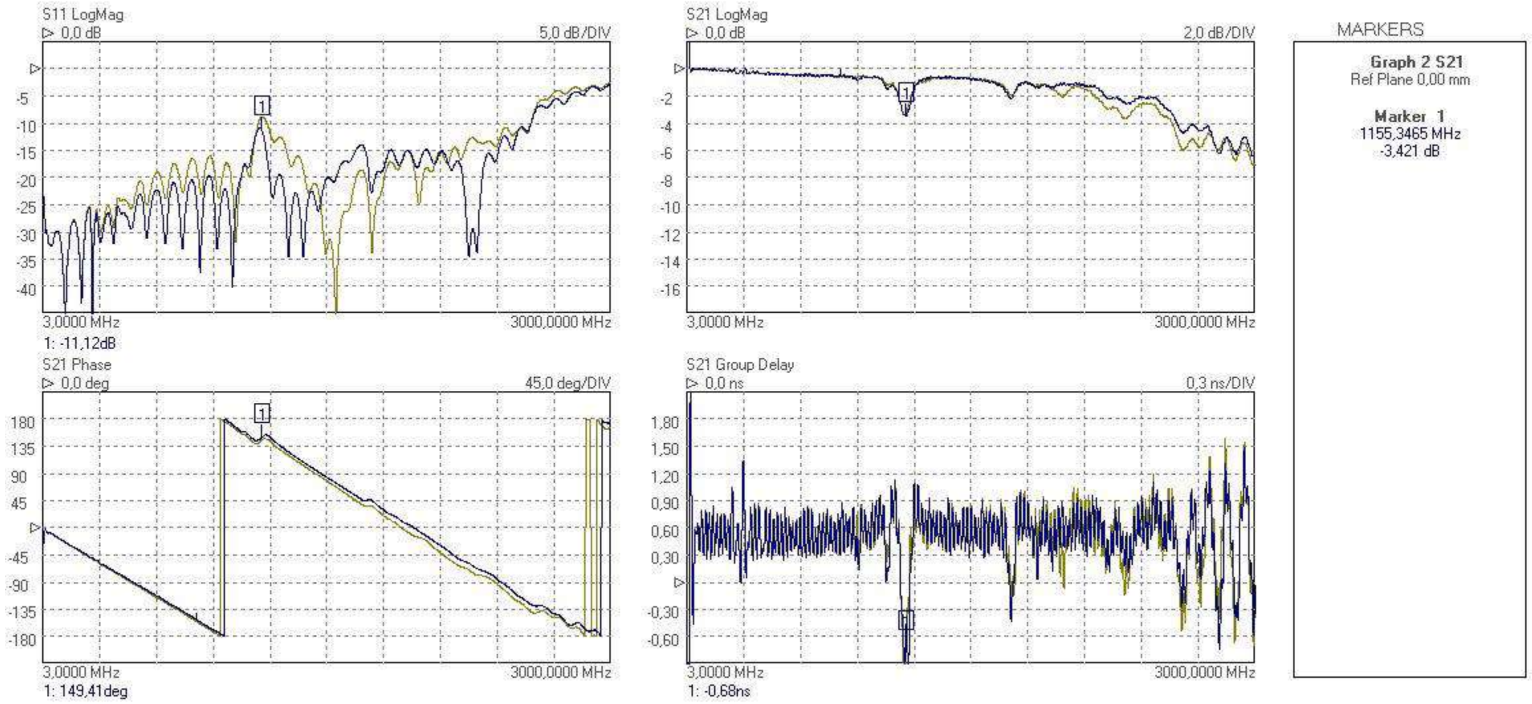
- Current - 3A
- DC resistance - ≈ 37 mΩ
- Signals - 3 GHz
- Data - 5 GBit/s USB 3.0





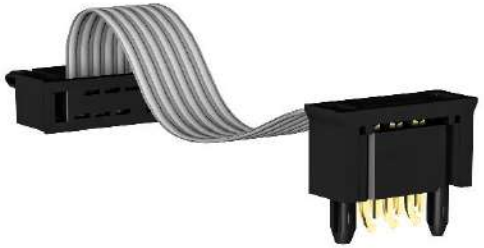
Board to board connection

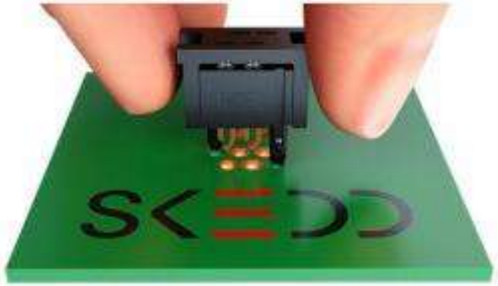
Horizontal boards



Wire to board connection

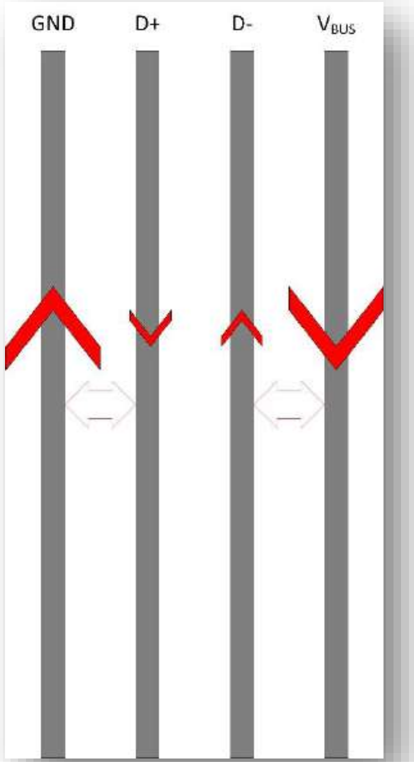
SKEDD and USB 2.0

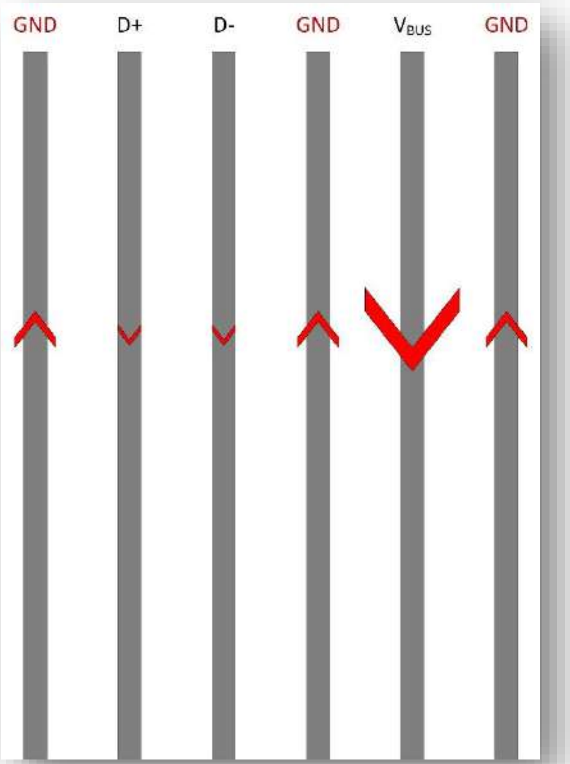




Wire to board connection

SKEDD and USB 2.0 – From differential to common mode





WE-CNSW SMT

Wire to board connection

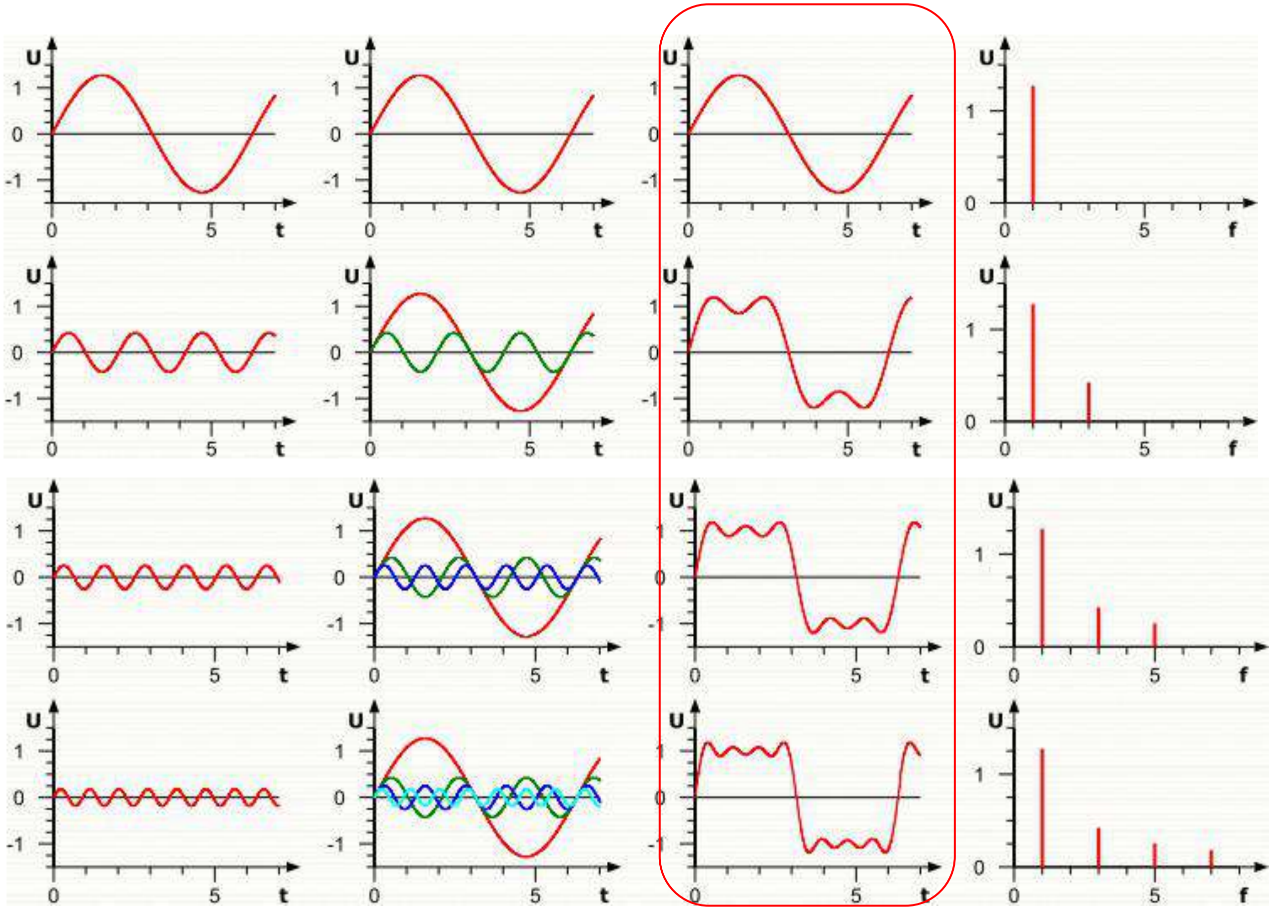
SKEDD and USB 2.0 – Data rate and cable length

1.

1+3.

1+3+5.

1+3+5+7.



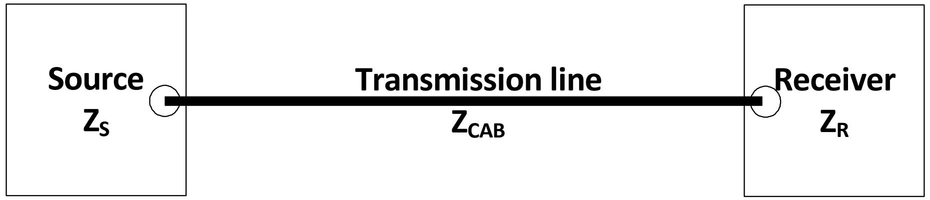
High-speed(480 Mbps) 240 MHz
Full-speed(15Mbps) 7,5 MHz

High-speed(480 Mbps) 720 MHz
Full-speed(15Mbps) 22,5 MHz

720MHz	λ_{720}	40 cm
22,5MHz	$\lambda_{22,5}$	13,3 m

Wire to board connection

Impedance measurement of an FFC



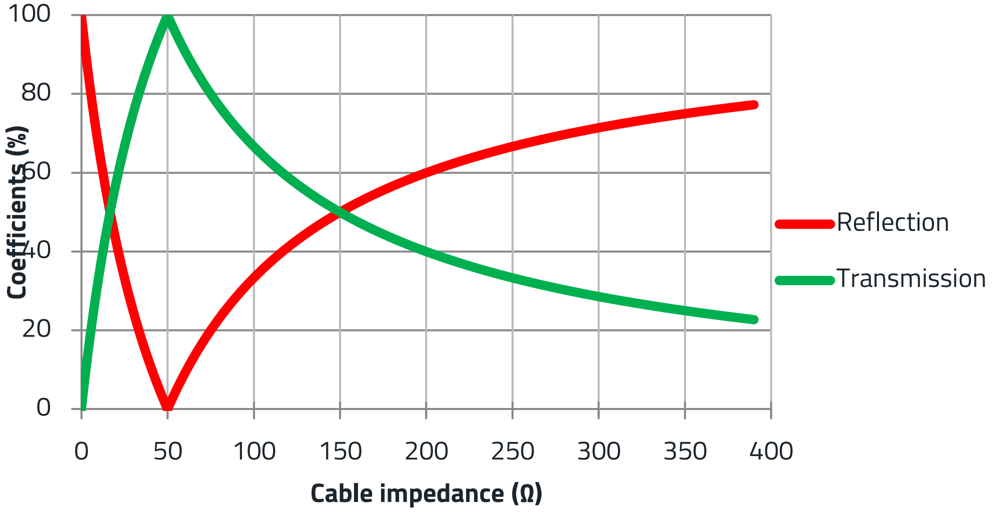
Z_{CAB}	40Ω	50Ω	60Ω	75Ω	100Ω	120Ω	150Ω	200Ω
ρ	11.1%	0%	9.1%	20%	33.3%	41.2%	50%	60%
τ	88.9%	100%	90.9%	80%	66.7%	58.8%	50%	40%

Reflection coefficient

$$\rho = \frac{Z_{CAB} - Z_s}{Z_{CAB} + Z_s}$$

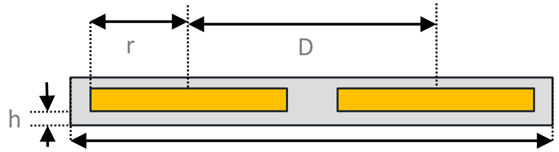
Transmission coefficient

$$\tau = 1 - \rho$$



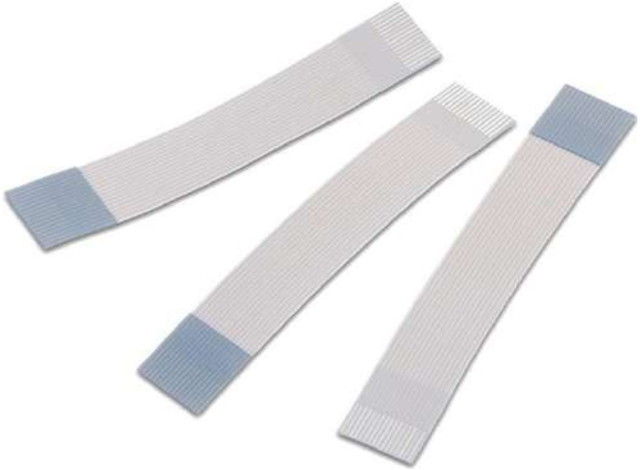
Wire to board connection

Impedance measurement of an FFC



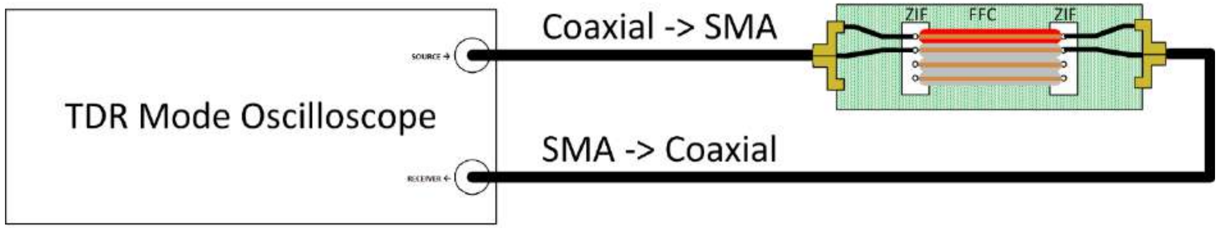
r	: Copper half width
D	: Distance between the 2 conductors (pitch)
h	: Dielectric height

$$Z_{CAB} = \frac{276}{\sqrt{\varepsilon_r}} \ln(f\{r; D; h\})$$

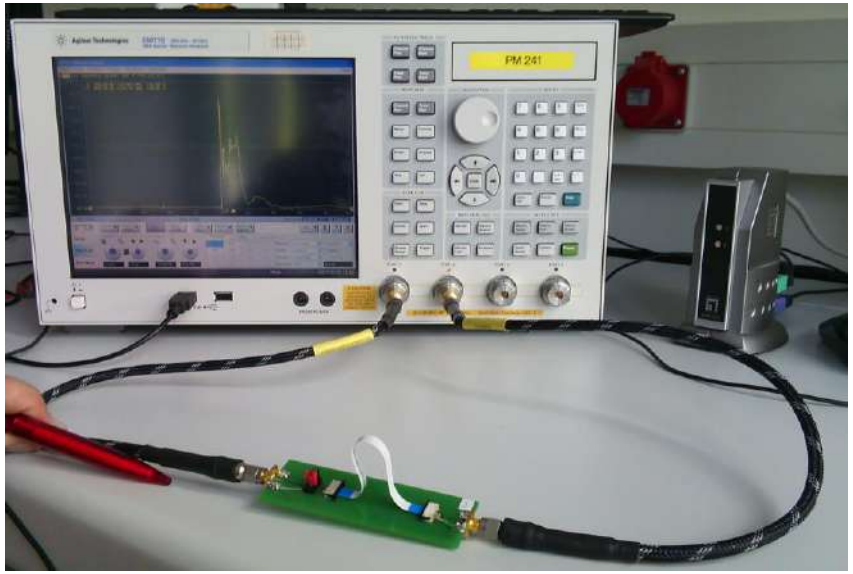


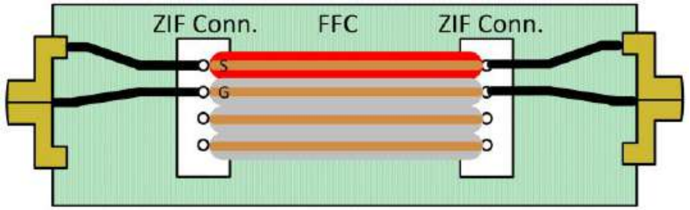
Wire to board connection

Impedance measurement of an FFC

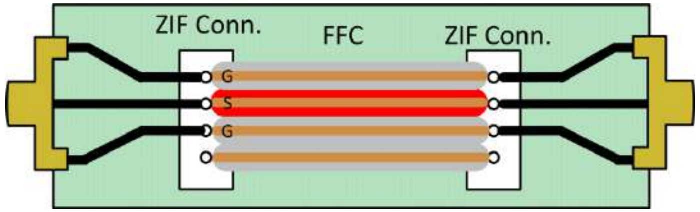


$$BW = \frac{0,22}{rise\ time_{10\%-90\%}}$$





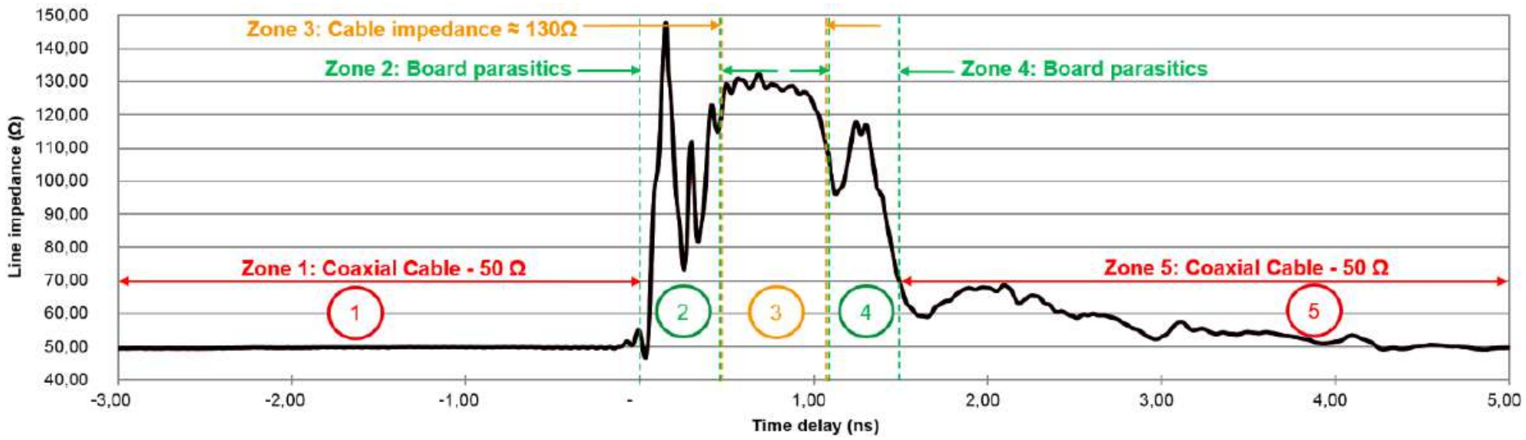
Unbalanced measurement (single)



Balanced measurement (differential)

Wire to board connection

Impedance measurement of an FFC



	0.5mm pitch	1mm pitch
Unbalanced	125 Ω	130 Ω
Balanced	85 Ω	85 Ω

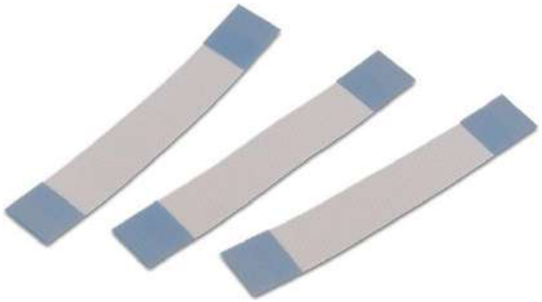
	0.5mm pitch		1mm pitch	
	Reflection	Losses	Reflection	Losses
Unbalanced	42.9 %	2.43 dB	44.4%	2.55 dB
Balanced	25.9 %	1.30 dB	25.9 %	1.30 dB

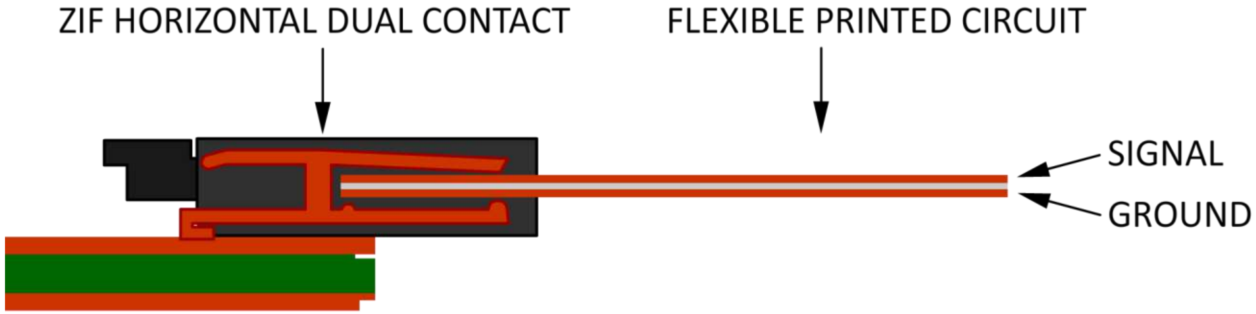
ZIF connector

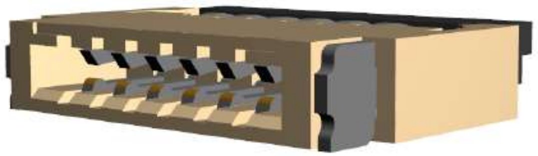
FFC cables

FFC cables

- 0,5mm pitch - 125 Ω
- 1,0mm pitch - 130Ω







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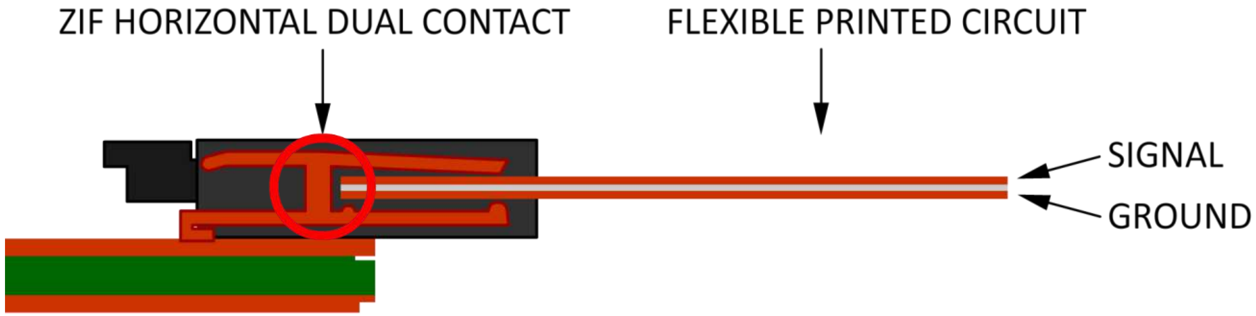
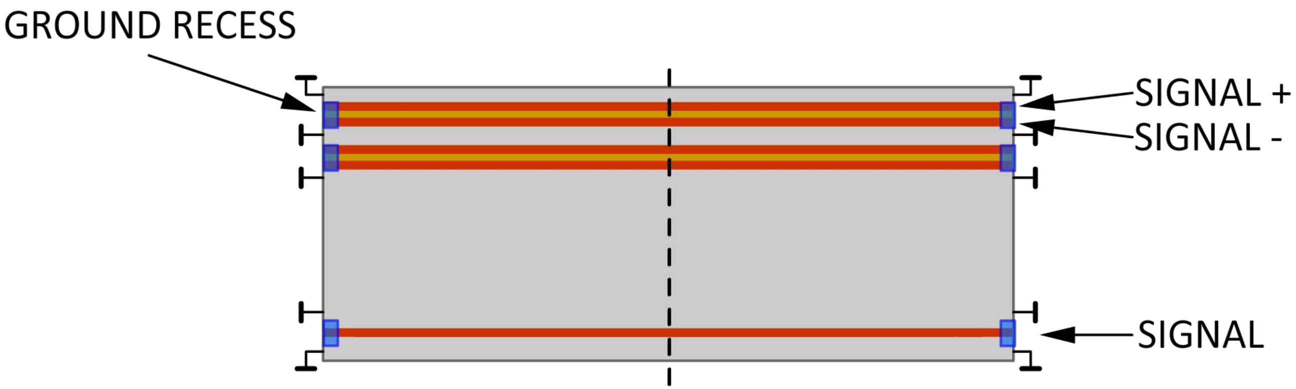
Wire to board connection

FPC cable or circuit board



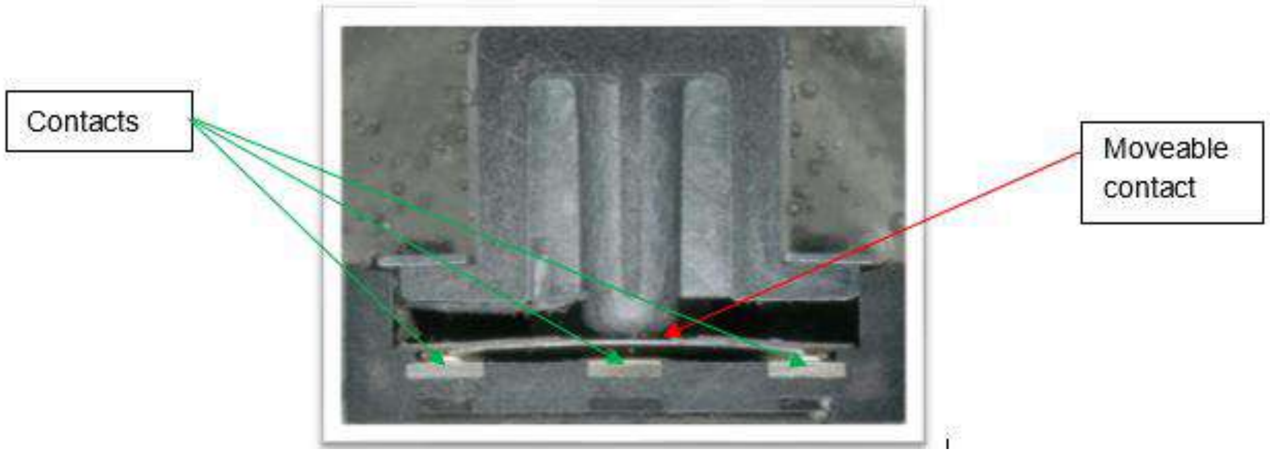
FLEXIBLE PRINTED CIRCUIT - TOP VIEW



Tact switch

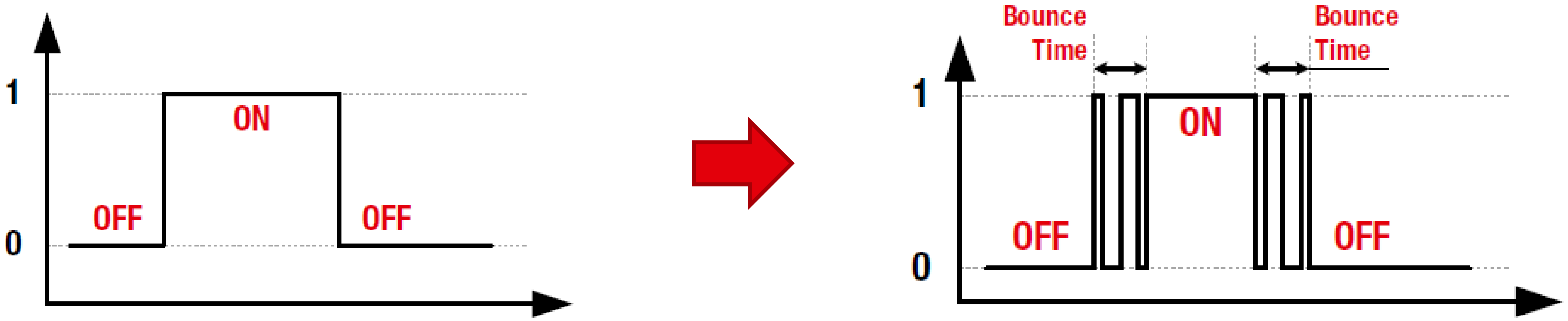
Bouncing

Spring components are used as transmitter of the nominal state, either as a metal plate or as a coiled spring, which have a certain mass and thus a certain moment of inertia.



Tact switch

Bouncing

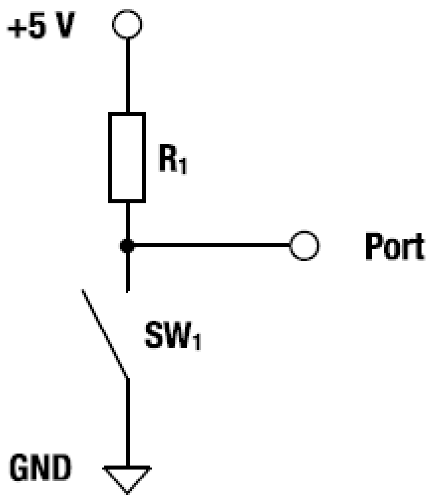


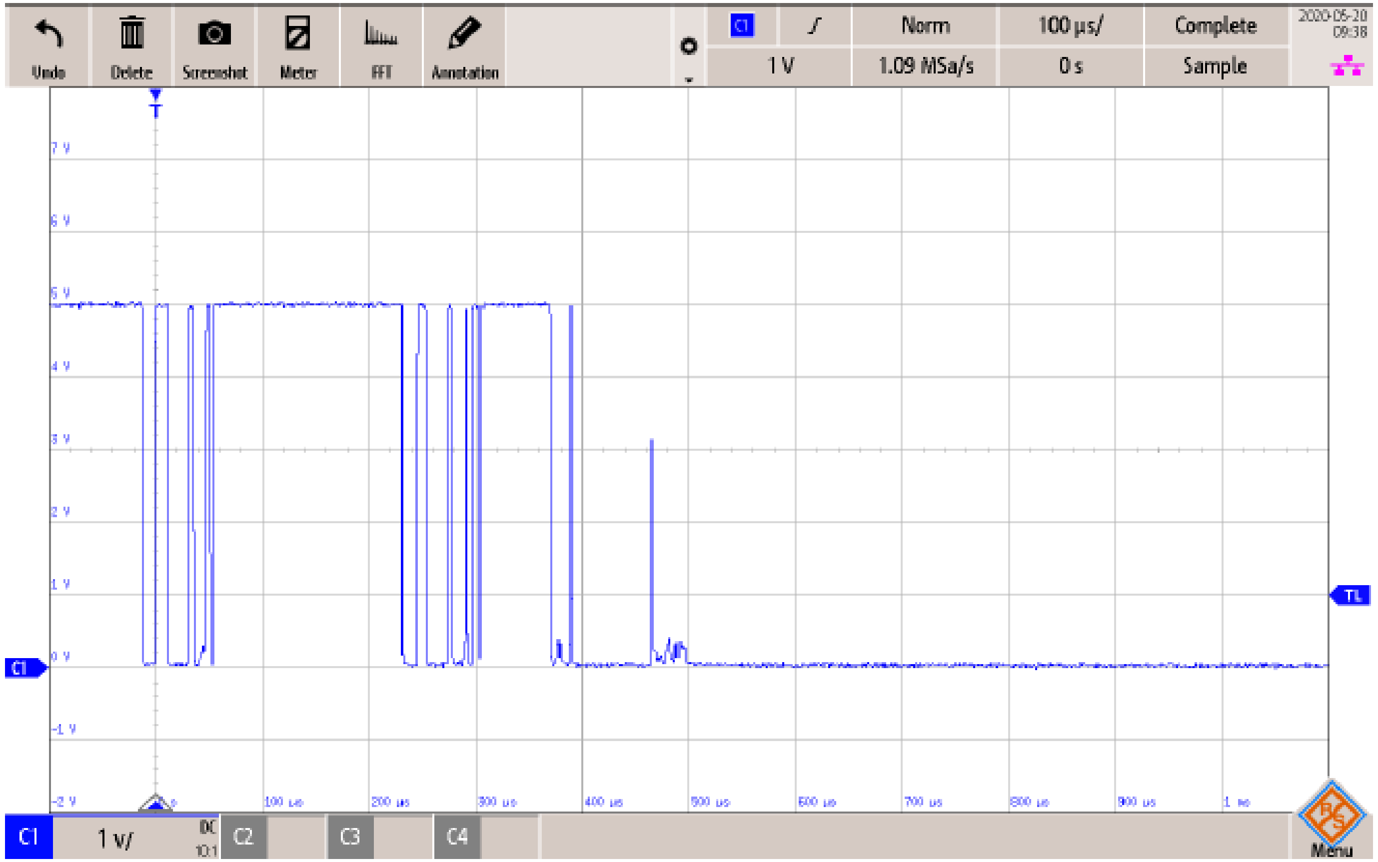
Tact switch

Bouncing

Classic values

- R1 = 1-10kΩ
- VCC = 5V





Tact switch

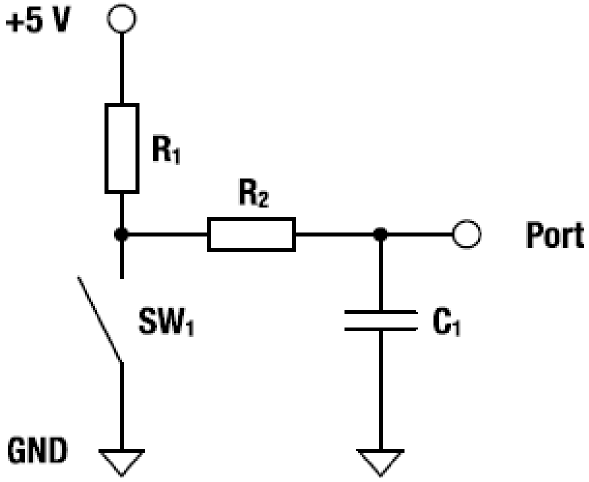
Bouncing

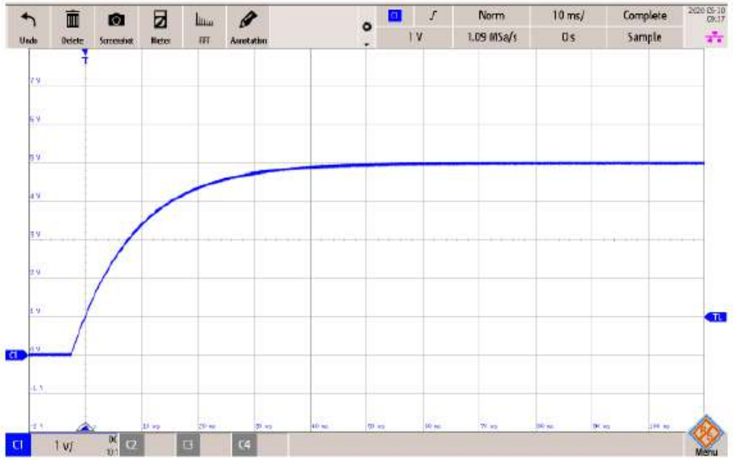
Classic values

- R1 = 1kΩ
- R2 = 10kΩ/47kΩ
- VCC = 5V
- C1 = 1µF/220nF

$$C_1 = \frac{\tau}{R_1 + R_2}$$

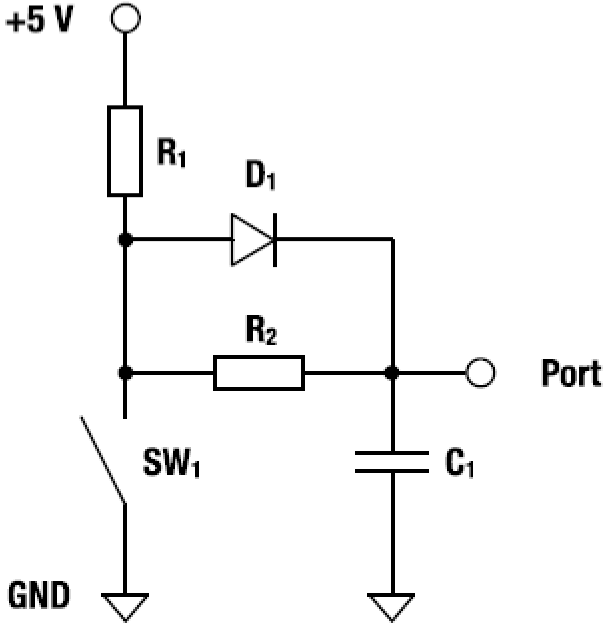
$$U_{out} = U_{in} \cdot \left(1 - e^{-\frac{t}{\tau}}\right)$$



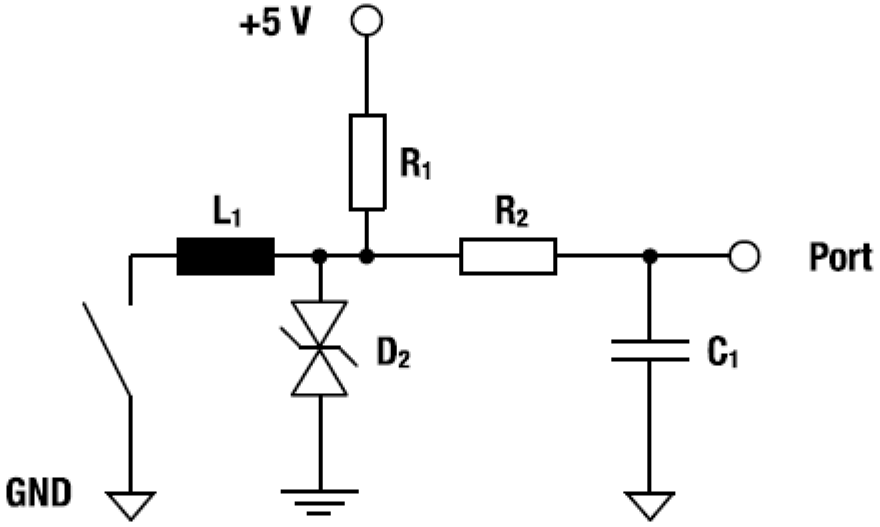


Tact switch

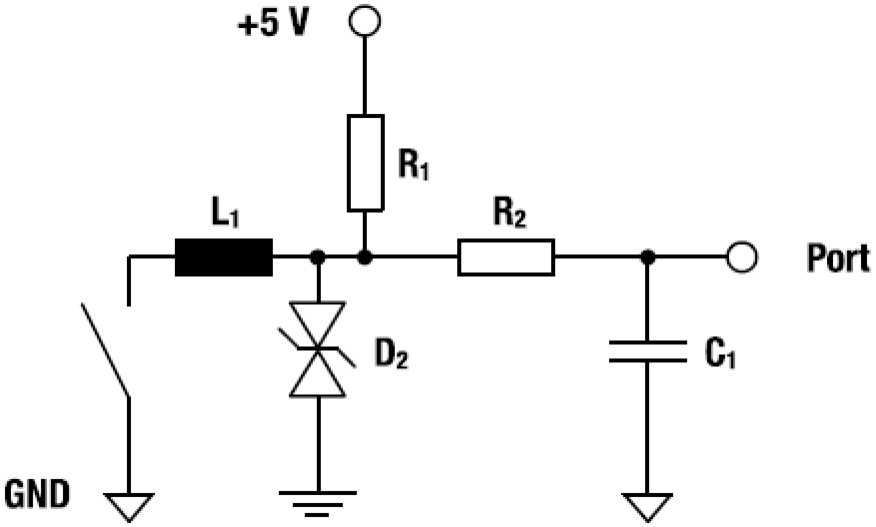
Additional



Diode



Schmitt trigger



Ferrite bead and TVS diode