40 GHz PCB Interconnect Validation: Expectations vs Reality

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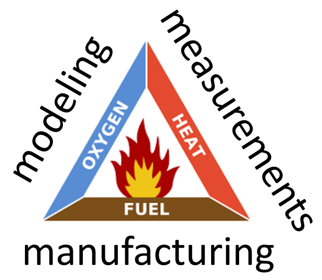
Outline

- Introduction
- “Sink or swim” validation process
- Test board design and preliminary results
- Measurements and GMS-parameters extraction
- Material parameters identification
- Validation: Expectations vs. Reality
- Reality above 30 GHz
- Conclusion - Lessons learned

Introduction

- What does it take to design PCB interconnects with good analysis to measurement correlation up to 40 GHz?
- Is it doable with typical low-cost PCB materials and fabrication process, typical trace width, via back-drilling and shortage of space to place the stitching vias?
  - Your EDA vendor shows excellent correlation of analysis to measurements up to 50 GHz
  - Your PCB fabricator ensures that the board will be built as designed
  - Measurements with the brand new easy-to-use TDNA or VNA should be a “piece of cake”
- There is nothing to worry about and the designed interconnects should behave as expected – right?
- We have decided to do a reality check with a real validation project…



Design success “fire triangle”

“Reference” projects

- PLRD-1 – first reported in Y. Shlepnev, A. Neves, T. Dagostino, S. McMorrow, Measurement-Assisted Electromagnetic Extraction of Interconnect Parameters on Low-Cost FR-4 boards for 6-20 Gb/sec Applications, DesignCon2009.
- CMP-08 – first reported in D. Dunham, J. Lee, S. McMorrow, Y. Shlepnev, 2.4mm Design/Optimization with 50 GHz Material Characterization, DesignCon2011.
- Rambus test boards - W. Beyene, Y.-C. Hahm, J. Ren, D. Secker, D. Mullen, Y. Shlepnev, Lessons learned: How to Make Predictable PCB Interconnects for Data Rates of 50 Gbps and Beyond, DesignCon2014.
- CPM-28 – available from Wild River Technology with Simbeor modeling kit, used in Y. Shlepnev, Sink or swim at 28 Gbps, The PCB Design Magazine, October 2014, p. 12-23.
- Many companies build validation boards and report some results…

"Sink or Swim" validation

1. Select materials and define PCB stackup with the manufacturer
2. Design test structures with the EM analysis (simple links, launches, vias,…)
3. Manufacture the board, mount connectors
4. Measure S-parameters and validate quality of the measurements
5. Cross-section the board and identify the manufacturing adjustments (if any)
6. Identify broad-band dielectric and conductor roughness models with GMS-parameters or SPP Light techniques
7. Simulate all structures with the identified or validated material models and confirmed adjustments consistently and compare S-parameters and TDR with the measurements (no further manipulations with the data)

… and get it done in 1-3 months!

Example: Y. Shlepnev, Sink or Swim at 28 Gbps - The PCB Design Magazine, October 2014, p. 12-23.

Project timeline (low budget and priority)

- Expectations: about 3 months from design to complete validation (Nov. 2016 – Jan. 2017)
- Reality: 12 months (Nov. 2016 – Nov. 2017)
  - Delay is caused mostly by availability of the measurement equipment and matching cables/connectors

Validation Board Design

20-layer test board design

1. We specify the impedance that the PCB manufacturer has to fulfill with the tolerances specified (usual choice)
2. Vias with 0.20mm (7.9 mil) padstack are to be drilled with 0.250mm diameter drill (9.85 mil)
3. Non-functional pads on signal vias on any layer are not allowed
4. Via backdrilling is to be done on some instances

General Information	Value
PCB revision	PCB230-0220_R1
Dimension	261,35 x 237.36 mm +0,00/-0,20
Unit	mm
Number of layers	20
Thickness	2 mm
Quality requirements	IPC-6012 Class 2
Controlled impedance	Yes, 8% tolerance
UL-Requirement	94v0
High Voltage	No
Material	Panasonic Megtron6 R-5775(K) (2x1035) “core” with ½ oz H-VLP copper (spread weave) Panasonic Megtron6 R-5670(K) Pre-preg 1035 (75% RC) spread weave) Panasonic Megtron6 R-5670(K) Pre-preg 1035 (70% RC) (spread weave) Panasonic Megtron6 R-5670(K) Pre-preg 1027 (75% RC) (spread weave) Vend. “core”, 50 um thick with ½ oz copper
PCB-Finish	Immersion silver
General Info	
Solder Mask Color	Green

No roughness model

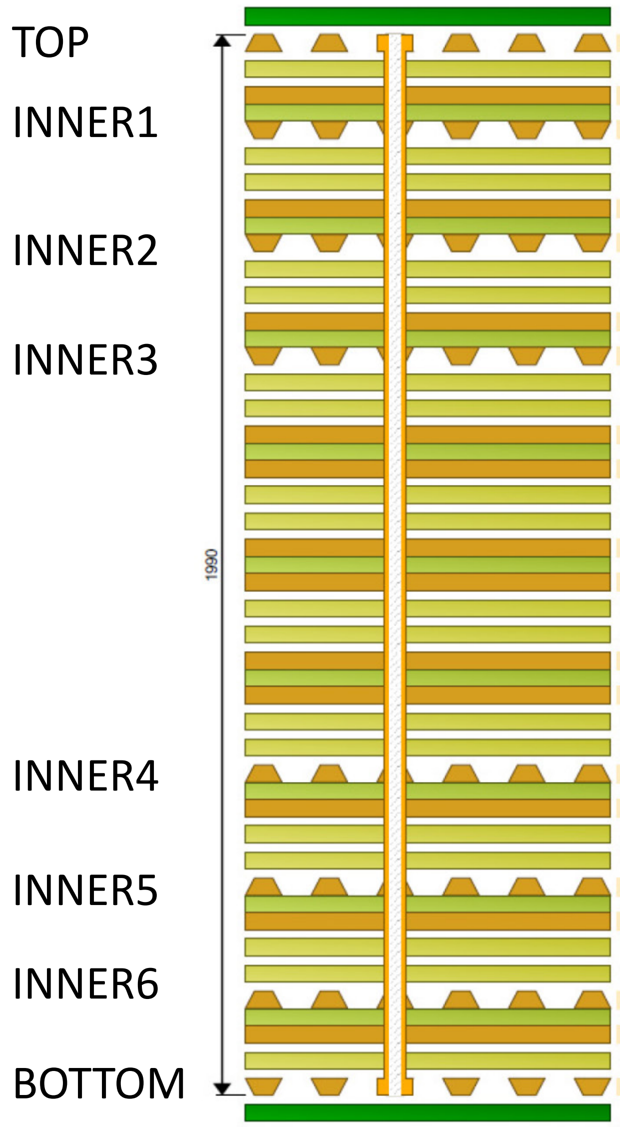
Layer	Z (ohm)	Tolerance (%)	Our conductor dimensions (mm)	Vend. conductor dimensions (mm)
L1, L20 (MS)	40	≤ 8	0.200	
L1, L20 (MS)	50	≤ 8	0.135	0.127
L1, L20 (MS)	80 Diff.	≤ 8	0.170 (edge-to-edge gap: 0.250)	
L1, L20 (MS)	100 Diff.	≤ 8	0.120 (edge-to-edge gap: 0.250)	0.112 (edge-to-edge gap: 0.258)
L3, L18 (SL)	40	≤ 8	0.160	
L3, L18 (SL)	50	≤ 8	0.110	0.109
L3, L18 (SL)	79 Diff.	≤ 8	0.160 (edge-to-edge gap: 0.250)	
L3, L18 (SL)	99 Diff.	≤ 8	0.110 (edge-to-edge gap: 0.250)	0.107 (edge-to-edge gap: 0.250)
L5, L7, L14, L16 (SL)	40	≤ 8	0.150	
L5, L7, L14, L16 (SL)	50	≤ 8	0.100	0.099
L5, L7, L14, L16 (SL)	79 Diff.	≤ 8	0.150 (edge-to-edge gap: 0.250)	
L5, L7, L14, L16 (SL)	99 Diff.	≤ 8	0.100 (edge-to-edge gap: 0.250)	0.099 (edge-to-edge gap: 0.245)

Broadband models can be defined from specs

Large tolerance!

Can we rely on that?
No info on shape

Stackup design and initial models



Stack up	Description	Base Thickness	Processed Thickness	εr	Impedance ID	Copper Coverage	Comments
	Liquid PhotoImageable Mask			4.00			
	Copper Foil	18.00	35.00		1, 2	60.00	
	Panasonic Meg-6 PrePreg 1035 (75% RC)	74.00	73.25	3.19			Spread glass weave
		18.00	15.00			80.00	
	Panasonic Meg-6 (2*1035)	100.00	100.00	3.37			Core with H-VLP copper
		18.00	15.00		3, 4	20.00	
	Panasonic Meg-6 PrePreg 1035 (70% RC)	60.00	54.00	3.23			Spread glass weave
	Panasonic Meg-6 PrePreg 1035 (70% RC)	60.00	54.00	3.23			Spread glass weave
		18.00	15.00			80.00	
	Panasonic Meg-6 (2*1035)	100.00	100.00	3.37			Core with H-VLP copper
		18.00	15.00		5, 6	20.00	
	Panasonic Meg-6 PrePreg 1027 (75% RC)	49.00	43.00	3.19			Spread glass weave
	Panasonic Meg-6 PrePreg 1027 (75% RC)	49.00	43.00	3.19			Spread glass weave
		18.00	15.00			80.00	
	Panasonic Meg-6 (2*1035)	100.00	100.00	3.37			Core with H-VLP copper
		18.00	15.00		7, 8	20.00	
	Panasonic Meg-6 PrePreg 1027 (75% RC)	49.00	43.00	3.19			Spread glass weave
	Panasonic Meg-6 PrePreg 1027 (75% RC)	49.00	43.00	3.19			Spread glass weave
		18.00	15.00			80.00	
	ShengYi S1000-2 (1*106)	50.00	50.00	3.72			
		18.00	15.00			80.00	
	Panasonic Meg-6 PrePreg 1027 (75% RC)	49.00	48.25	3.19			Spread glass weave
	Panasonic Meg-6 PrePreg 1027 (75% RC)	49.00	48.25	3.19			Spread glass weave
		18.00	15.00			80.00	
	ShengYi S1000-2 (1*106)	50.00	50.00	3.72			
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		18.00	15.00			20.00	
	Panasonic Meg-6 (2*1035)	100.00	100.00	3.37			Core with H-VLP copper
		18.00	15.00			80.00	
	Panasonic Meg-6 PrePreg 1027 (75% RC)	49.00	43.00	3.19			Spread glass weave
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		18.00	15.00			20.00	
	Panasonic Meg-6 (2*1035)	100.00	100.00	3.37			Core with H-VLP copper
		18.00	15.00			80.00	
	Panasonic Meg-6 PrePreg 1035 (70% RC)	60.00	54.00	3.23			Spread glass weave
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		18.00	15.00			20.00	
	Panasonic Meg-6 (2*1035)	100.00	100.00	3.37			Core with H-VLP copper
		18.00	15.00			80.00	
	Panasonic Meg-6 PrePreg 1035 (75% RC)	74.00	73.25	3.19			Spread glass weave
	Copper Foil	18.00	35.00			60.00	
	Liquid PhotoImageable Mask			4.00			

Prepreg and core have different Dk – why?

- Materials: T=20[°C],...
  - "COPPER", RR=1
  - "035.56UM_CU", RR=1
  - "017.78UM_CU", RR=1
  - "FR-4", Dk=3.72, LT=0.02, PLM=WD, Dk(0)=4.48, Dk(inf)=3.39
  - "Air"
  - "Solder Mask", Dk=4, LT=0.02, PLM=WD, Dk(0)=4.82, Dk(inf)=3.65
  - "Meg-6 TopBot", Dk=3.19, LT=0.002, PLM=WD, Dk(0)=3.26, Dk(inf)=3.16
  - "Meg-6 Inner1 (P)", Dk=3.23, LT=0.002, PLM=WD, Dk(0)=3.3, Dk(inf)=3.2
  - "Meg-6 2x1035 (C)", Dk=3.37, LT=0.002, PLM=WD, Dk(0)=3.44, Dk(inf)=3.34
  - "Meg-6 Inner2 (P)", Dk=3.19, LT=0.002, PLM=WD, Dk(0)=3.26, Dk(inf)=3.16
  - "Meg-6 Inner3 (P)", Dk=3.19, LT=0.002, PLM=WD, Dk(0)=3.26, Dk(inf)=3.16
  - "Meg-6 Av", Dk=3.19, LT=0.002, PLM=WD, Dk(0)=3.26, Dk(inf)=3.16
- StackUp: LU=[um], NL=20, T=2030.12[um], CSM=("Solder Mask", 40[um])
  - 1| Signal: "TOP", T=35.56, Ins="Air", Cond="035.56UM_CU"
  - 2| Medium: T=73.25, Ins="Meg-6 TopBot", DIE_003
  - 3| Plane: "GND1", Cond="017.78UM_CU", T=15, Ins="Meg-6 TopBot"
  - 4| Medium: T=100, Ins="Meg-6 2x1035 (C)", DIE_005
  - 5| Signal: "INNER1", T=15, Ins="Meg-6 Inner1 (P)", Cond="017.78UM_CU"
  - 6| Medium: T=108, Ins="Meg-6 Inner1 (P)", DIE_007
  - 7| Plane: "GND2", Cond="017.78UM_CU", T=15, Ins="Meg-6 Av"
  - 8| Medium: T=100, Ins="Meg-6 2x1035 (C)", DIE_009
  - 9| Signal: "INNER2", T=15, Ins="Meg-6 Inner2 (P)", Cond="017.78UM_CU"
  - 10| Medium: T=86, Ins="Meg-6 Inner2 (P)", DIE_011
  - 11| Plane: "GND3", Cond="017.78UM_CU", T=15, Ins="Meg-6 Inner2 (P)"
  - 12| Medium: T=100, Ins="Meg-6 2x1035 (C)", DIE_013
  - 13| Signal: "INNER3", T=15, Ins="Meg-6 Inner3 (P)", Cond="017.78UM_CU"
  - 14| Medium: T=86, Ins="Meg-6 Inner3 (P)", DIE_015
  - 15| Plane: "GND4", Cond="017.78UM_CU", T=15, Ins="Meg-6 Av"
  - 16| Medium: T=50, Ins="FR-4", DIE_017
  - 17| Plane: "VCC1", Cond="017.78UM_CU", T=15, Ins="Meg-6 Av"
  - 18| Medium: T=96.5, Ins="Meg-6 Av", DIE_019
  - 19| Plane: "GND5", Cond="017.78UM_CU", T=15, Ins="Meg-6 Av"
  - 20| Medium: T=50, Ins="FR-4", DIE_021

No resistivity and roughness for conductors

Wideband Debye with Dk and LT @ 1 GHz

Half

This is the best we can do – we will see how accurate it is…

Validation structures

- Structures for the material model identification/validation
  - For identification with GMS-parameters or SPP Light: Two segments of differential or single-ended t-lines for each unique layer
  - Beatty standard (series resonator) for model confirmation
- Structures similar to signal links
  - Simple straight links – same as for the material identification
  - Diff. and single-ended (SE) via-holes for each routing layer
  - AC coupling capacitors similar to used on SERDES links
  - Meandering line segment similar to used on DDR links
  - Diff. link skew compensation structures

Validation board design

5 cm and 10 cm diff. microstrips (BOTTOM)

5 cm and 10 cm diff. strips (INNER1)

5 cm and 10 cm diff. strips (INNER2)

5 cm and 10 cm diff. strips (INNER3)

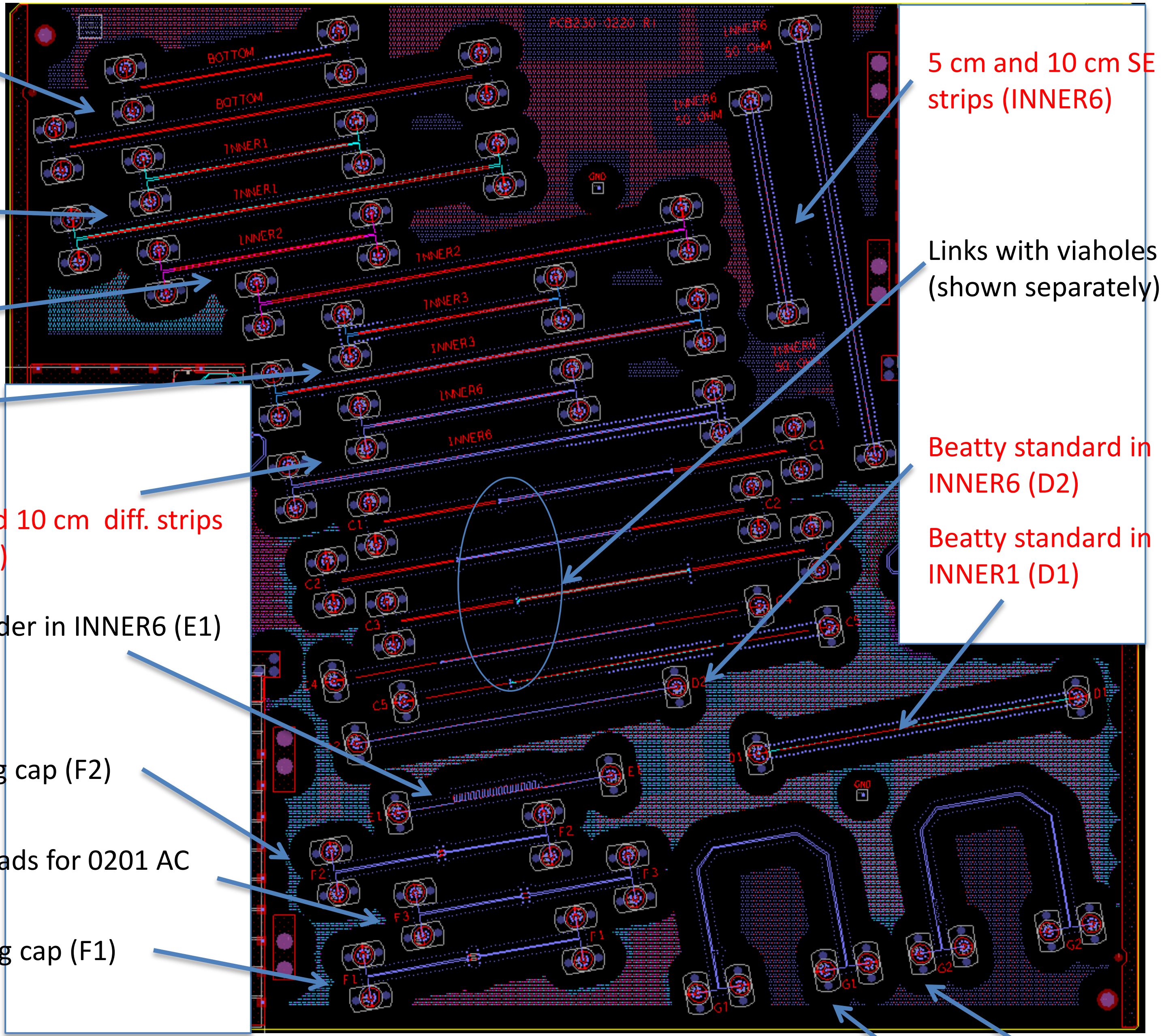
5 cm and 10 cm diff. strips (INNER6)

SE meander in INNER6 (E1)

0201 AC coupling cap (F2)

Short-circuited pads for 0201 AC coupling cap (F3)

0402 AC coupling cap (F1)



5 cm and 10 cm SE strips (INNER6)

Links with viaholes (shown separately)

Beatty standard in INNER6 (D2)

Beatty standard in INNER1 (D1)

Diff. trace length compensation structures (G1 and G2)

Material identification structures - red

Designed trace dimensions:

BOTTOM: 120-250-120 [um]

INNER1/6: 110-250-110 [um]

INNER2/3: 100-250-100 [um]

INNER6 SE: 110 [um]

BEATTY INNER1 and INNER6: 110 um 2.5 cm, 330 um 2.5 cm

Dimensions from manufacturer:

BOTTOM: 112-258-112 [um]

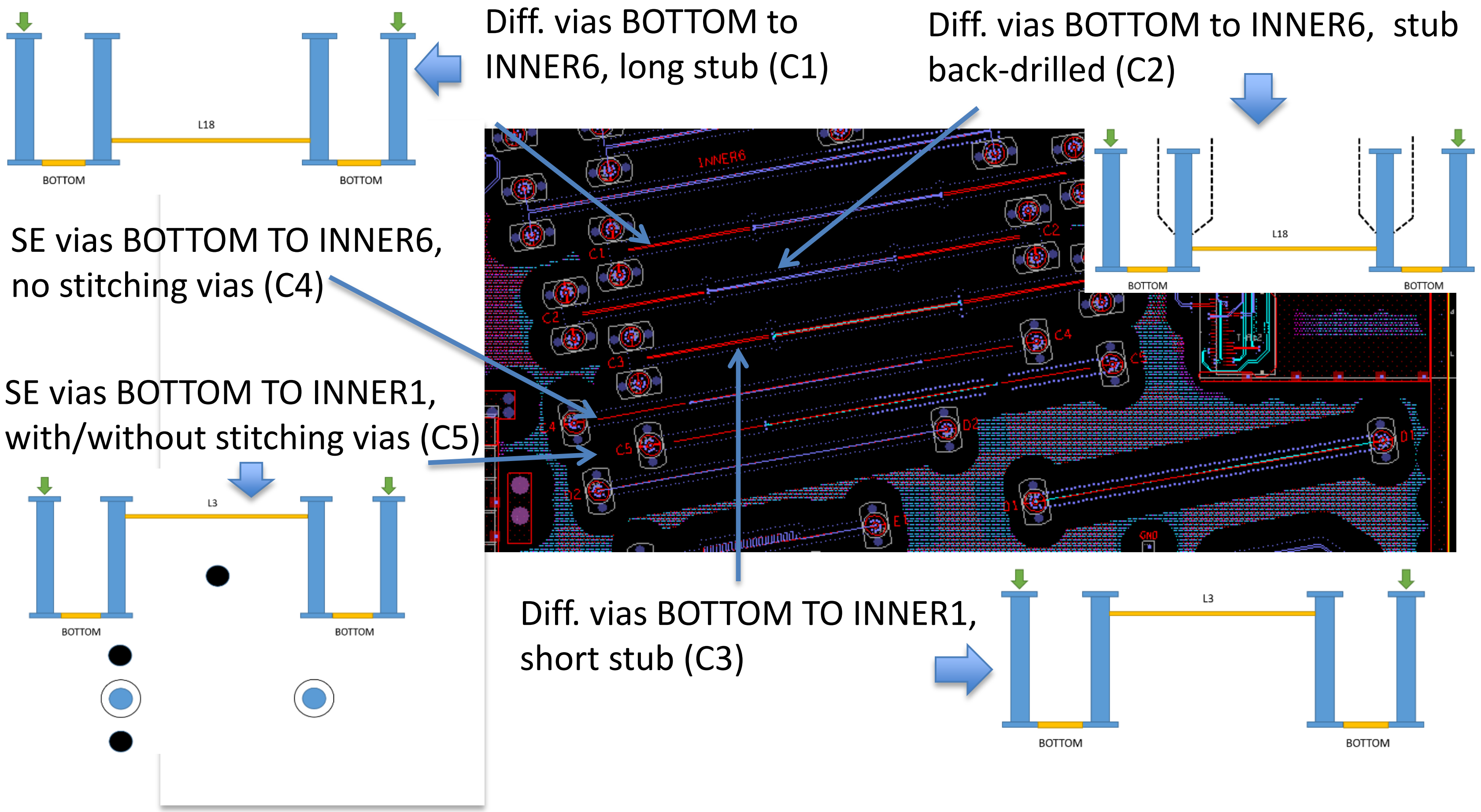
INNER1/6: 107-250-107 [um]

INNER2/3: 99-245-99 [um]

INNER6 SE: 109 [um]

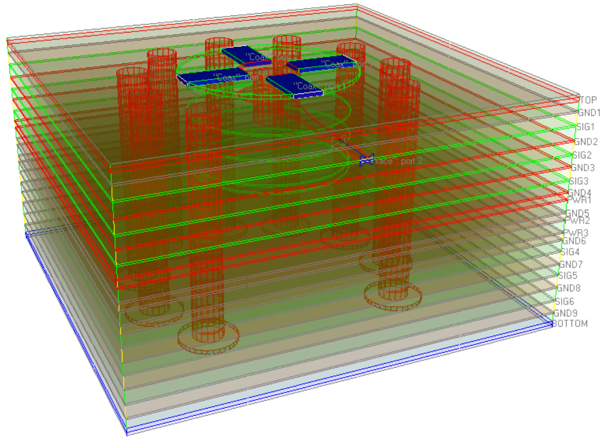
BOTTOM SE: 127 [um]

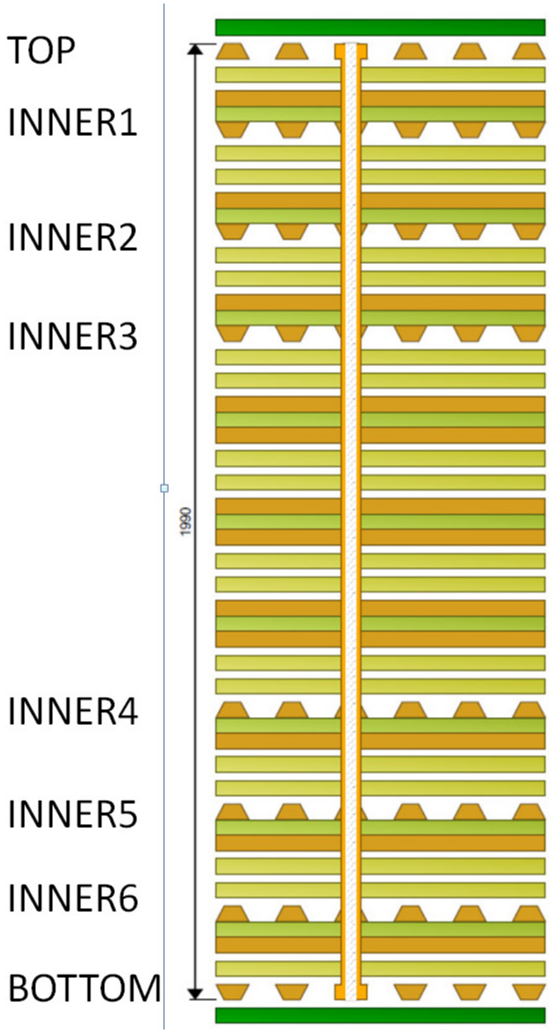
Viahole structures



Launch – the most important element

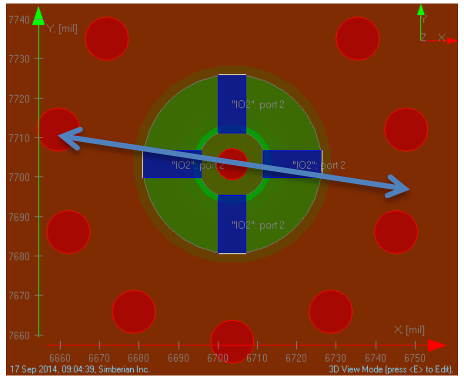
- To mount either 2.92 or 2.4 mm press-fit connector on TOP layer
- For testing microstrips we need launch TOP-BOTTOM
- For testing INNER1, TOP – INNER1 (with backdrilling)
- For testing INNER2, TOP – INNER2 (with backdrilling)
- For testing INNER3, TOP – INNER3 (with backdrilling)
- For testing INNER6, TOP – INNER6 (no backdrilling)
- We can rely only on the stackup/materials obtained from the manufacturer

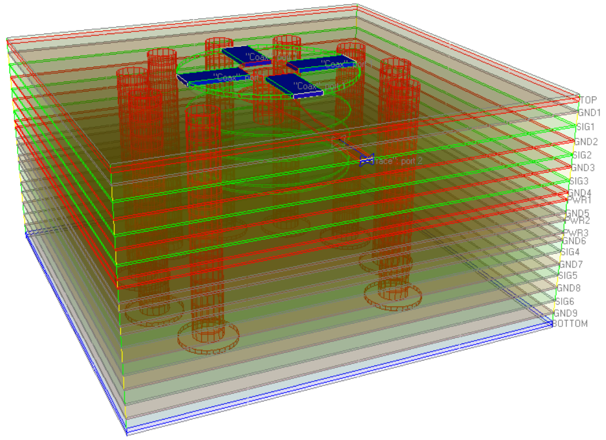




Launch design - localization

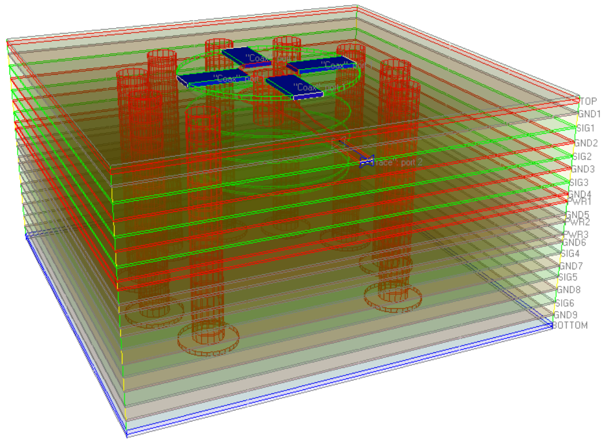
- 9 stitching vias located on a circle of diameter 2.3mm
- Stitching vias connect all GND planes together and the TOP layer
- GND vias have drill hole diameter 0.250mm and pad size 0.5mm
- Distance from signal via to stitching vias is about quarter of wavelength at 30 GHz
  - Launch should loose the localization at about 30 GHz by design
- We cannot expect good correlation above that frequency
- Though the impedance of the return path remains low due to plenty of stitching vias (expectation)
- Optimized without the connector – the launch only

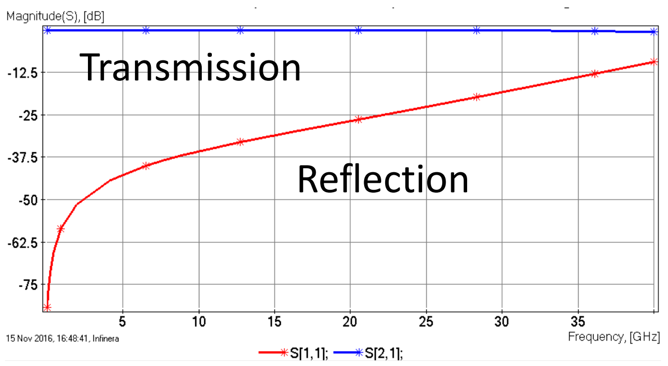


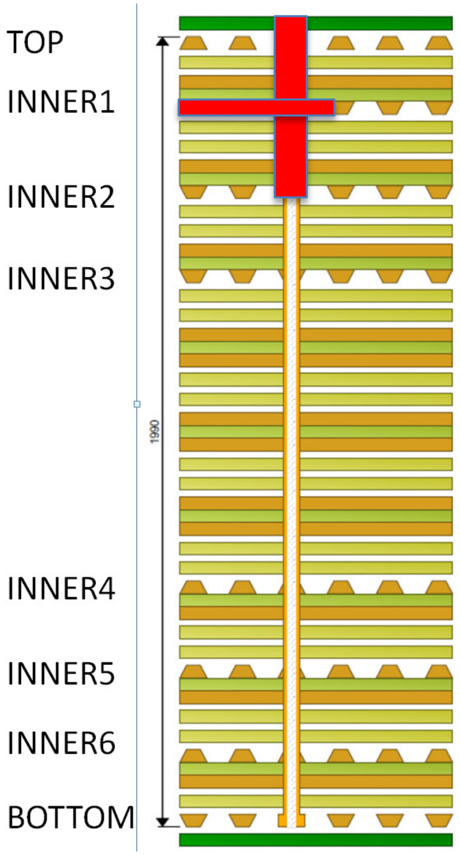


Launch design: TOP-INNER1

- Signal via drill hole diameter: 0.250mm
- signal pad diameter: 0.51mm
- Antipads:
  - TOP: Diameter: 1.54mm
  - GND1: Diameter: 1.4mm
  - GND2: Diameter: 1.4mm
  - GND3: Diameter: 1.4mm
  - GND4: Diameter: 1.4mm
  - PWR1: Diameter: 1.4mm
  - …
  - GND9: Diameter: 1.4mm



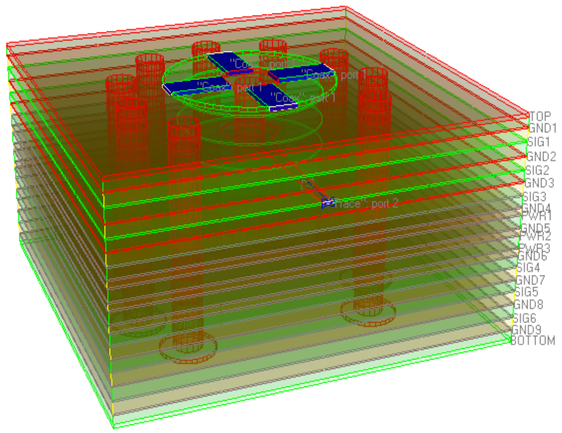


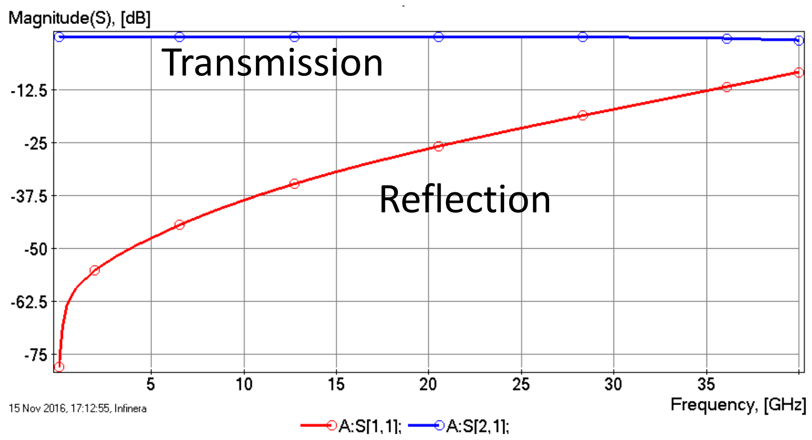


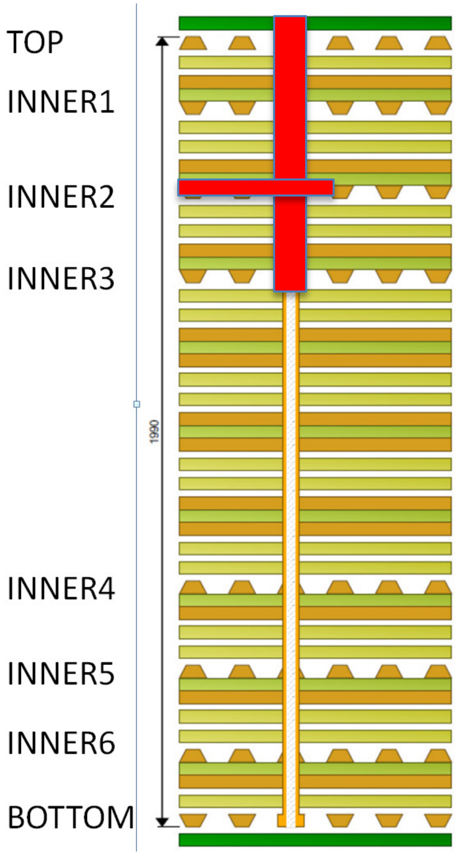
- Up to 28 GHz, return loss below -20dB (less than 10%), below 0.1dB loss
- We assume that the stub ends at INNER2 - the stub length is: 108+15+100 = 223um

Launch design: TOP-INNER2

- Signal via drill hole diameter: 0.250mm
- Signal pad diameter: 0.51mm
- Antipads:
  - TOP: Diameter: 1.54mm
  - GND1: Diameter: 1.3mm
  - GND2: Diameter: 1.3mm
  - GND3: Diameter: 1.3mm
  - GND4: Diameter: 1.3mm
  - PWR1: Diameter: 1.3mm
  - …
  - GND9: Diameter: 1.3mm



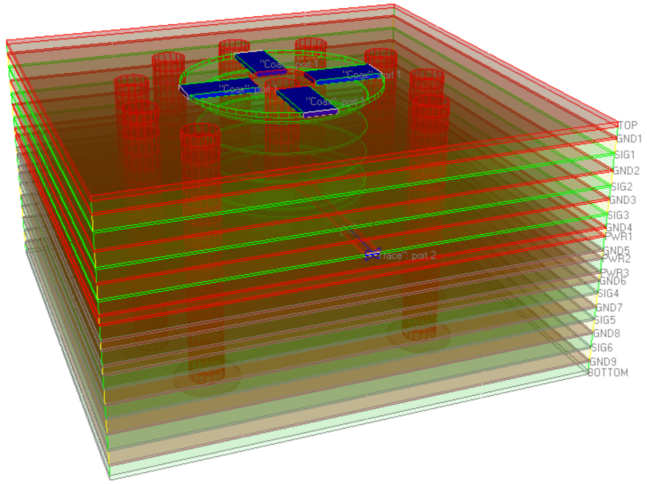


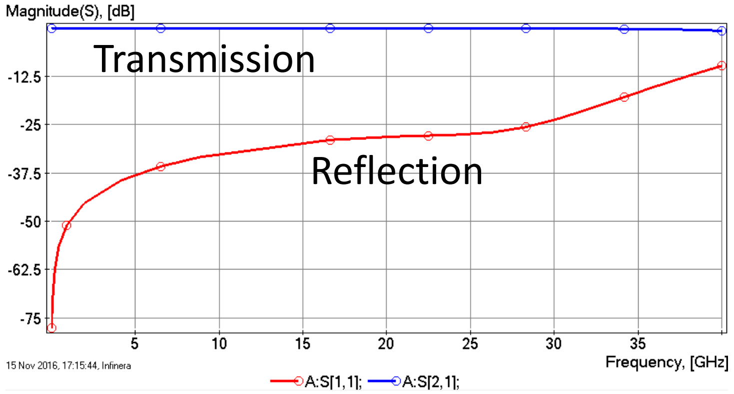


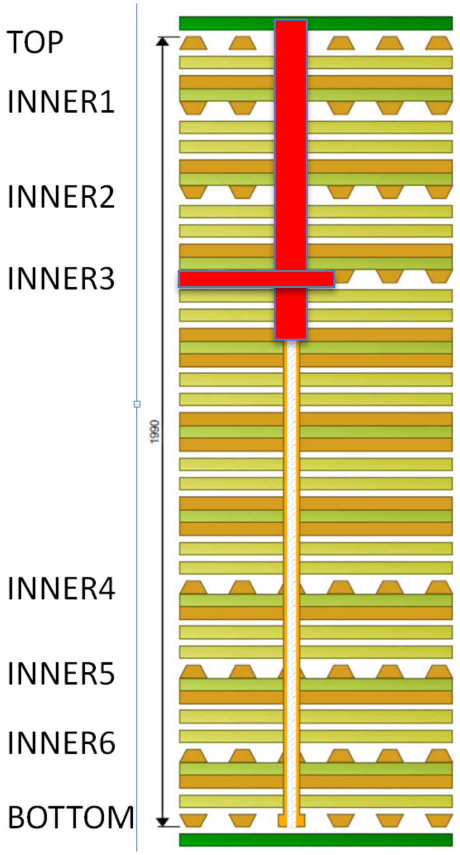
- Up to 28 GHz, return loss below -20dB (less than 10%), below 0.1dB loss
- We assume that the stub ends at INNER3 - the stub length is: 86+15+100 = 203um

Launch design: TOP-INNER3

- Signal via drill hole diameter: 0.250mm
- Signal pad diameter: 0.51mm
- Antipads:
  - TOP: Diameter: 1.54mm
  - GND1: Diameter: 1.3mm
  - GND2: Diameter: 1.3mm
  - GND3: Diameter: 1.3mm
  - GND4: Diameter: 1.3mm
  - PWR1: Diameter: 1.3mm
  - …
  - GND9: Diameter: 1.3mm



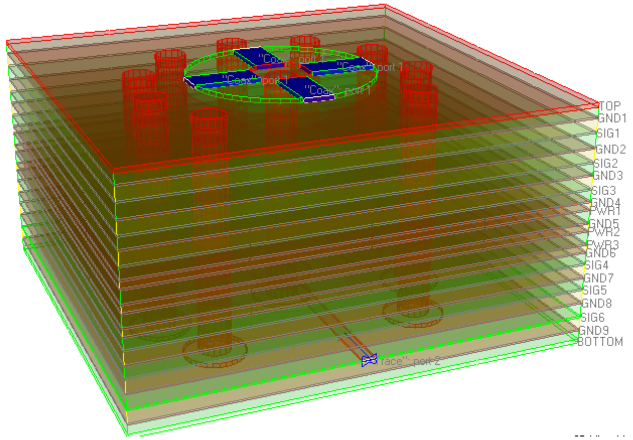


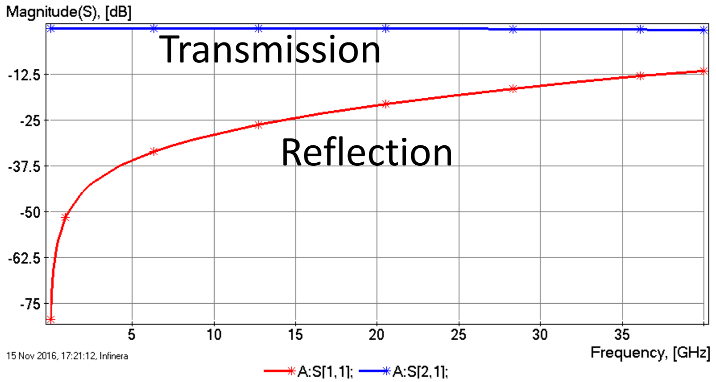


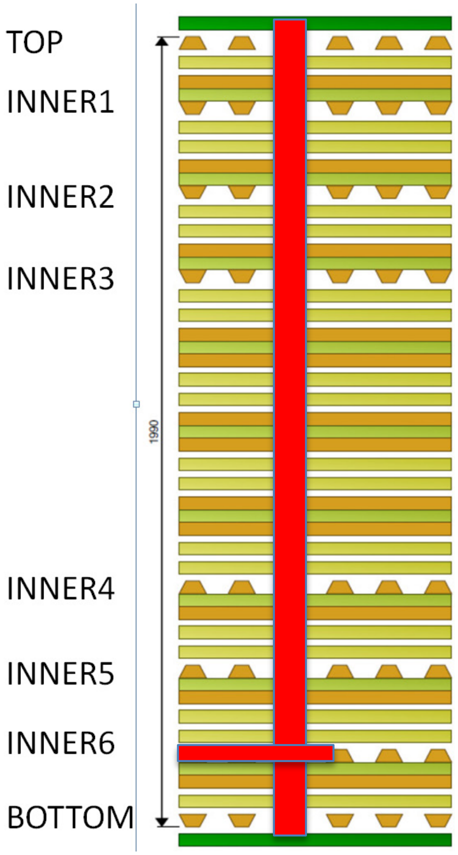
- Up to 33 GHz, return loss below -20dB (less than 10%), below 0.1dB loss
- We assument that the stub ends on PWR1, that is the stub length is: 86+15+50+15 = 166um

Launch design: TOP-INNER6

- Signal via drill hole diameter: 0.250mm
- Signal pad diameter: 0.51mm
- Antipads:
  - TOP: Diameter: 1.54mm
  - GND1: Diameter: 1.54mm
  - GND2: Diameter: 0.8mm
  - GND3: Diameter: 0.8mm
  - GND4: Diameter: 0.8mm
  - PWR1: Diameter: 0.8mm
  - …
  - GND9: Diameter: 1.1mm



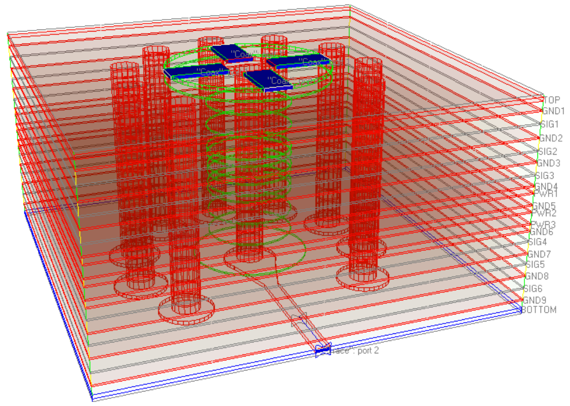


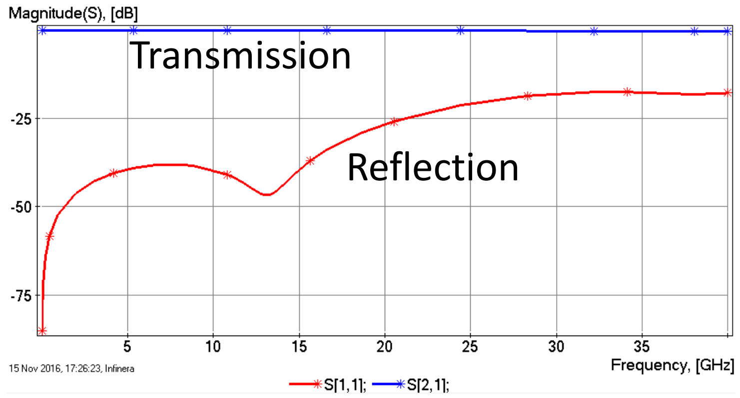


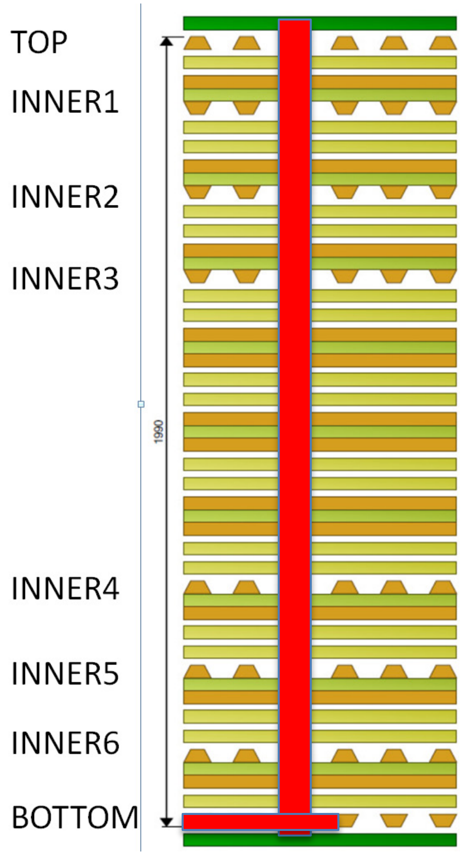
- Up to 22 GHz, return loss below -20dB (less than 10%), below 0.1dB loss
- No backdrilling

Launch design: TOP-BOTTOM

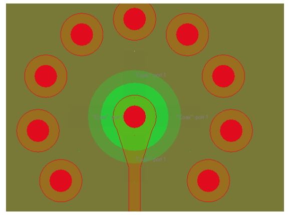
- Signal via drill hole diameter: 0.250mm
- Signal pad diameter: 0.51mm
- Antipads:
  - TOP: Diameter: 1.54mm
  - GND1: Diameter: 1.54mm
  - GND2: Diameter: 0.8mm
  - GND3: Diameter: 0.8mm
  - …
  - GND8: Diameter: 0.8mm
  - GND9: Diameter: 1.1mm







- Tapering of the entry trace to the via pad (BOTTOM)



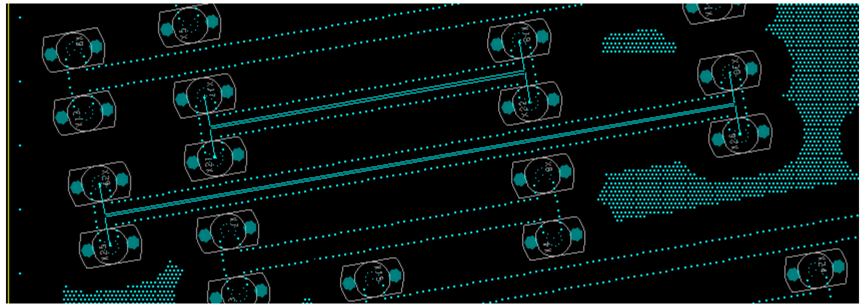
- Up to 27 GHz, return loss below -20dB (less than 10%), below 0.1dB loss up to 22 GHz.

Reality: Layout peculiarities

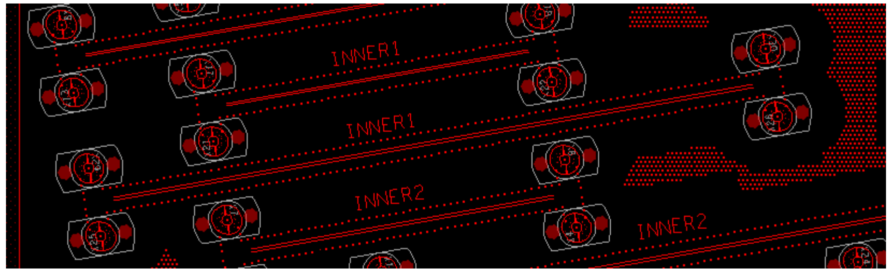
- Via drill diameter defined 7.9 mil in layout file, but 9.85 mil (0.25 mm) used by manufacturer
- The PCB is manufactured with the “impedance control” – all trace width and spacing are adjusted by the PCB manufacturer, that is not reflected in the layout file
- No information on trace shape (important for losses)
- No information on solder mask shape/parameters
- No information on conductor roughness
- No information on the backdrilling

Reality: Layout peculiarities

INNER1 - strips

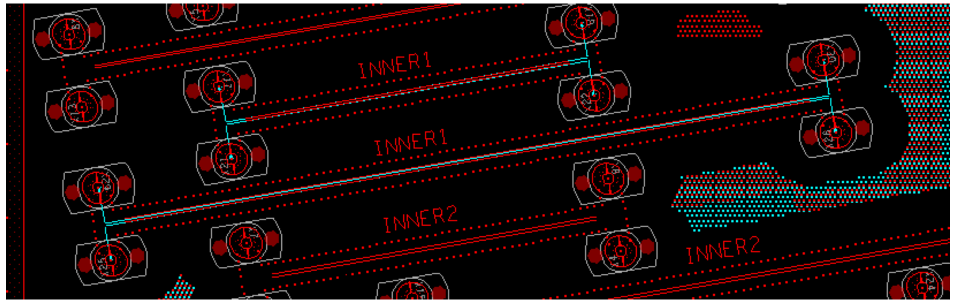


TOP



January 16, 2017 – board in production

Will metal in top layer make difference?



It depends on the isolation of the top layer from the rest of the structures – no difference in this case, because of solid plane separates the top from the rest of the board and nothing in top layer, except the launches …

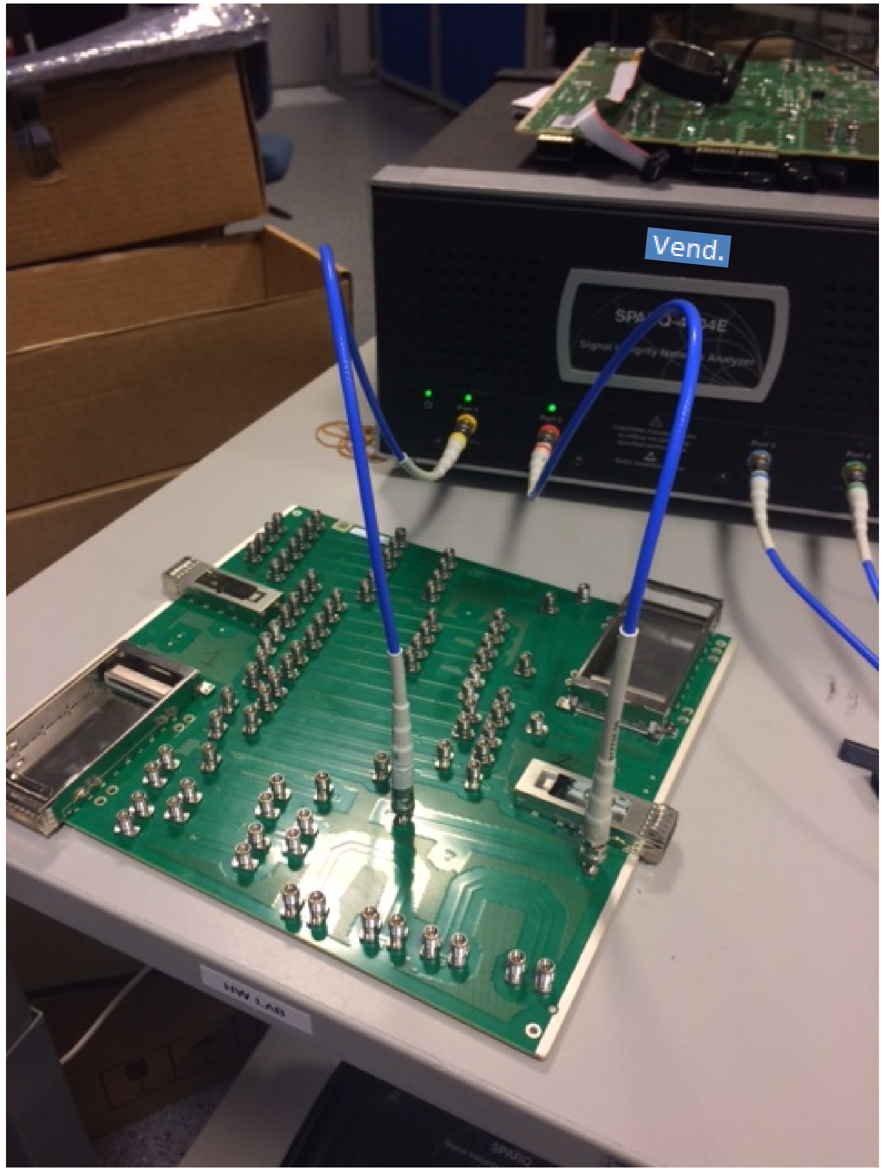
Measurements and GMS-parameters extraction

Measurements

- TDNA, 2.92 mm connectors (not acceptable for material identification)
- 27 GHz VNA, 2.92 mm connectors (failure)
- 40 GHz VNA, 2.92 mm connectors (acceptable)
- 50 GHz VNA, 2.4 mm connectors (acceptable)
- A few VNA from different vendors evaluated – may be suitable for a separate report…

First measurement attempt with TDNA

- January 20, 2017
- Quality metrics are acceptable
- Large noise in data
- GMS-parameters are very noisy
- Not acceptable to proceed
- Here are some observations…



S-parameters quality evaluation

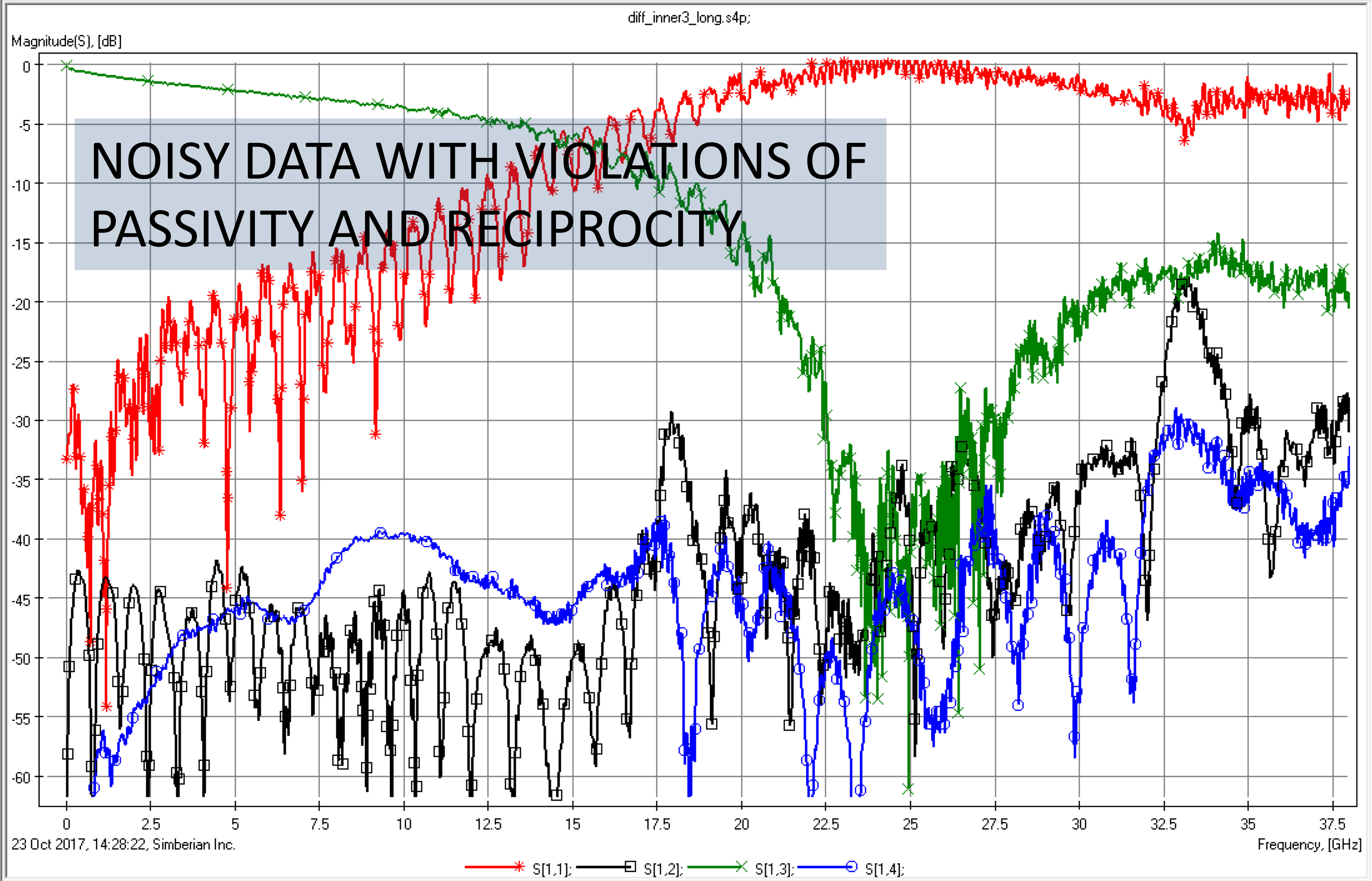
Graph(1) | GMS_INNER1 | GMS_INNER2 | GMS_INNER3 | GMS_INNER6 | GMS_BOTTOM | S-par-SE | Touchstone Analyzer

C:\Repository\Simbeor\Support\Infinera\March31_2017_board_and_measure...

File name	Quality	Passivity	Reciprocity	Causality
C1_c.s4p	91.5	100	90.2	-
C2_c.s4p	90.8	100	90.4	-
C3_c.s4p	90.2	100	90.9	-
C4.s2p	90.4	100	87.2	-
C5.s2p	89.4	100	89.5	-
D1.s2p	89.9	98.1	83.8	-
D2.s2p	90.8	100	82.8	-
diff_bottom_long.s4p	90.3	100	90.7	-
diff_bottom_short.s4p	89.4	100	88.7	-
diff_inner1_long.s4p	89.3	100	91.8	-
diff_inner1_short.s4p	90.2	100	90.6	-
diff_inner2_long.s4p	89.5	100	92.5	-
diff_inner2_short.s4p	90.1	100	90.7	-
diff_inner3_long.s4p	88.7	93.8	92.4	-
diff_inner3_short.s4p	88.5	93.1	91.5	-
diff_inner6_long.s4p	91.4	100	92.9	-
diff_inner6_short.s4p	57	100	90.7	-
E1_Meander.s2p	89.7	100	87.2	-
F1_0402.s4p	89.6	99.8	88.9	-
F2_0201.s4p	90.2	100	88.8	-
F3_strips.s4p	88.3	99.9	88.5	-
se_inner6_long.s2p	91	100	86.9	-
se_inner6_short.s2p	90.3	100	84.5	-

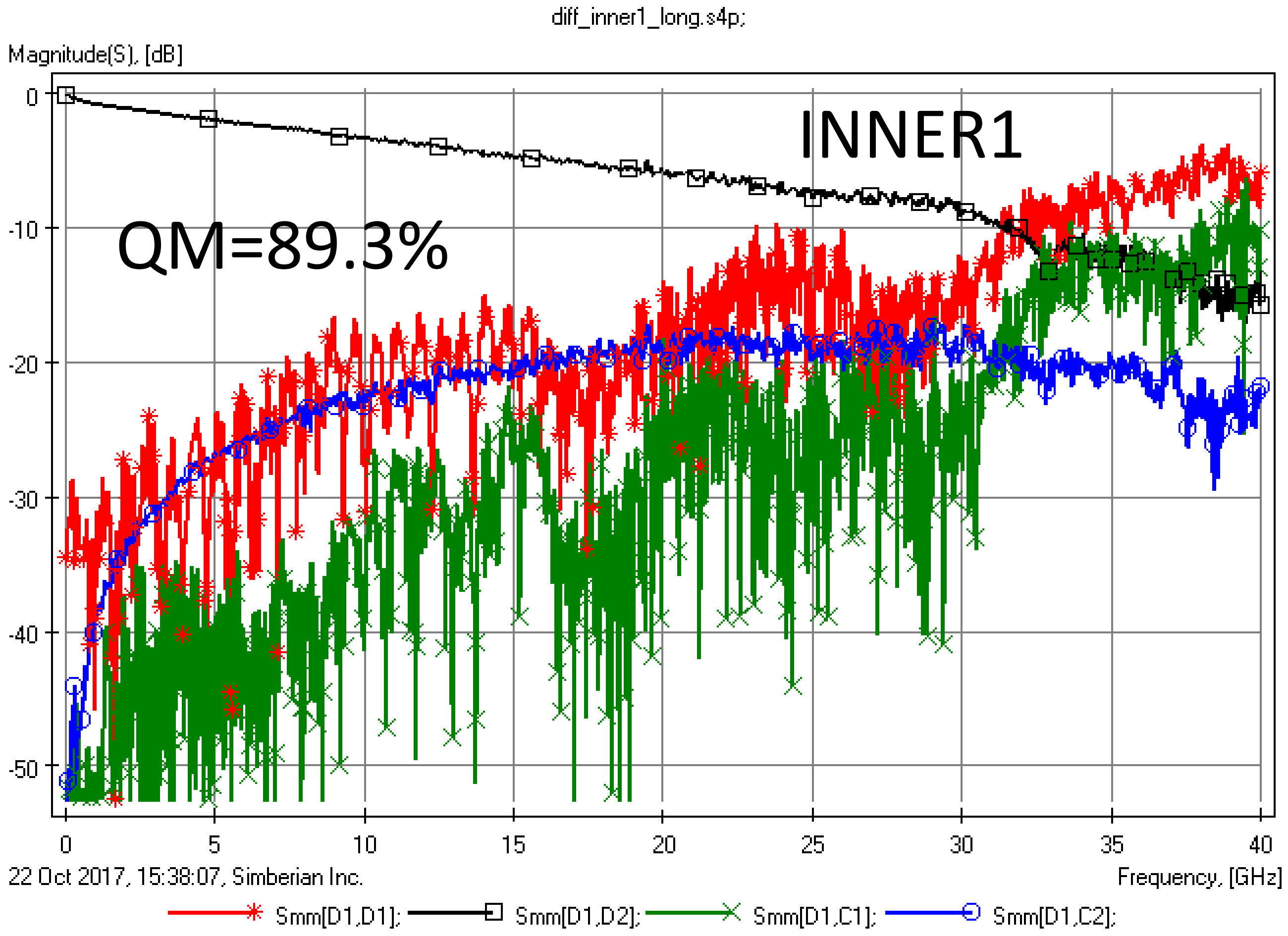
Rotation metric (causality) is low because of the noise

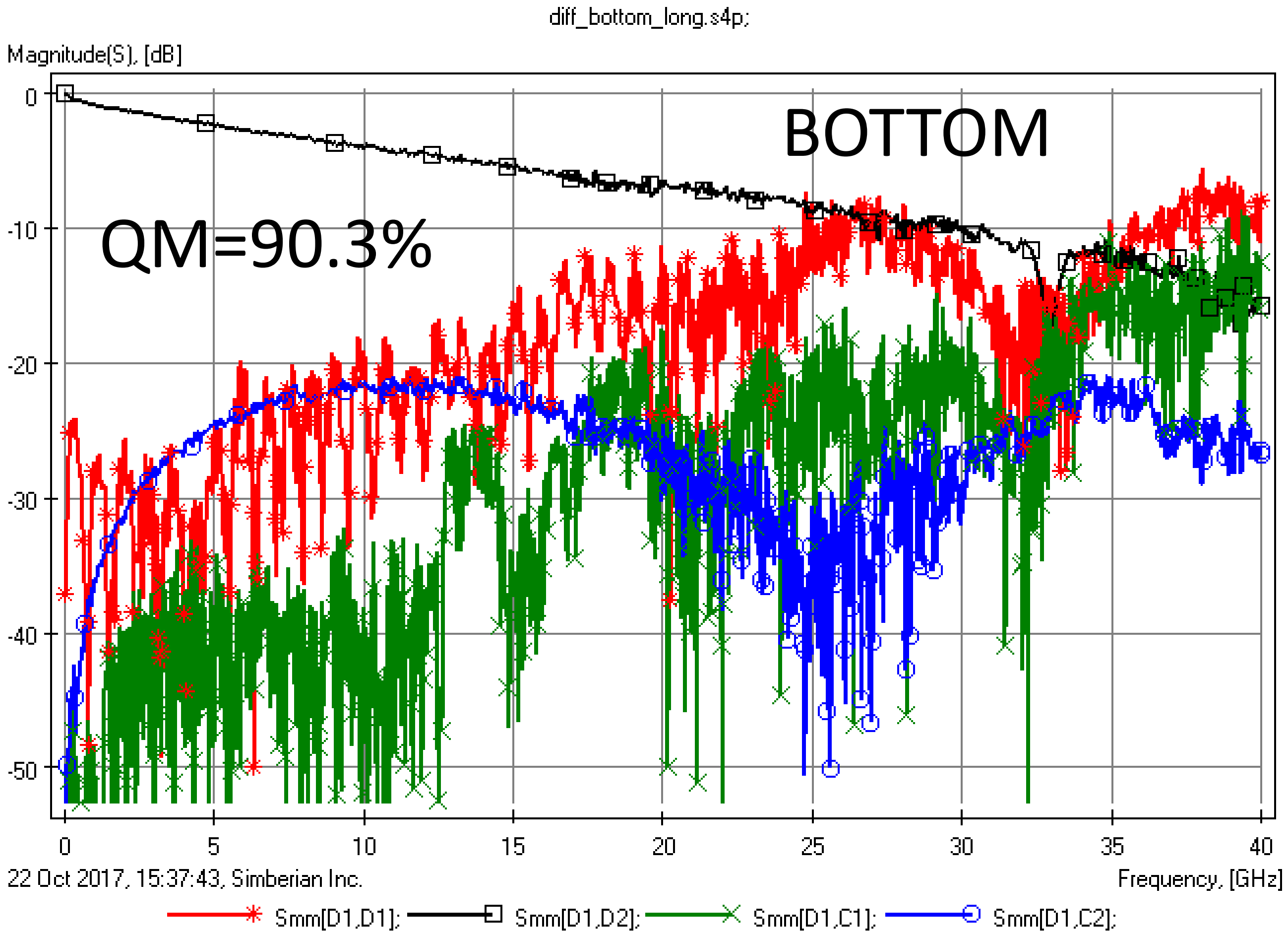
Ready



S-parameter quality evaluation

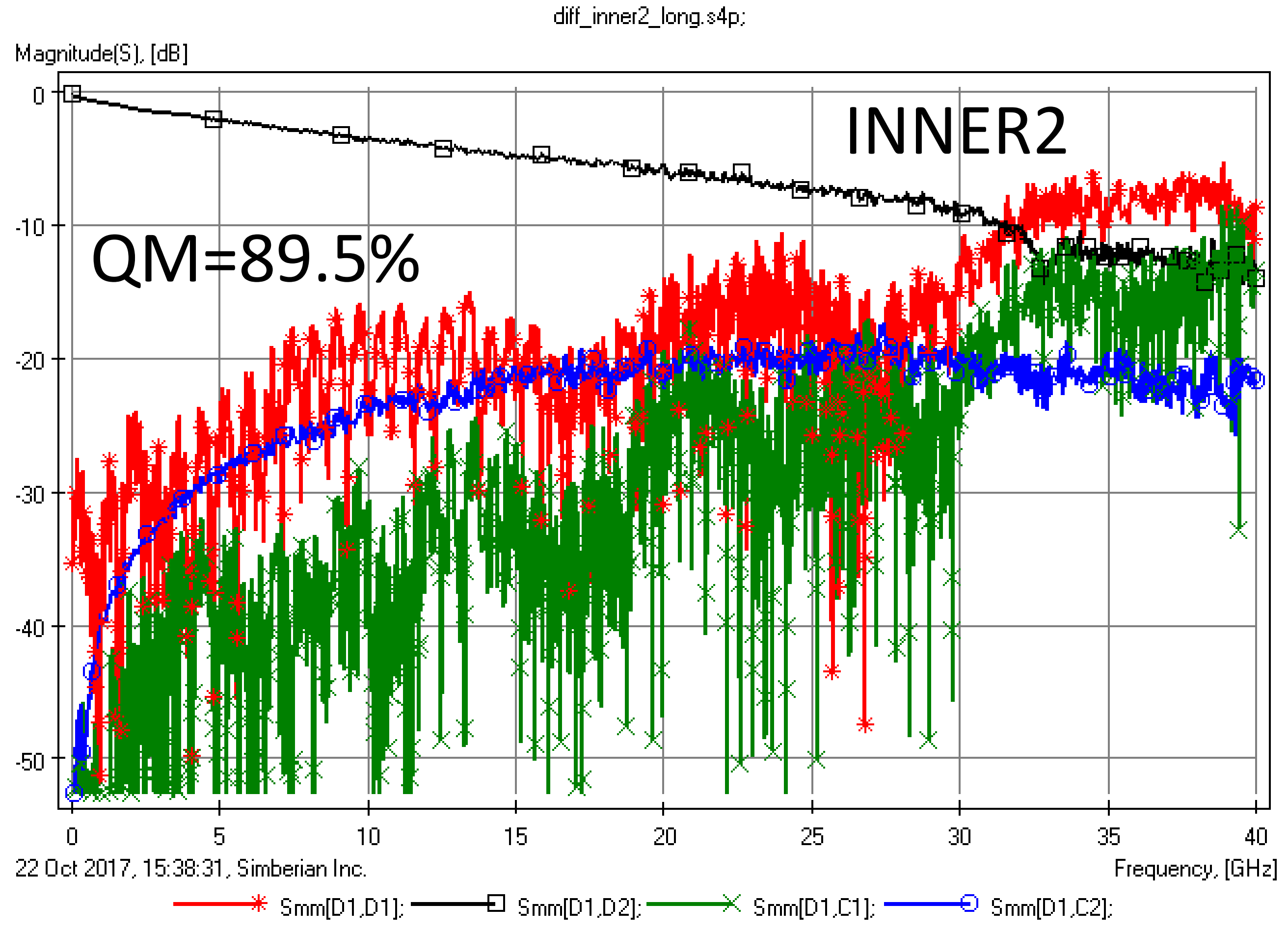
- Acceptable quality, but very noisy



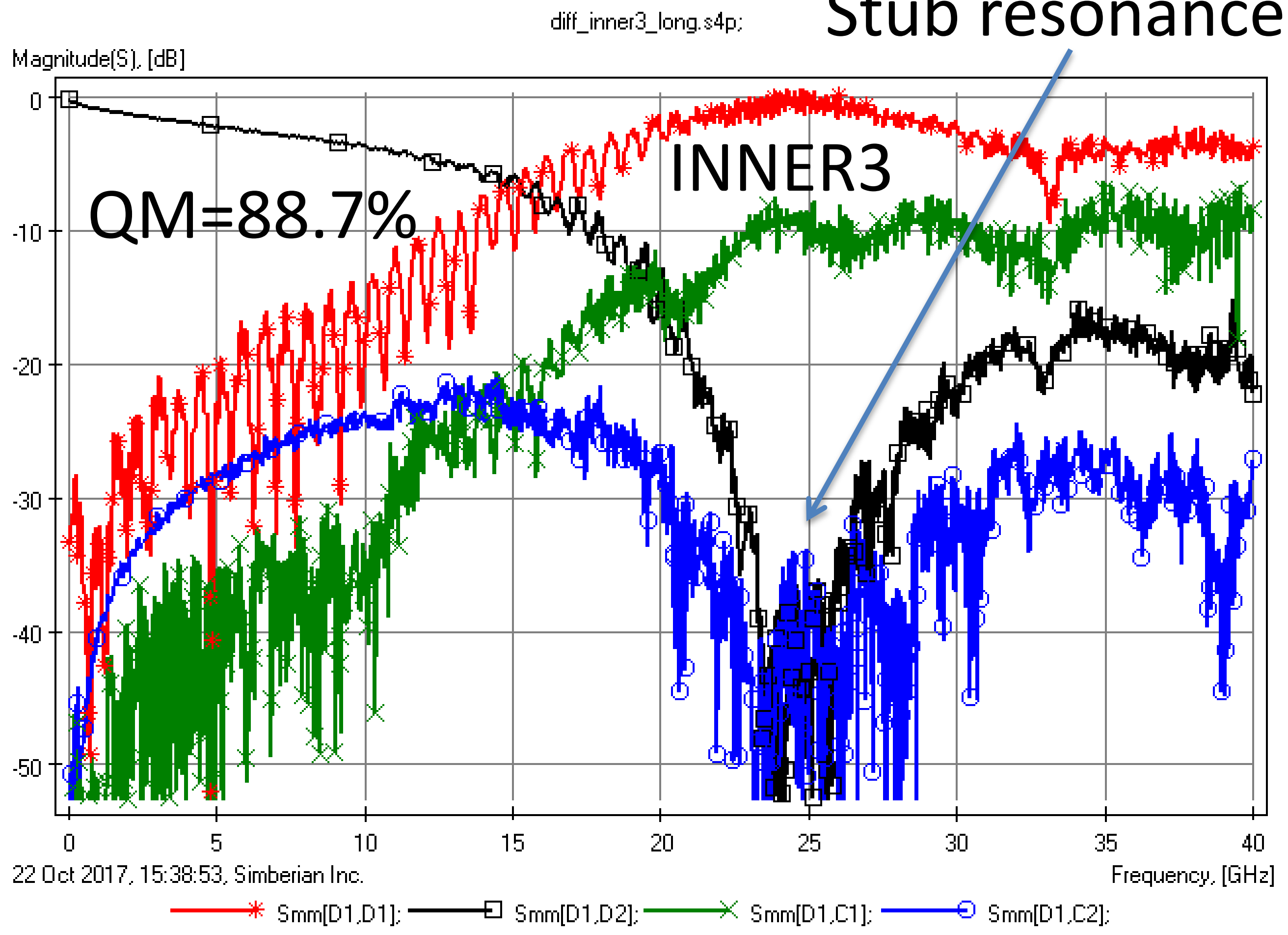


S-parameters quality evaluation

Acceptable, but noisy



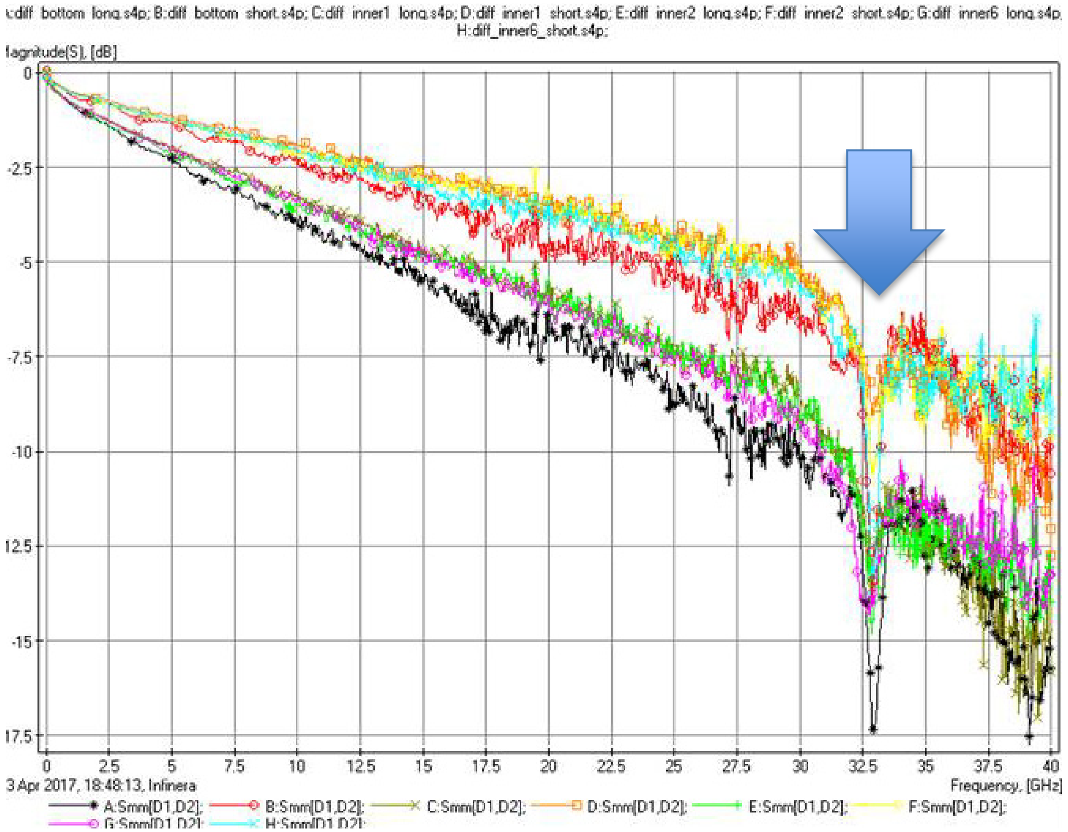
Questionable above 20 GHz



Reality: INNER3 launch is not backdrilled!

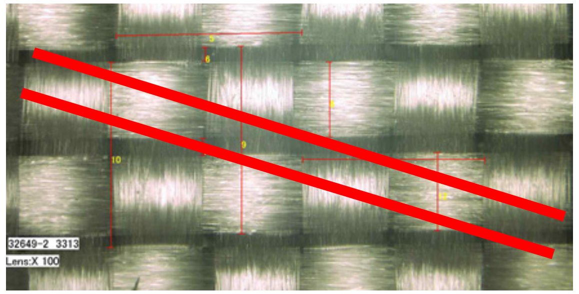
Measurement observation

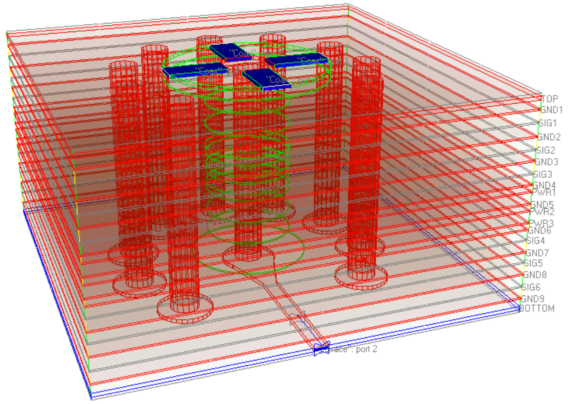
- Resonance around 33 GHz



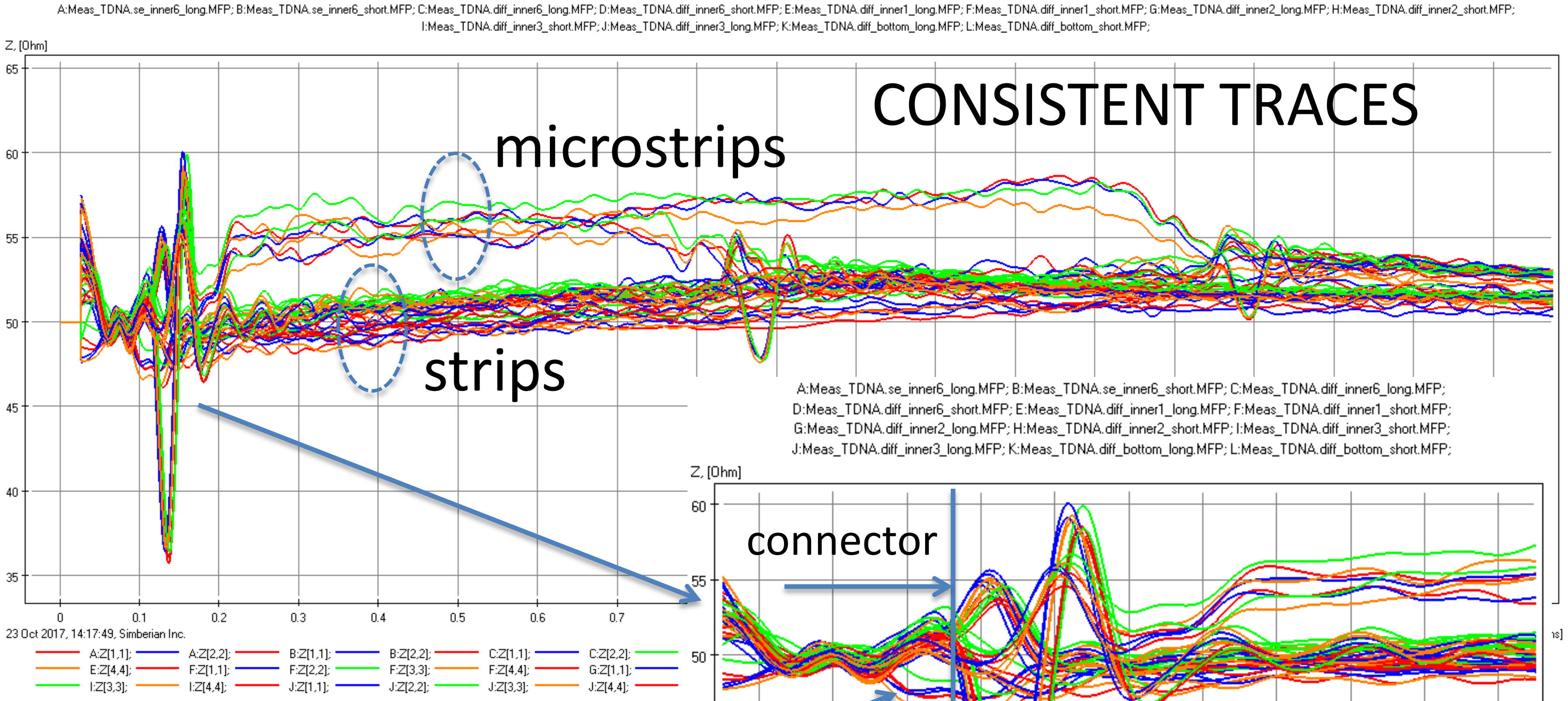
What caused it?

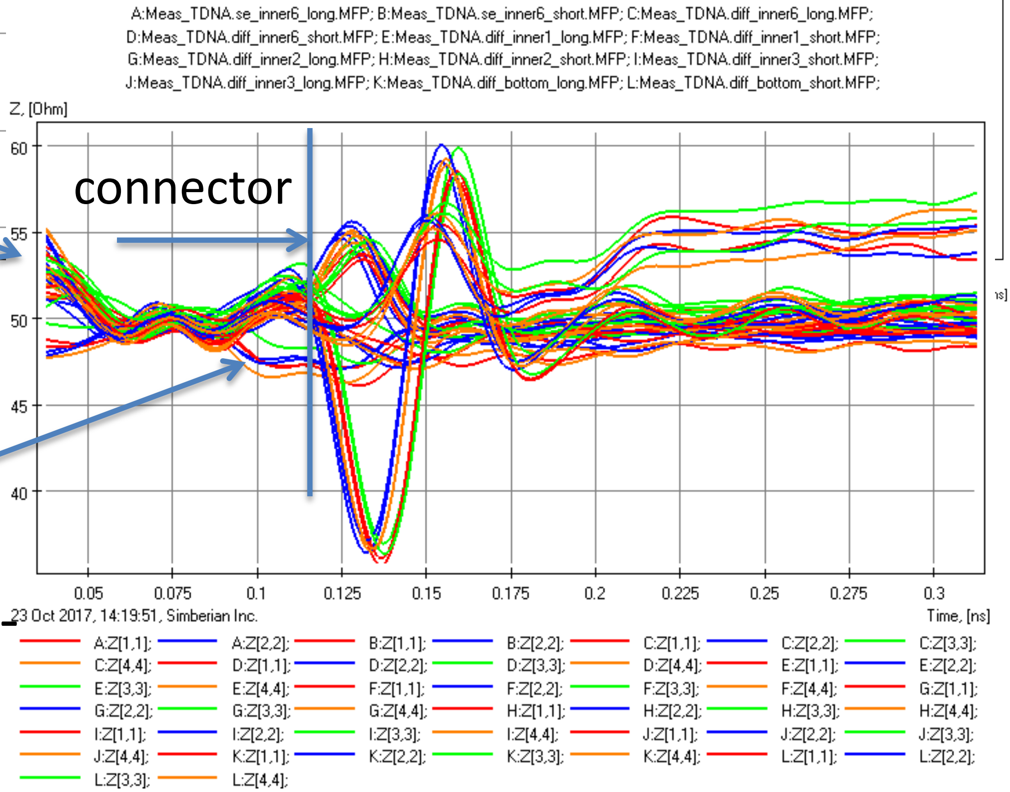
1. Measurement defect?
2. Fiber Weave Effect?
3. Connector or adapter?
4. Launch localization?
5. Non of the above?





TDR pre-qualification

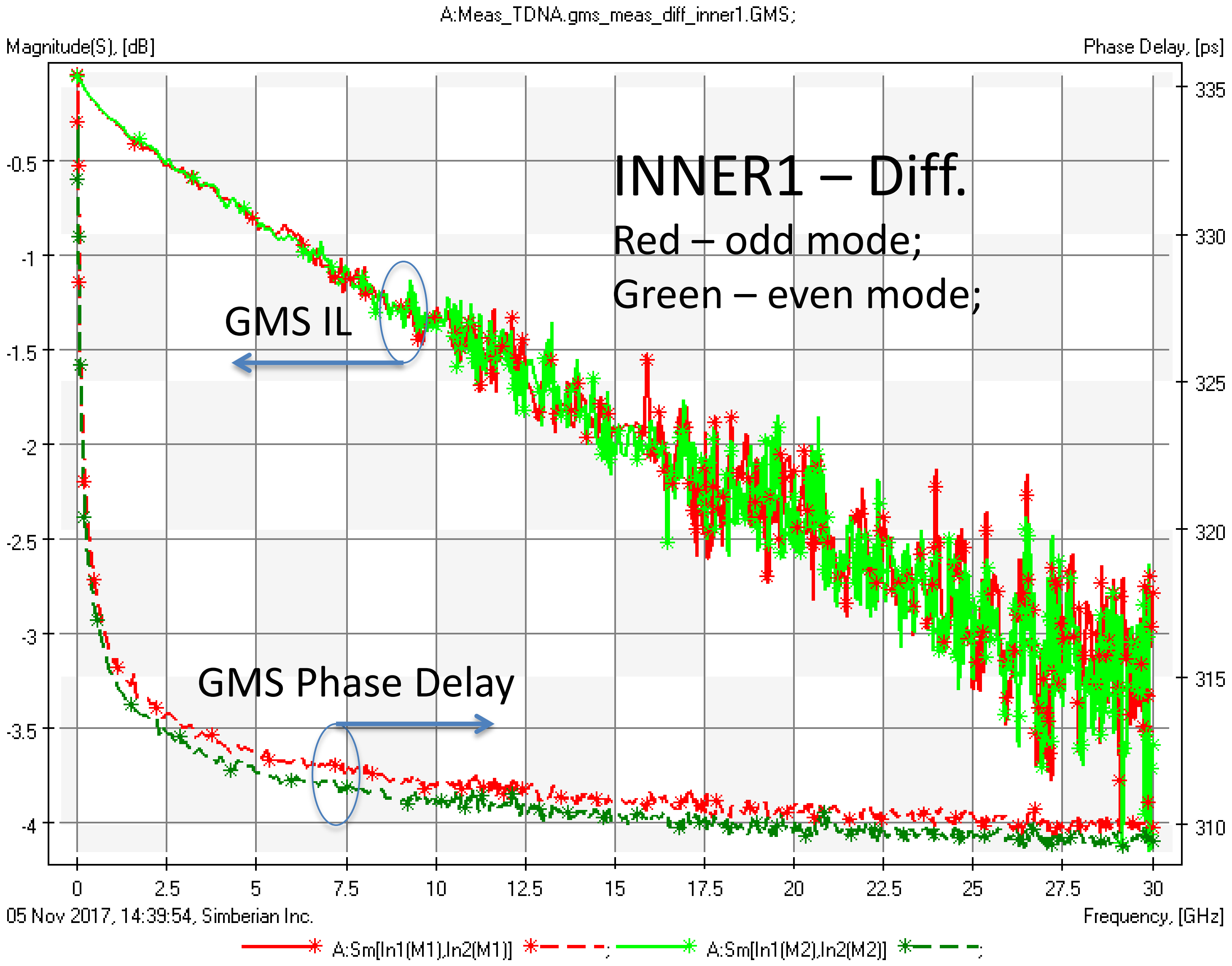


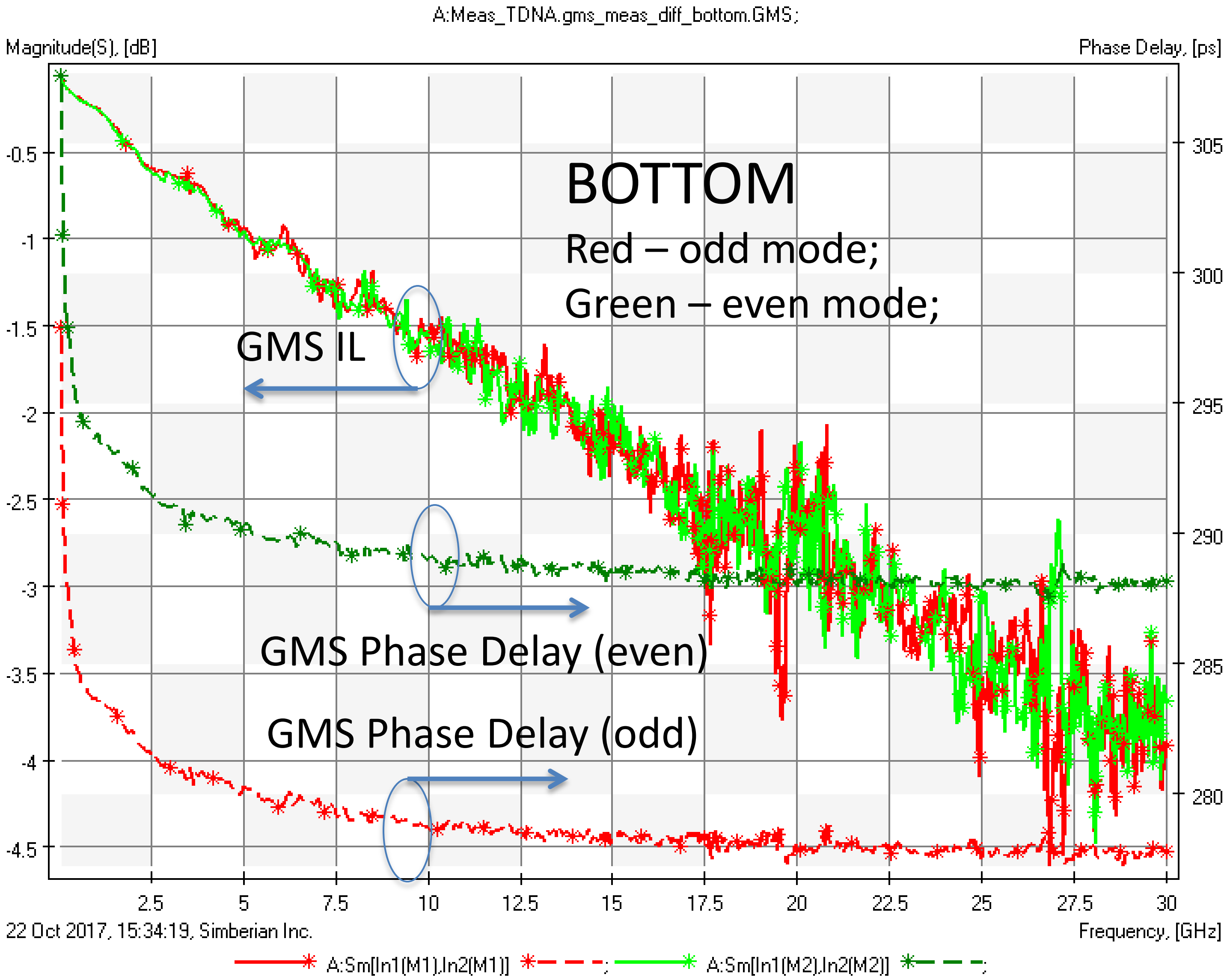


Reality: Two segments in INNER6 have different connectors – change and re-measure!

GMS-parameters

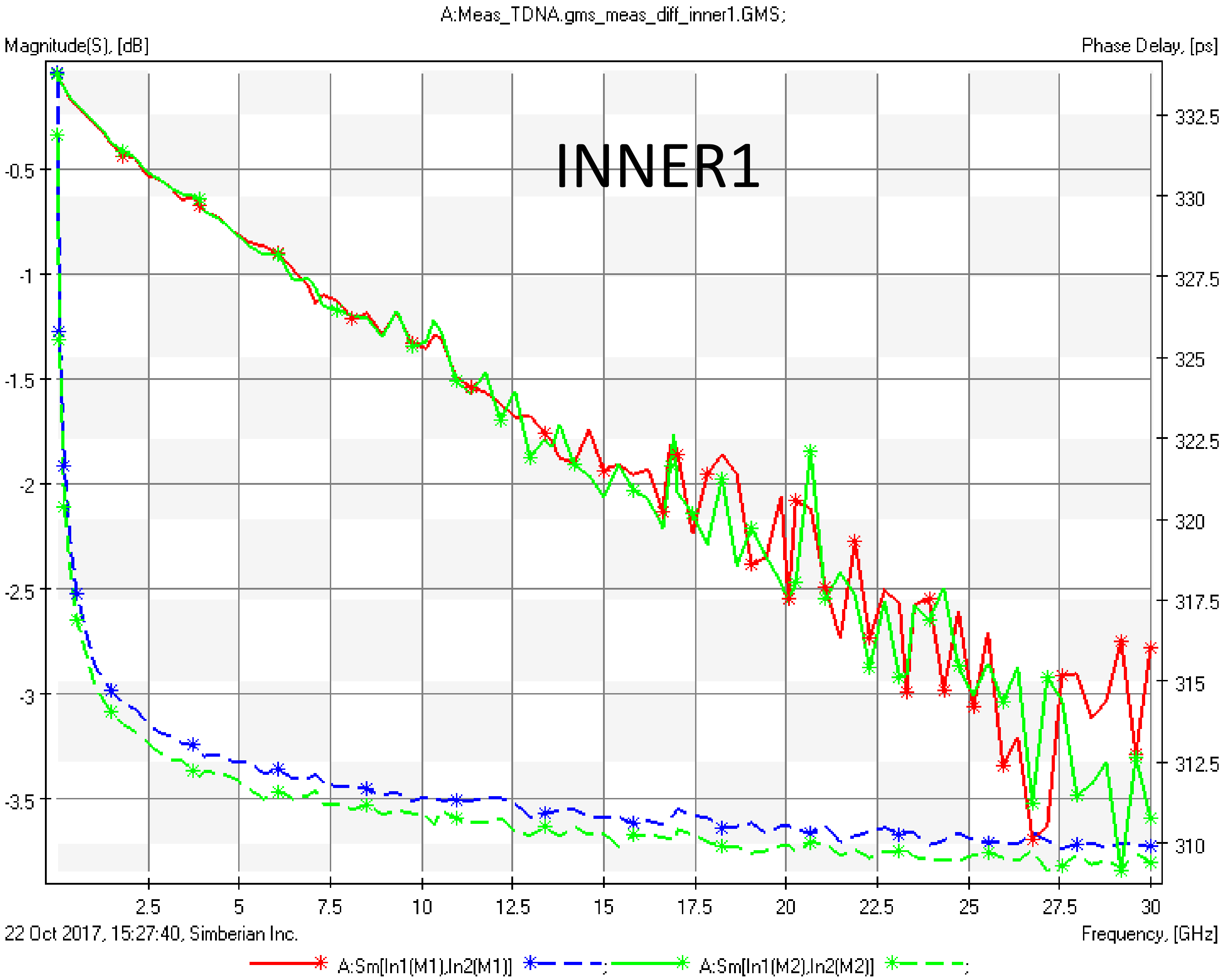
Noisy S-parameters or geometry problem?



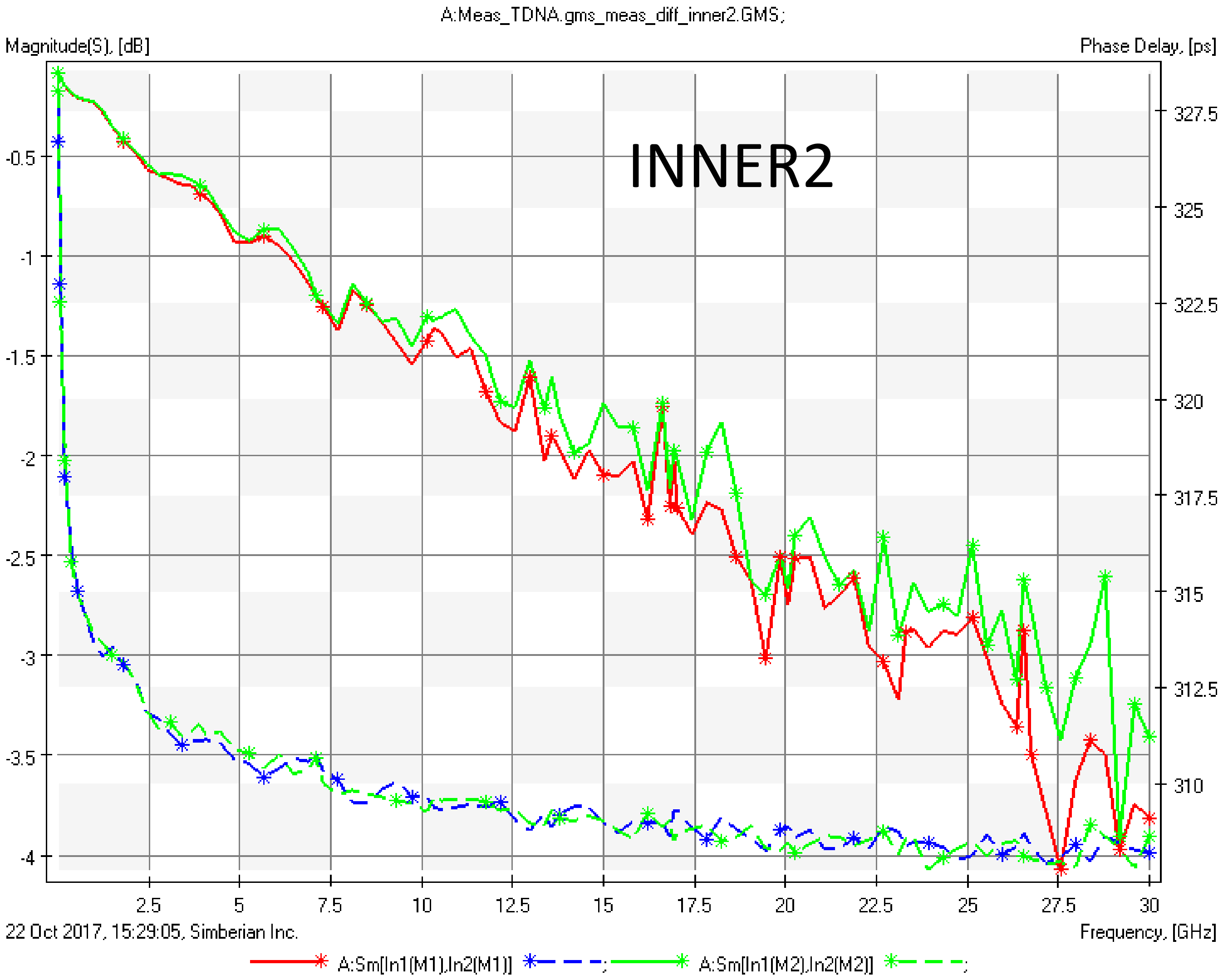


May be acceptable up to 10 GHz

GMS-parameters

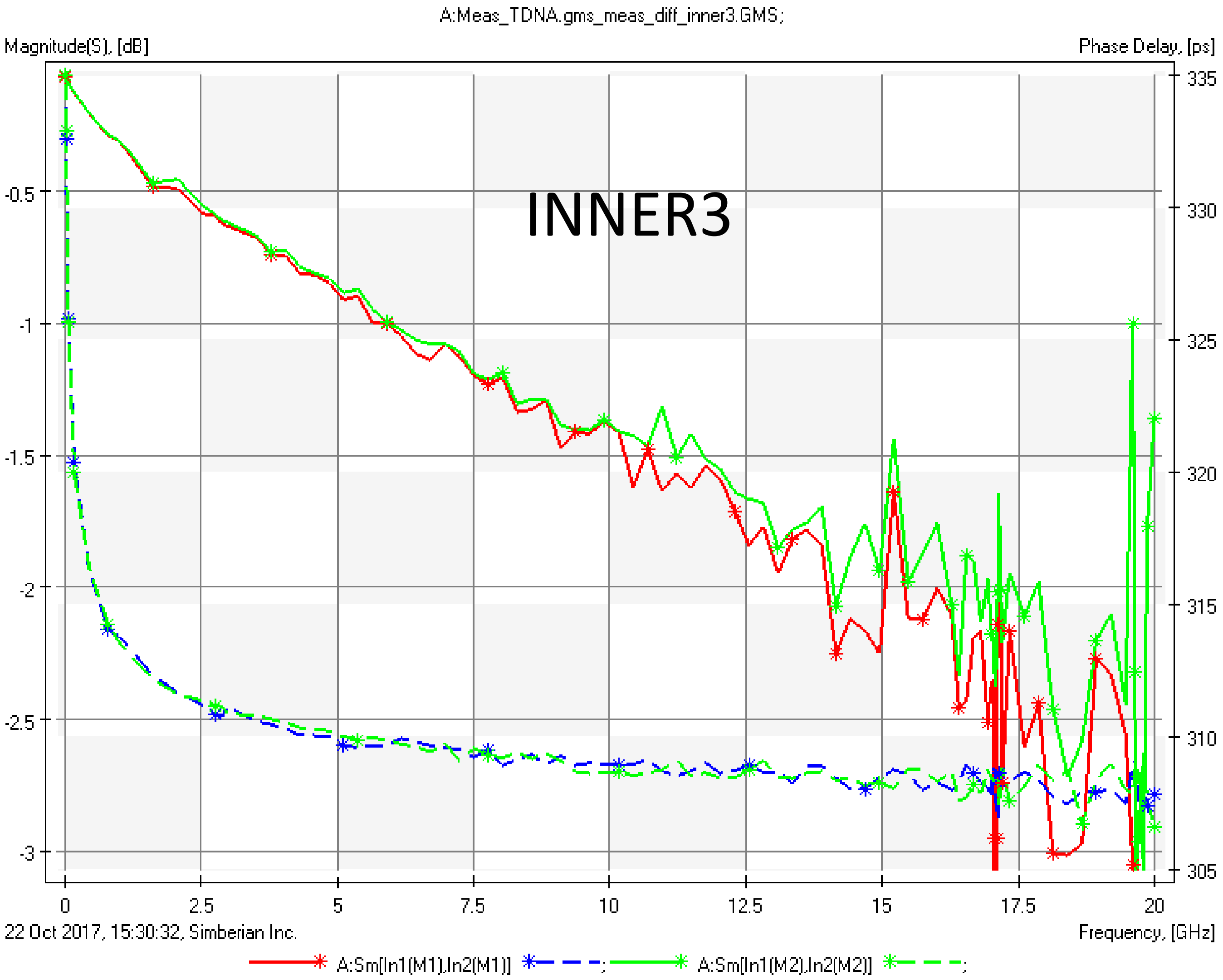


Acceptable up to 10 GHz

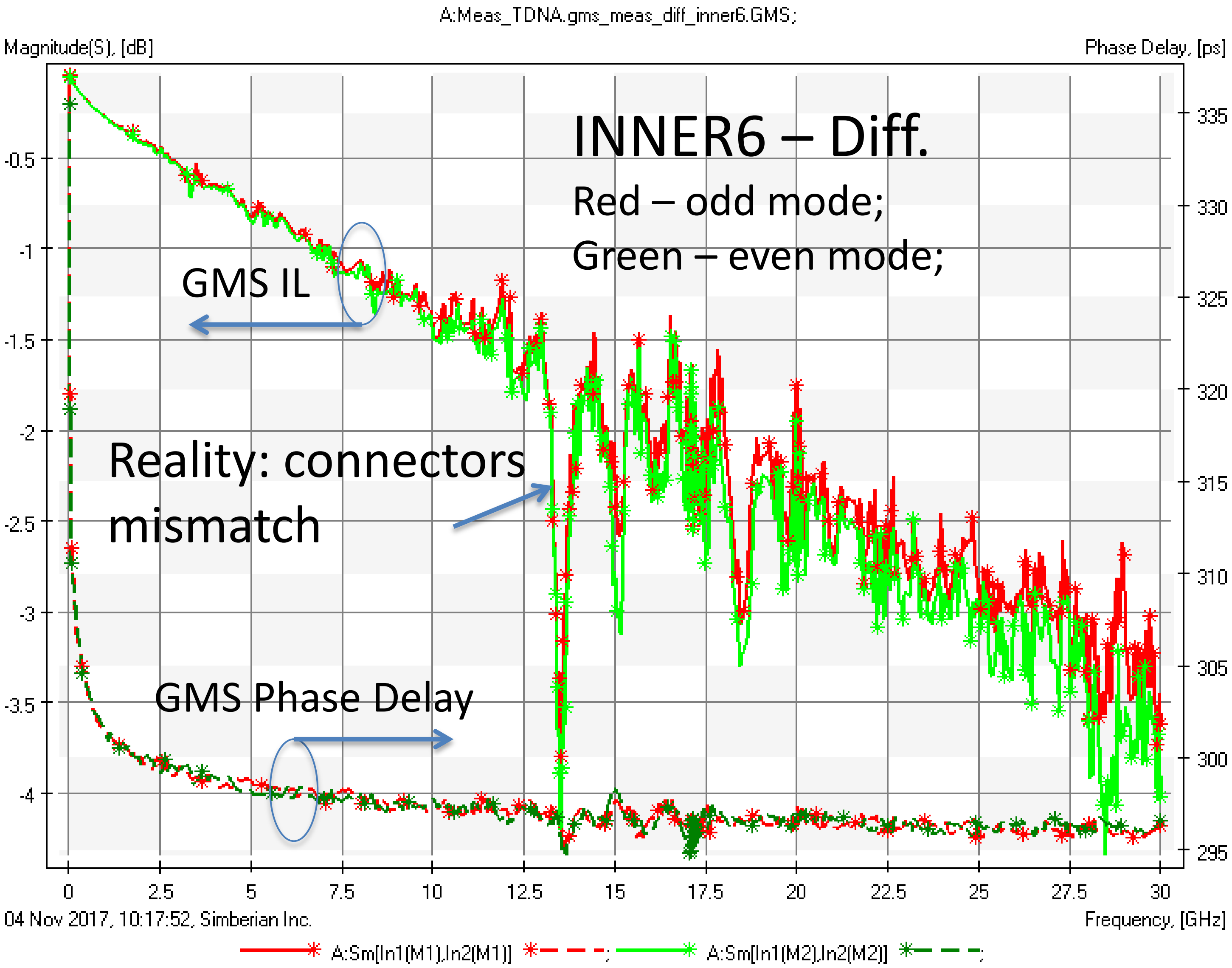


Not acceptable – backdrilling problem?

GMS-parameters



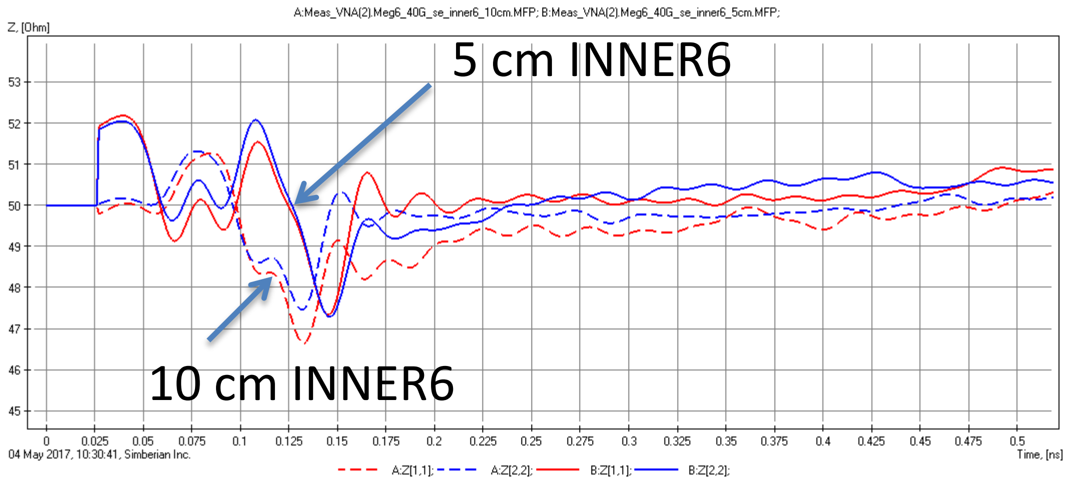
Acceptable up to 10 GHz



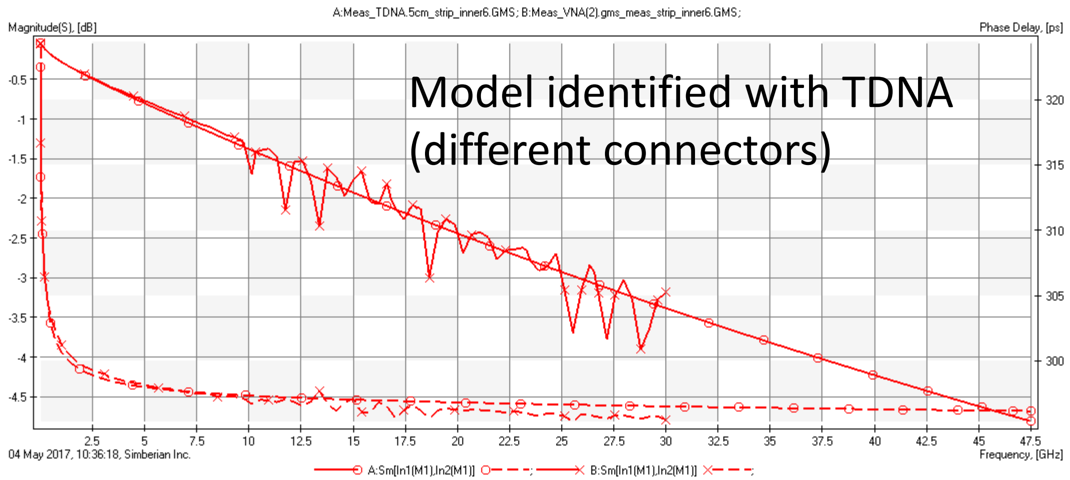
May be acceptable up to 8 GHz

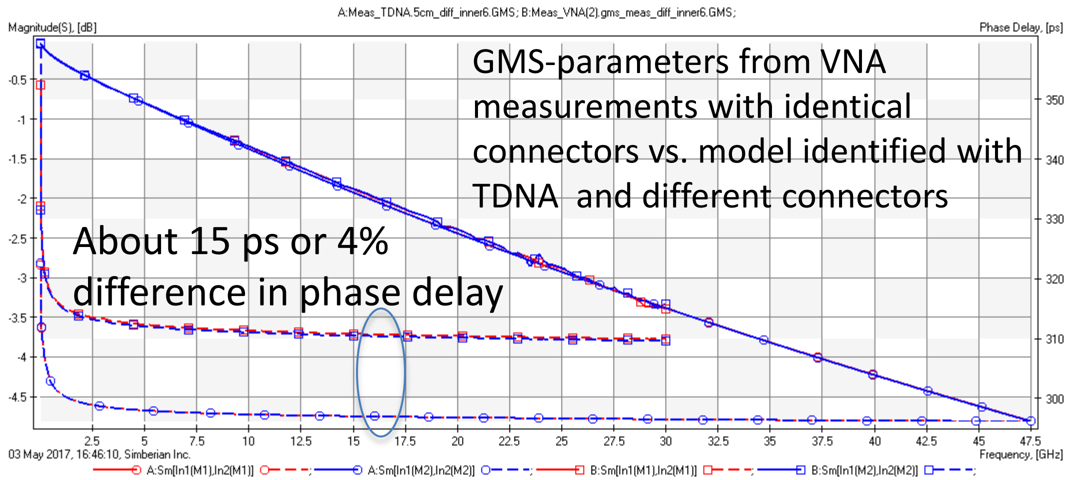
Reality: Connector mismatch problem

- 5 cm and 10 cm traces on INNER6



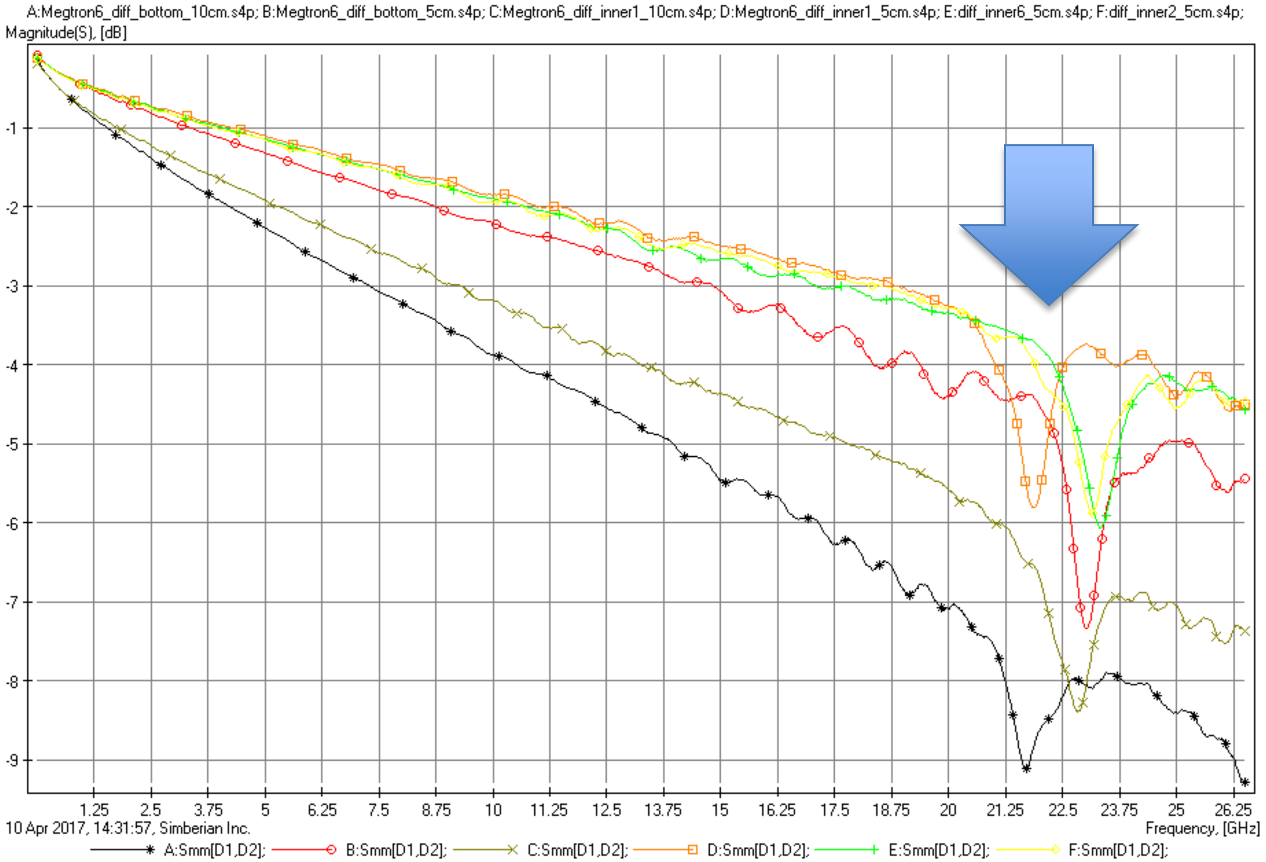
2.92 mm connectors from different manufacturers were used on two t-lines – one of the connectors is longer





First measurements with 27 GHz VNA

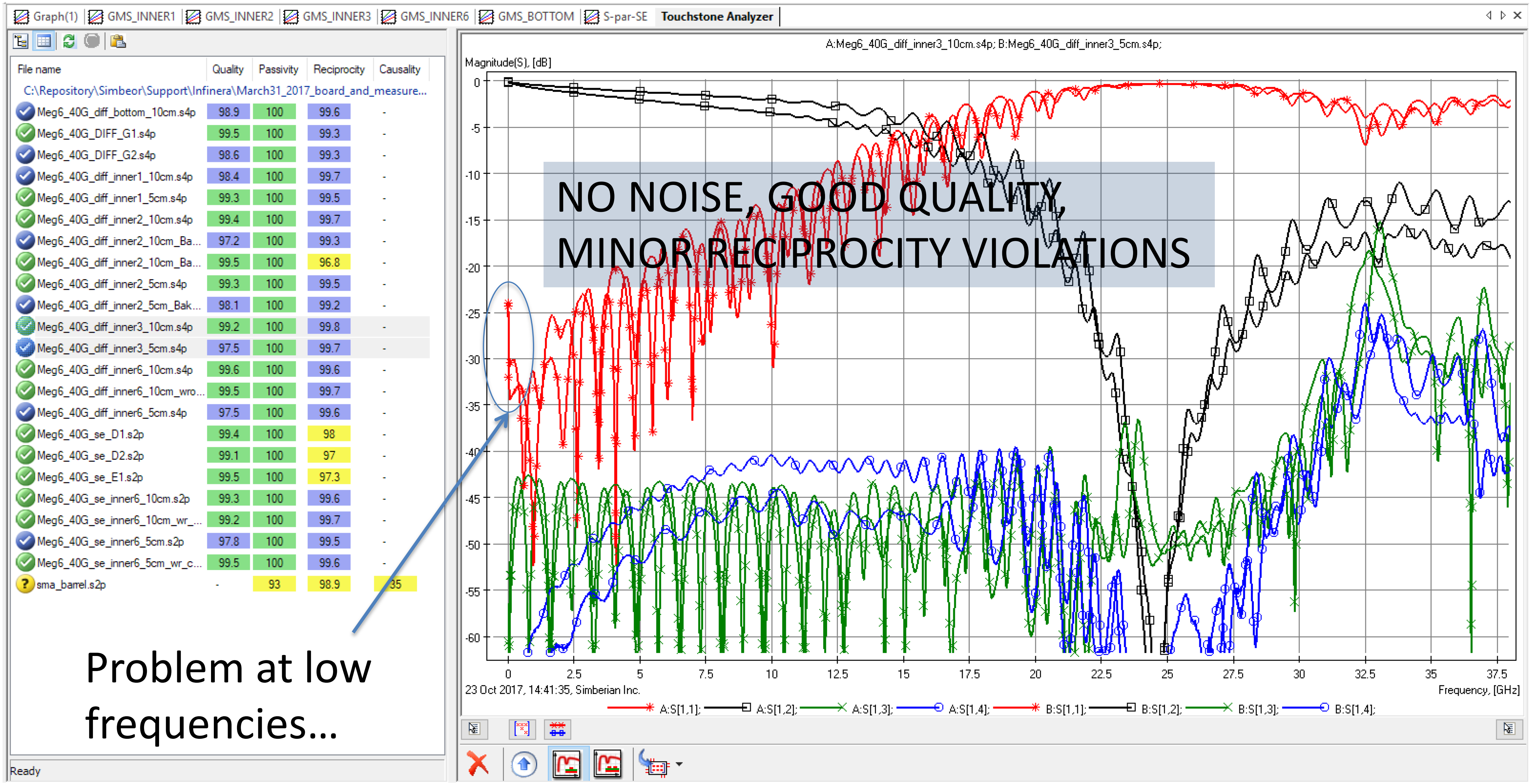
- Strange dips around 22 GHz



Questions arisen:
Did you take VNA and TDNA measurements with the same connectors? – connectors with adapters were used
Did connectors were installed with the TDR monitoring? - NO
Did you wash the connectors in pure alcohol right before taking the measurements? - NO
Did you pre-qualified the cables for the measurements? – VNA measurements are done off site, TDNA had 4 cables
Did you calibrated the VNA right before taking the measurements? – YES, ECAL kit was used
How long agot VNA was serviced? - just recently

We did not find out the problem – most likely it was problem with the calibration

Measurements with 40 GHz VNA

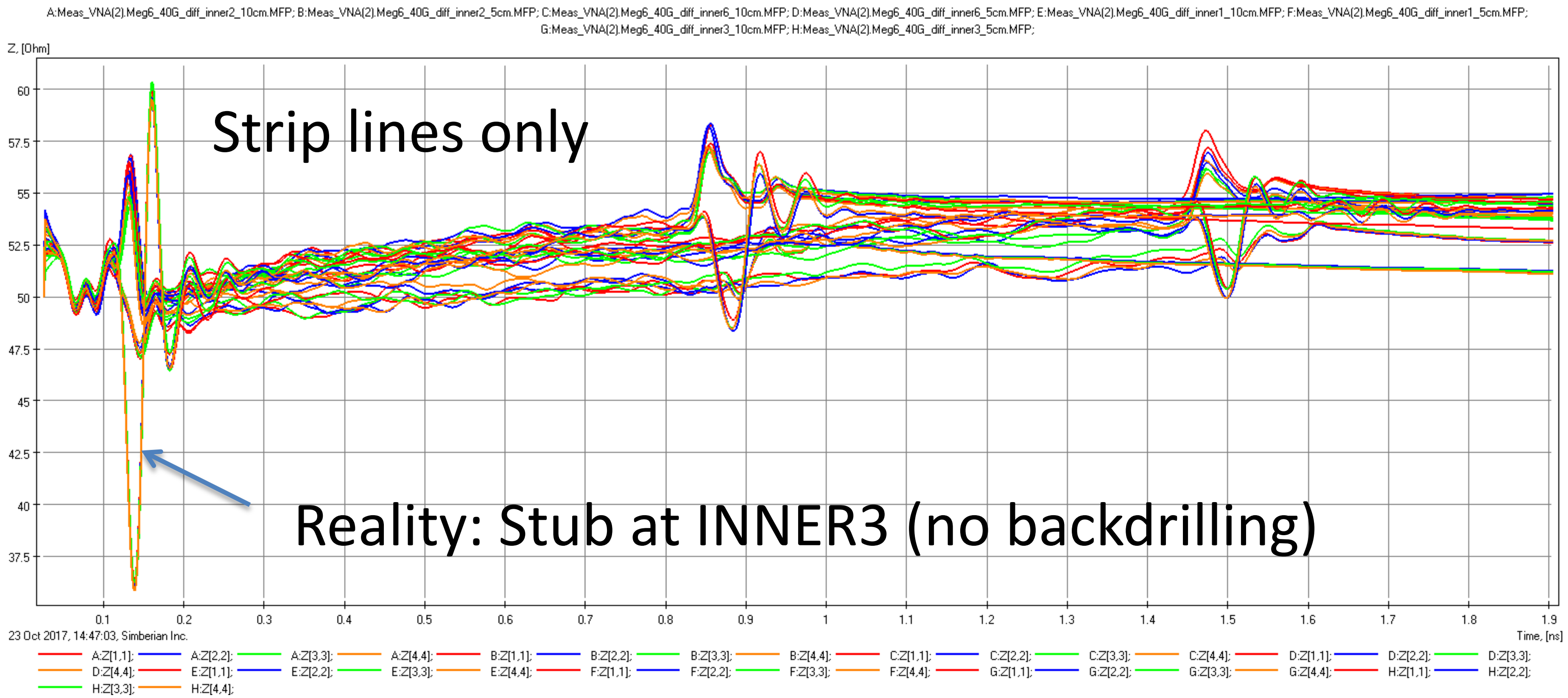


File name	Quality	Passivity	Reciprocity	Causality
Meg6_40G_diff_bottom_10cm.s4p	98.9	100	99.6	-
Meg6_40G_DIFF_G1.s4p	99.5	100	99.3	-
Meg6_40G_DIFF_G2.s4p	98.6	100	99.3	-
Meg6_40G_diff_inner1_10cm.s4p	98.4	100	99.7	-
Meg6_40G_diff_inner1_5cm.s4p	99.3	100	99.5	-
Meg6_40G_diff_inner2_10cm.s4p	99.4	100	99.7	-
Meg6_40G_diff_inner2_10cm_Ba...	97.2	100	99.3	-
Meg6_40G_diff_inner2_10cm_Ba...	99.5	100	96.8	-
Meg6_40G_diff_inner2_5cm.s4p	99.3	100	99.5	-
Meg6_40G_diff_inner2_5cm_Bak...	98.1	100	99.2	-
Meg6_40G_diff_inner3_10cm.s4p	99.2	100	99.8	-
Meg6_40G_diff_inner3_5cm.s4p	97.5	100	99.7	-
Meg6_40G_diff_inner6_10cm.s4p	99.6	100	99.6	-
Meg6_40G_diff_inner6_10cm_wro...	99.5	100	99.7	-
Meg6_40G_diff_inner6_5cm.s4p	97.5	100	99.6	-
Meg6_40G_se_D1.s2p	99.4	100	98	-
Meg6_40G_se_D2.s2p	99.1	100	97	-
Meg6_40G_se_E1.s2p	99.5	100	97.3	-
Meg6_40G_se_inner6_10cm.s2p	99.3	100	99.6	-
Meg6_40G_se_inner6_10cm_wr_...	99.2	100	99.7	-
Meg6_40G_se_inner6_5cm.s2p	97.8	100	99.5	-
Meg6_40G_se_inner6_5cm_wr_c...	99.5	100	99.6	-
sma_barrel.s2p	-	93	98.9	35

Problem at low frequencies…

TDR pre-qualification (40 GHz VNA)

- Acceptable



- All measurements are done with connectors from unknown vendor
- No measurements for microstrips
- At this point the project was paused for a few months…

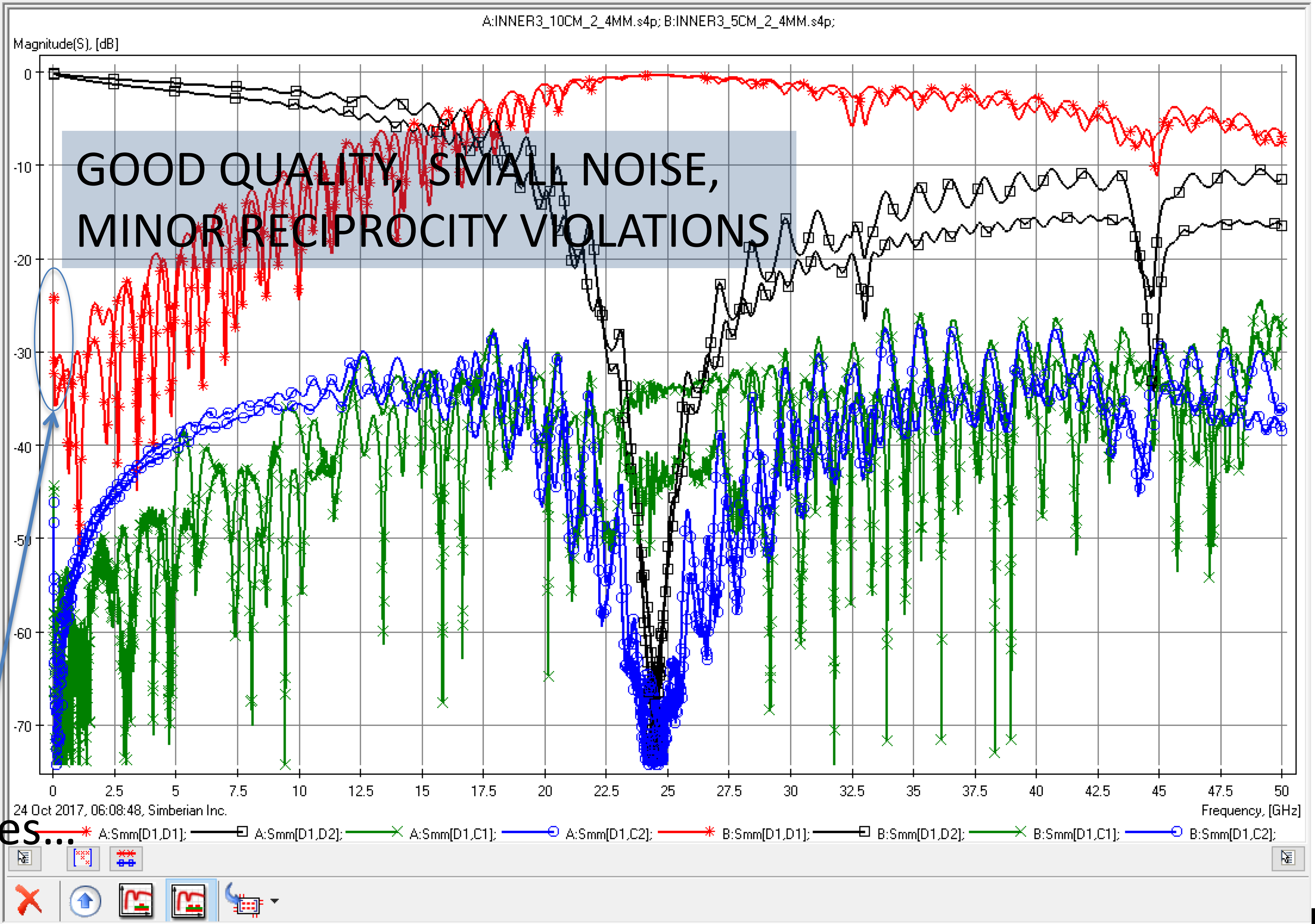
Measurements with 50 GHz VNA

C:\Repository\Simbeor\Support\Infinera\March31_2017_board_and_measurement

File name	Quality	Passivity	Reciprocity	C
BOTTOM_10CM_2_4MM.s4p	99	100	99.6	-
BOTTOM_5CM_2_4MM.s4p	99.1	100	99.5	-
C1_2_4MM.s4p	99.2	100	99.7	-
C2_2_4MM.s4p	99.3	100	99.7	-
C3_2_4MM.s4p	99.2	100	99.6	-
C4_VIA_HIROSE_IFBW_500HZ.s2p	99.7	100	99.9	-
C5_VIA_HIROSE_IFBW_500HZ.s2p	99.7	100	99.8	-
D1_BEATTY_25OHM_INNER1.s2p	99.6	100	99.7	-
D2_BEATTY_25OHM_INNER6.s2p	99.7	100	99.6	-
E1_Meander_10cm_Hirose_con_IFBW_500H...	99	100	99.8	-
F1_2_4MM.s4p	99.3	100	99.6	-
F2_2_4MM.s4p	99.3	100	99.7	-
F3_2_4MM.s4p	99.2	100	99.5	-
G1_2_4MM.s4p	91	100	99.6	-
G2_2_4MM.s4p	97.5	100	99.6	-
INNER1_10CM_2_4MM.s4p	96.6	100	99.8	-
INNER1_5CM_2_4MM.s4p	99.1	100	99.8	-
INNER2_10CM_2_4MM.s4p	93.6	100	99.8	-
INNER2_5CM_2_4MM.s4p	99.2	100	99.8	-
INNER3_10CM_2_4MM.s4p	91.2	100	99.8	-
INNER3_5CM_2_4MM.s4p	99.2	100	99.8	-
INNER6_10CM_2_4MM.s4p	97.7	100	99.8	-
Inner6_10cm_SE_Amp_con_IFBW_500Hz.s2p	99.5	100	99.9	-
Inner6_10cm_SE_Hirose_con_IFBW_1kHz.s2p	99.4	100	97	-
Inner6_50Ohm_10CM_Hirose_IFBW_500HZ.s...	99.6	100	99.7	-
Inner6_50Ohm_5CM_Hirose_IFBW_500HZ.s2p	99.5	100	99.8	-
INNER6_5CM_2_4MM.s4p	98.8	100	99.7	-

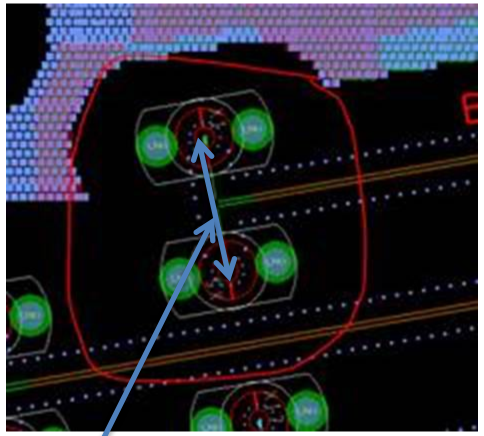
Problem at low frequencies...

Ready

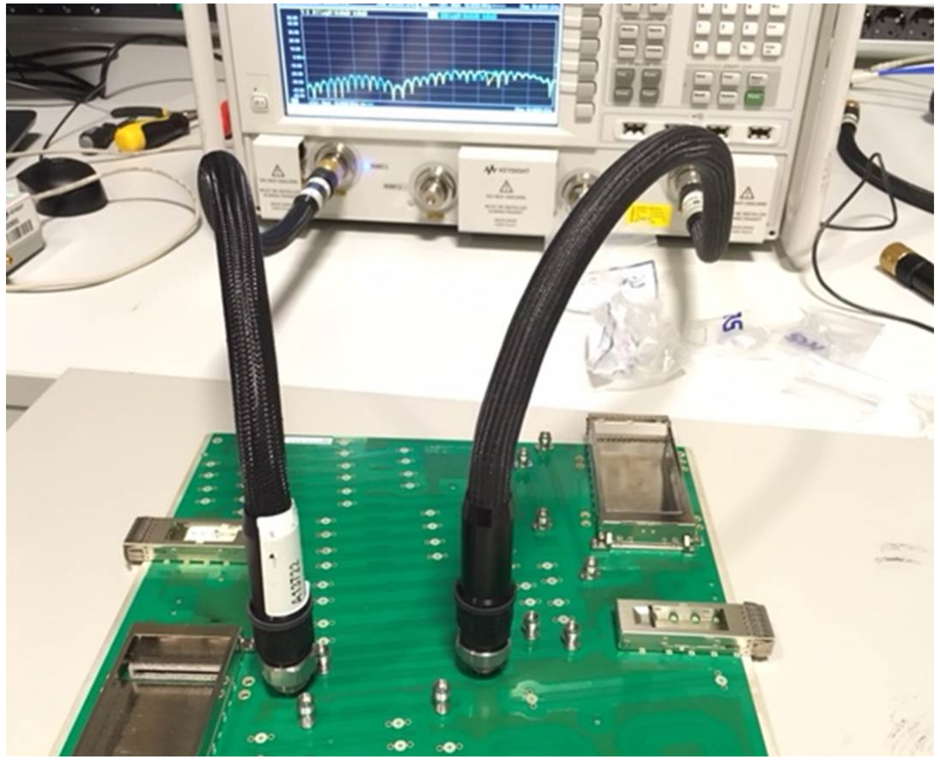


Measurements with 50 GHz VNA

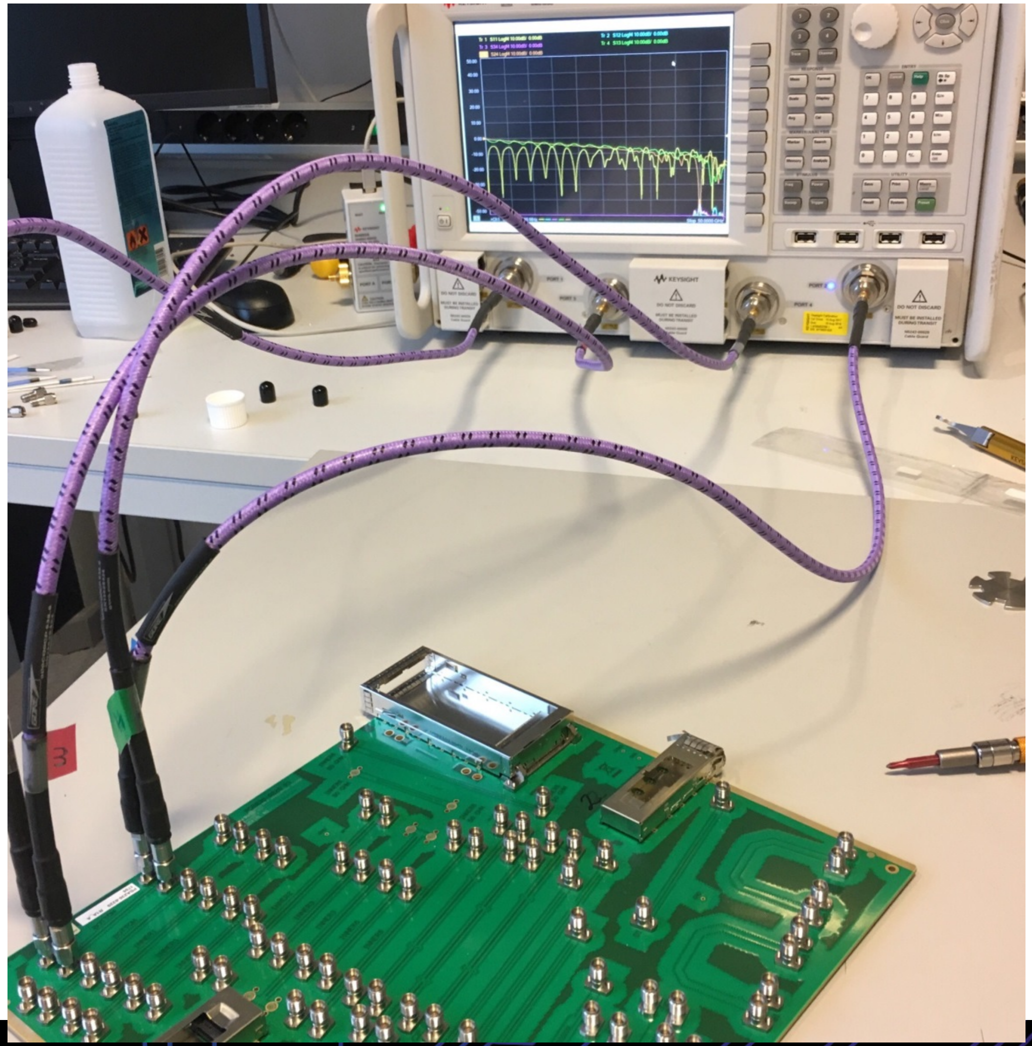
- Reality: Cables were too thick to make measurements on differential traces



This distance is too small to have two cables side by side

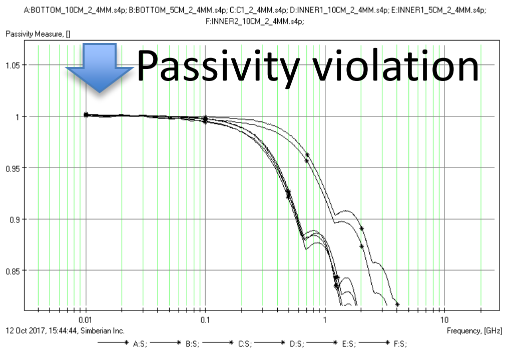


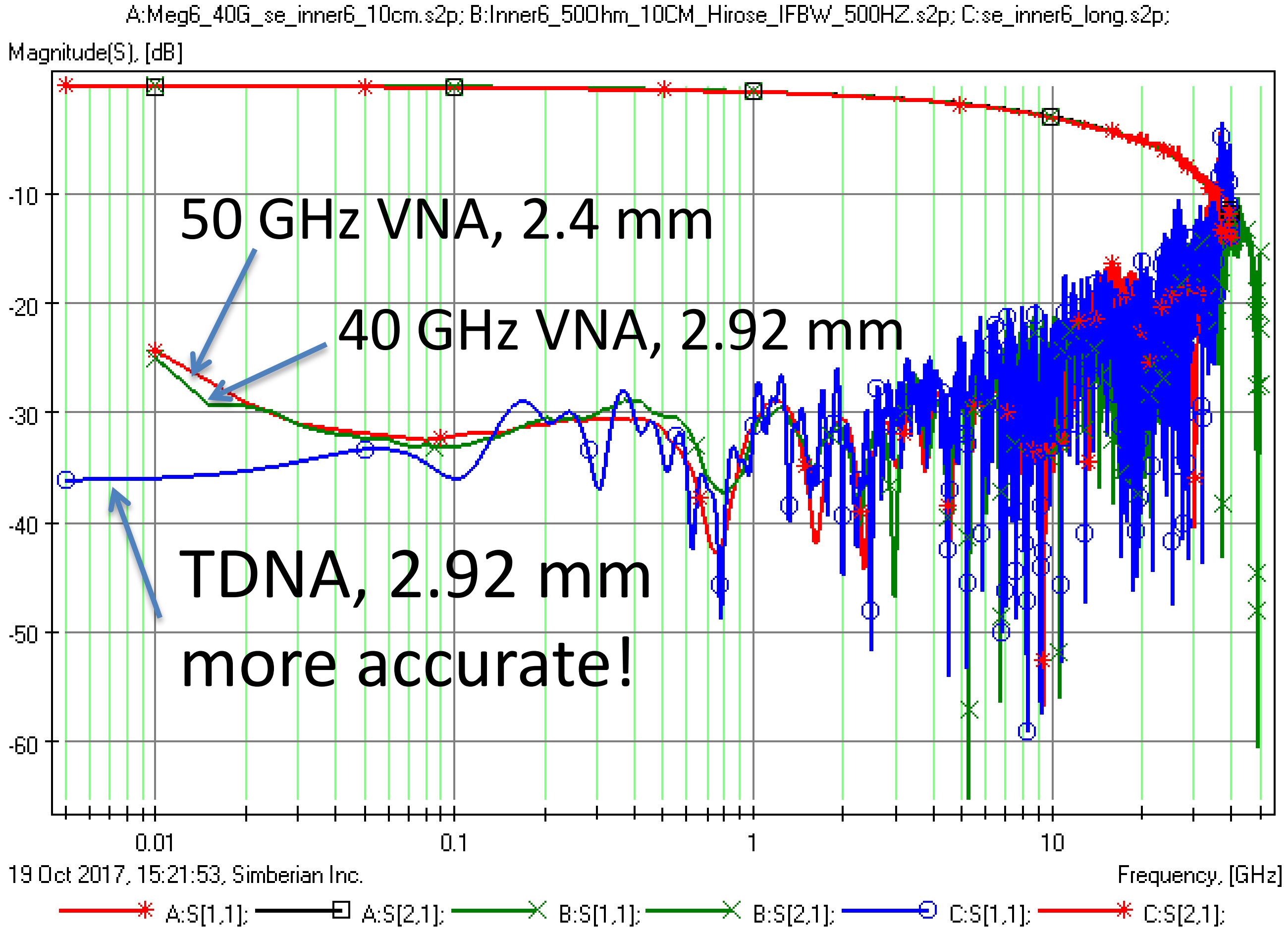
Reality: Thinner cables are used instead – may be not so high quality cables…



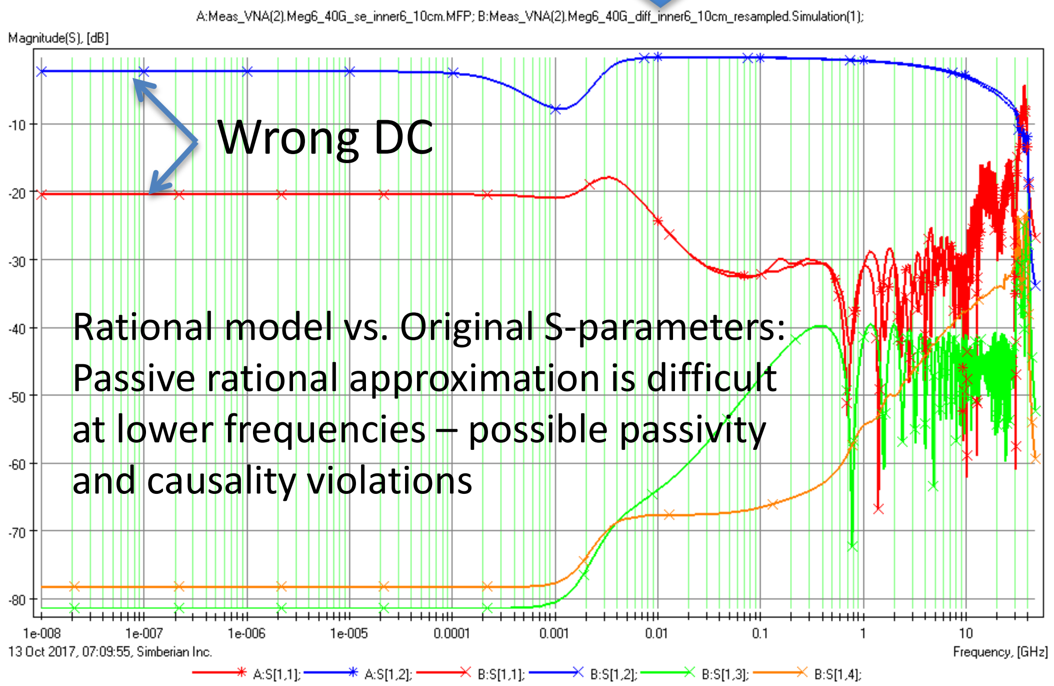
Reality: Low frequency problem

- Reflection parameters measured with both VNAs converges to wrong value at DC
- Caused by ECAL calibration kit



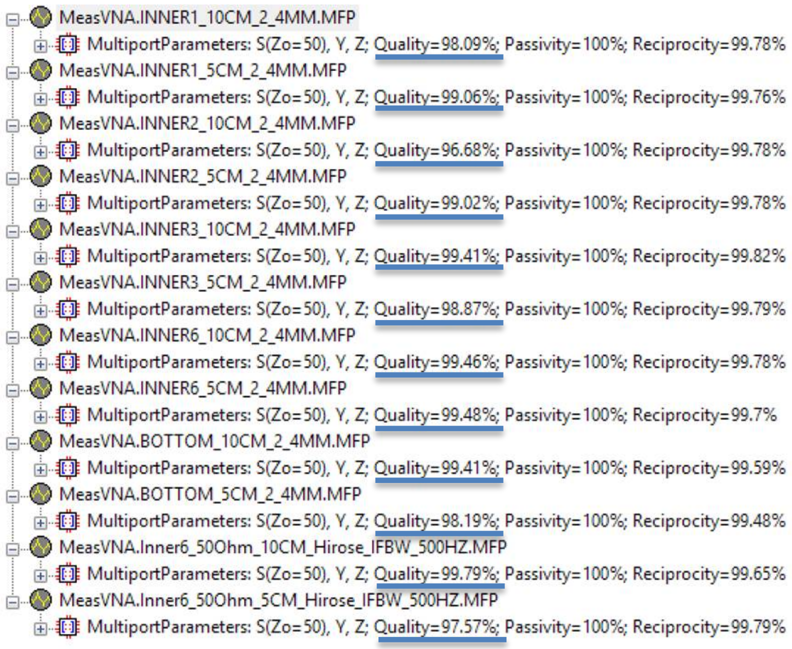


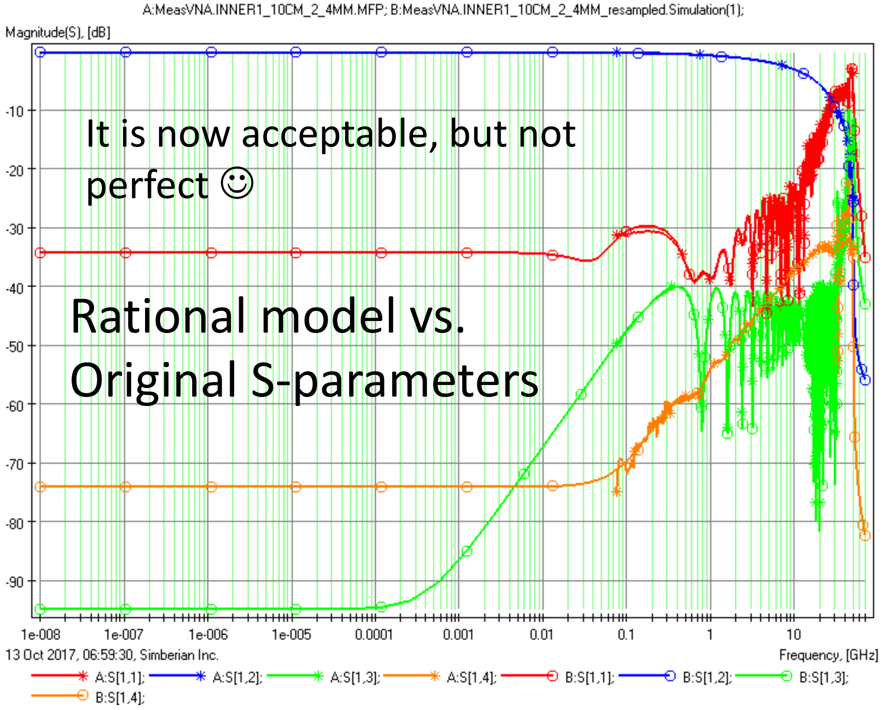
Passivity violation here makes extrapolation wrong



Possible correction (workaround)

- Use mechanical calibration kit
- Use another VNA type/brand
- Just to go forward, cut the data below 75 MHz and use the extrapolation with the rational approximation (not reliable to predict the DC)



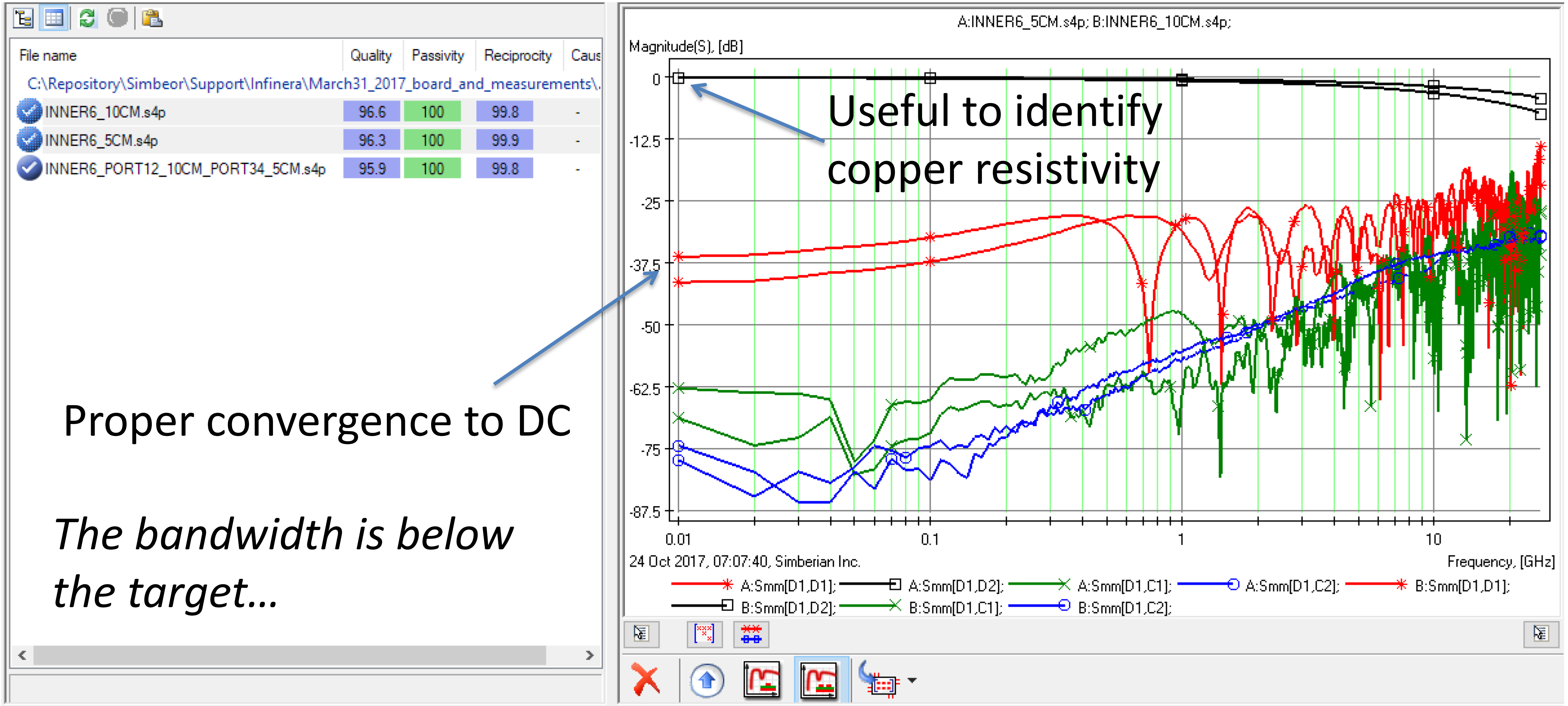


Reality: Without frequency points below the skin-effect onset frequency (no DC) – it is not possible to extract copper resistivity

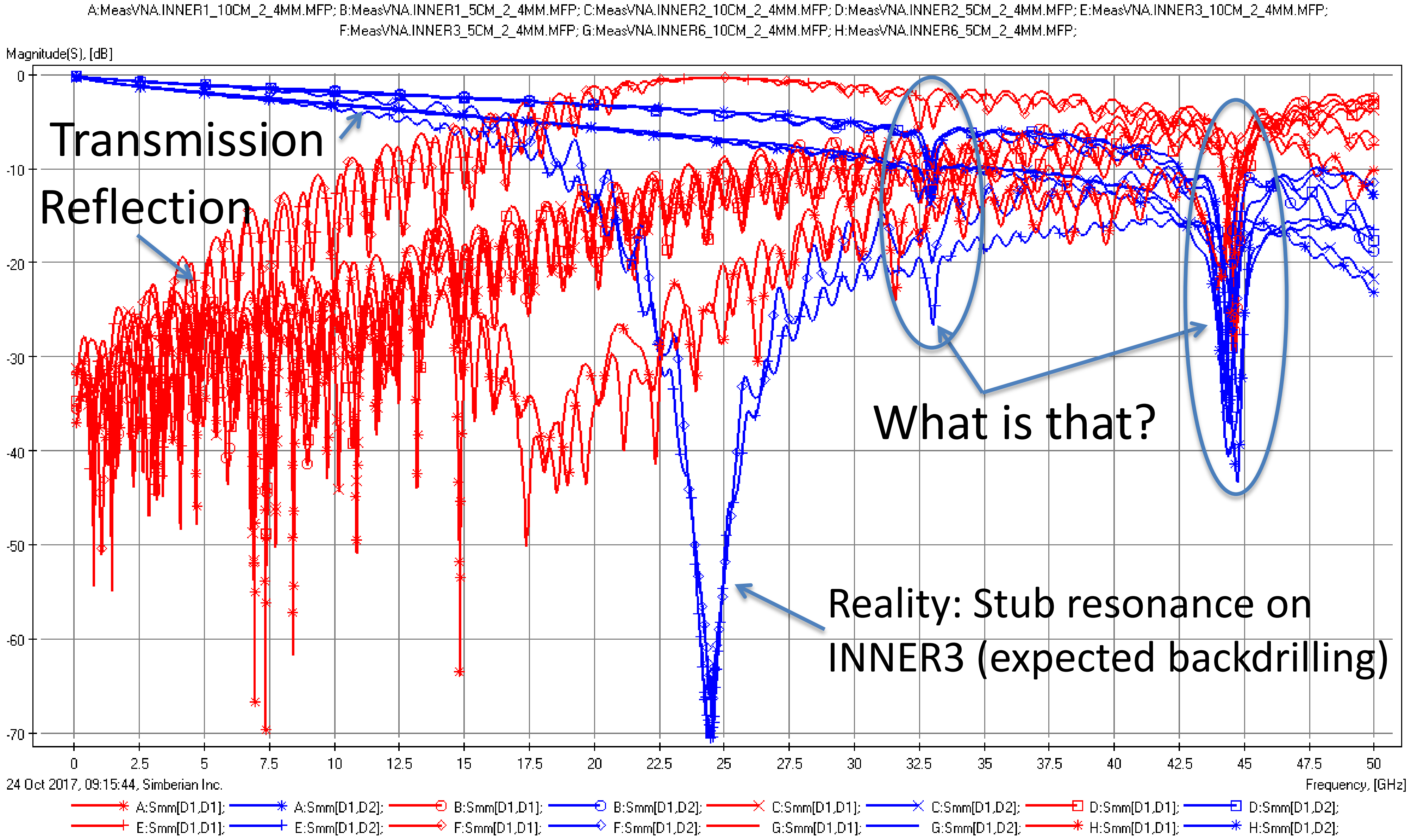
"…a 0.5 dB error injected at a lower frequency (<10 MHz) on transmission could take an 85% open eye to a fully closed eye", J. Martens, B. Buxton, Signal Integrity: Frequency range matters, Anritsu

Measurements with low frequency data

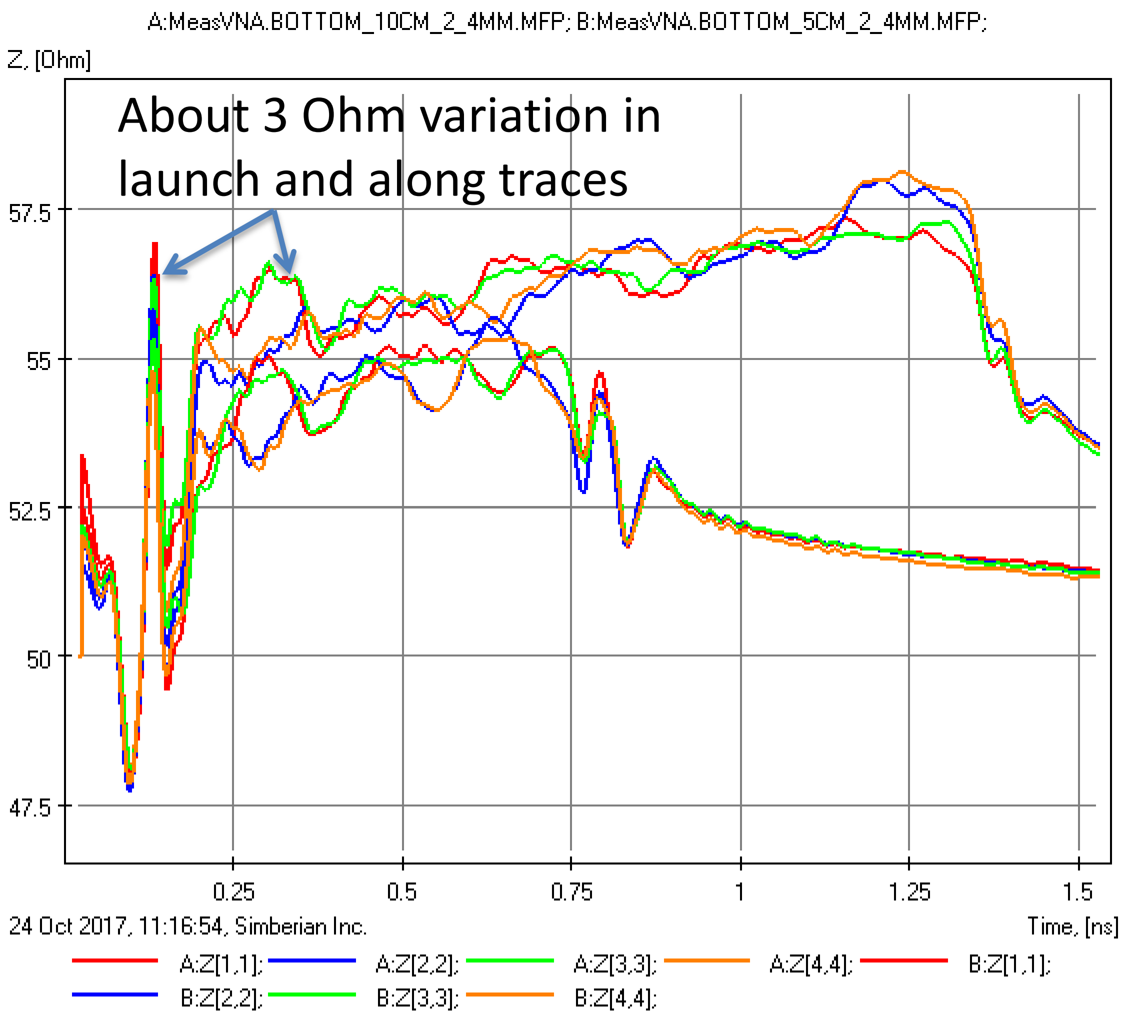
- 10MHz-26.5 GHz on INNER6 – measurements with mechanical calibration kit:

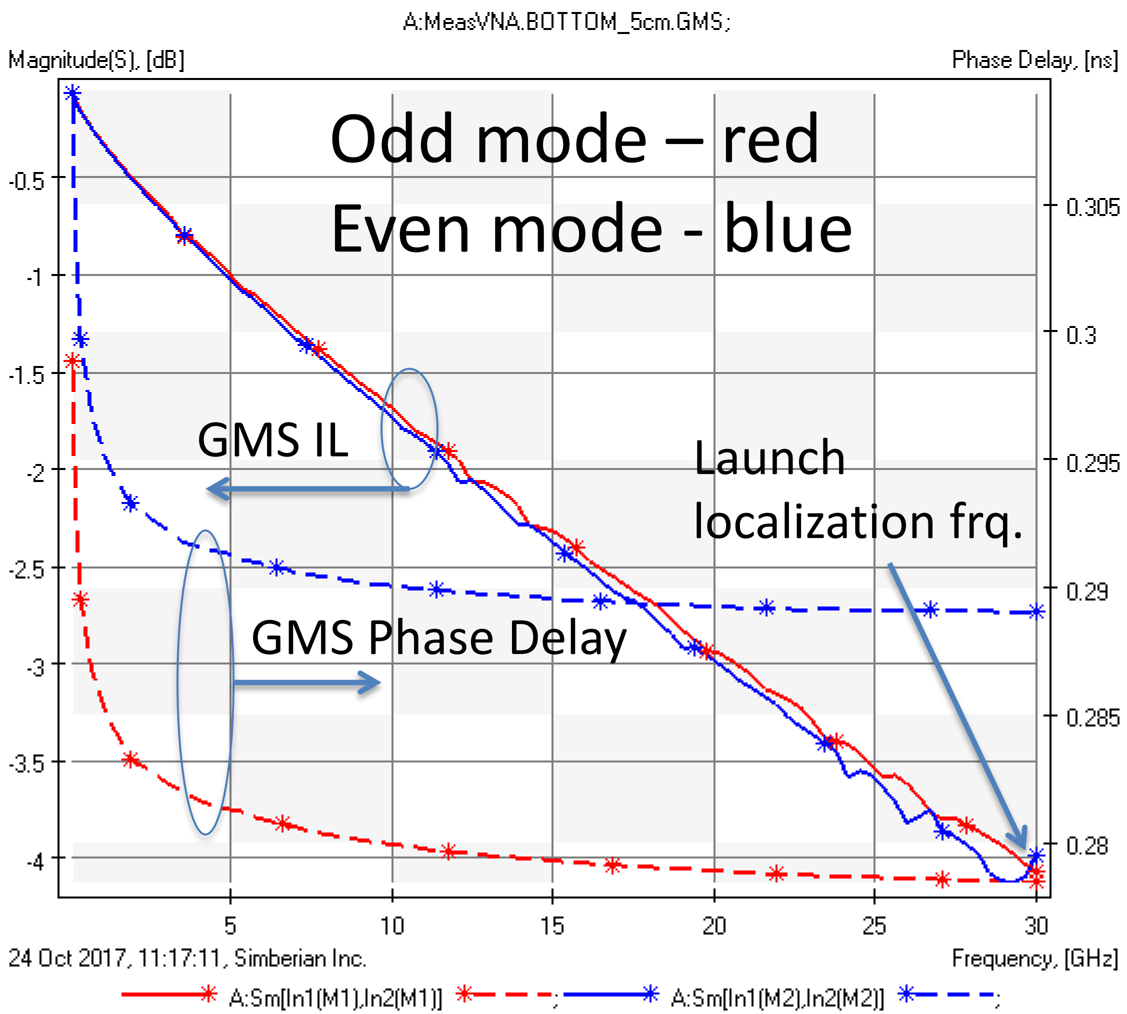


S-parameters for differential material identification structures (simple links)



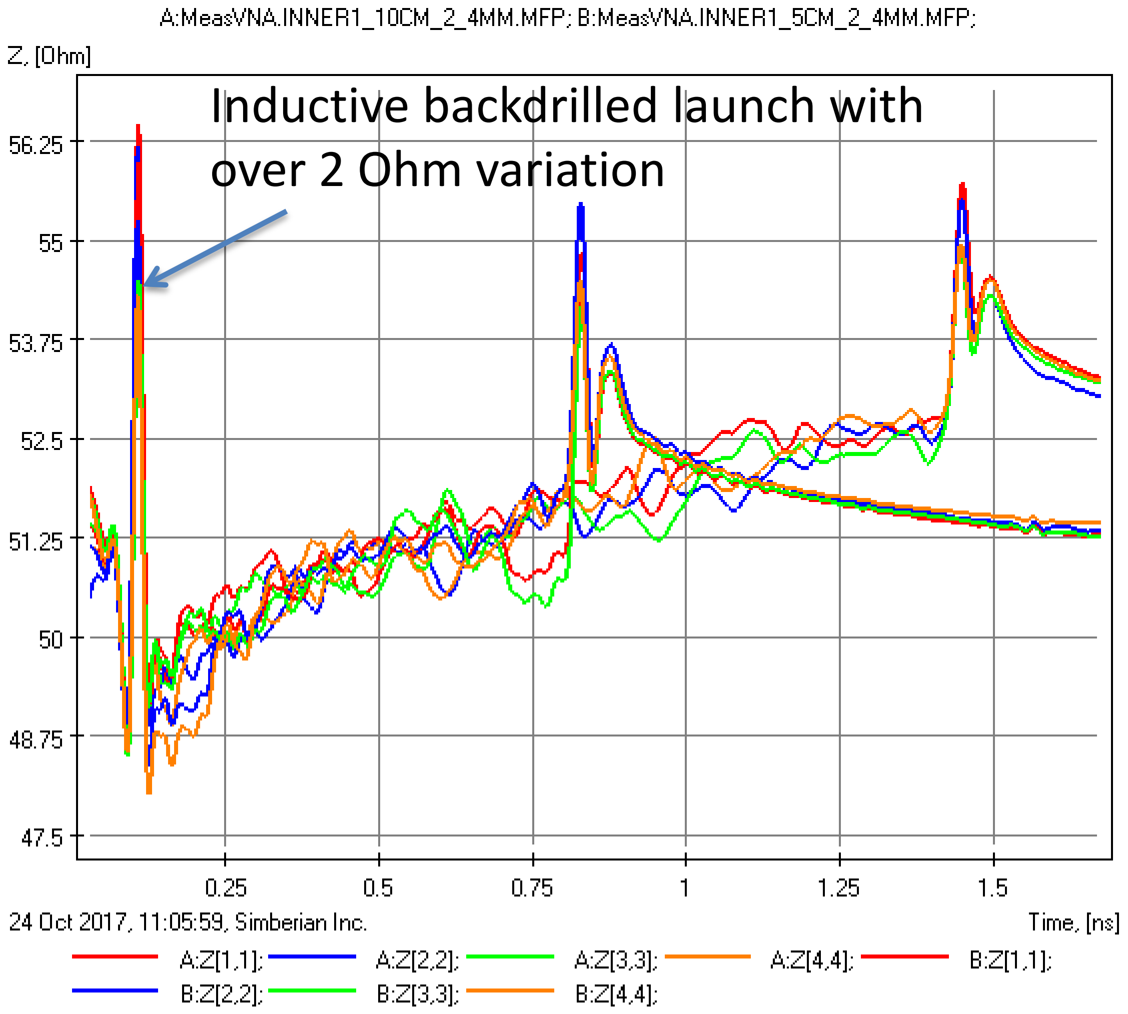
TDR and GMS-parameters: BOTTOM

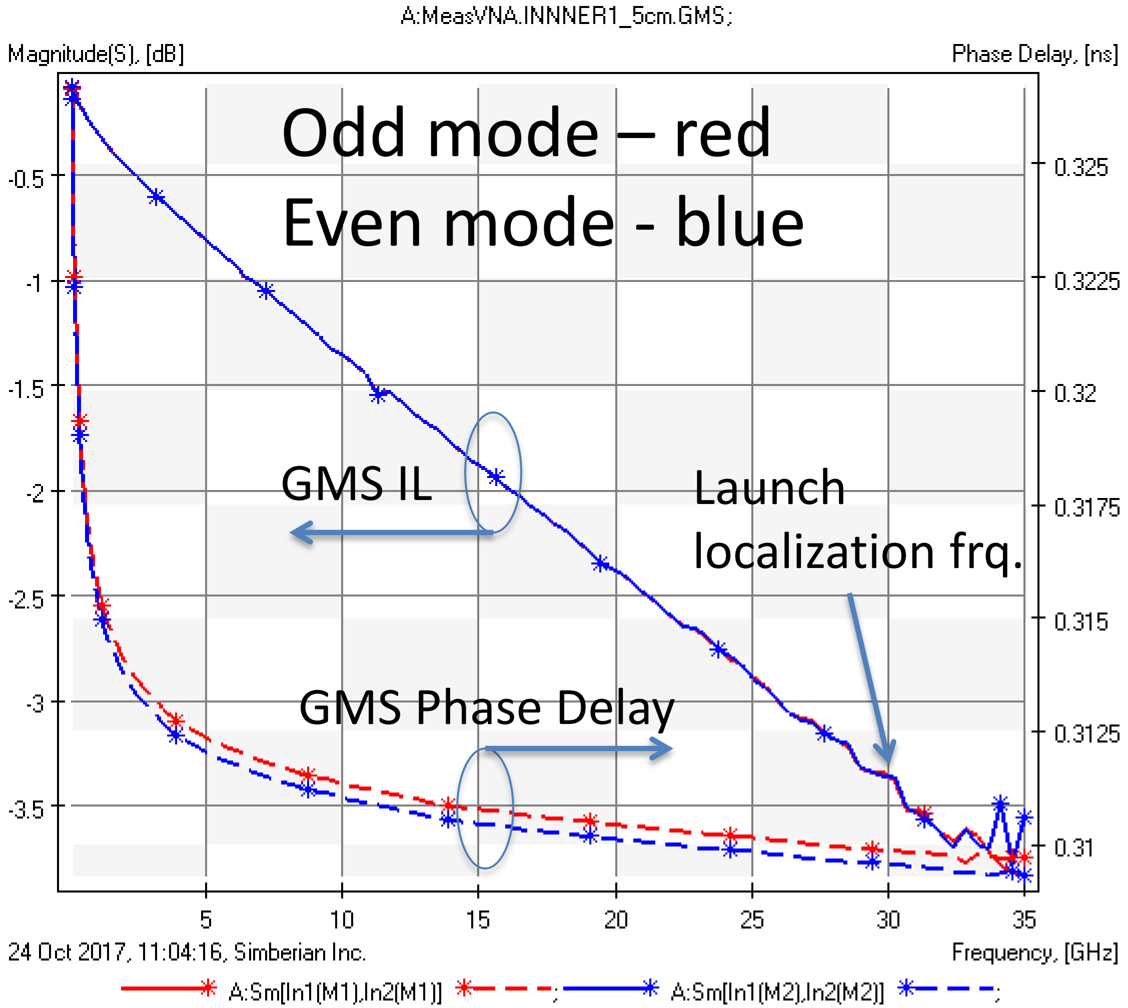




Difference in phase delay (cause FEXT) is expected…

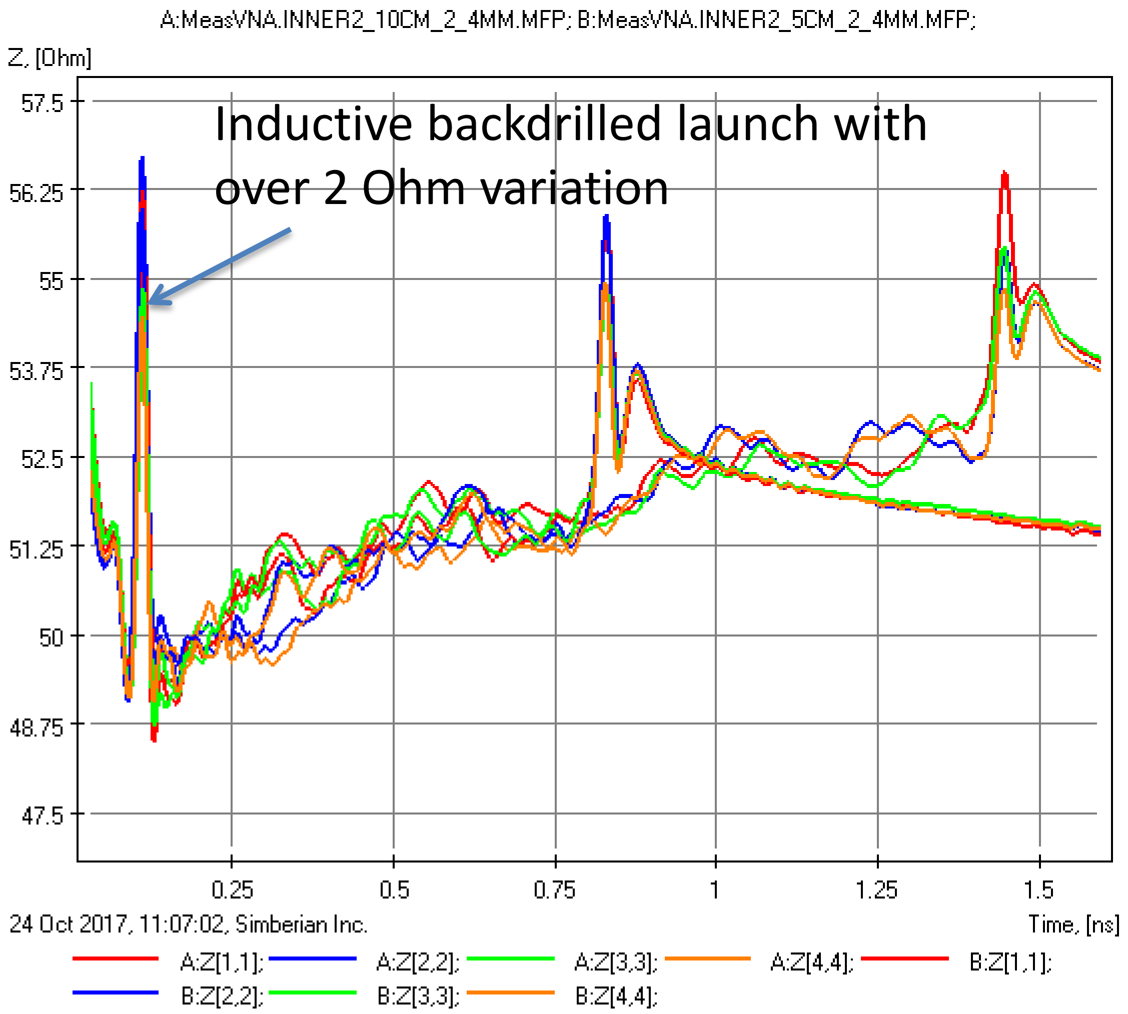
TDR and GMS-parameters: INNER1

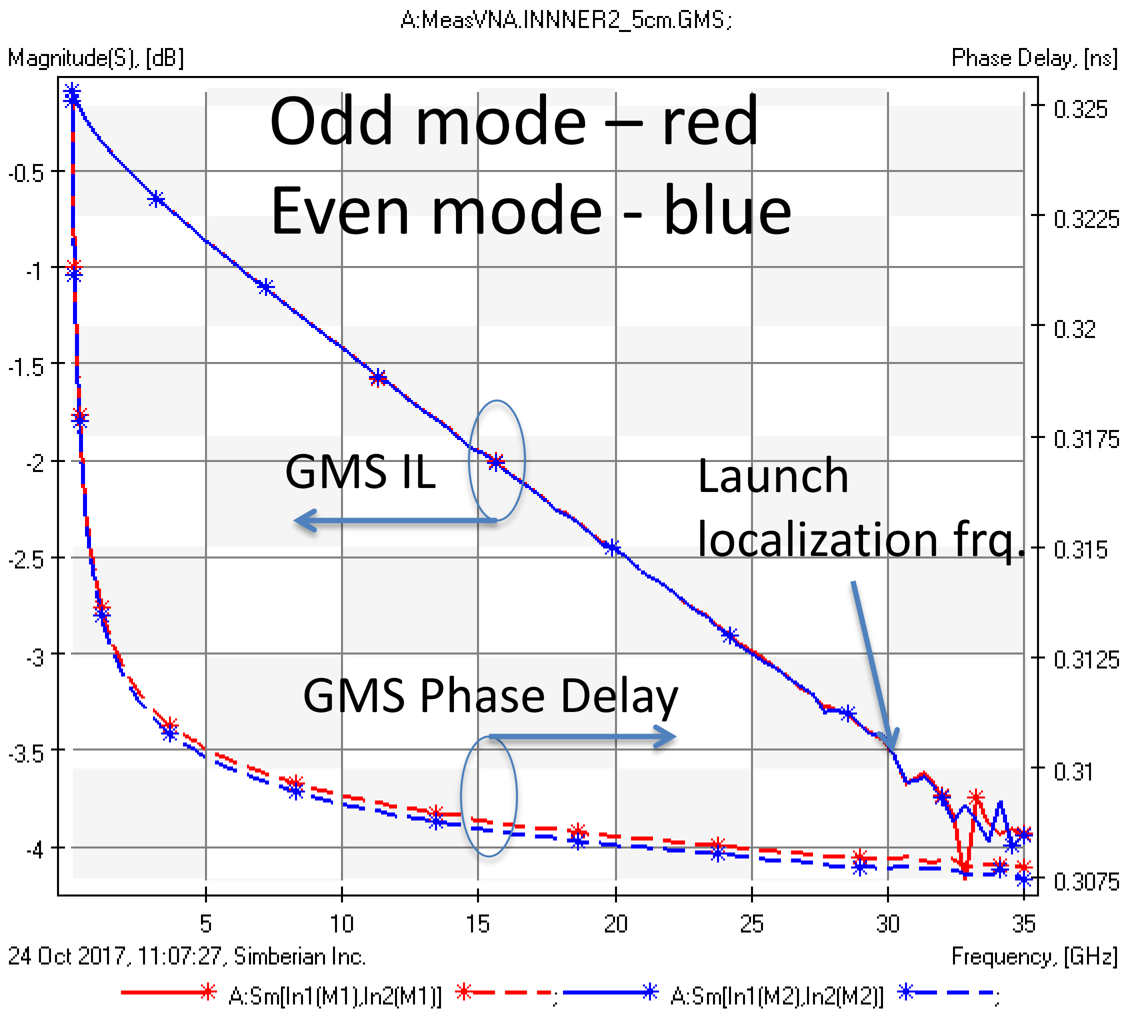




Difference in phase delay (cause FEXT) indicated dielectric inhomogeneity…

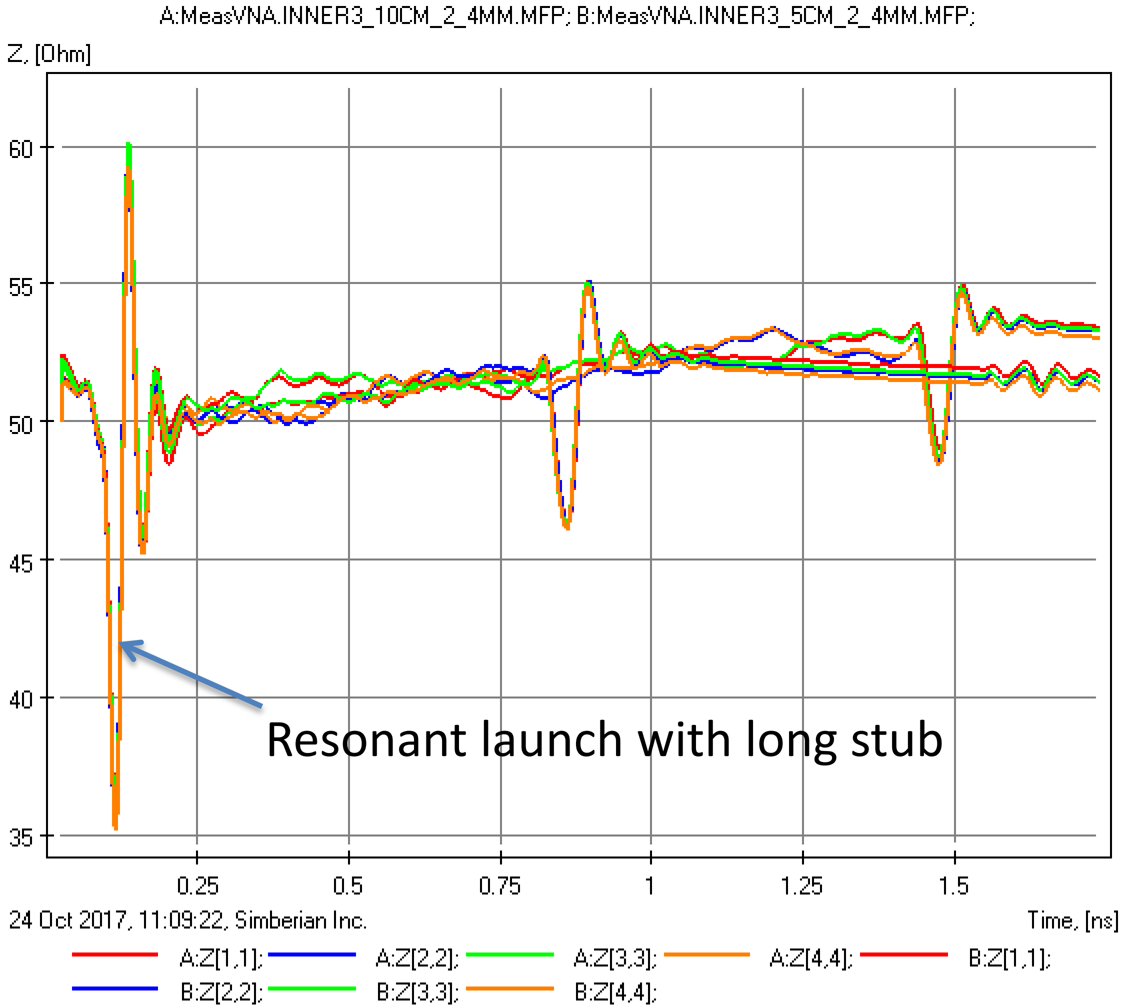
TDR and GMS-parameters: INNER2

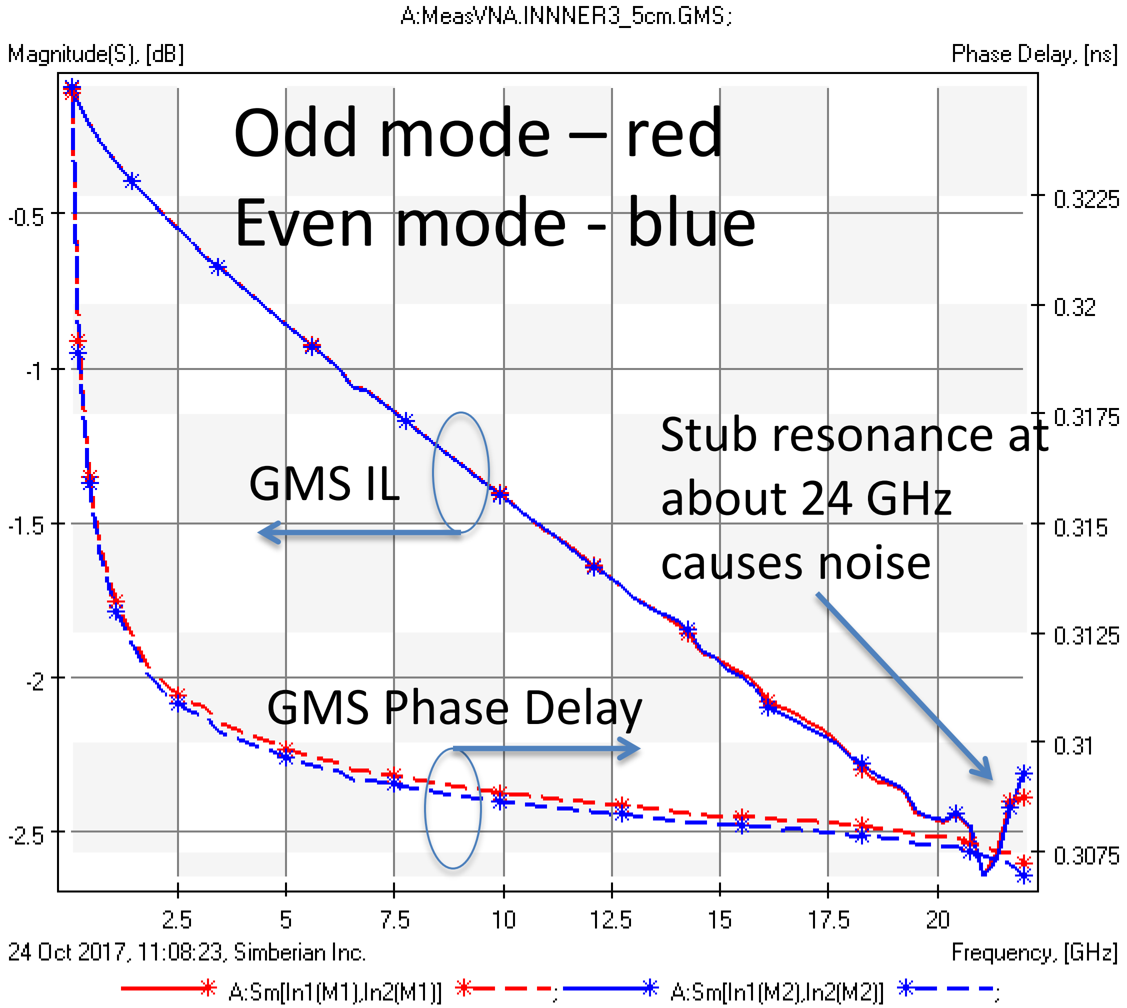




Difference in phase delay (cause FEXT) indicated dielectric inhomogeneity…

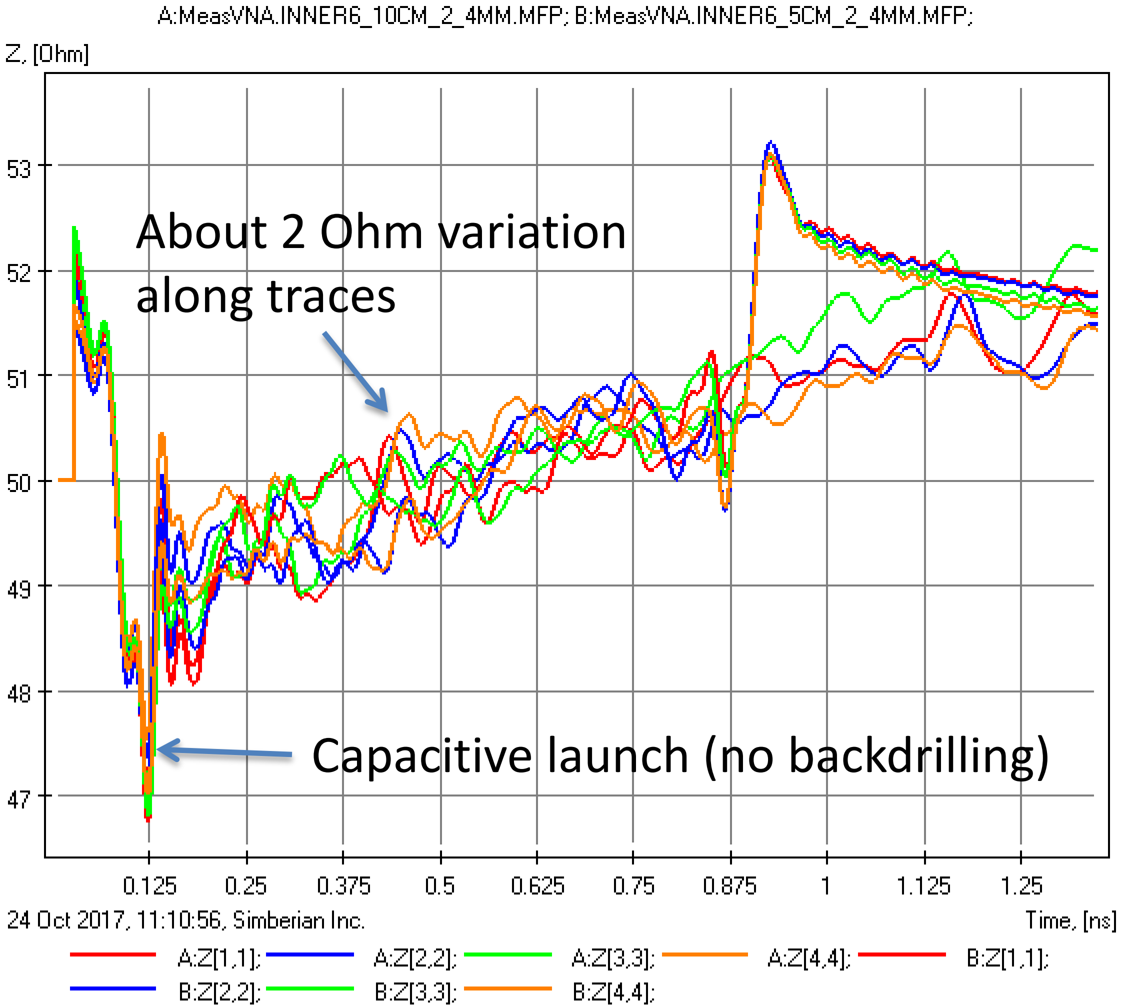
TDR and GMS-parameters: INNER3

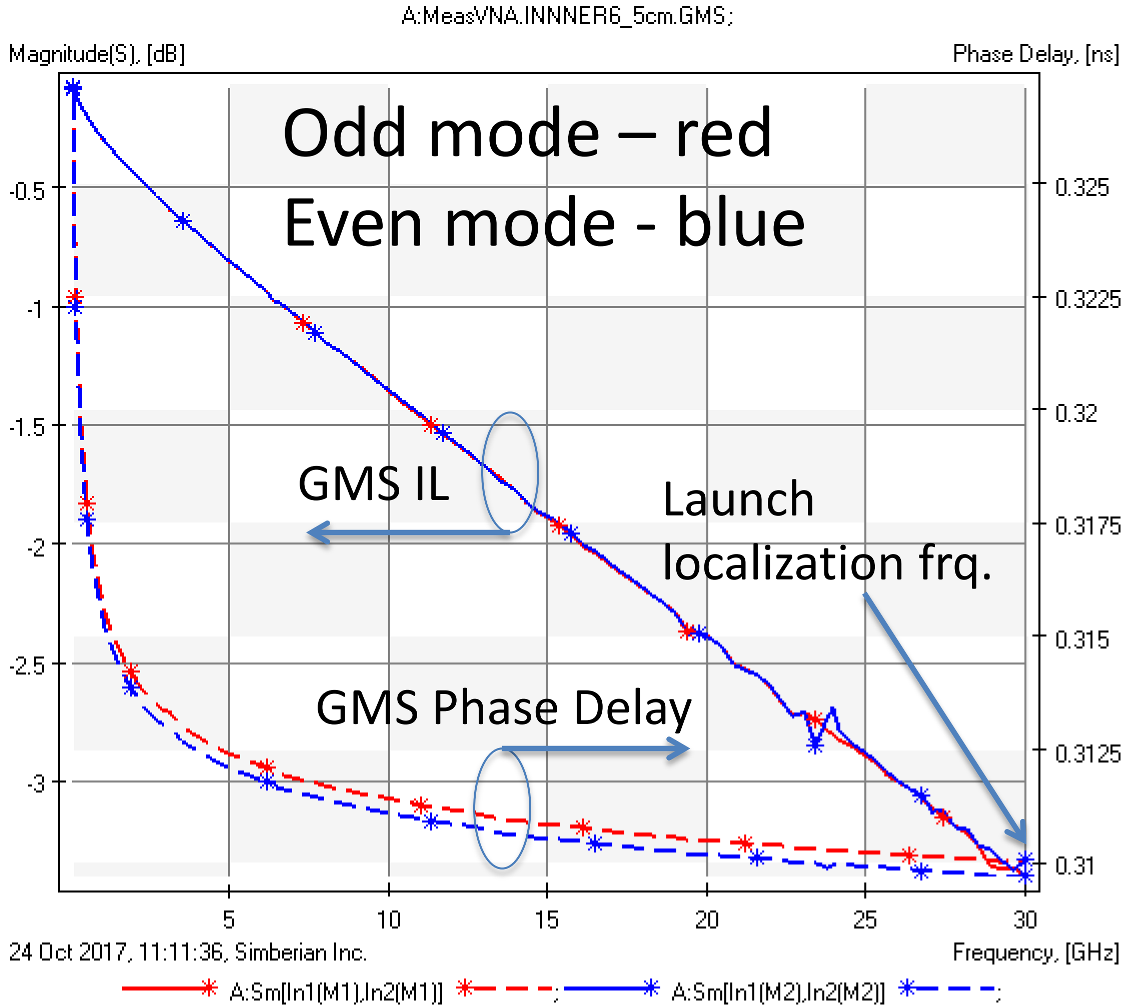




Difference in phase delay (cause FEXT) indicated dielectric inhomogeneity…

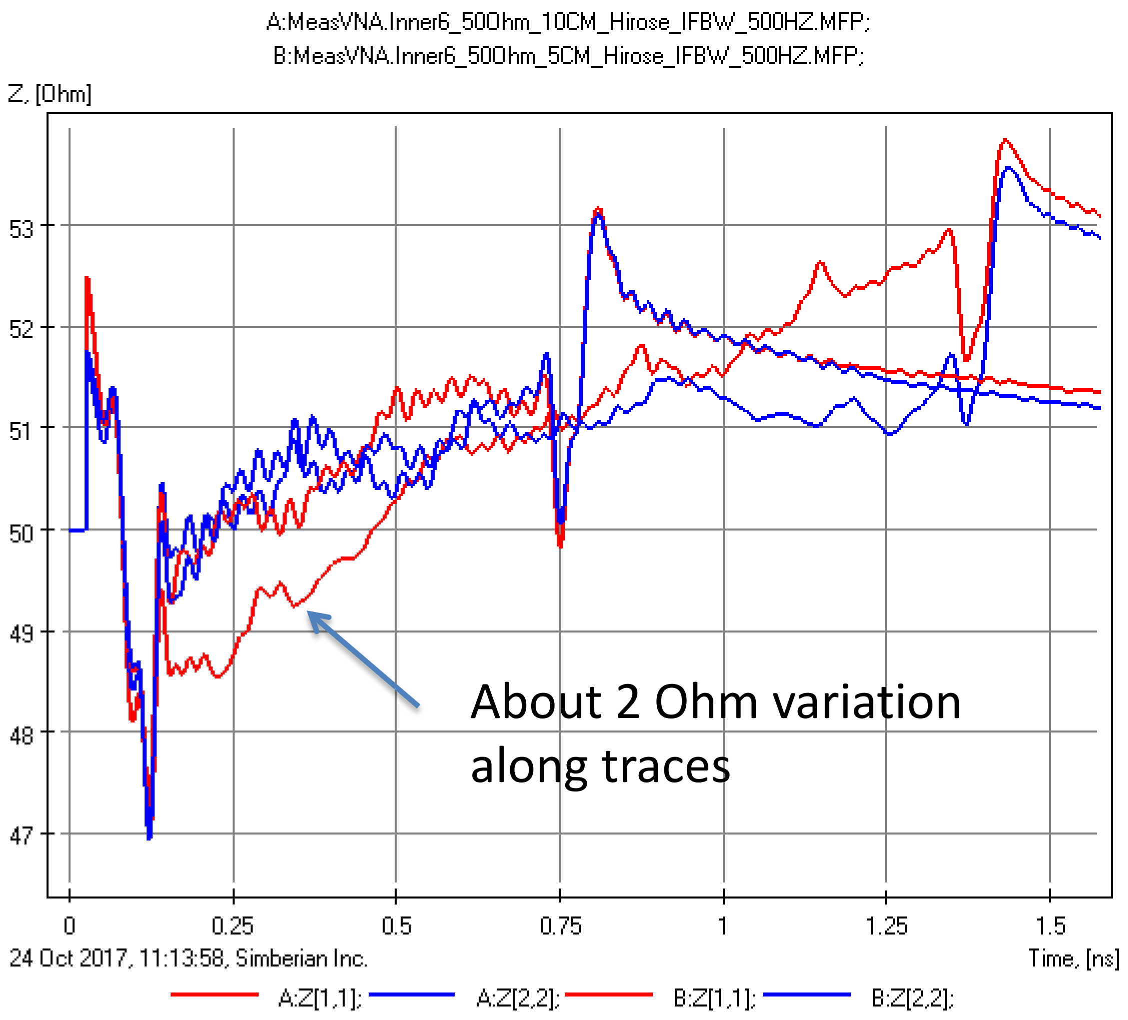
TDR and GMS-parameters: INNER6

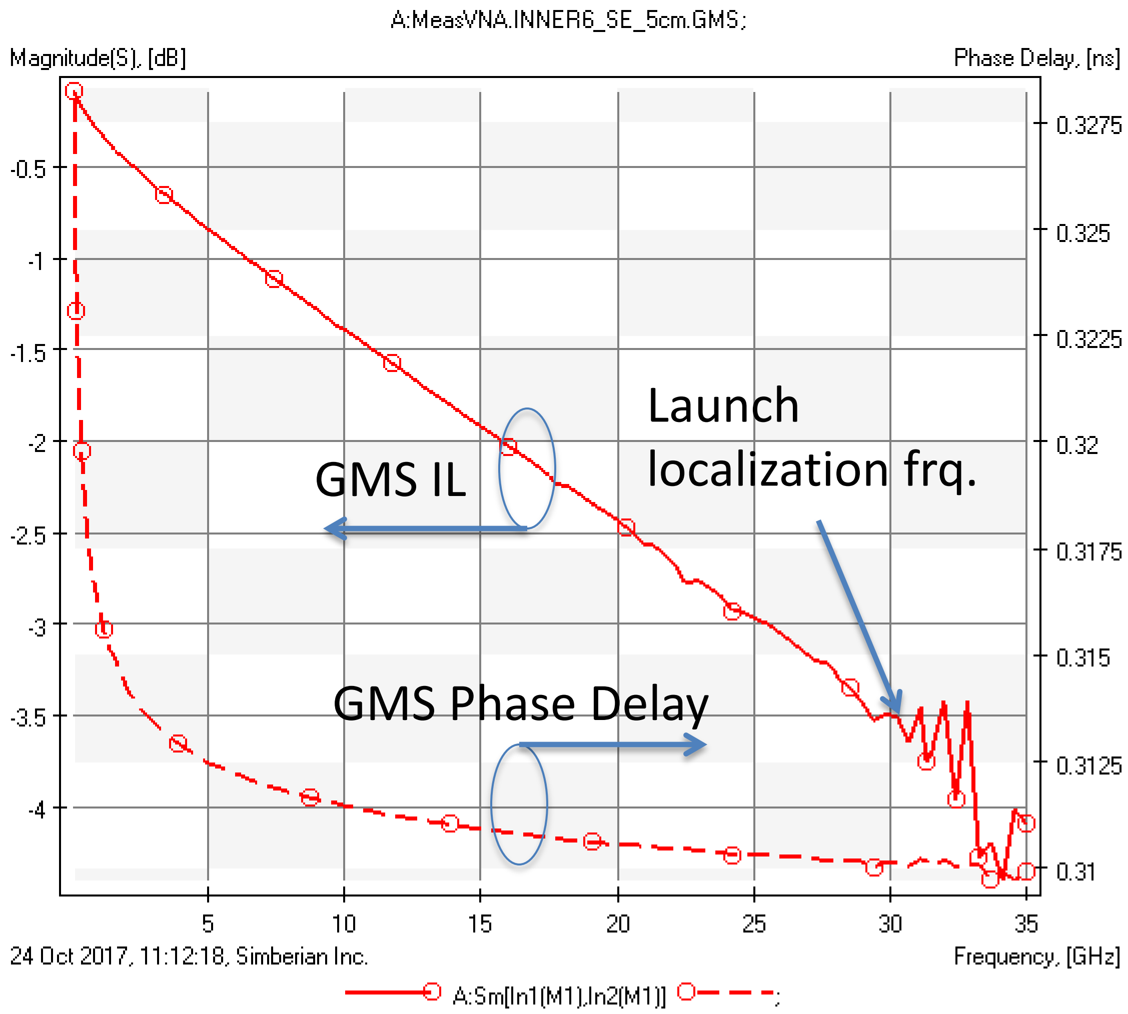




Difference in phase delay (cause FEXT) indicated dielectric inhomogeneity…

TDR and GMS-parameters: INNER6

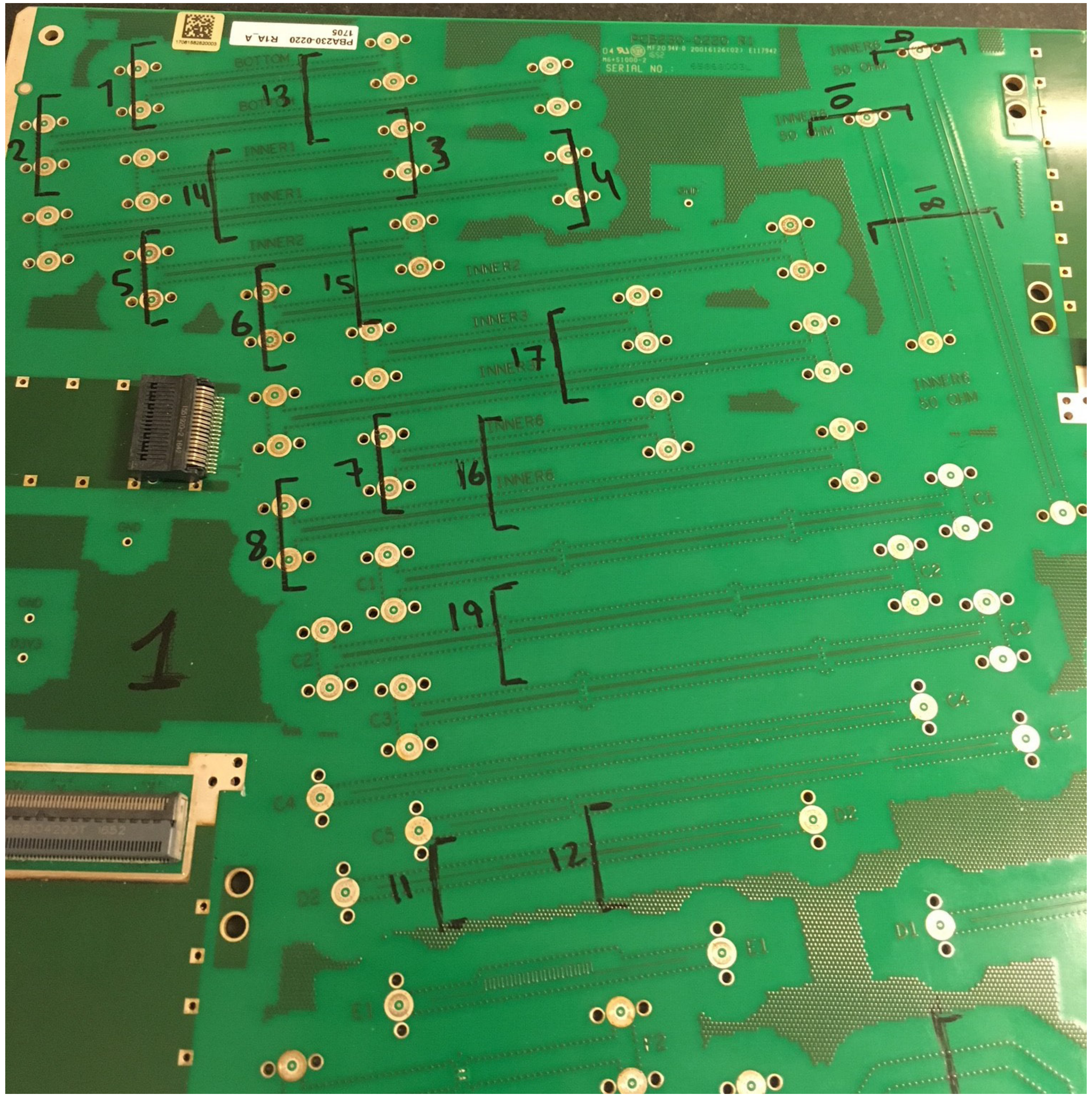


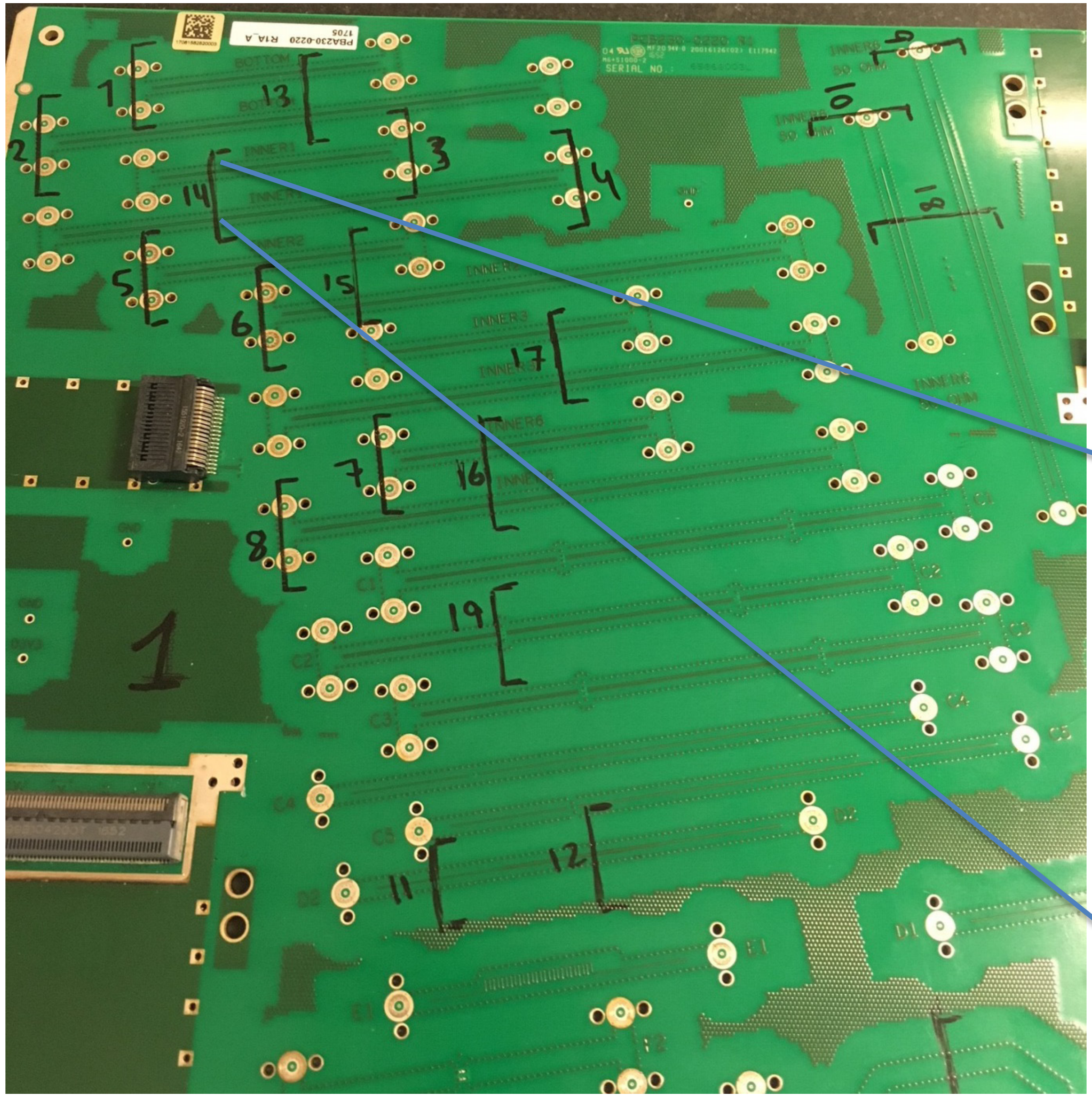


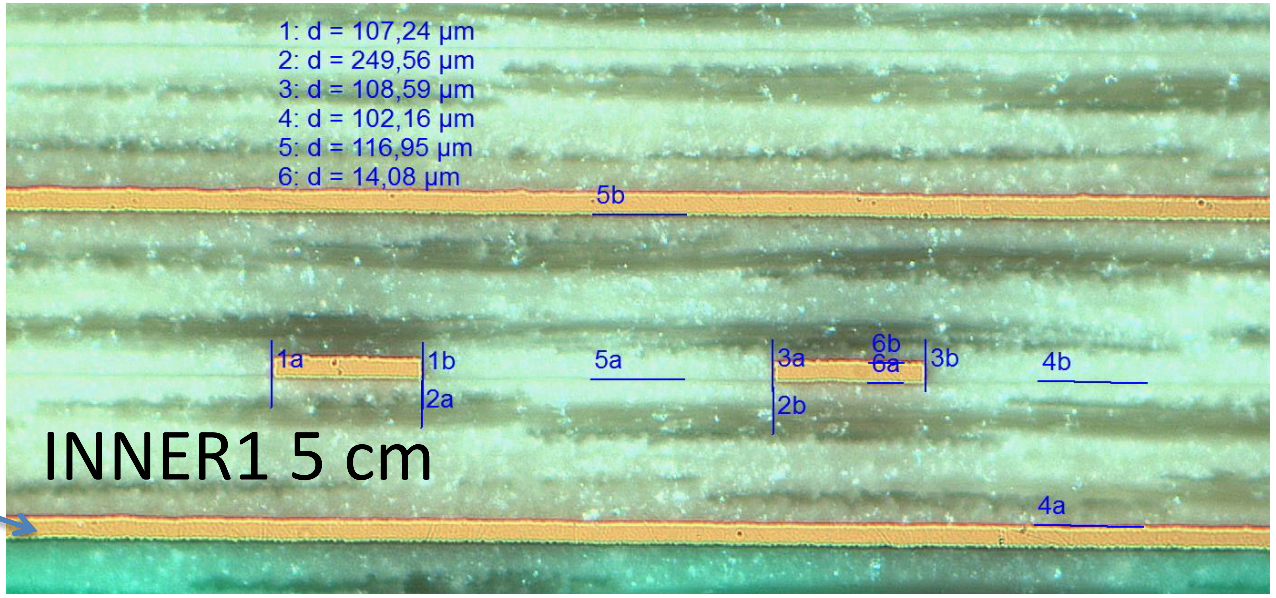
Reality: What is in the board?

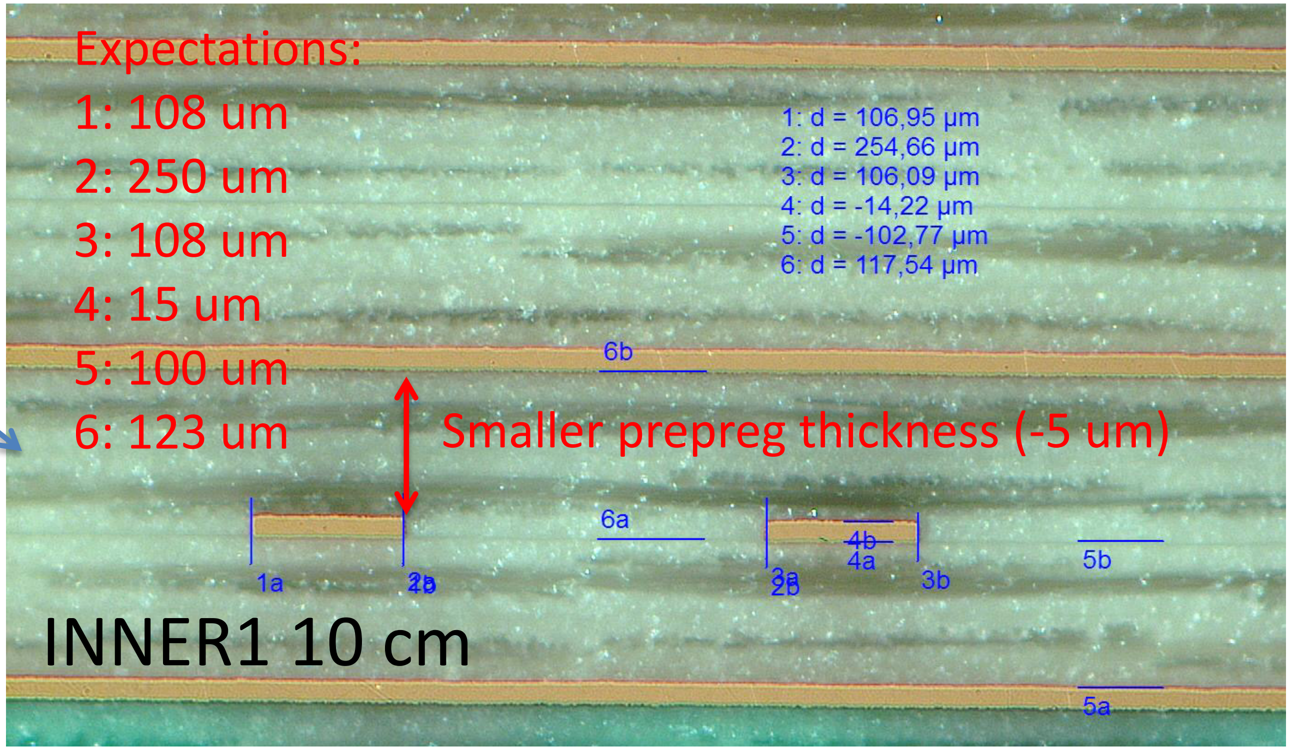
Validation board cross-sectioning

- Traces on material identification structures, launches, Beatty in INNER6 and viaholes
- Not a statistical investigation, but let's see how our expectations are close to reality…





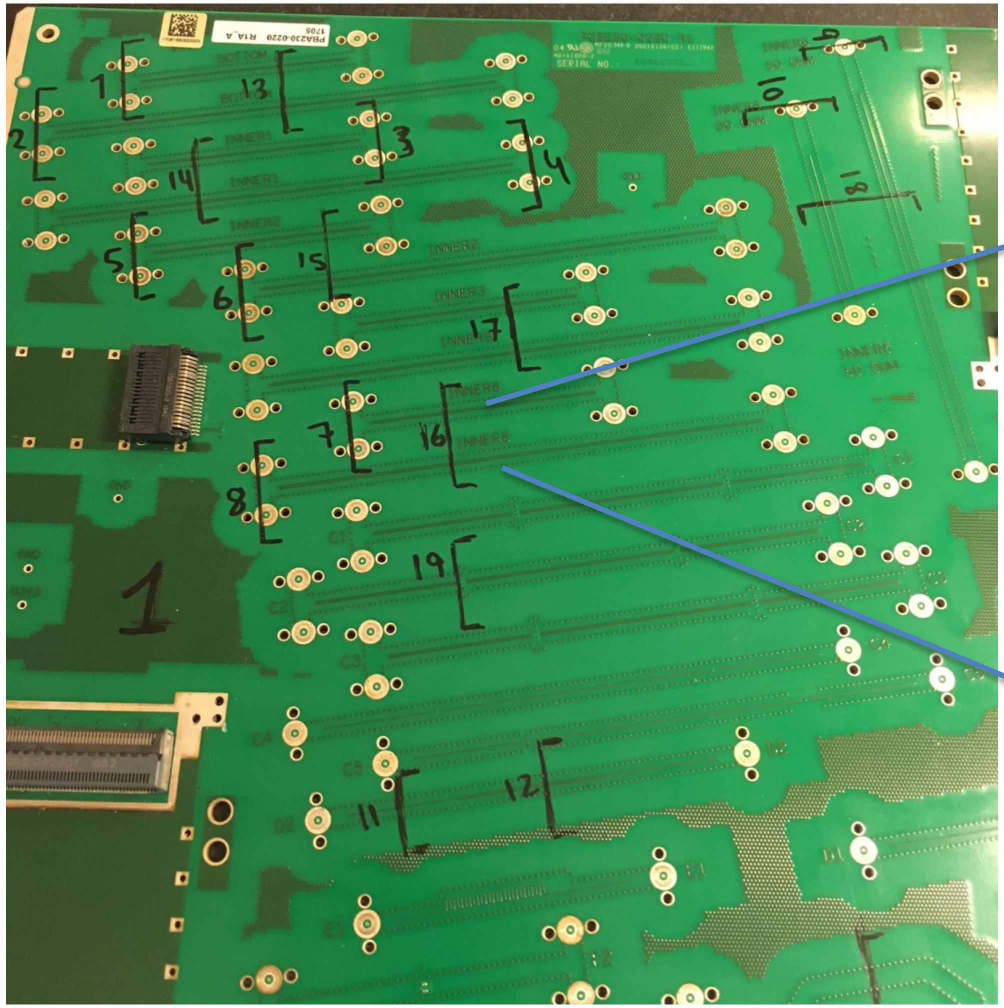

1: d = 107,24 µm
2: d = 249,56 µm
3: d = 108,59 µm
4: d = 102,16 µm
5: d = 116,95 µm
6: d = 14,08 µm
INNER1 5 cm

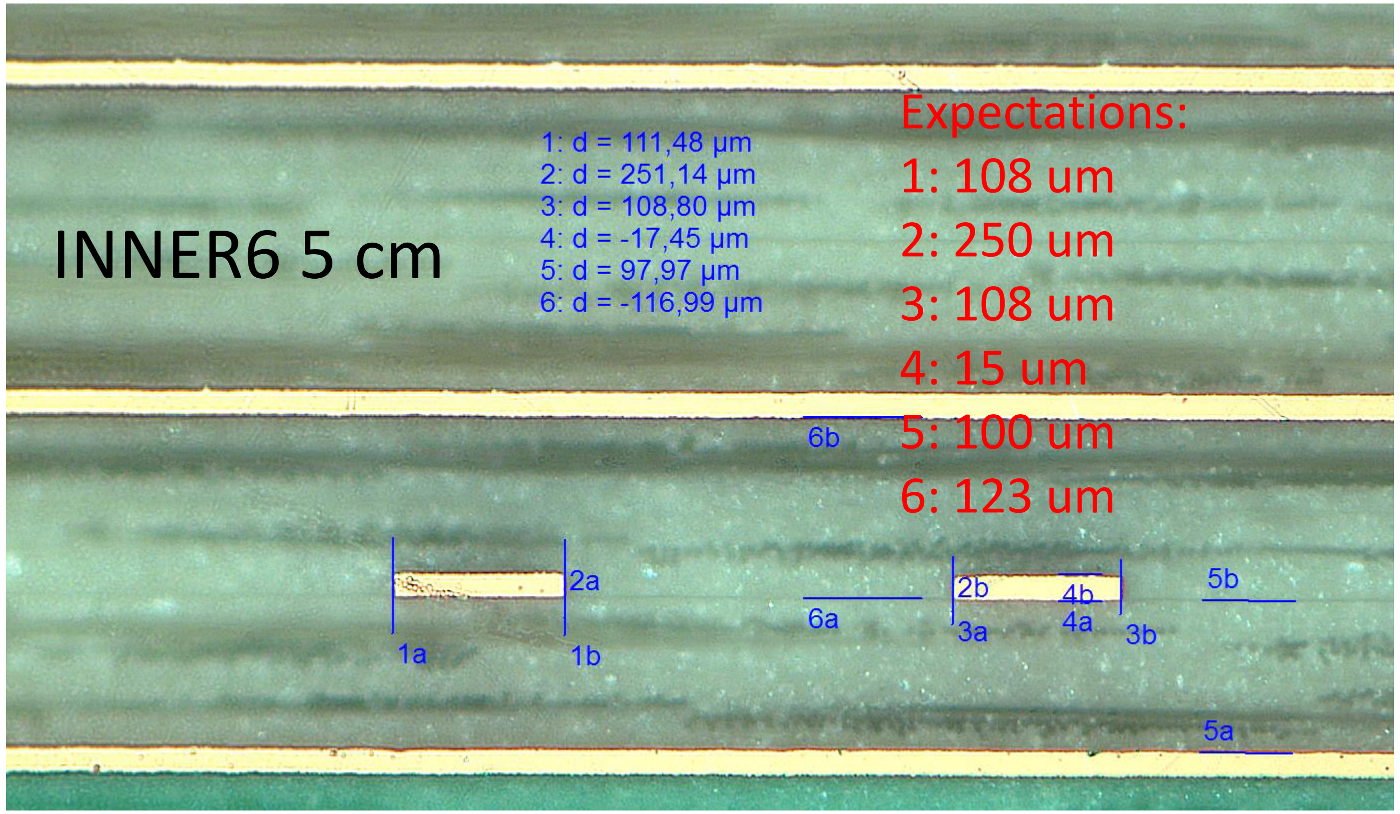

Expectations:
1: 108 um
2: 250 um
3: 108 um
4: 15 um
5: 100 um
6: 123 um
Smaller prepreg thickness (-5 um)
1: d = 106,95 µm
2: d = 254,66 µm
3: d = 106,09 µm
4: d = -14,22 µm
5: d = -102,77 µm
6: d = 117,54 µm
INNER1 10 cm

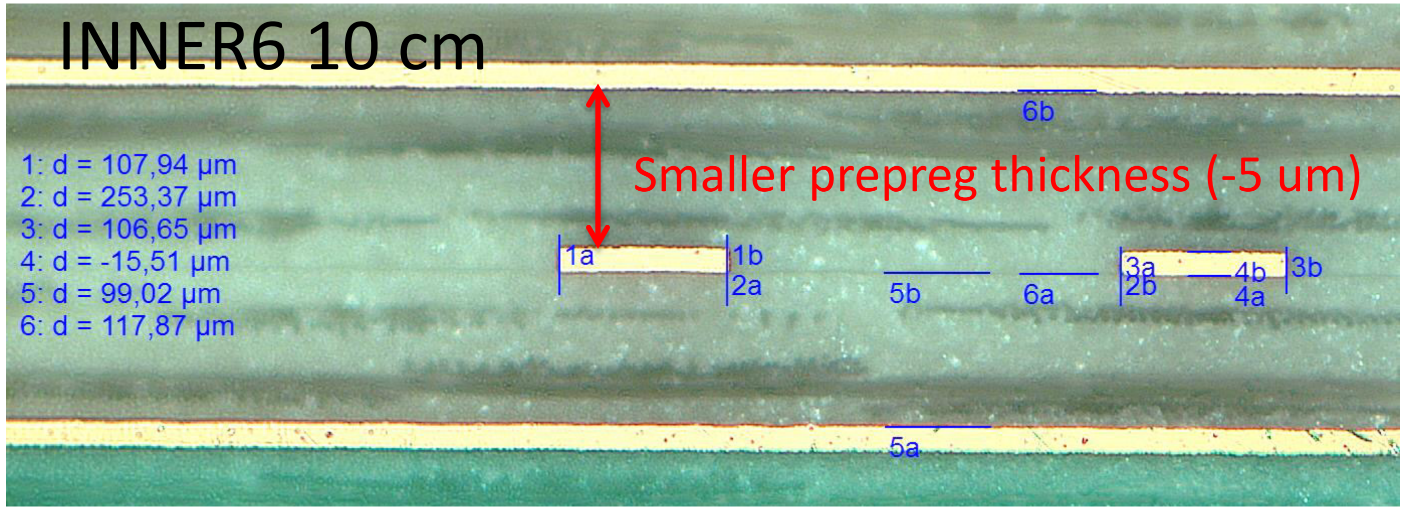
INNER6

Difference in prepreg thickness

Close shape and geometry

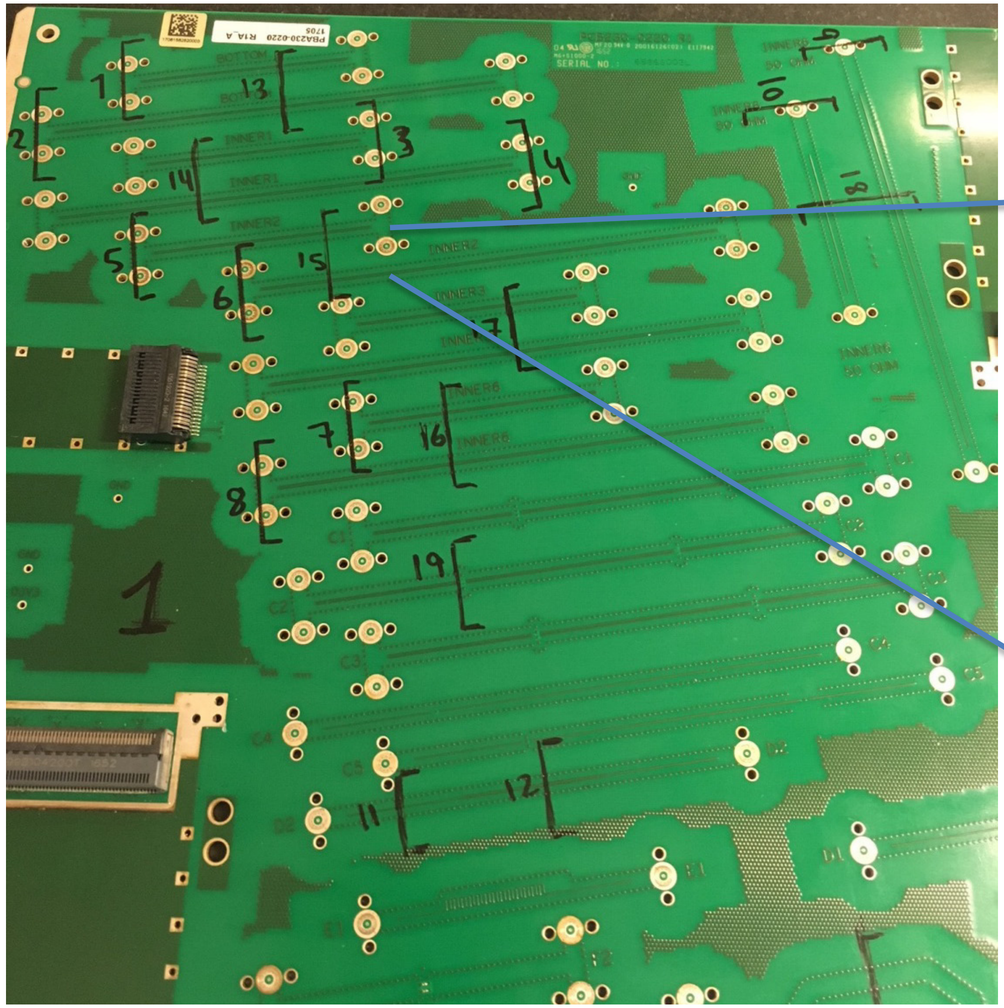


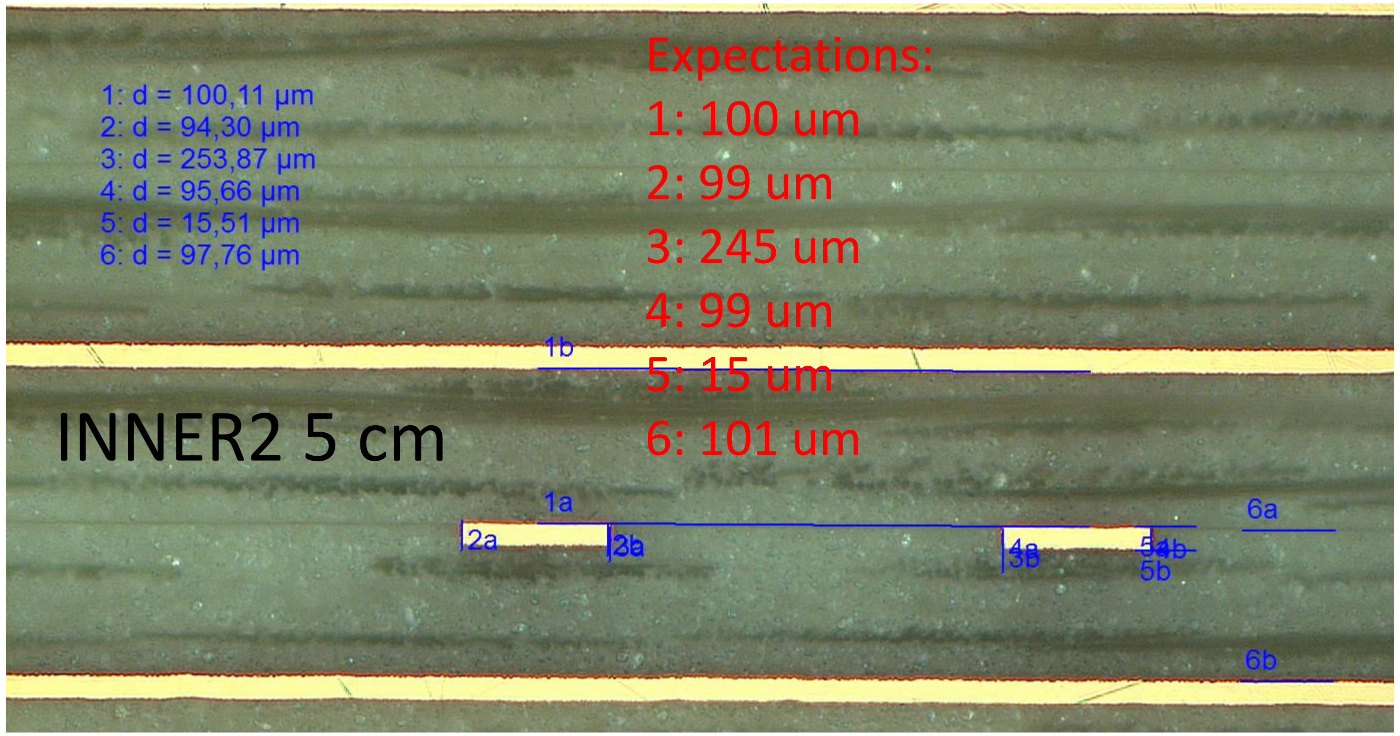


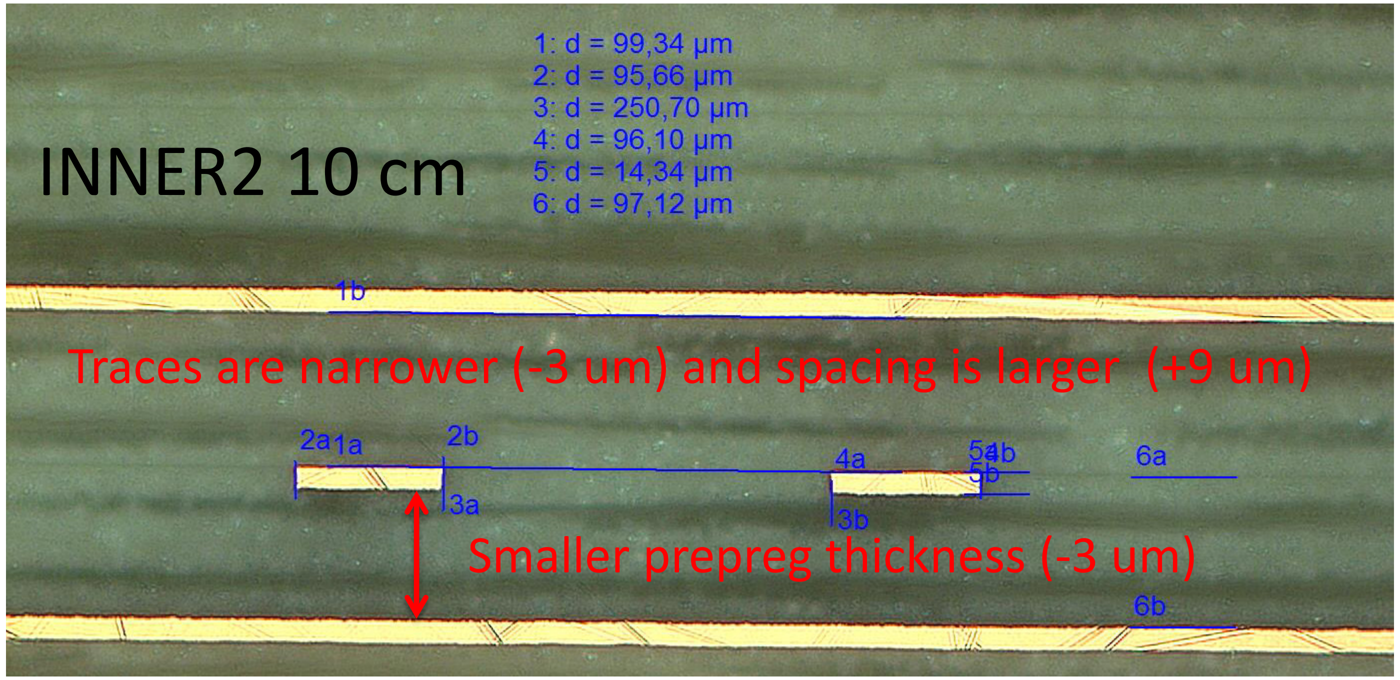


INNER2

Differences in prepreg thickness as well as in thace width/spacing

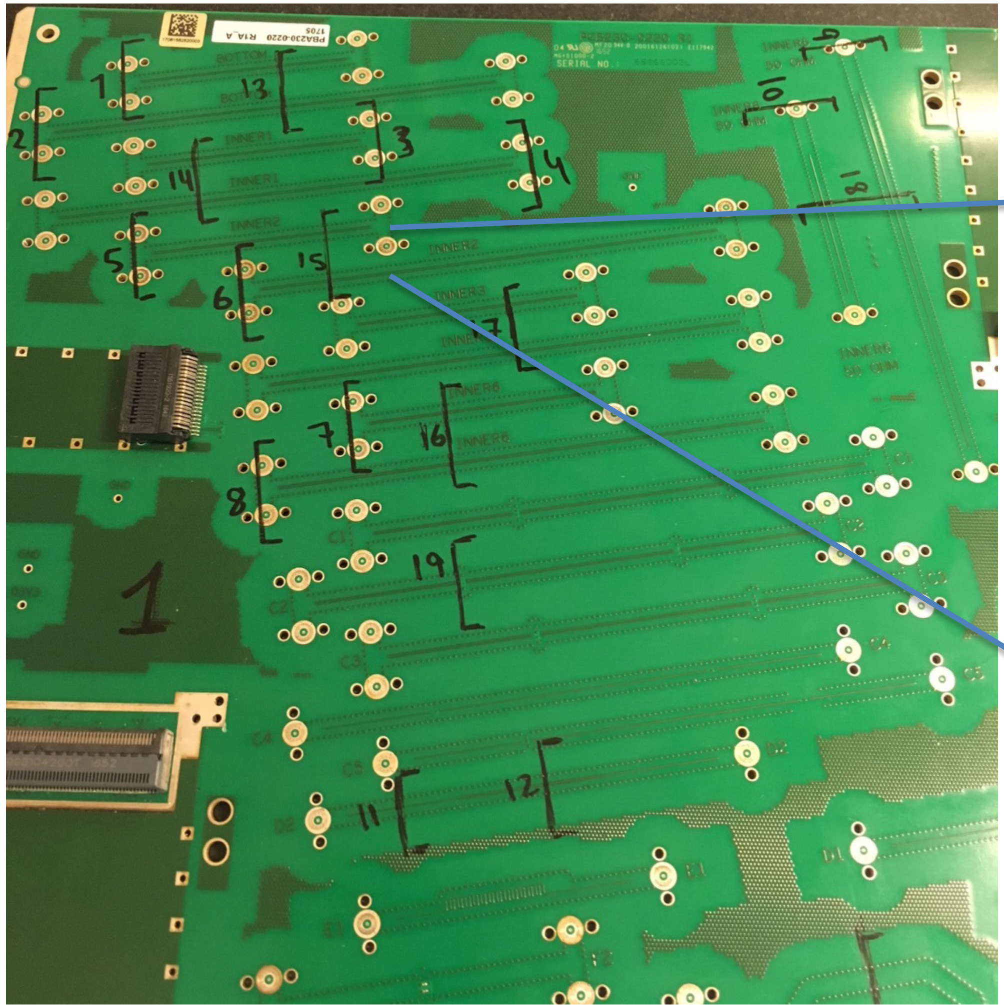


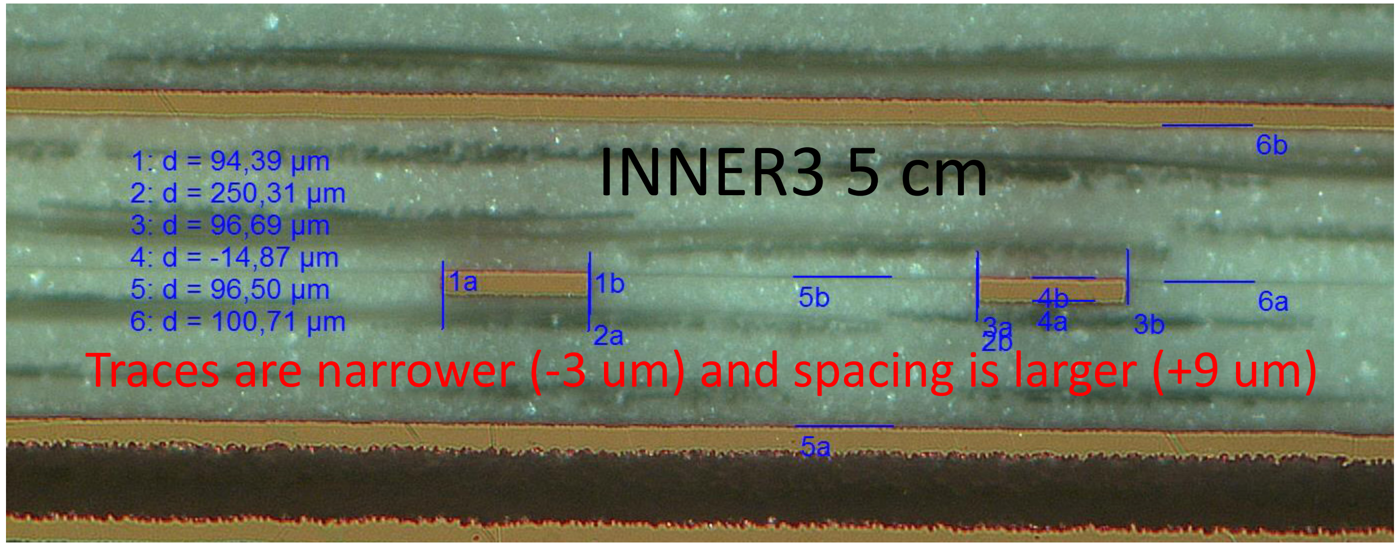


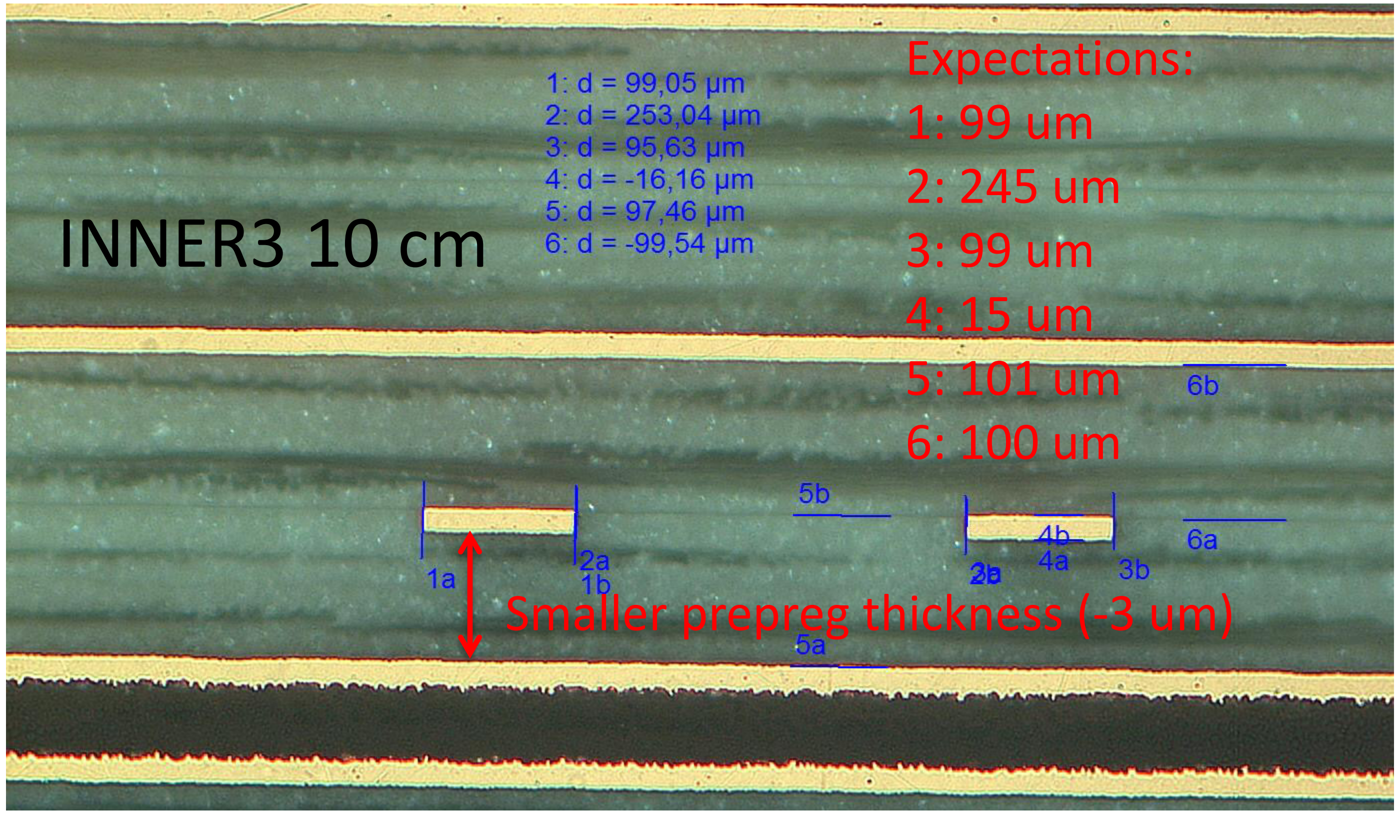


INNER3

Differences in prepreg thickness as well as in thace width/spacing

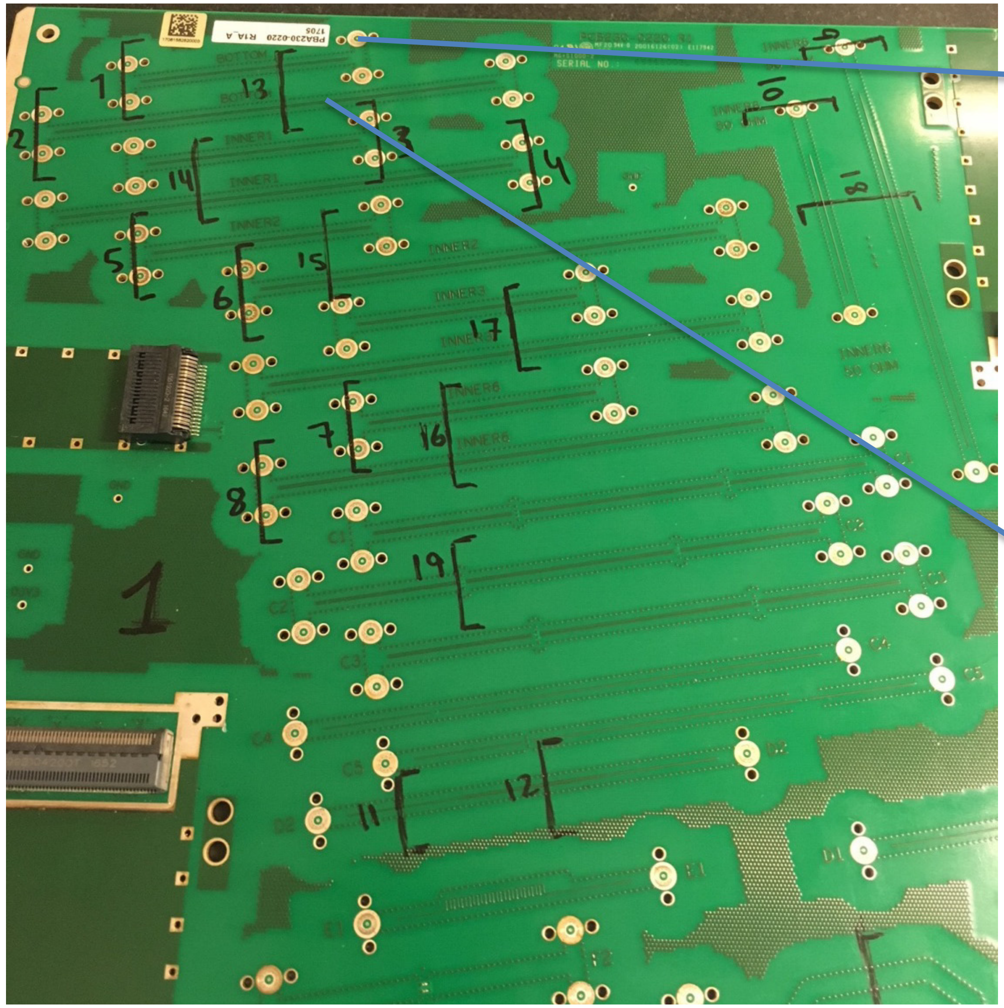


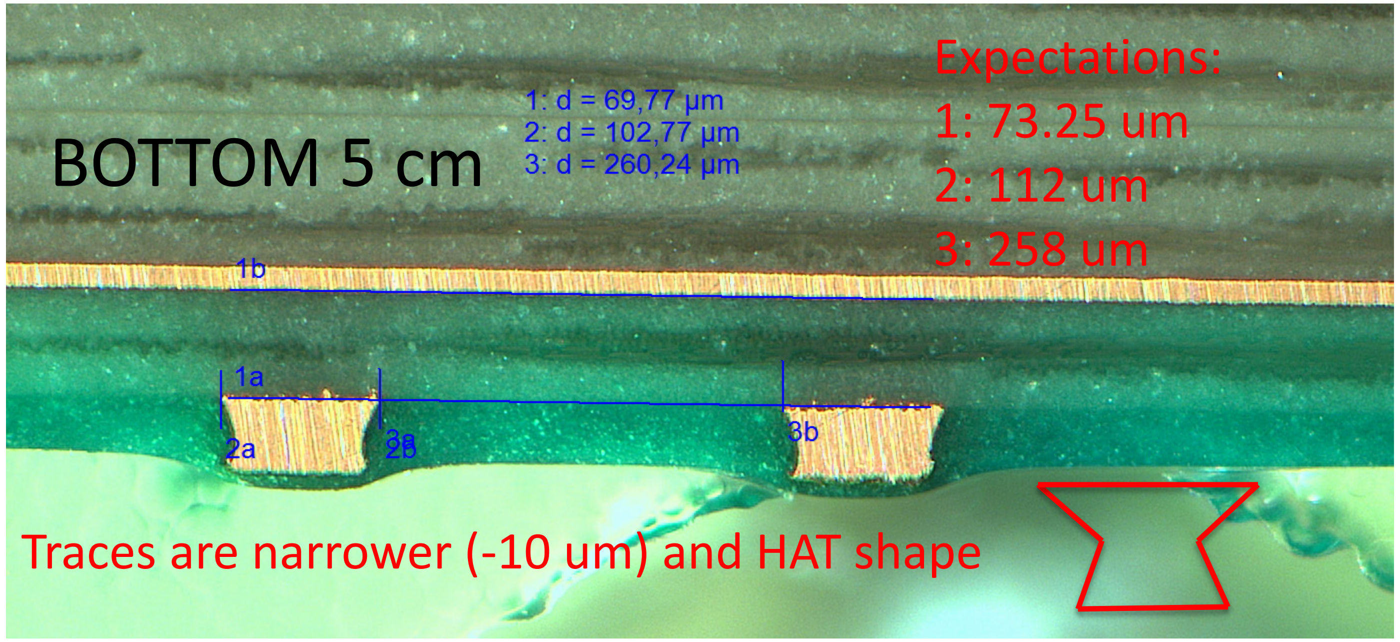


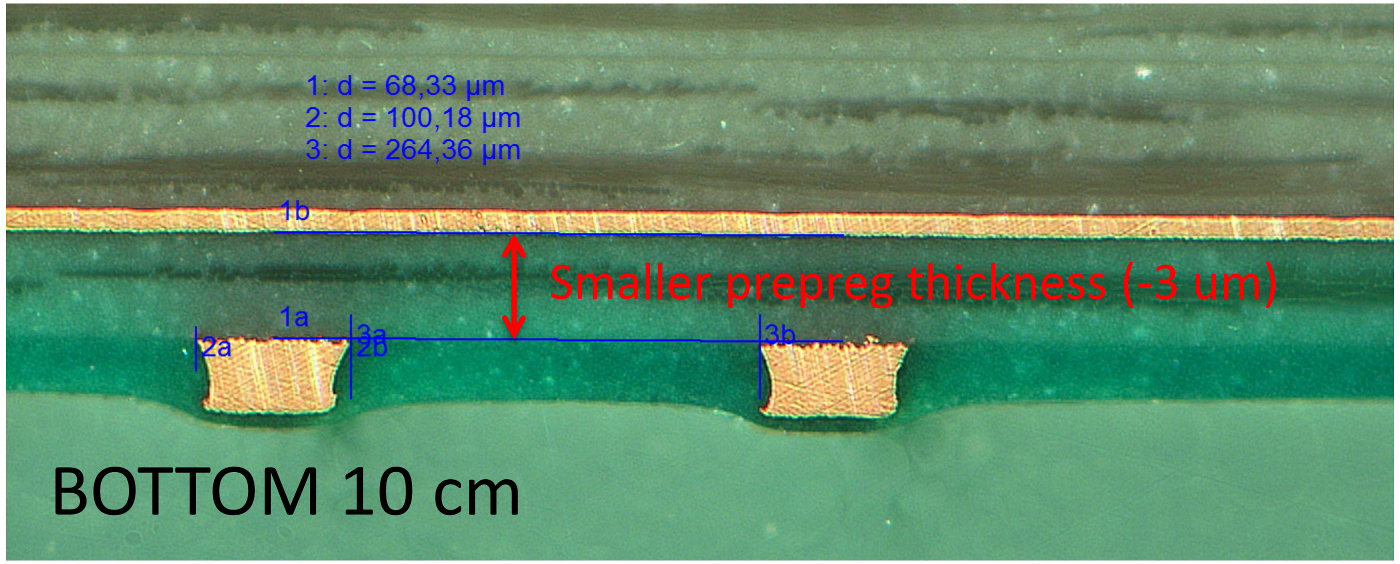


BOTTOM

Difference in prepreg thickness as well as in thace width, shape and solder mask parameters!

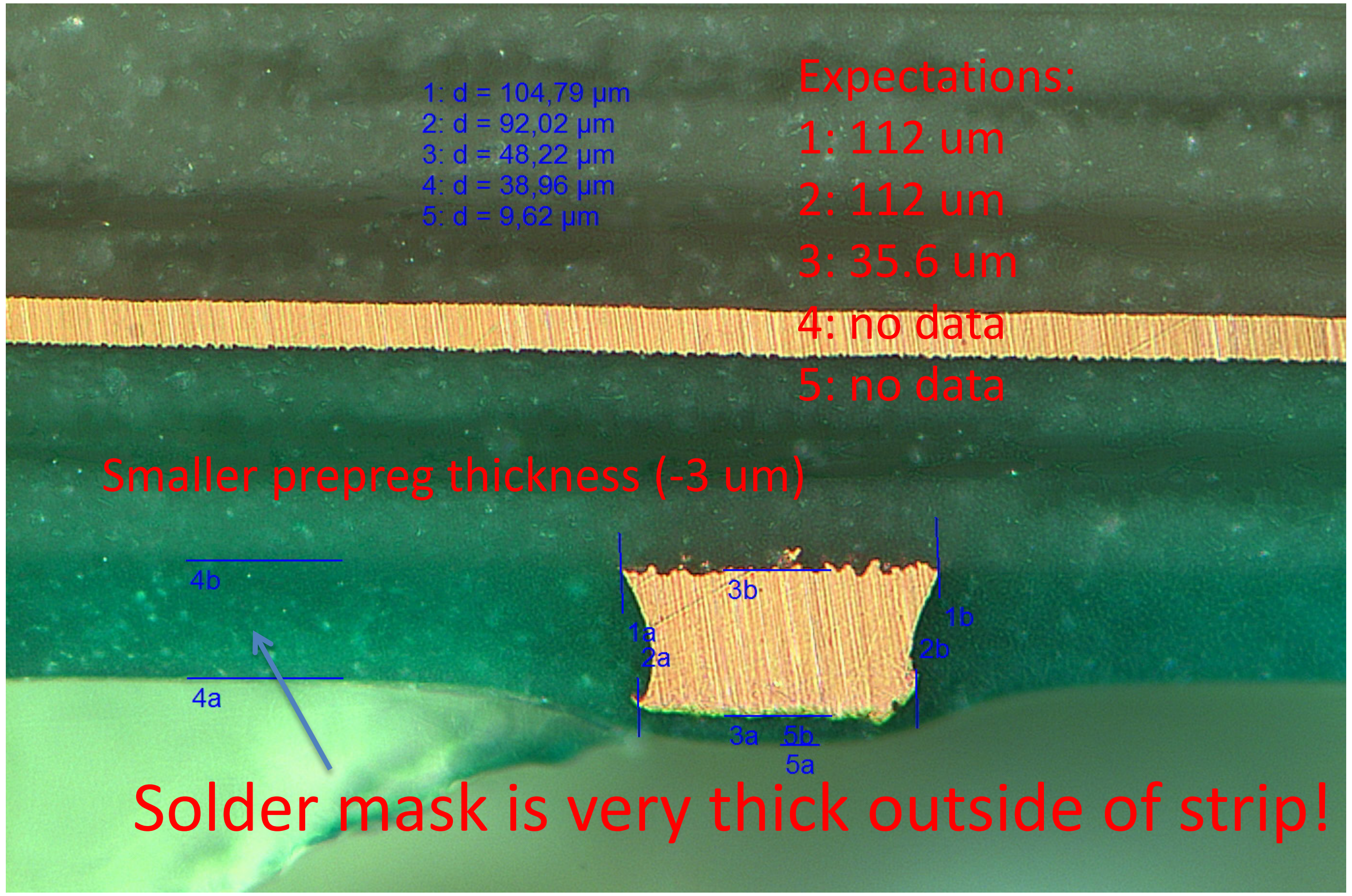


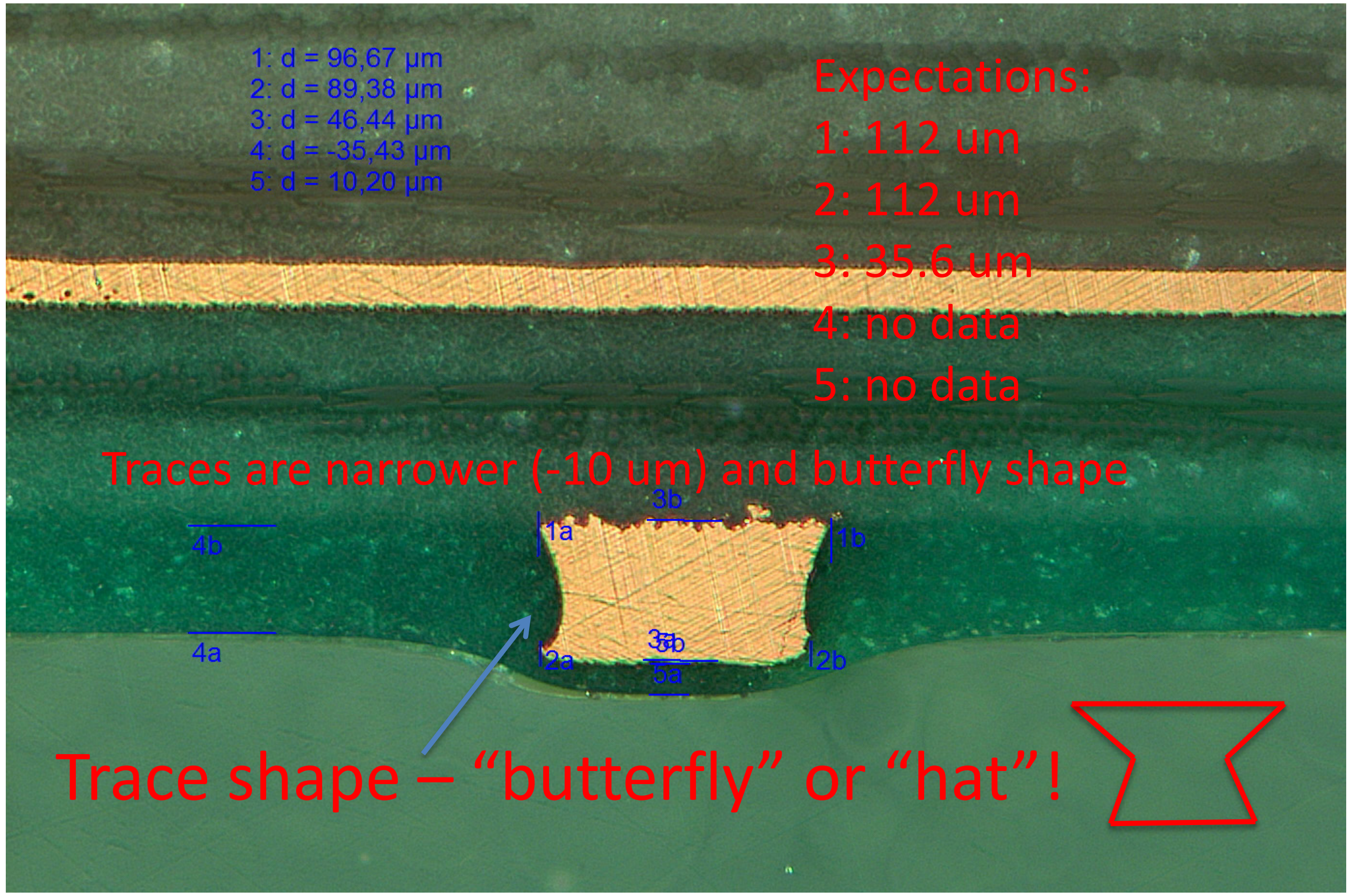




BOTTOM: Differential microstrips

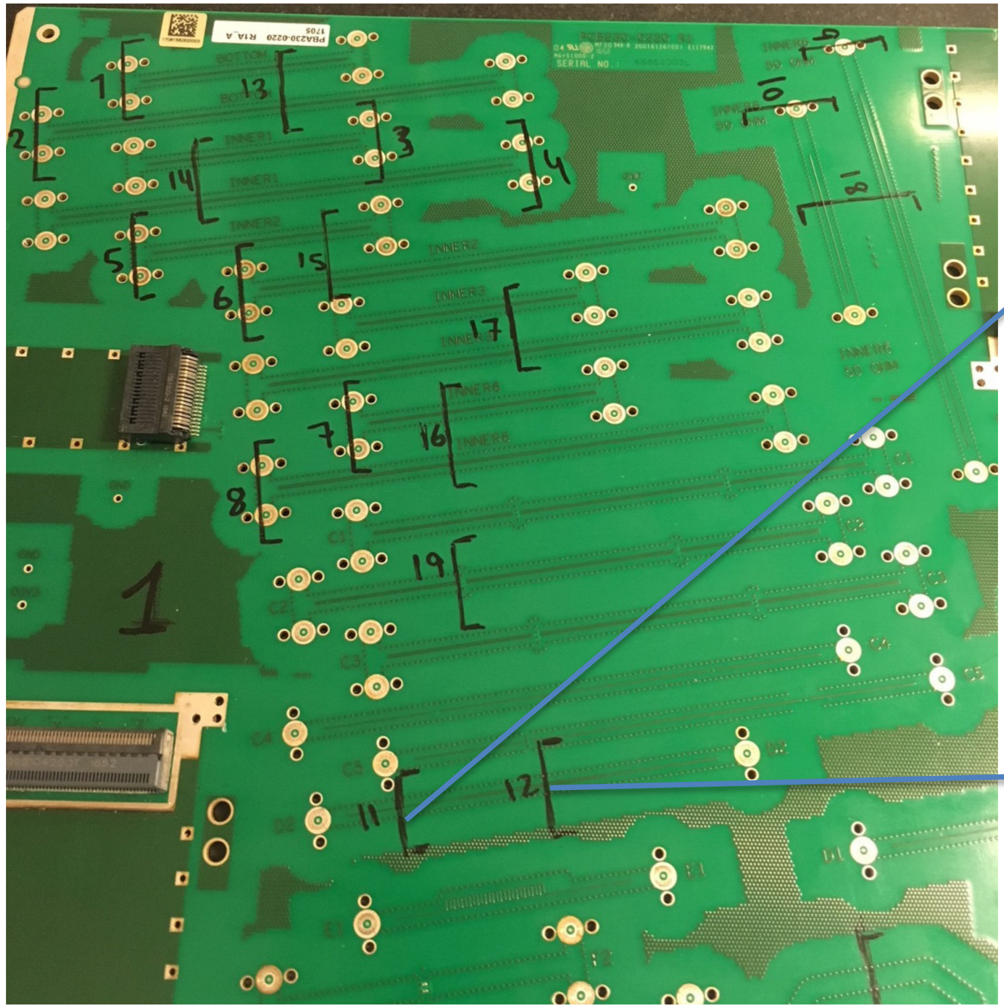
Substantial differences that makes the microstrip links practically unpredictable without these data!

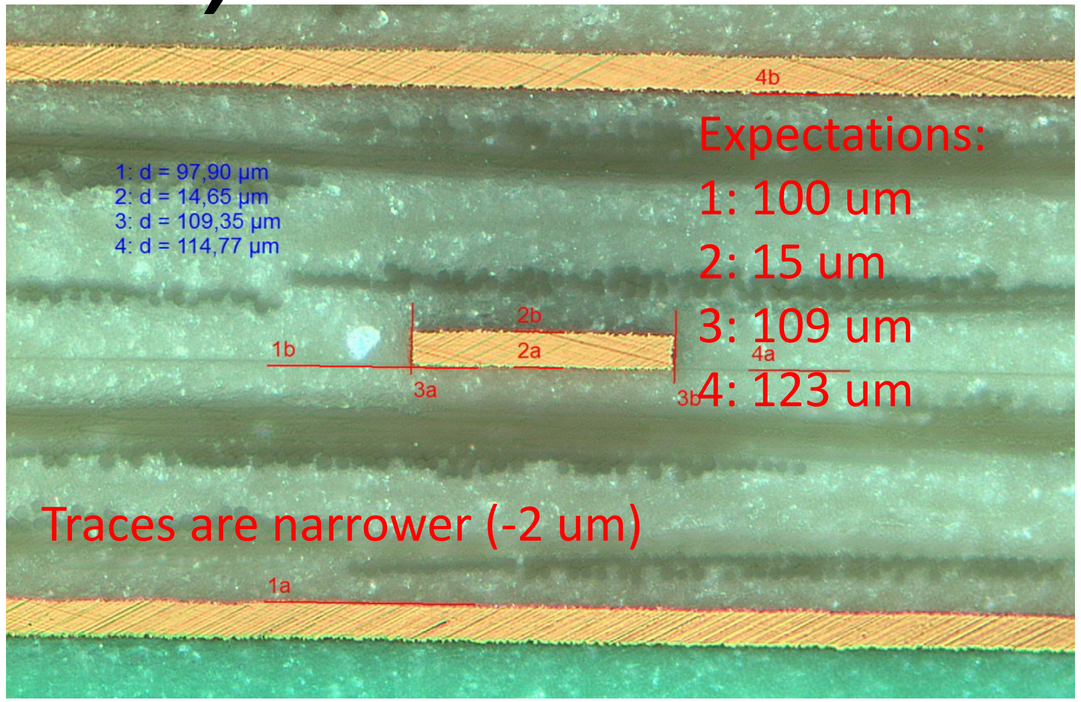


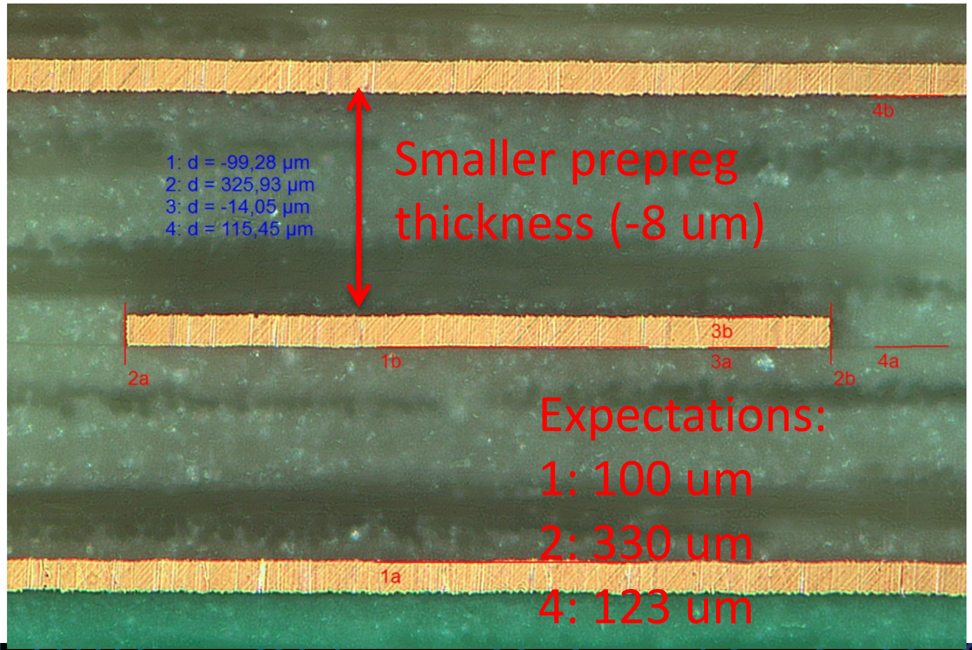


Betty in INNER6 (D2)

Difference in prepreg thickness as well as in thace width, shape and solder mask parameters!

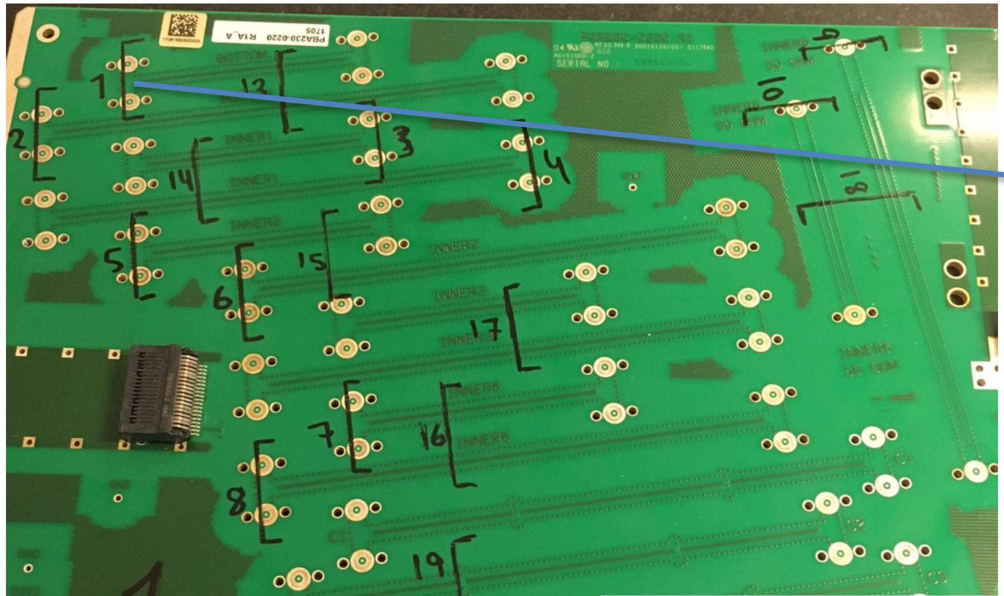


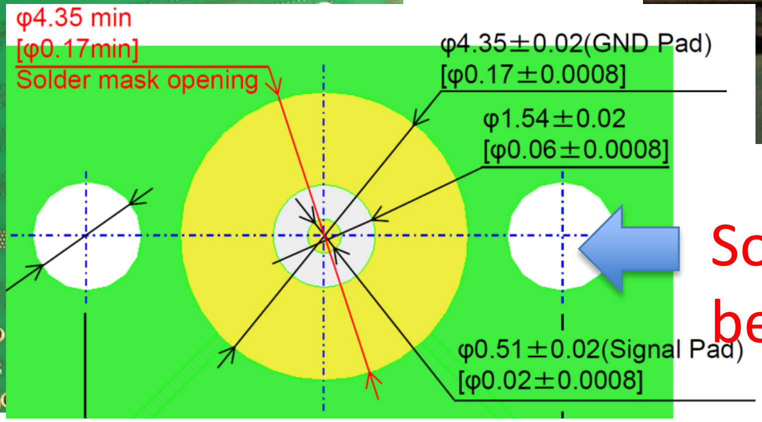


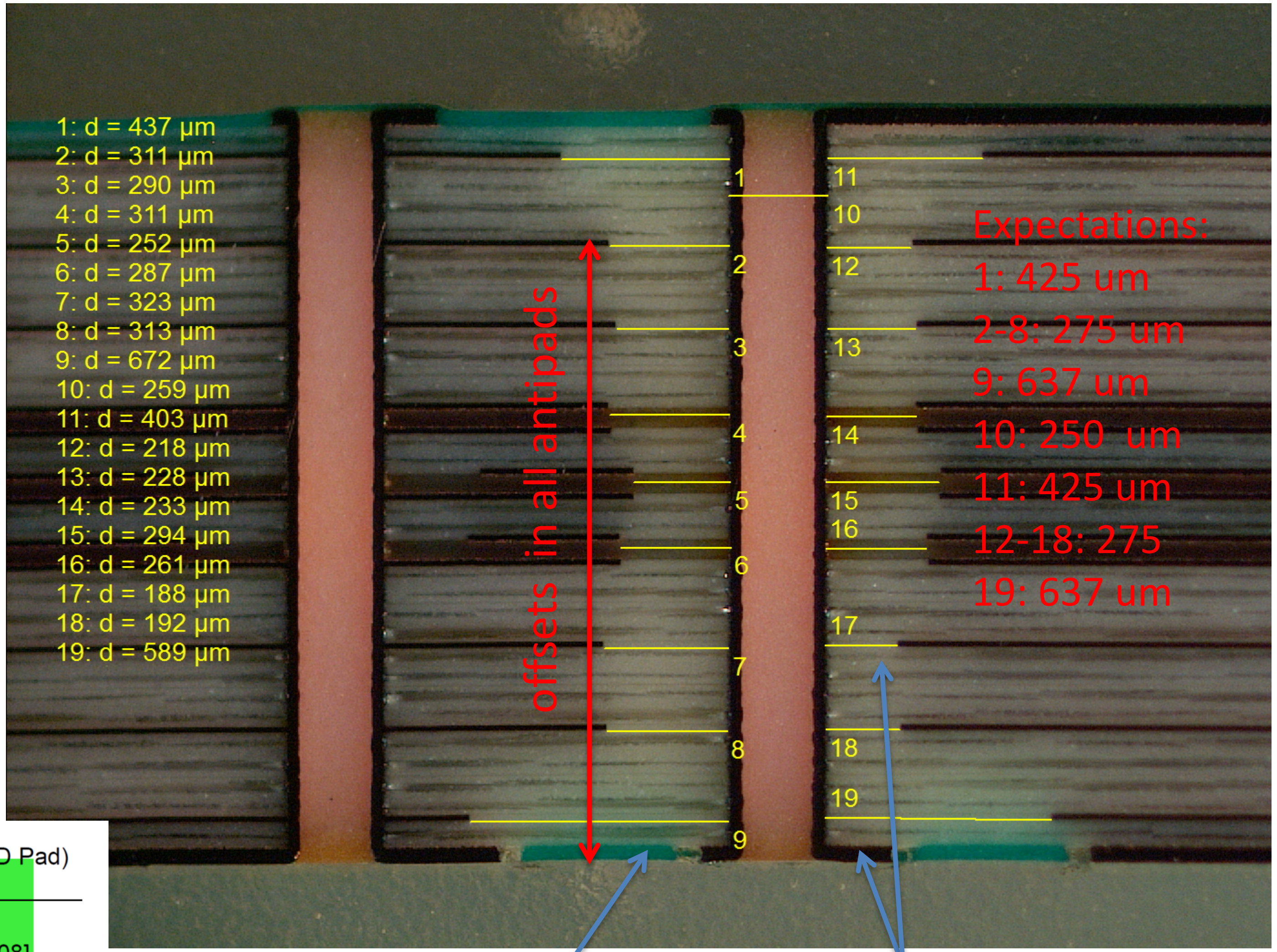


Launch to BOTTOM

Difference in prepreg thickness as well as in thace width, shape and solder mask parameters!



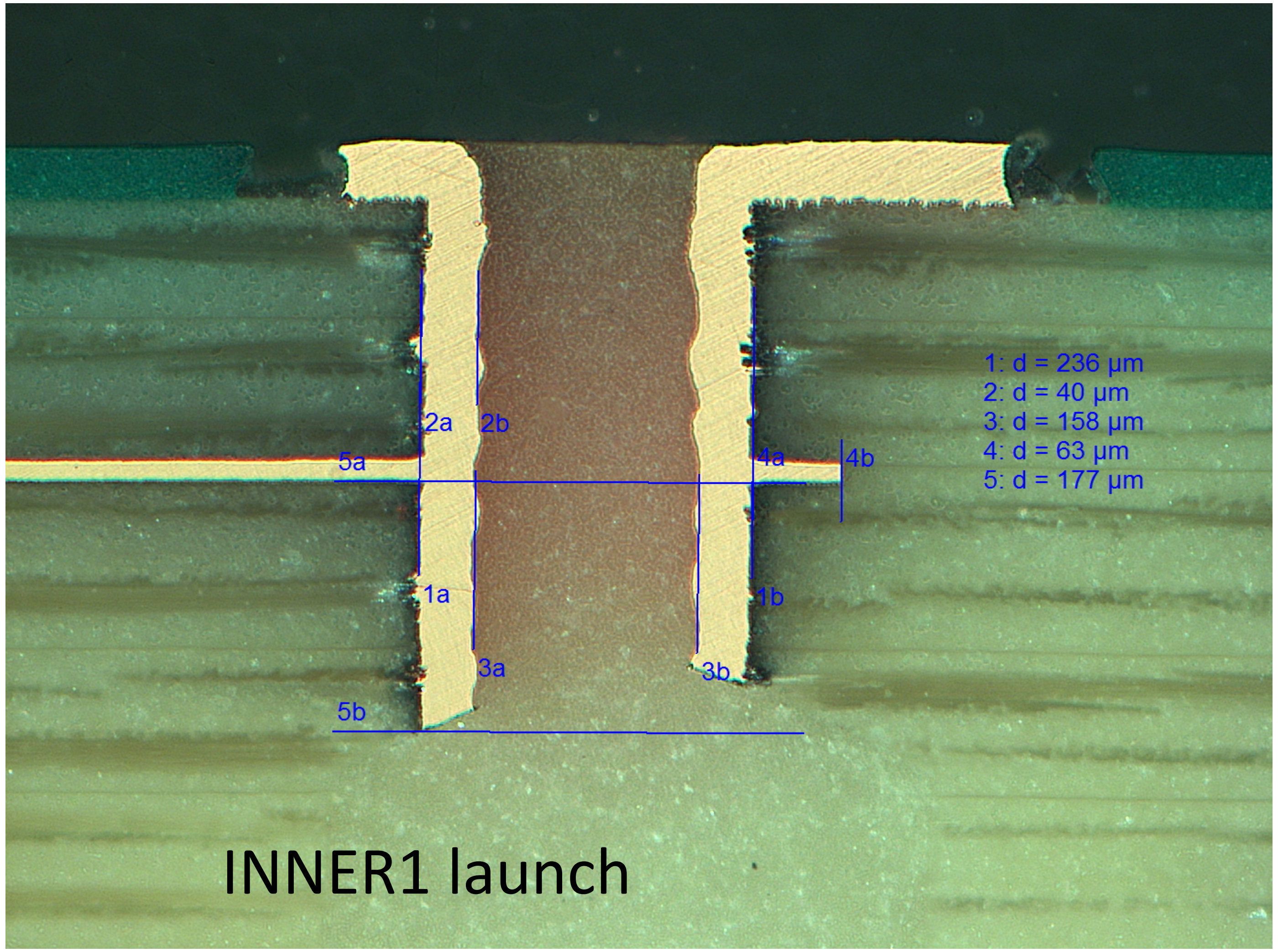


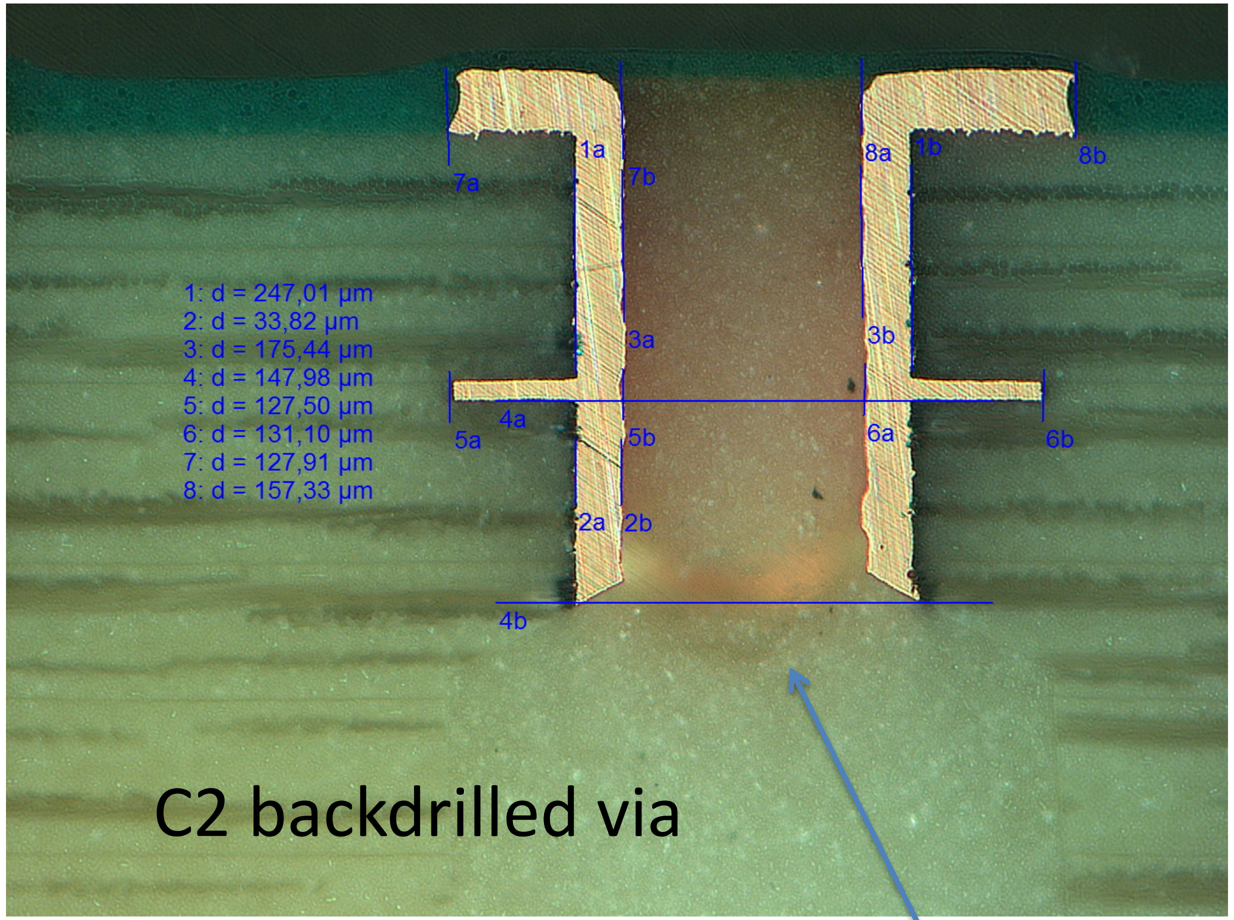


Solder mask (should not be there)!

Offset in pads and antipads

Backdrilling

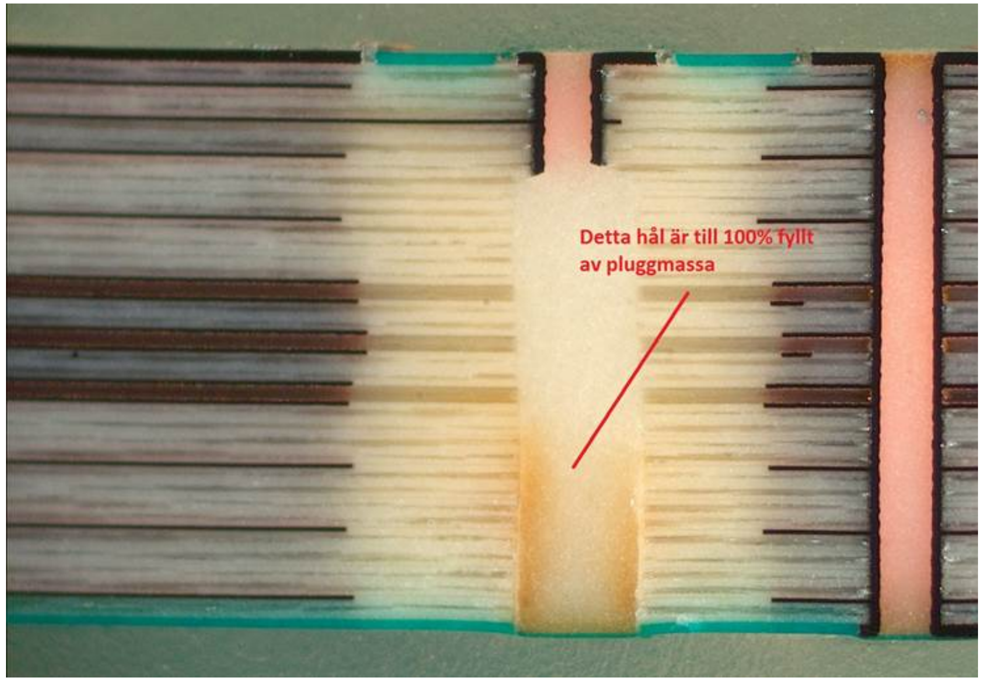


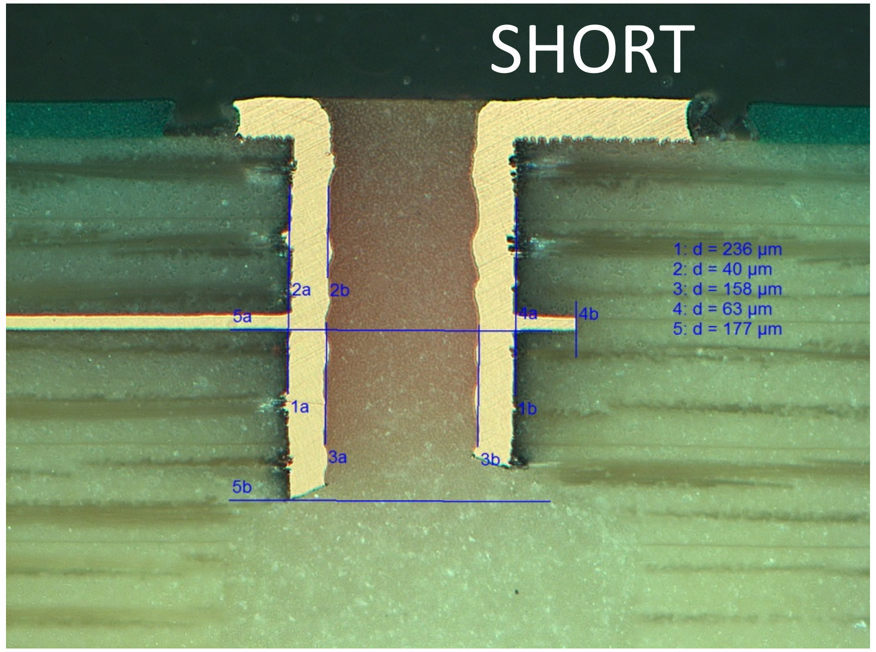


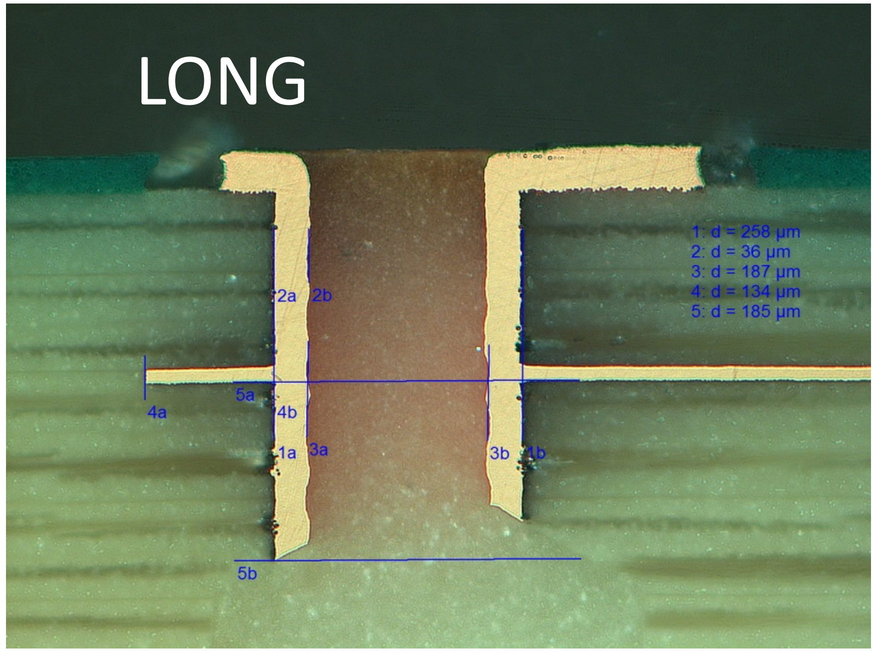
Clearly visible epoxy filling

Backdrilling of INNER1 launch

- Looks like not completely filled with the resin?



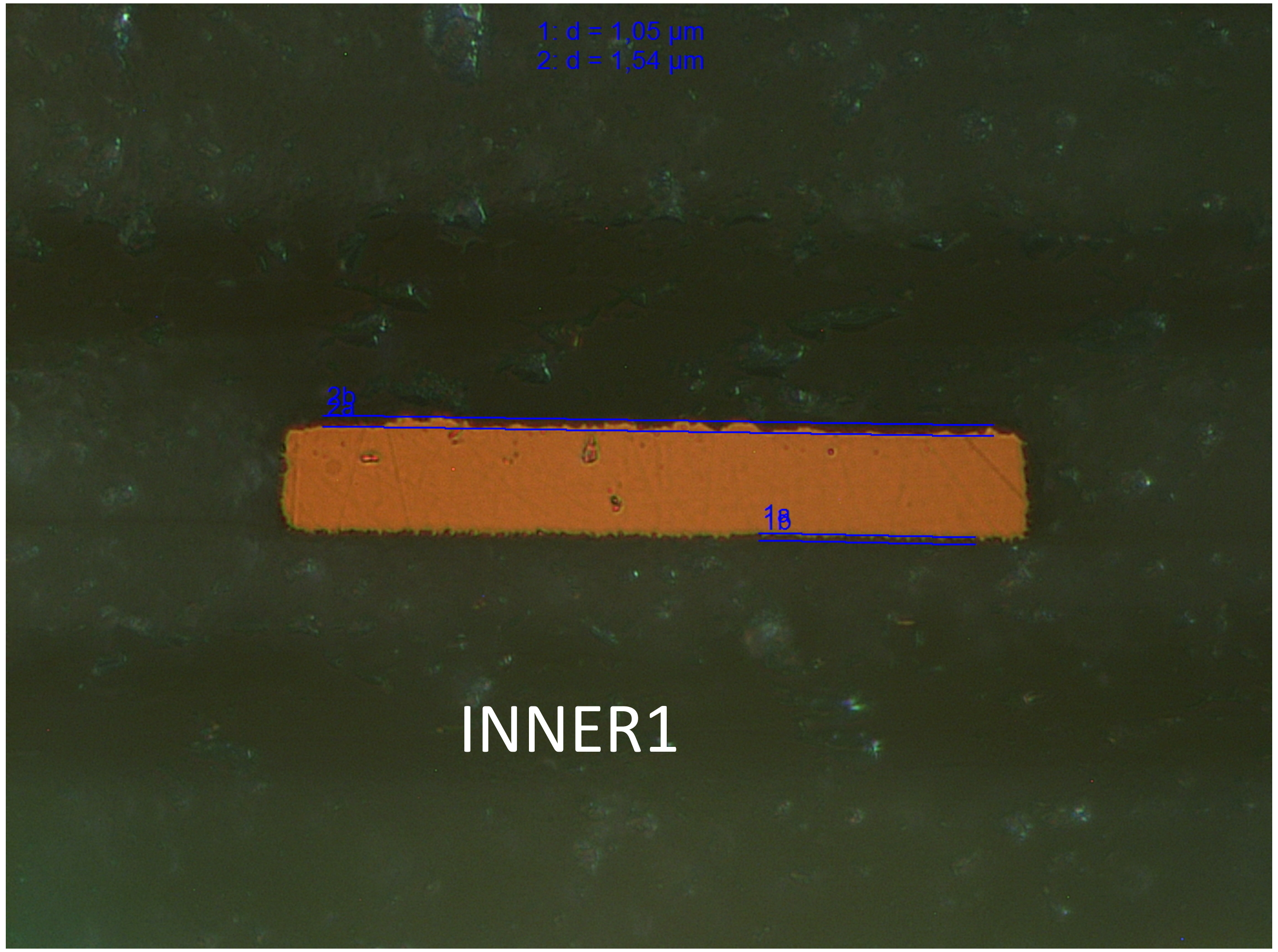


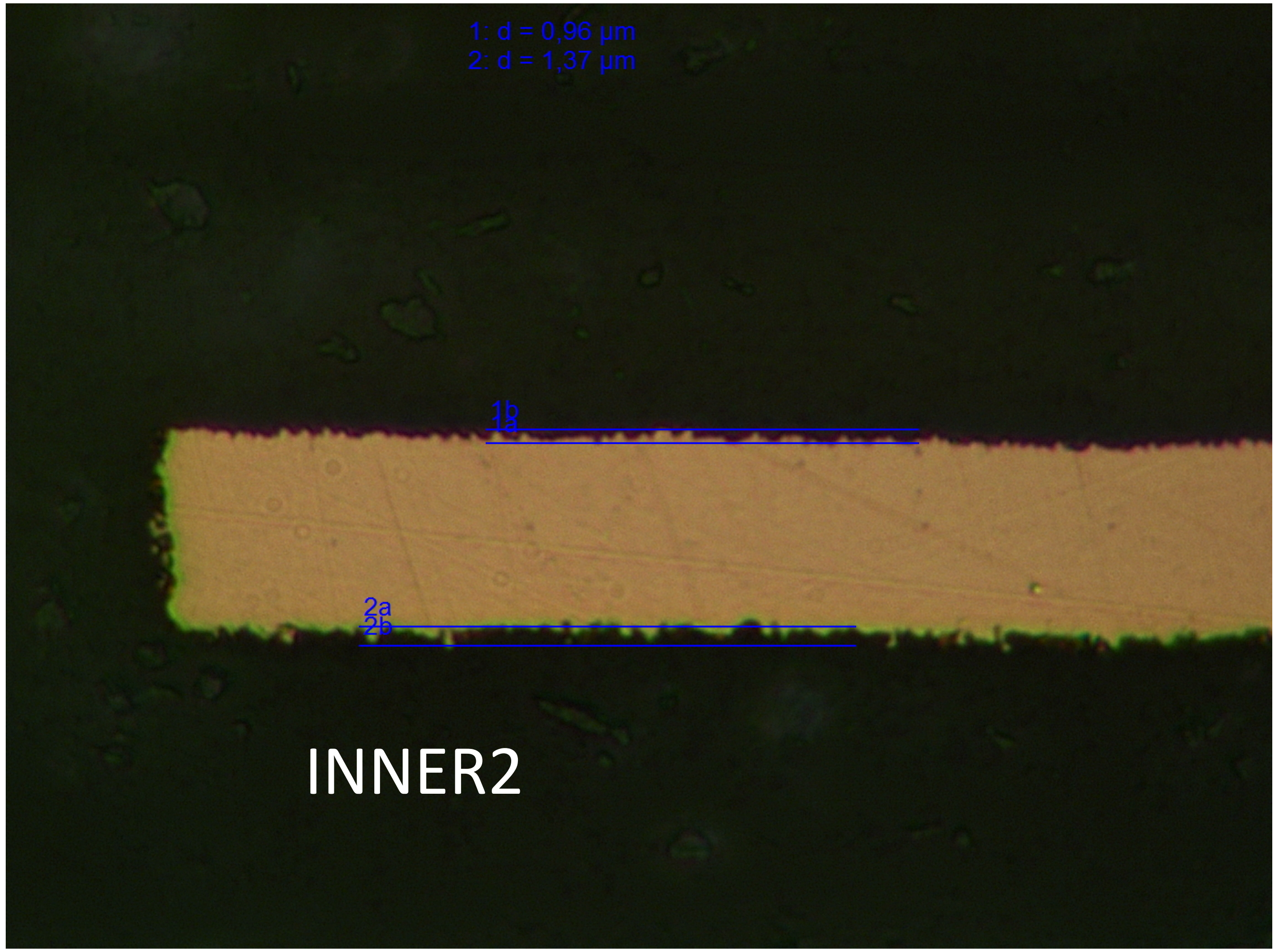


Filled or not filled up to the stub?

Roughness

- One side roughened by copper foil manufacturer, another by PCB manufacturer
- Unfortunately, these data cannot be used to define roughness models…





Final adjustments

Designed trace dimensions:
BOTTOM: 120-250-120 [um]
INNER1/6: 110-250-110 [um]
INNER2/3: 100-250-100 [um]
INNER6 SE: 110 [um]
BEATTY INNER1 and INNER6:
110 um 2.5 cm, 330 um 2.5 cm

Dimensions from manufacturer:
BOTTOM: 112-258-112 [um]
INNER1/6: 107-250-107 [um]
INNER2/3: 99-245-99 [um]
INNER6 SE: 109 [um]

Dimensions after cross-sectioning:
BOTTOM: HAT(89/97)-260-HAT(89/97) [um]
INNER1/6: 107-255-107 [um]
INNER2/3: 96-254-96 [um]
INNER6 SE: 109 [um]
BEATTY INNER 6:
109 um 2.5 cm + 326 um 2.5 cm

This ones are very critical!

Parameters for strip layers are closer to expectations

Only differential traces are adjusted in the analysis!

Thickness of prepreg layers is reduced by 3-5 um – it is almost the same thickness as for the core (it should be)

Microstrip layer metal thickness is 48 um instead of 35 um

Solder mask layer – 10 um over strips and 38 um between the strips!

Material Model Identification

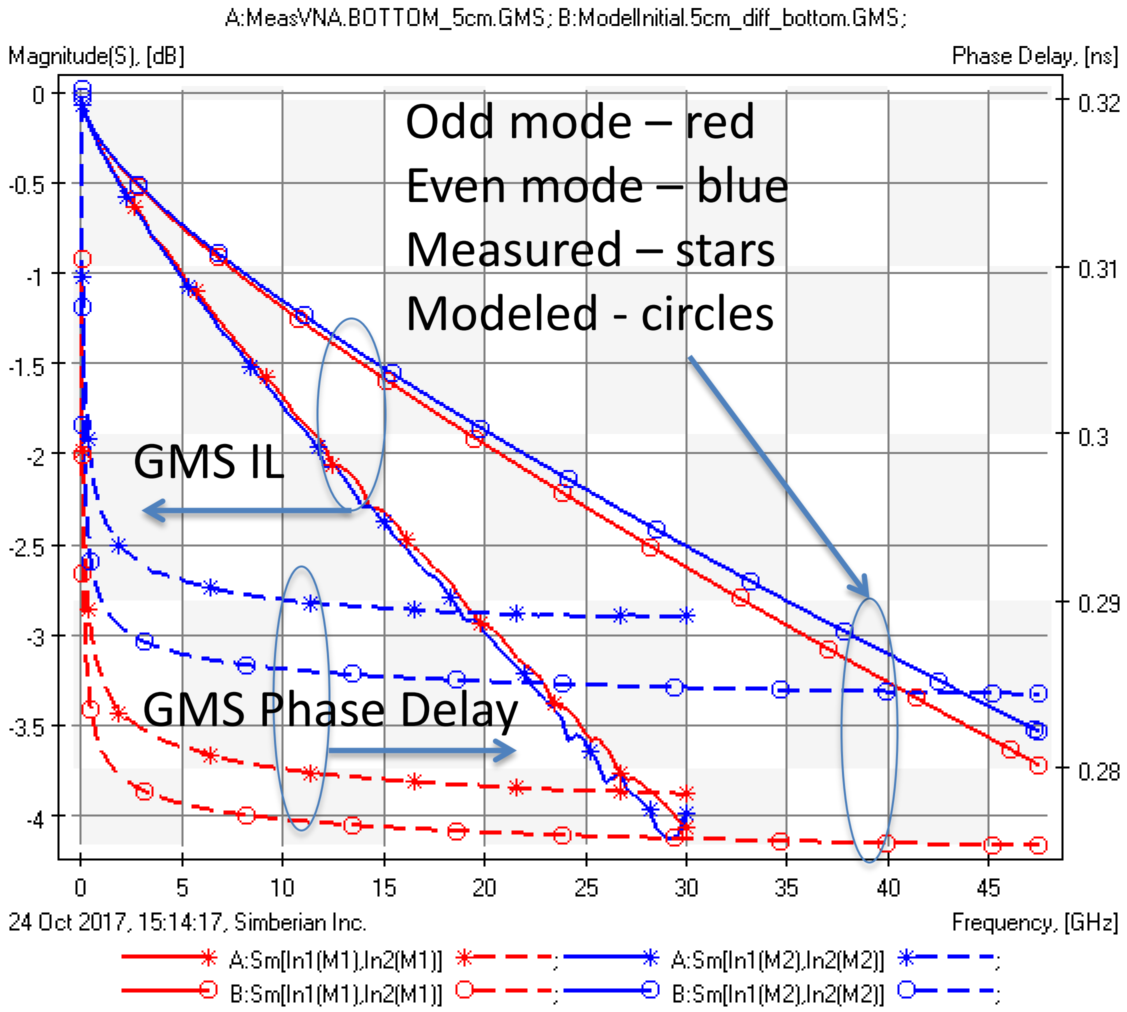
Measured GMS vs. model with the spreadsheet data

Data from the spreadsheets

```
Materials: T=20[°C],...
  "COPPER", RR=1
  "035.56UM_CU", RR=1
  "017.78UM_CU", RR=1
  "FR-4", Dk=3.72, LT=0.02, PLM=WD, Dk(0)=4.48, Dk(inf)=3.39
  "Air"
  "Solder Mask", Dk=4, LT=0.02, PLM=WD, Dk(0)=4.82, Dk(inf)=3.65
  "Meg-6 TopBot", Dk=3.19, LT=0.002, PLM=WD, Dk(0)=3.26, Dk(inf)=3.16
  "Meg-6 Inner1 (P)", Dk=3.23, LT=0.002, PLM=WD, Dk(0)=3.3, Dk(inf)=3.2
  "Meg-6 2x1035 (C)", Dk=3.37, LT=0.002, PLM=WD, Dk(0)=3.44, Dk(inf)=3.34
  "Meg-6 Inner2 (P)", Dk=3.19, LT=0.002, PLM=WD, Dk(0)=3.26, Dk(inf)=3.16
  "Meg-6 Inner3 (P)", Dk=3.19, LT=0.002, PLM=WD, Dk(0)=3.26, Dk(inf)=3.16
  "Meg-6 Av", Dk=3.19, LT=0.002, PLM=WD, Dk(0)=3.26, Dk(inf)=3.16
StackUp: LU=[um], NL=20, T=2030.12[um], CSM=("Solder Mask", 40[um])
  1| Signal: "TOP", T=35.56, Ins="Air", Cond="035.56UM_CU"
  2| Medium: T=73.25, Ins="Meg-6 TopBot", DIE_003
  3| Plane: "GND1", Cond="017.78UM_CU", T=15, Ins="Meg-6 TopBot"
  4| Medium: T=100, Ins="Meg-6 2x1035 (C)", DIE_005
  5| Signal: "INNER1", T=15, Ins="Meg-6 Inner1 (P)", Cond="017.78UM_CU"
  6| Medium: T=108, Ins="Meg-6 Inner1 (P)", DIE_007
  7| Plane: "GND2", Cond="017.78UM_CU", T=15, Ins="Meg-6 Av"
  8| Medium: T=100, Ins="Meg-6 2x1035 (C)", DIE_009
  9| Signal: "INNER2", T=15, Ins="Meg-6 Inner2 (P)", Cond="017.78UM_CU"
  10| Medium: T=86, Ins="Meg-6 Inner2 (P)", DIE_011
  11| Plane: "GND3", Cond="017.78UM_CU", T=15, Ins="Meg-6 Inner2 (P)"
  12| Medium: T=100, Ins="Meg-6 2x1035 (C)", DIE_013
  13| Signal: "INNER3", T=15, Ins="Meg-6 Inner3 (P)", Cond="017.78UM_CU"
  14| Medium: T=86, Ins="Meg-6 Inner3 (P)", DIE_015
  15| Plane: "GND4", Cond="017.78UM_CU", T=15, Ins="Meg-6 Av"
  16| Medium: T=50, Ins="FR-4", DIE_017
  17| Plane: "VCC1", Cond="017.78UM_CU", T=15, Ins="Meg-6 Av"
  18| Medium: T=96.5, Ins="Meg-6 Av", DIE_019
  19| Plane: "GND5", Cond="017.78UM_CU", T=15, Ins="Meg-6 Av"
  20| Medium: T=50, Ins="FR-4", DIE_021
```

+cross-sections adjustments of manufacturer

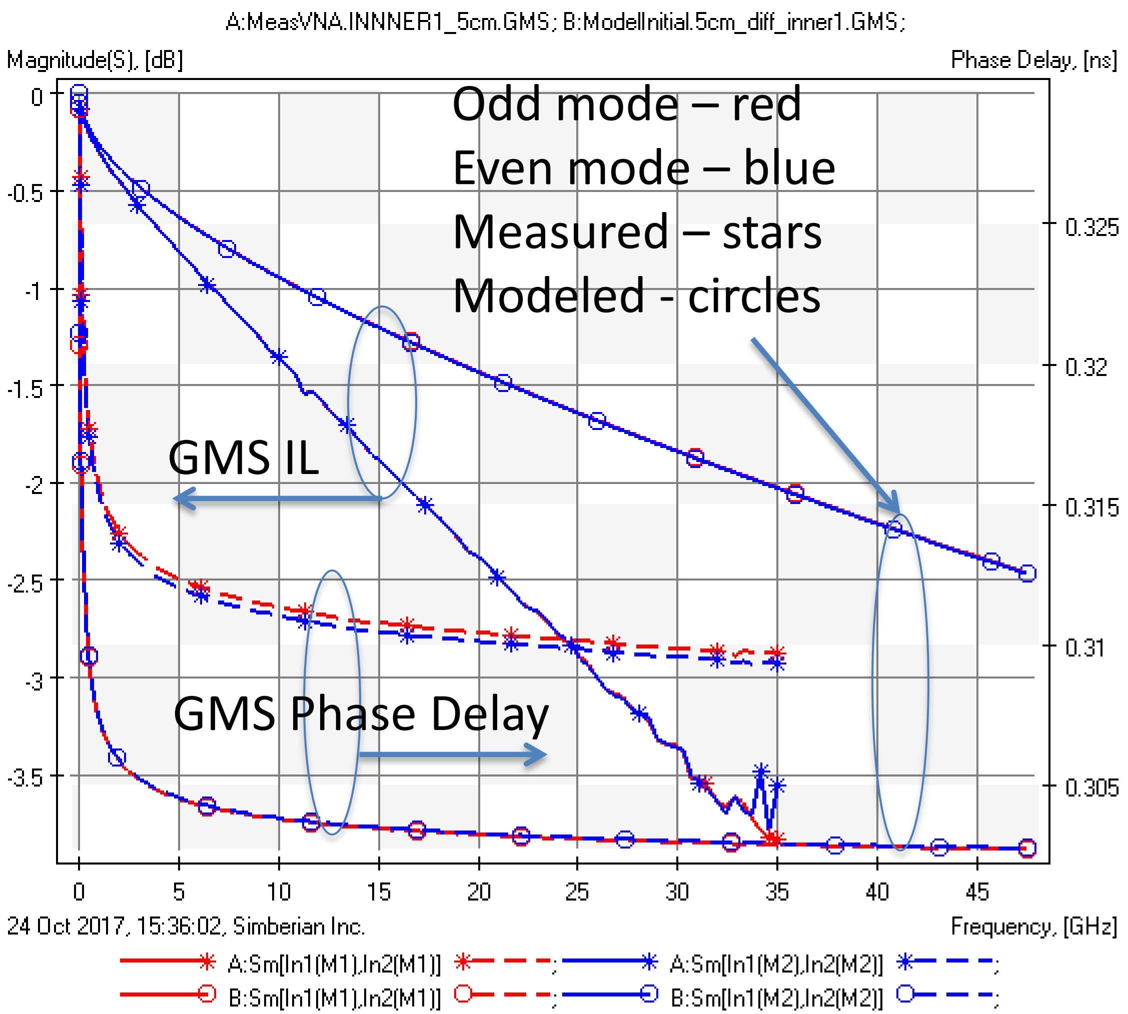
BOTTOM



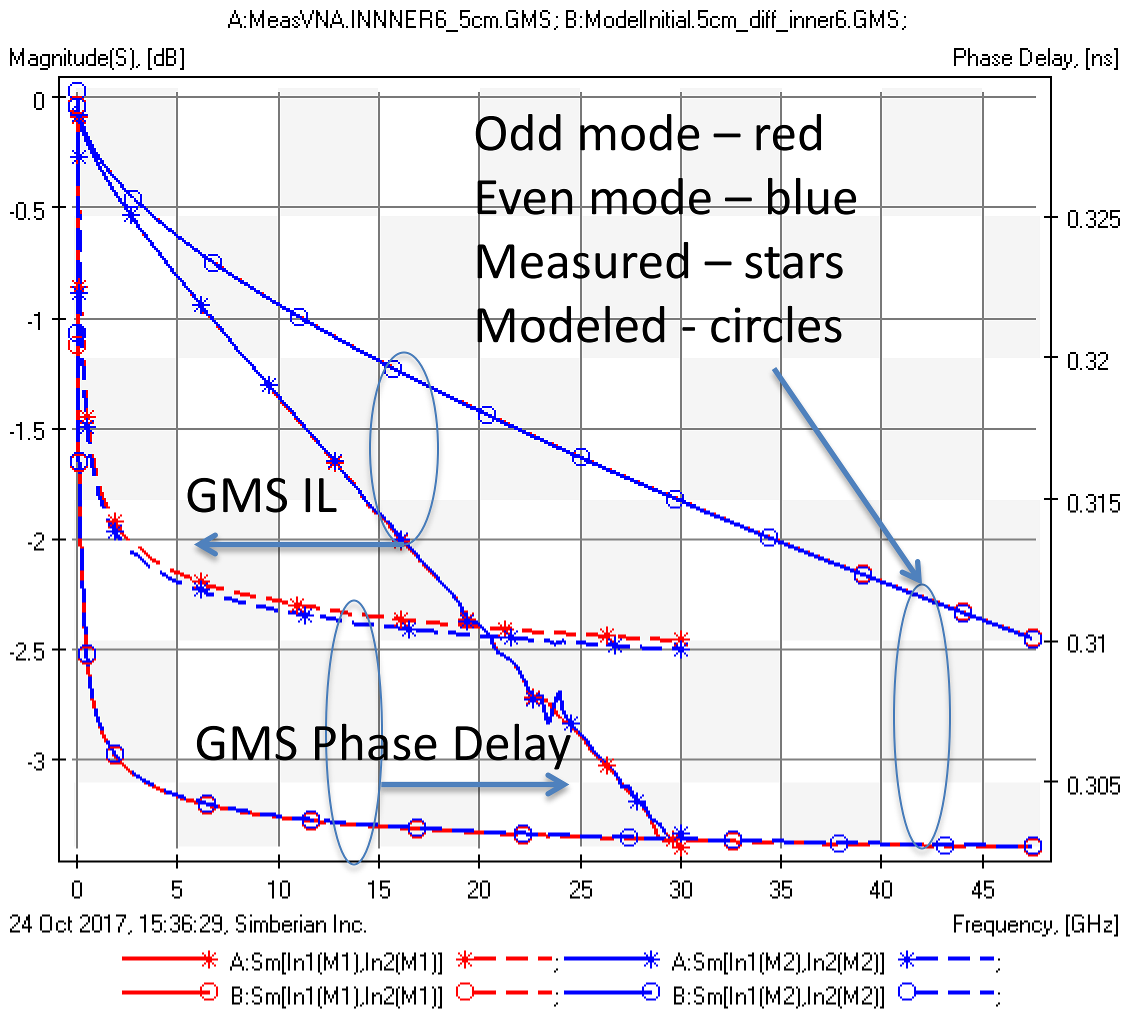
Model phase delay and loss are much smaller…

Measured GMS vs. model with the spreadsheet data

INNER1



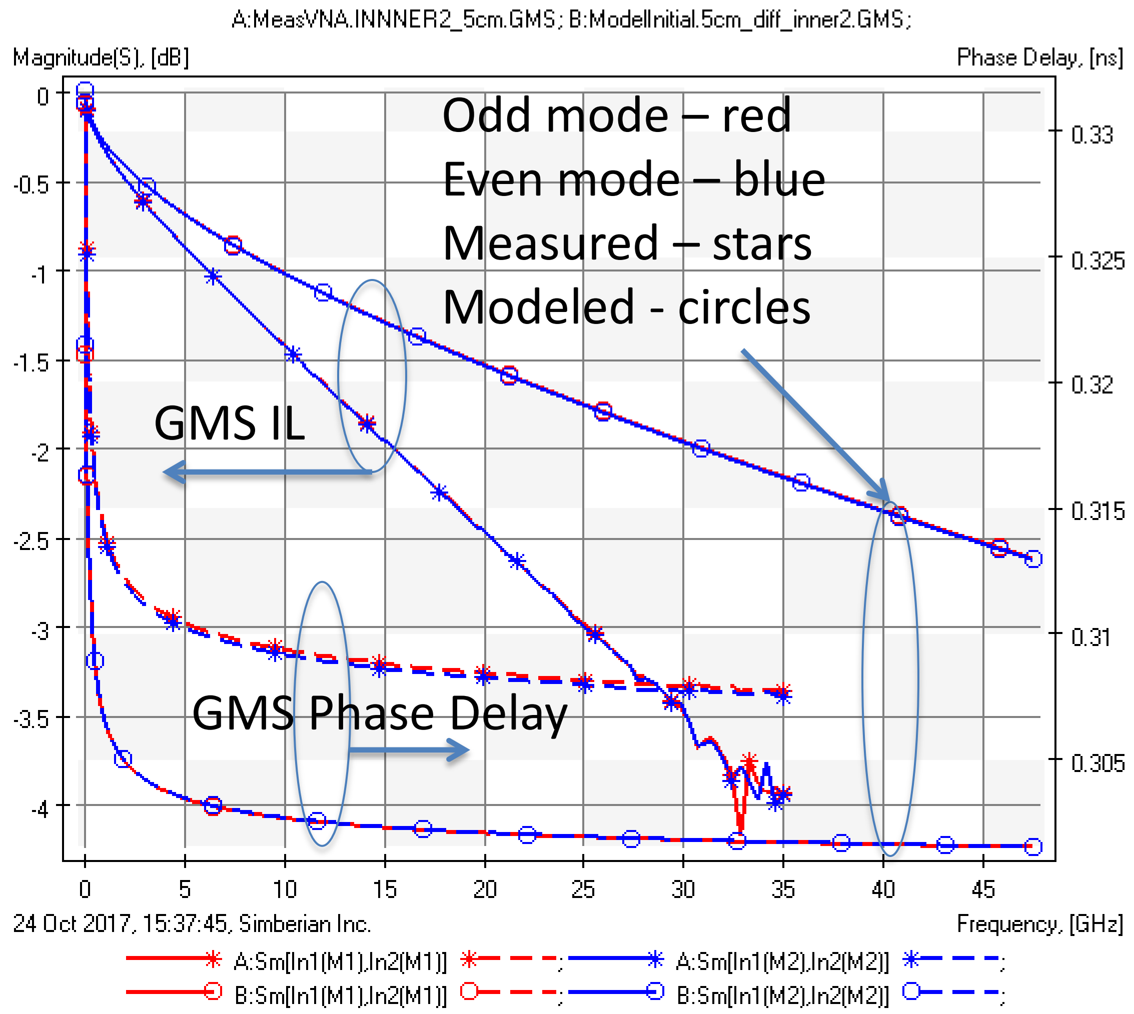
INNER6



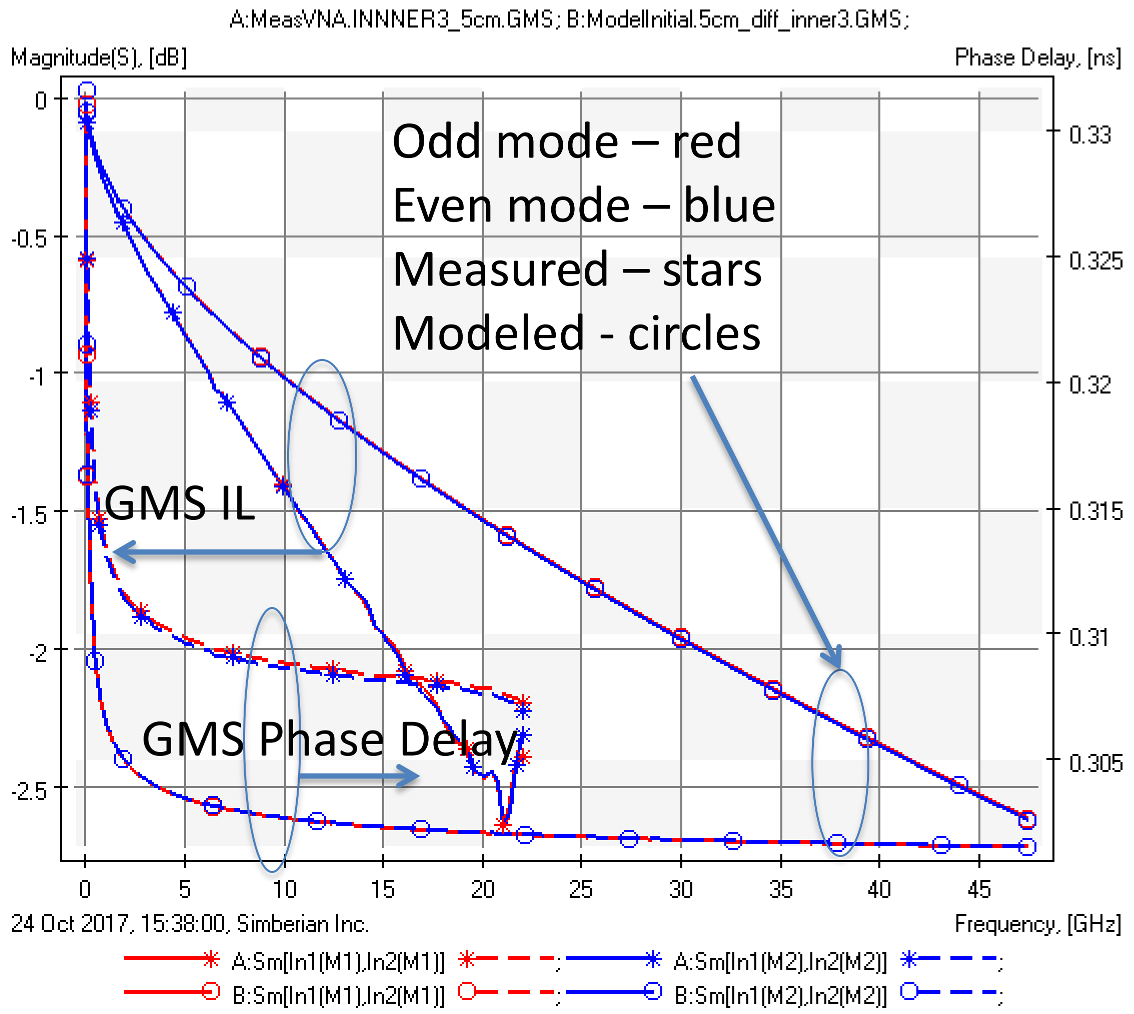
Model phase delay and loss are much smaller, no visible difference between the modes…

Measured GMS vs. model with the spreadsheet data

INNER2



INNER3



Model phase delay and loss are much smaller, no visible difference between the modes…

REALITY: DEFINITE FAILURE OF DESIGN!!!

Material model identification

Using measured and simulated GMS-parameters:

a) Identify copper resistivity by matching GMS IL at lowest frequencies

b) Identify dielectric Dk by matching GMS phase delay (GMS PD)

c) Identify LT by matching GMS IL at lower frequencies

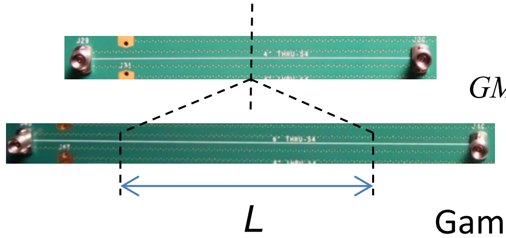
   Re-adjust Dk to match GMS PD

d) Identify roughness model parameters by matching GMS IL at high frequencies

   Re-adjust Dk to match GMS PD

e) Do it for all unique dielectrics

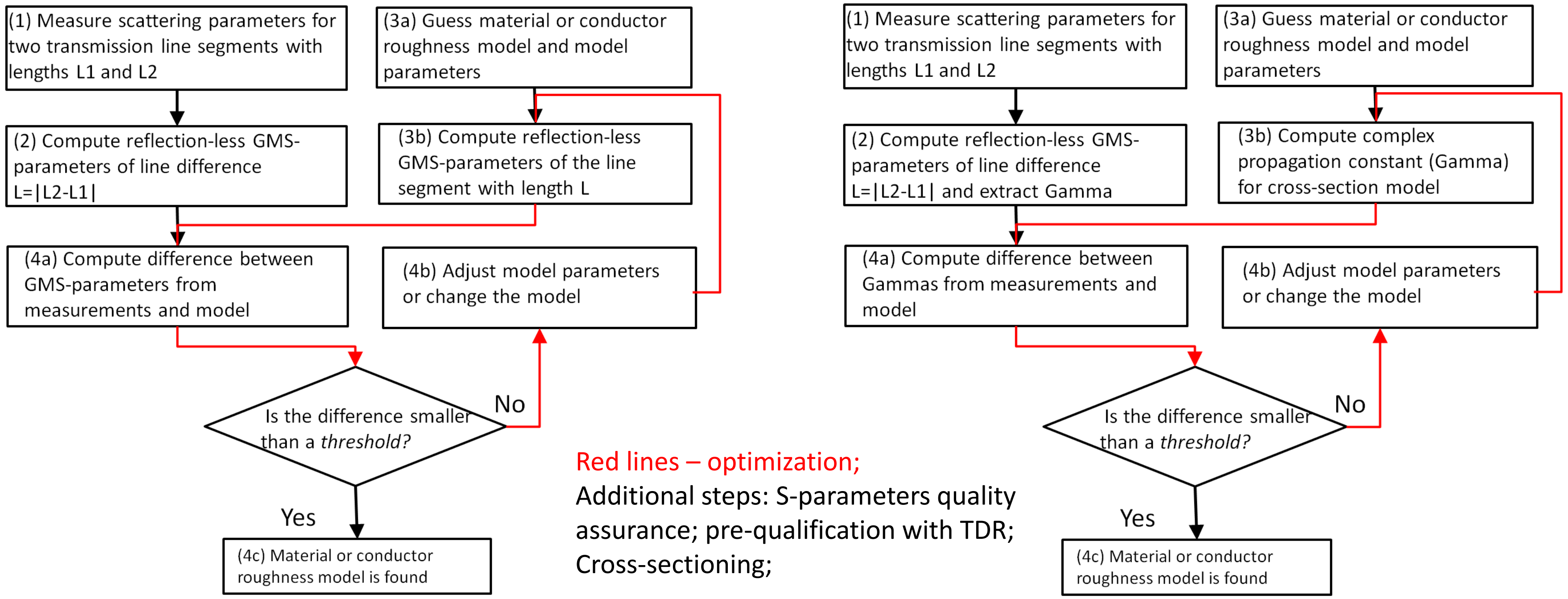
$$GMS = \begin{pmatrix} 0 & \exp(-\Gamma \cdot L) \\ \exp(-\Gamma \cdot L) & 0 \end{pmatrix}$$



$$GMT = eigenvals\left(T2 \cdot T1^{-1}\right) = \begin{pmatrix} \exp(-\Gamma \cdot L) & 0 \\ 0 & \exp(\Gamma \cdot L) \end{pmatrix}$$

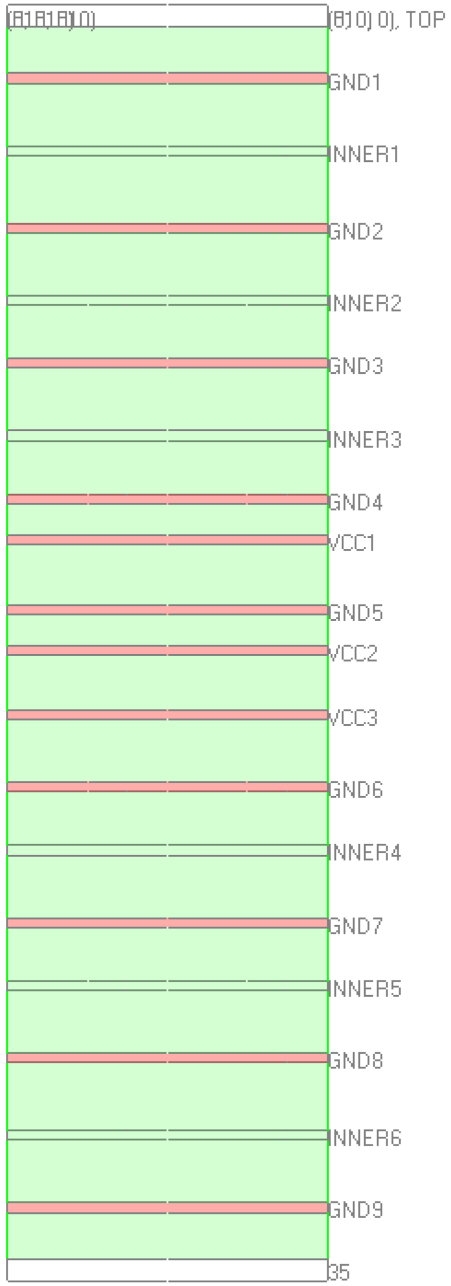
Use of raw GMS-parameters

Gamma extraction – “SPP Light”



Y. Shlepnev, Broadband material model identification with GMS-parameters, EPEPS 2015.
Y. Shlepnev, Y. Choi, C. Cheng, Y. Damgaci, Drawbacks and Possible Improvements of Short Pulse Propagation Technique, EPEPS 2016.

Identification results (crude, 40 GHz VNA)



Materials: T=20[°C],...
"COPPER", RR=1
"035.56UM_CU", RR=1, ModifiedHammerstad: SR1=0.4 [um], RF1=2.5;
"017.78UM_CU", RR=1, ModifiedHammerstad: SR1=0.35 [um], RF1=2.5;
"FR-4", Dk=3.72, LT=0.02, PLM=WD, Dk(0)=4.48, Dk(inf)=3.39
"Air"
"Solder Mask", Dk=4.2, LT=0.02, PLM=WD, Dk(0)=5.06, Dk(inf)=3.83
"Meg-6 TopBot", Dk=3.28, LT=0.0035, PLM=WD, Dk(0)=3.4, Dk(inf)=3.23
"Meg-6 Inner1", Dk=3.45, LT=0.0035, PLM=WD, Dk(0)=3.57, Dk(inf)=3.4
"Meg-6 Inner2", Dk=3.4, LT=0.003, PLM=WD, Dk(0)=3.5, Dk(inf)=3.36
"Meg-6 Inner3", Dk=3.4, LT=0.003, PLM=WD, Dk(0)=3.5, Dk(inf)=3.36
"Meg-6 Inner6", Dk=3.45, LT=0.0035, PLM=WD, Dk(0)=3.57, Dk(inf)=3.4
"Meg-6 Av", Dk=3.19, LT=0.003, PLM=WD, Dk(0)=3.29, Dk(inf)=3.15
StackUp: LU=[um], NL=20, T=2030.12[um], CSM=("Solder Mask", 40[um])
1| Signal: "TOP", T=35.56, Ins="Air", Cond="035.56UM_CU"
2| Medium: T=73.25, Ins="Meg-6 TopBot", DIE_003
3| Plane: "GND1", Cond="017.78UM_CU", T=15, Ins="Meg-6 Av"
4| Medium: T=100, Ins="Meg-6 Inner1", DIE_005
5| Signal: "INNER1", T=15, Ins="Meg-6 Inner1", Cond="017.78UM_CU"
6| Medium: T=108, Ins="Meg-6 Inner1", DIE_007
7| Plane: "GND2", Cond="017.78UM_CU", T=15, Ins="Meg-6 Av"
8| Medium: T=100, Ins="Meg-6 Inner2", DIE_009
9| Signal: "INNER2", T=15, Ins="Meg-6 Inner2", Cond="017.78UM_CU"
10| Medium: T=86, Ins="Meg-6 Inner2", DIE_011
11| Plane: "GND3", Cond="017.78UM_CU", T=15, Ins="Meg-6 Av"
12| Medium: T=100, Ins="Meg-6 Inner3", DIE_013
13| Signal: "INNER3", T=15, Ins="Meg-6 Inner3", Cond="017.78UM_CU"
14| Medium: T=86, Ins="Meg-6 Inner3", DIE_015
15| Plane: "GND4", Cond="017.78UM_CU", T=15, Ins="Meg-6 Av"
16| Medium: T=50, Ins="FR-4", DIE_017
17| Plane: "VCC1", Cond="017.78UM_CU", T=15, Ins="Meg-6 Av"
18| Medium: T=96.5, Ins="Meg-6 Av", DIE_019
19| Plane: "GND5", Cond="017.78UM_CU", T=15, Ins="Meg-6 Av"
20| Medium: T=50, Ins="FR-4", DIE_021
21| Plane: "VCC2", Cond="017.78UM_CU", T=15, Ins="Meg-6 Av"
22| Medium: T=86, Ins="Meg-6 Av", DIE_023
23| Plane: "VCC3", Cond="017.78UM_CU", T=15, Ins="Meg-6 Av"
24| Medium: T=100, Ins="Meg-6 Av", DIE_025
25| Plane: "GND6", Cond="017.78UM_CU", T=15, Ins="Meg-6 Av"
26| Medium: T=86, Ins="Meg-6 Inner3", DIE_027

Modified Hammerstad Roughness Models (different for strip and microstrip layers) – non causal model

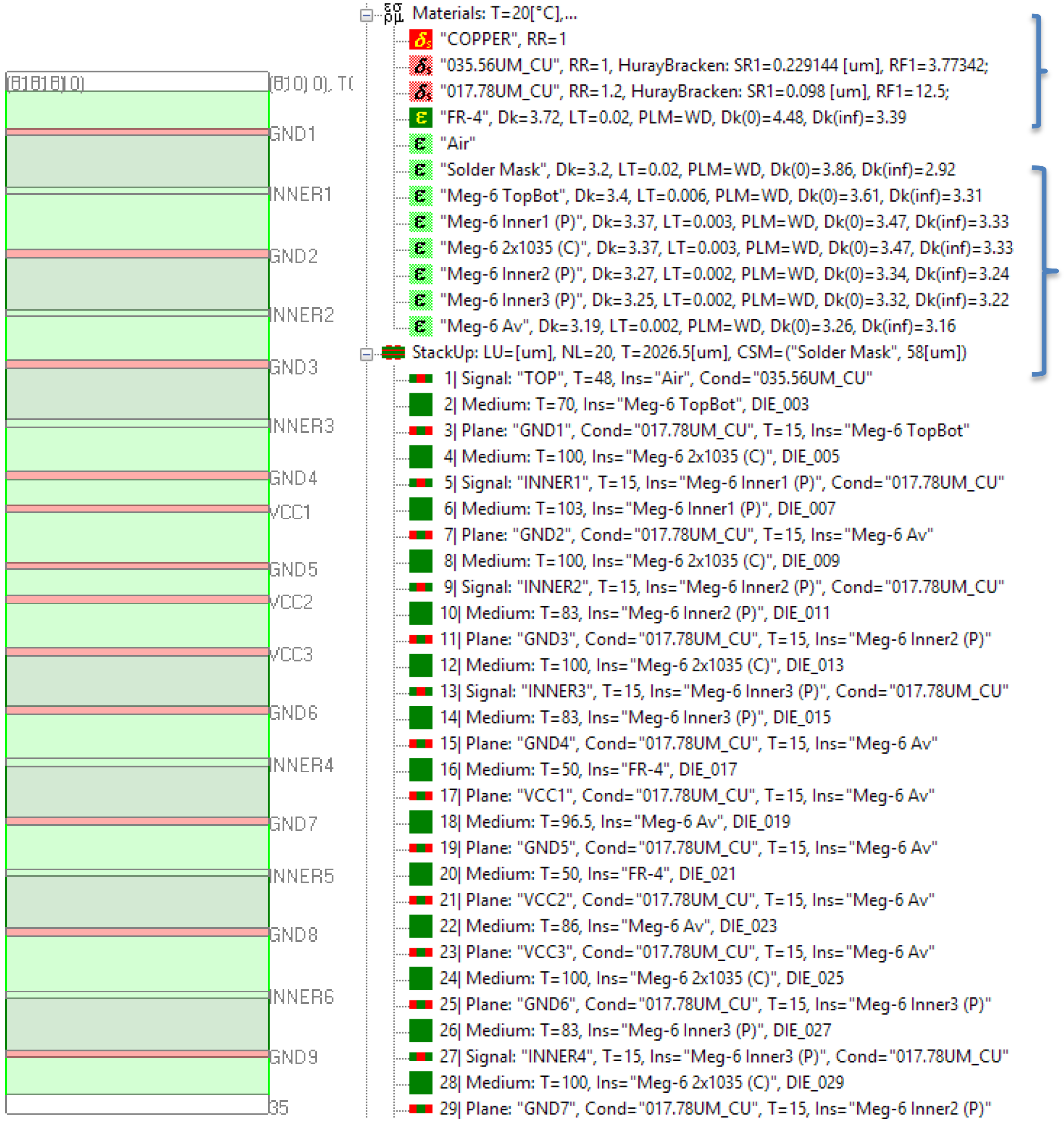
Wideband Debye models with Dk and LT @ 1 GHz (initial in brackets):
INNER1/INNER6: Dk=3.45 (3.23 & 3.37), LT=0.0035 (0.002)
INNER2/INNER3: Dk=3.4 (3.19 & 3.37), LT=0.003 (0.002)
TOP/BOTTOM: Dk=3.28 (3.19), LT=0.035 (0.002)
Solder Mask: Dk=4.2 (4.0), LT=0.02

2 roughness models and 4 dielectric models – relatively easy to identify, suitable for the analysis of vias and launches, but it compromises the accuracy of trace analysis:

Use of non-causal roughness models results in the differential strip impedance lower than observed on TDR by 2-3 Ohm

Use of homogeneous dielectric for each strip layer results in no difference in phase delay of the even and odd modes and no FEXT!

Identification results (better, 50 GHz VNA)



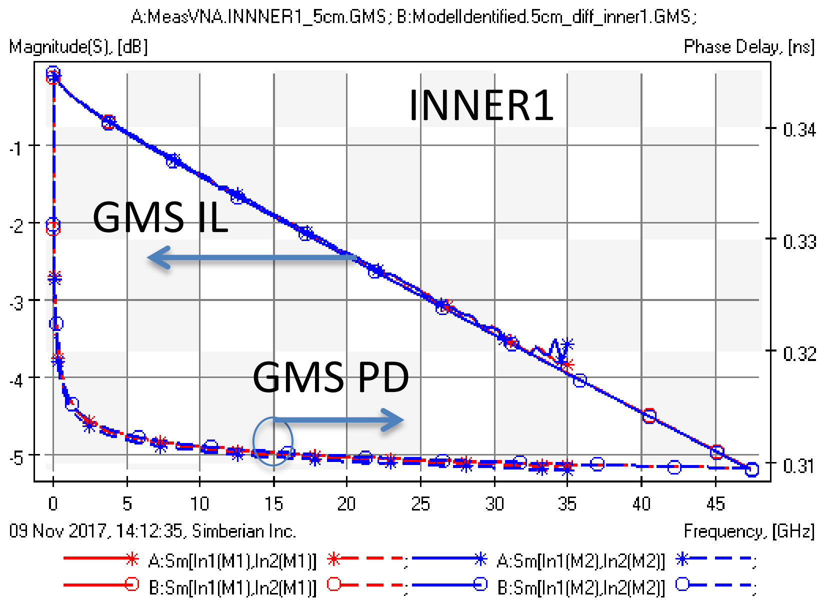
Huray-Bracken Roughness Models (causal):
Strips: SR=0.098 um, RF=1.25
Microstrips: SR=0.229 um, RF=3.77

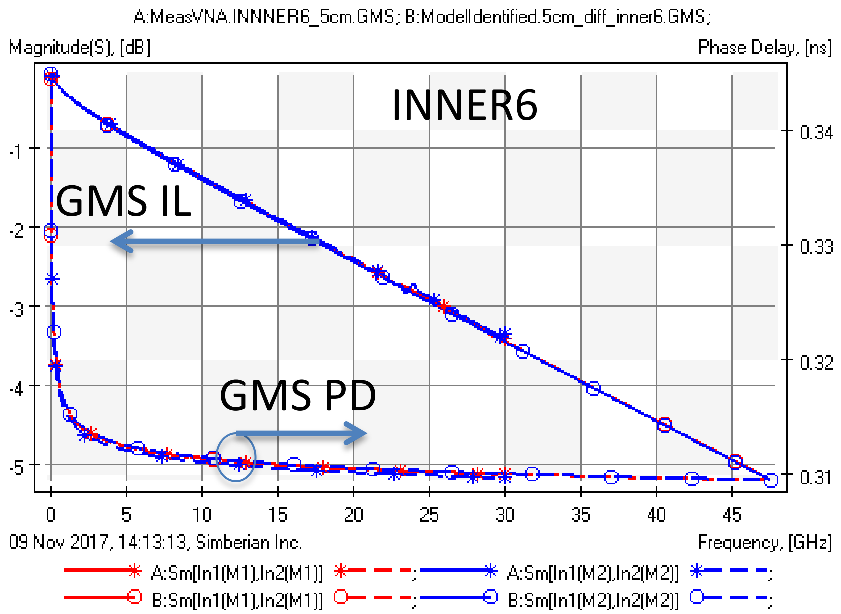
Wideband Debye models with Dk and LT @ 1 GHz (initial in brackets):
CORE (all layers): Dk=3.37 (3.37), LT=0.003 (0.002)
Prep. INNER1/INNER6: Dk=3.37 (3.23), LT=0.003 (0.002)
Prep. INNER2: Dk=3.27 (3.19), LT=0.002 (0.002)
Prep. INNER3: Dk=3.25 (3.19), LT=0.002 (0.002)
TOP/BOTTOM: Dk=3.4 (3.19), LT=0.006 (0.002)
Solder Mask: Dk=3.2 (4.0), LT=0.02

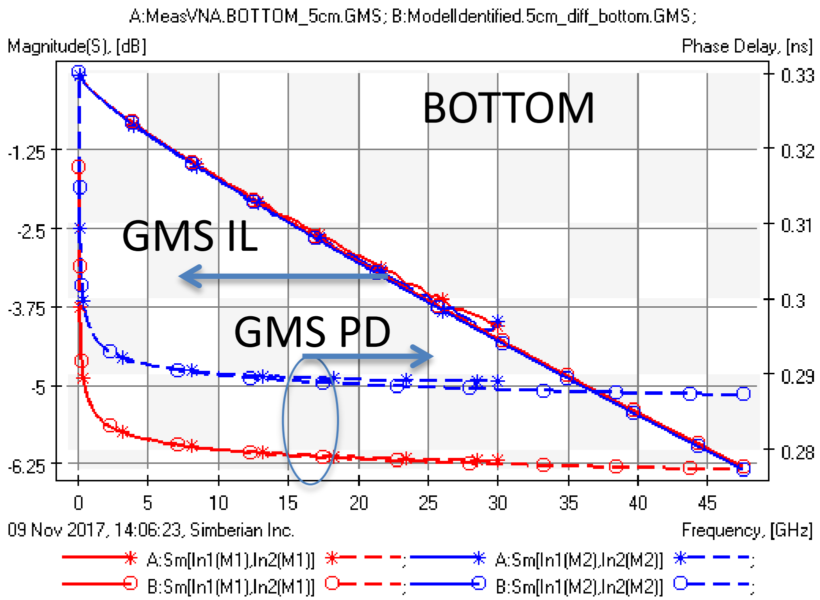
2 roughness models and 6 dielectric models – more time to identify, but models are closer to the numbers from the laminate manufacturer - accurate for trace impedance, but compromises the following:

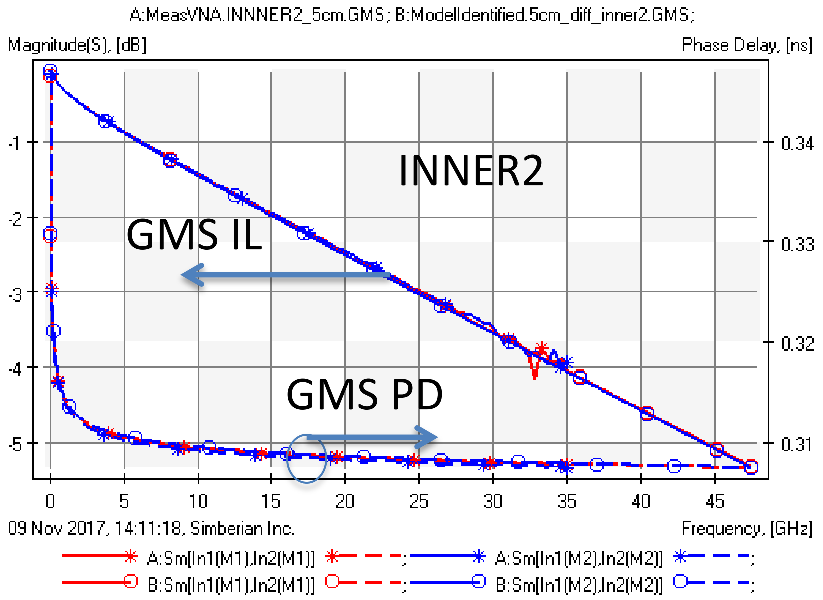
Not much inhomogeneity between core and prepreg for each strip layer results in no difference in phase delay of the even and odd modes and no FEXT!

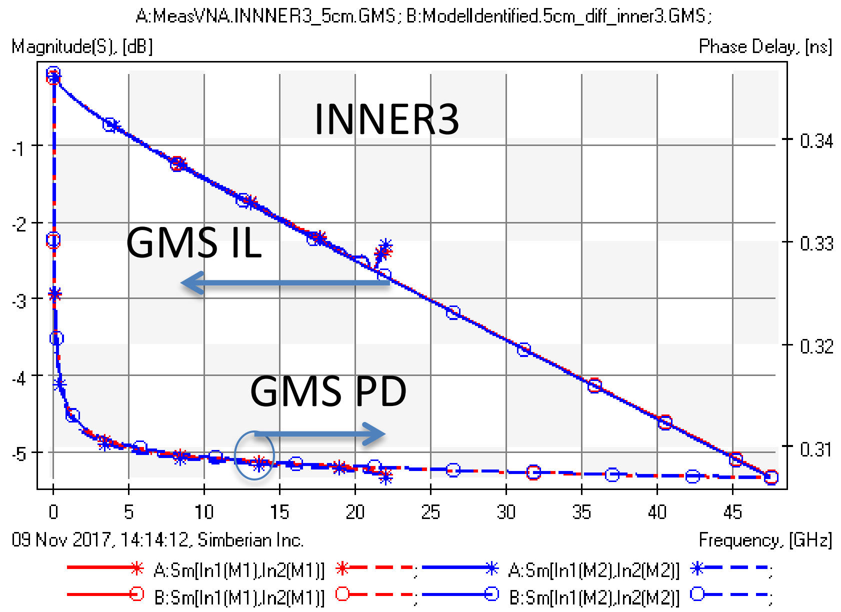
How close GMS-parameters?







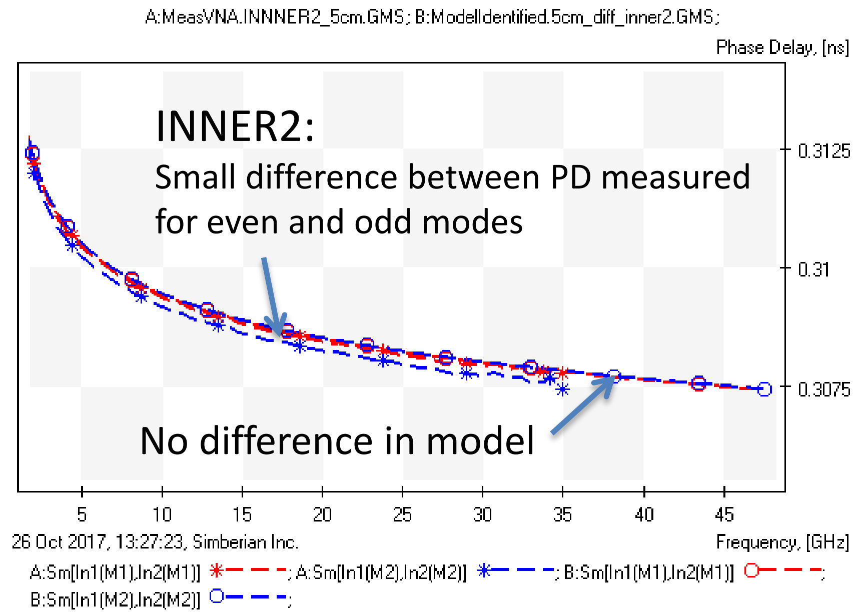


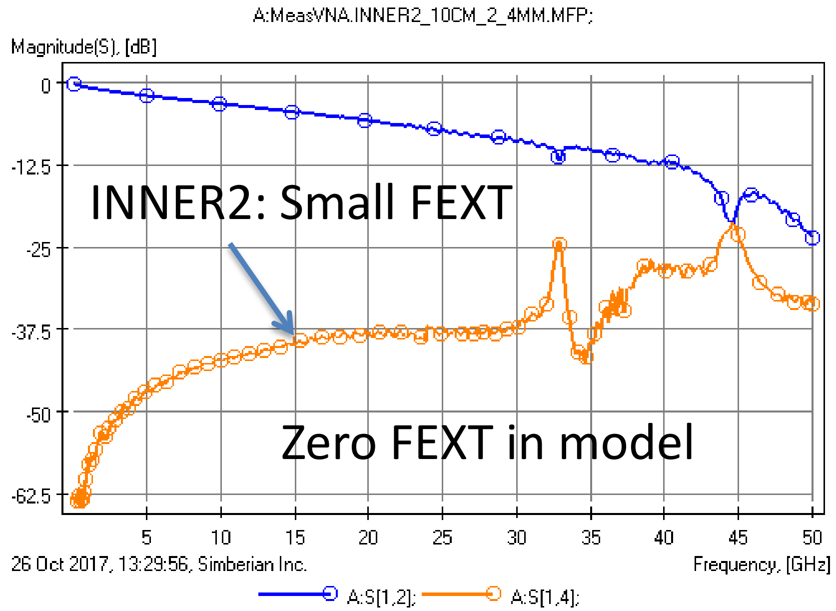


Odd mode – red
Even mode – blue
Measured – stars
Modeled – circles
Left Axis: GMS IL
Right Axis: GMS Phase Delay

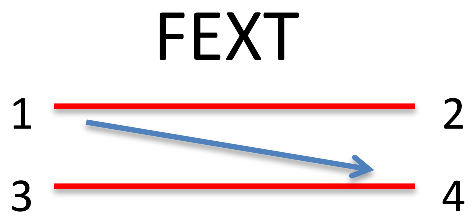
Nearly perfect match – what are the compromises?

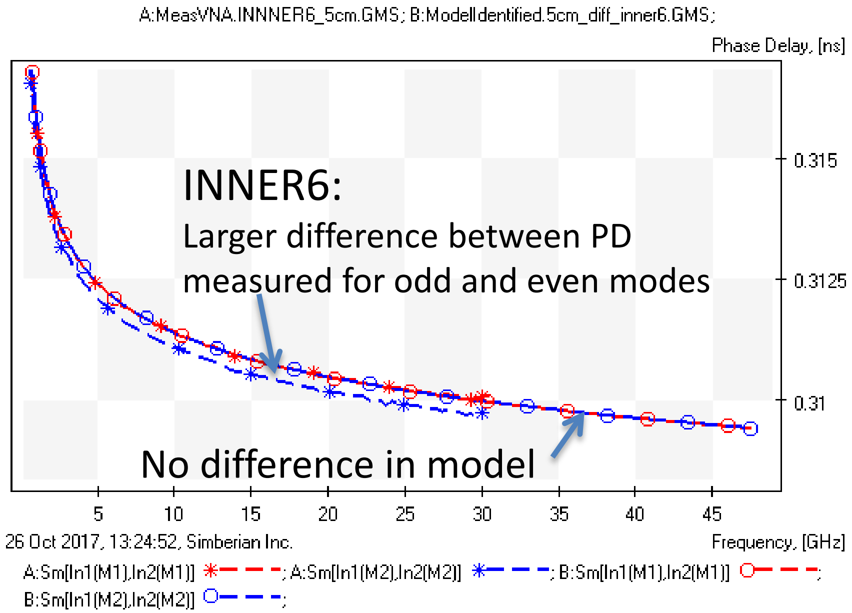
What is wrong with nearly homogeneous dielectric model?

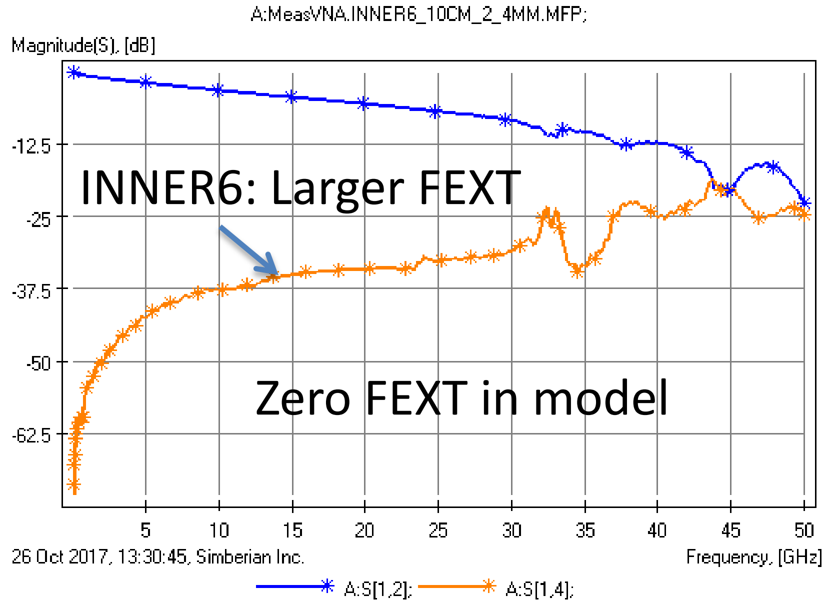




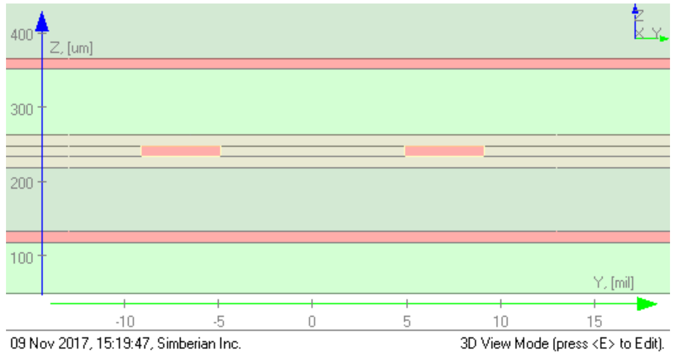
Odd mode – red
Even mode – blue
Measured – stars
Modeled – circles



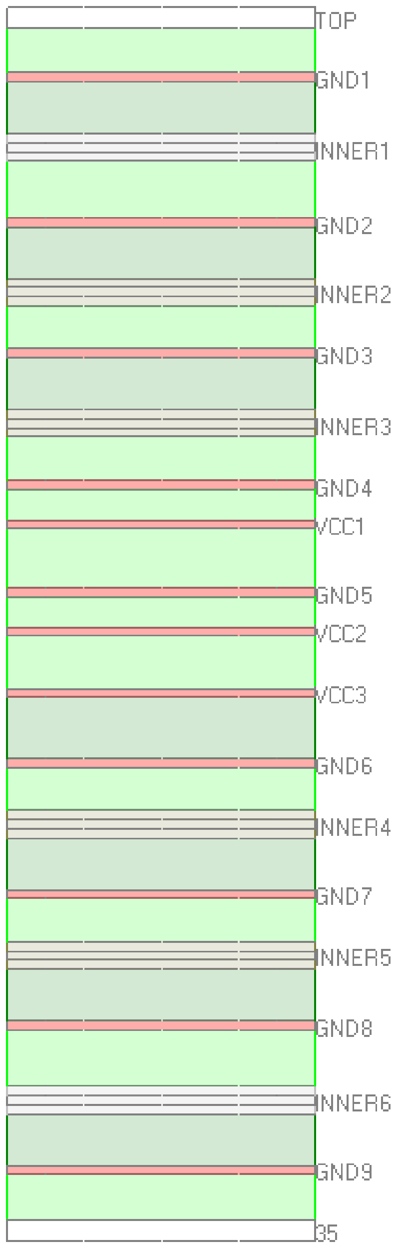




How to model it?
Create resin-rich layer around the strips with different Dk to "split" the odd and even modes...



Identification results (best)



Materials: T=20[°C],...
"COPPER", RR=1
"035.56UM_CU", RR=1, HurayBracken: SR1=0.203074 [um], RF1=4.33943;
"017.78UM_CU", RR=1.2, HurayBracken: SR1=0.098 [um], RF1=12.5;
"FR-4", Dk=3.72, LT=0.02, PLM=WD, Dk(0)=4.48, Dk(inf)=3.39
"Air"
"Solder Mask", Dk=3.2, LT=0.02, PLM=WD, Dk(0)=3.86, Dk(inf)=2.92
"Meg-6 TopBot", Dk=3.4, LT=0.006, PLM=WD, Dk(0)=3.61, Dk(inf)=3.31
"Meg-6 Inner1 (P)", Dk=3.17, LT=0.003, PLM=WD, Dk(0)=3.27, Dk(inf)=3.13
"Meg-6 Inner1 (Res)", Dk=3.562, LT=0.003, PLM=WD, Dk(0)=3.67, Dk(inf)=3.51
"Meg-6 2x1035 (C)", Dk=3.37, LT=0.003, PLM=WD, Dk(0)=3.47, Dk(inf)=3.33
"Meg-6 Inner2 (P)", Dk=3.124, LT=0.002, PLM=WD, Dk(0)=3.19, Dk(inf)=3.1
"Meg-6 Inner2 (Res)", Dk=3.425, LT=0.002, PLM=WD, Dk(0)=3.5, Dk(inf)=3.39
"Meg-6 Inner3 (P)", Dk=3.09, LT=0.002, PLM=WD, Dk(0)=3.15, Dk(inf)=3.06
"Meg-6 Av", Dk=3.19, LT=0.002, PLM=WD, Dk(0)=3.26, Dk(inf)=3.16
StackUp: LU=[um], NL=20, T=2026.5[um], CSM=("Solder Mask", 58[um])
1| Signal: "TOP", T=48, Ins="Air", Cond="035.56UM_CU"
2| Medium: T=70, Ins="Meg-6 TopBot", DIE_003
3| Plane: "GND1", Cond="017.78UM_CU", T=15, Ins="Meg-6 TopBot"
4| Medium: T=85, Ins="Meg-6 2x1035 (C)", DIE_005
5| Medium: T=15, Ins="Meg-6 Inner1 (Res)", DIE_035
6| Signal: "INNER1", T=15, Ins="Meg-6 Inner1 (Res)", Cond="017.78UM_CU"
7| Medium: T=15, Ins="Meg-6 Inner1 (Res)", DIE_035
8| Medium: T=88, Ins="Meg-6 Inner1 (P)", DIE_007
9| Plane: "GND2", Cond="017.78UM_CU", T=15, Ins="Meg-6 Av"
10| Medium: T=85, Ins="Meg-6 2x1035 (C)", DIE_009
11| Medium: T=15, Ins="Meg-6 Inner2 (Res)", DIE_009
12| Signal: "INNER2", T=15, Ins="Meg-6 Inner2 (Res)", Cond="017.78UM_CU"
13| Medium: T=15, Ins="Meg-6 Inner2 (Res)", DIE_009
14| Medium: T=68, Ins="Meg-6 Inner2 (P)", DIE_011
15| Plane: "GND3", Cond="017.78UM_CU", T=15, Ins="Meg-6 Inner2 (P)"
16| Medium: T=85, Ins="Meg-6 2x1035 (C)", DIE_013
17| Medium: T=15, Ins="Meg-6 Inner2 (Res)", DIE_009
18| Signal: "INNER3", T=15, Ins="Meg-6 Inner2 (Res)", Cond="017.78UM_CU"
19| Medium: T=15, Ins="Meg-6 Inner2 (Res)", DIE_009
20| Medium: T=68, Ins="Meg-6 Inner3 (P)", DIE_015
21| Plane: "GND4", Cond="017.78UM_CU", T=15, Ins="Meg-6 Av"
22| Medium: T=50, Ins="FR-4", DIE_017
23| Plane: "VCC1", Cond="017.78UM_CU", T=15, Ins="Meg-6 Av"
24| Medium: T=96.5, Ins="Meg-6 Av", DIE_019
25| Plane: "GND5", Cond="017.78UM_CU", T=15, Ins="Meg-6 Av"
26| Medium: T=50, Ins="FR-4", DIE_021
27| Plane: "VCC2", Cond="017.78UM_CU", T=15, Ins="Meg-6 Av"
28| Medium: T=86, Ins="Meg-6 Av", DIE_023
29| Plane: "VCC3", Cond="017.78UM_CU", T=15, Ins="Meg-6 Av"
30| Medium: T=100, Ins="Meg-6 2x1035 (C)", DIE_025
31| Plane: "GND6", Cond="017.78UM_CU", T=15, Ins="Meg-6 Inner3 (P)"

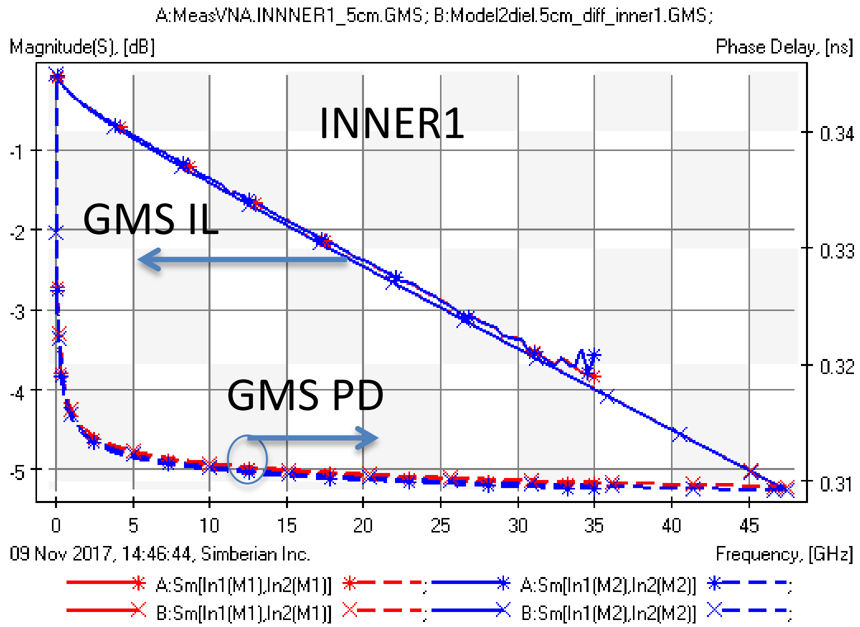
Huray-Bracken Roughness Models (causal):
Strips: SR=0.098 um, RF=1.25
Microstrips: SR=0.229 um, RF=3.77

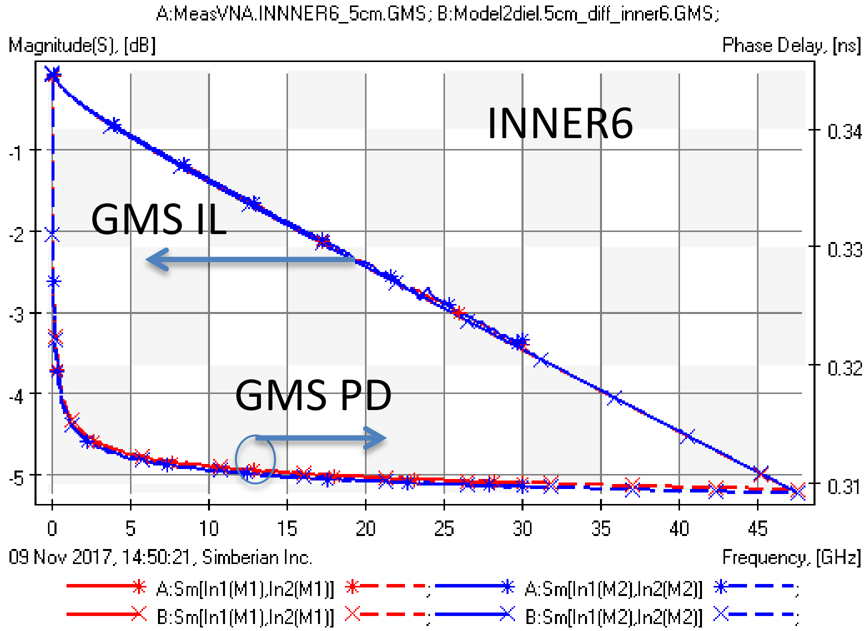
Wideband Debye models with Dk and LT @ 1 GHz (initial in brackets):
CORE (all layers): Dk=3.37 (3.37), LT=0.003 (0.002)
Prep. INNER1/INNER6: Dk=3.17 (3.23), LT=0.003 (0.002)
Resin INNER1/INNER6: Dk=3.562, LT=0.003
Prep. INNER2: Dk=3.124 (3.19), LT=0.002 (0.002)
Prep. INNER3: Dk=3.09 (3.19), LT=0.002 (0.002)
Resin INNER2/INNER3: Dk=3.425, LT=0.002
TOP/BOTTOM: Dk=3.4 (3.19), LT=0.006 (0.002)
Solder Mask: Dk=3.2 (4.0), LT=0.02

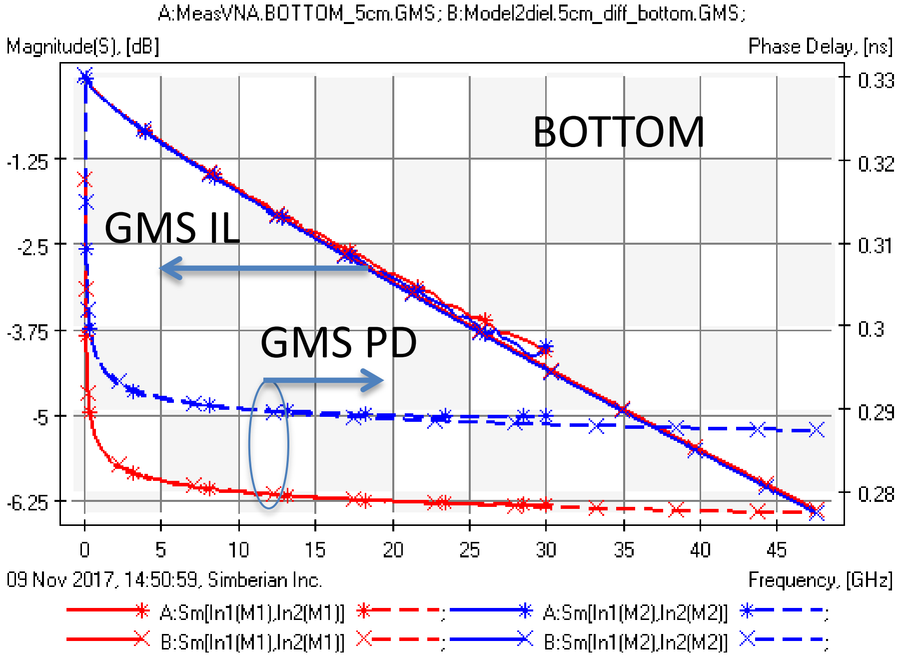
2 roughness models and 8 dielectric models – more difficult to identify, but is necessary for FEXT analysis

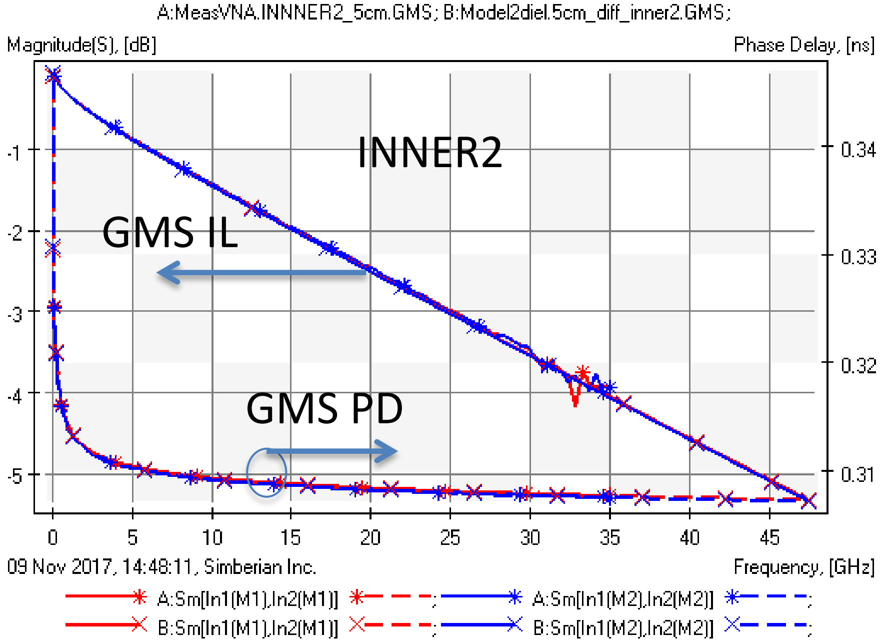
Let's see how close are GMS-parameters…

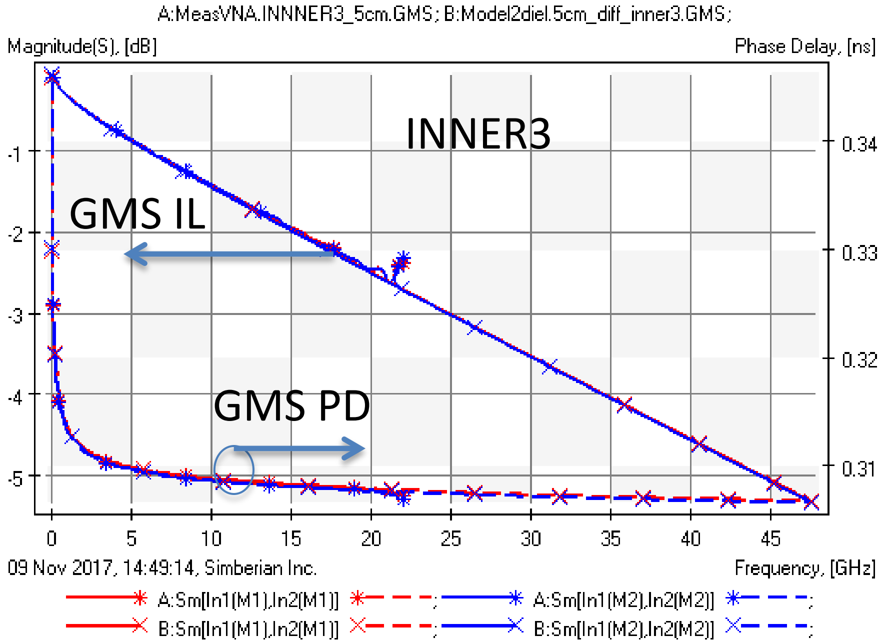
Measured and modeled GMS-parameters







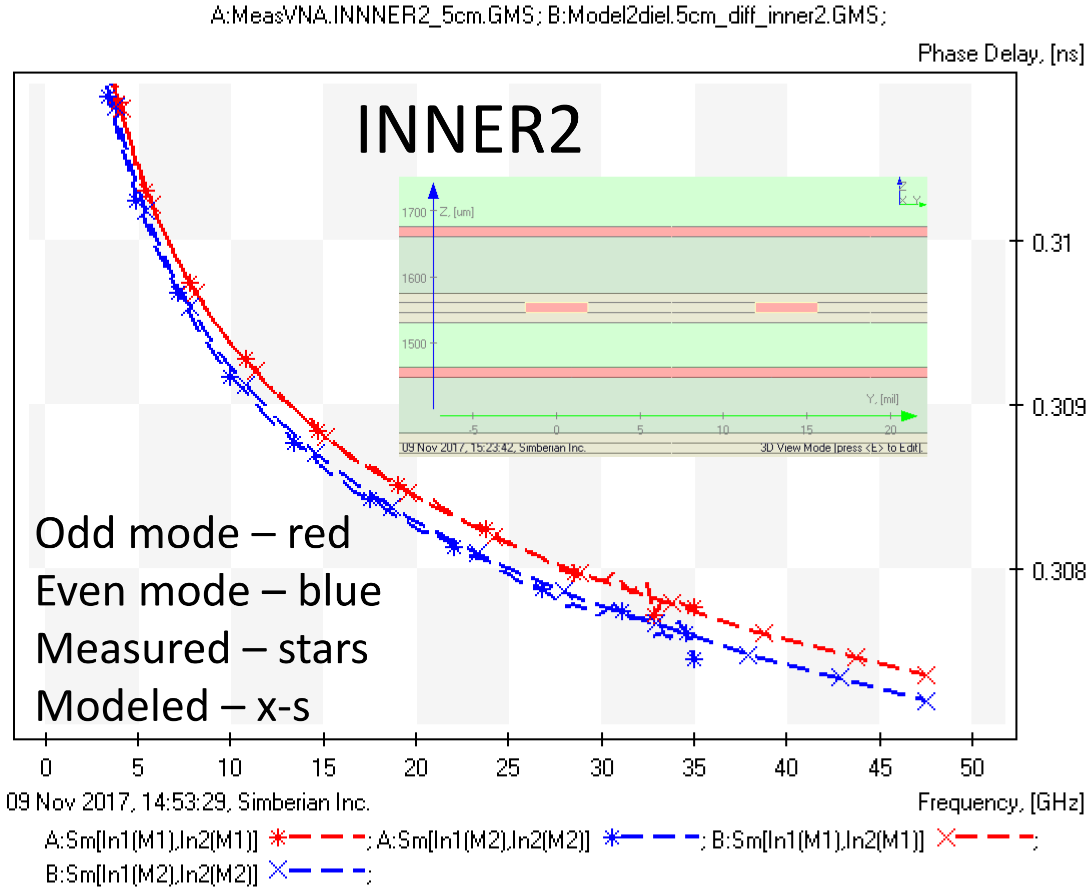


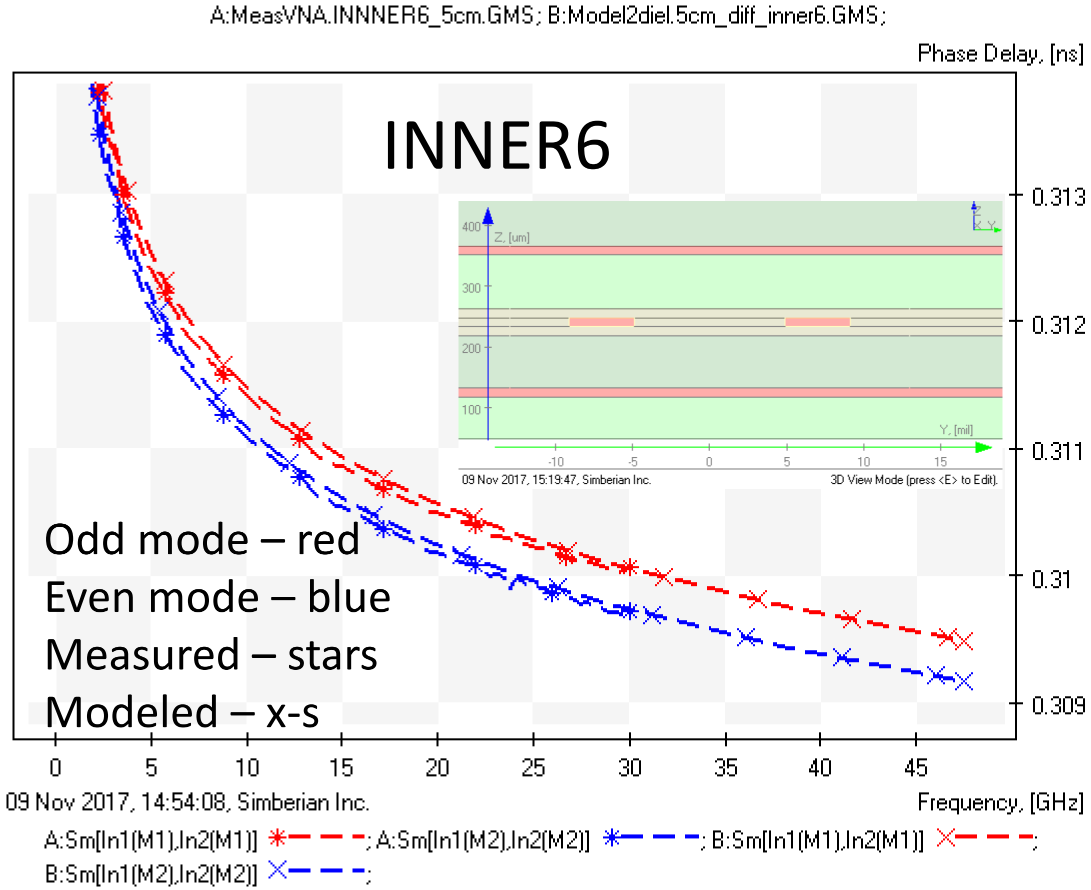


Odd mode – red
Even mode – blue
Measured – stars
Modeled – x-s

Modal phase delay

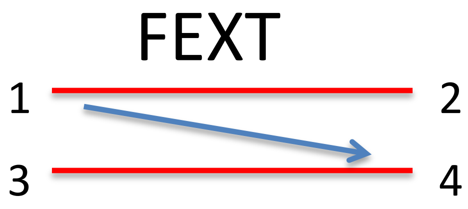
- Close match for odd and even modes

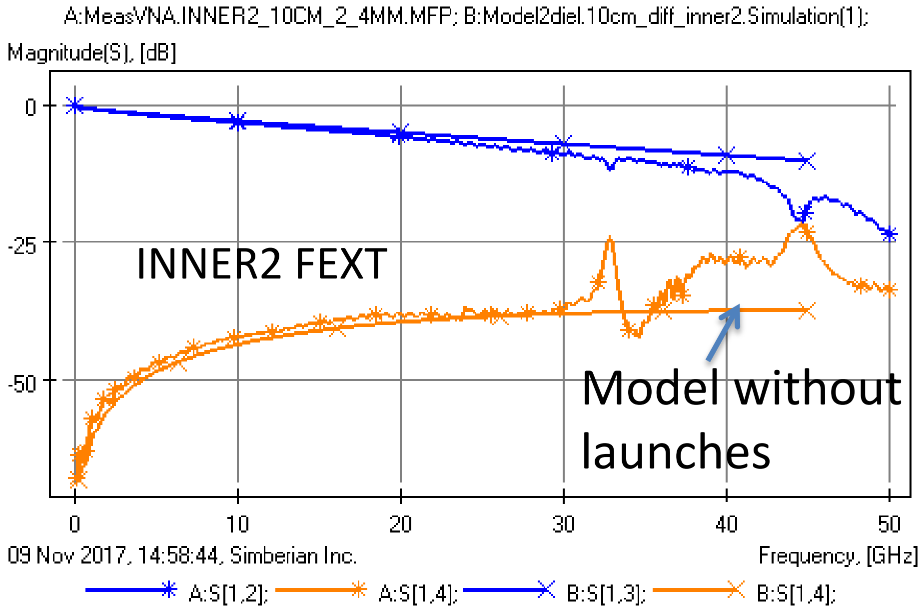


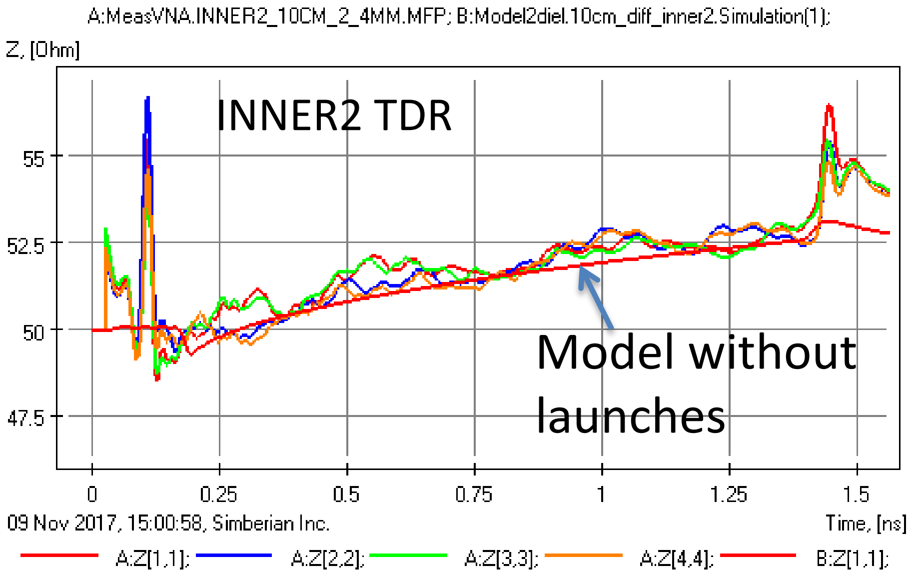


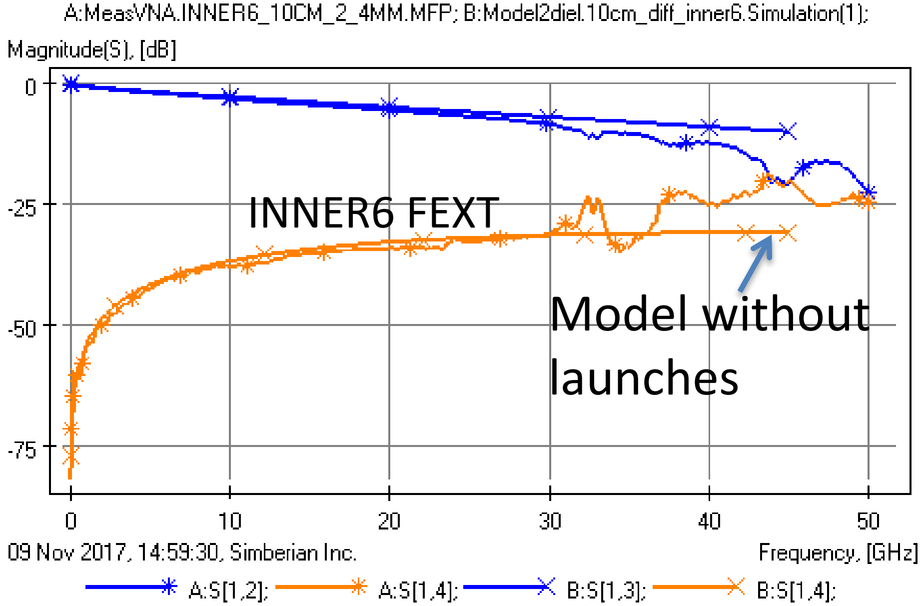
Preliminary checks before the post-layout analysis

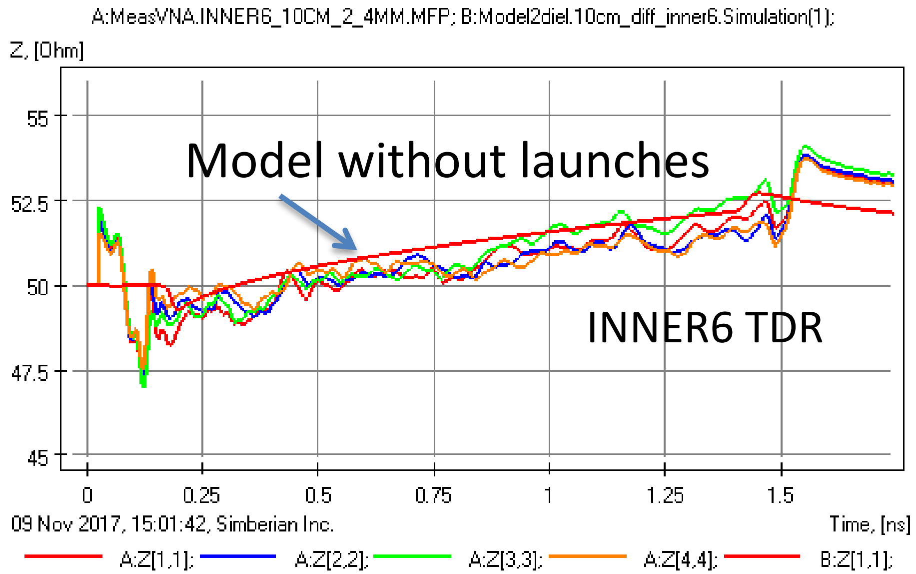
Simulate 10 cm line segment without launches to correlate the FEXT with measured S-parameters and impedance on TDR







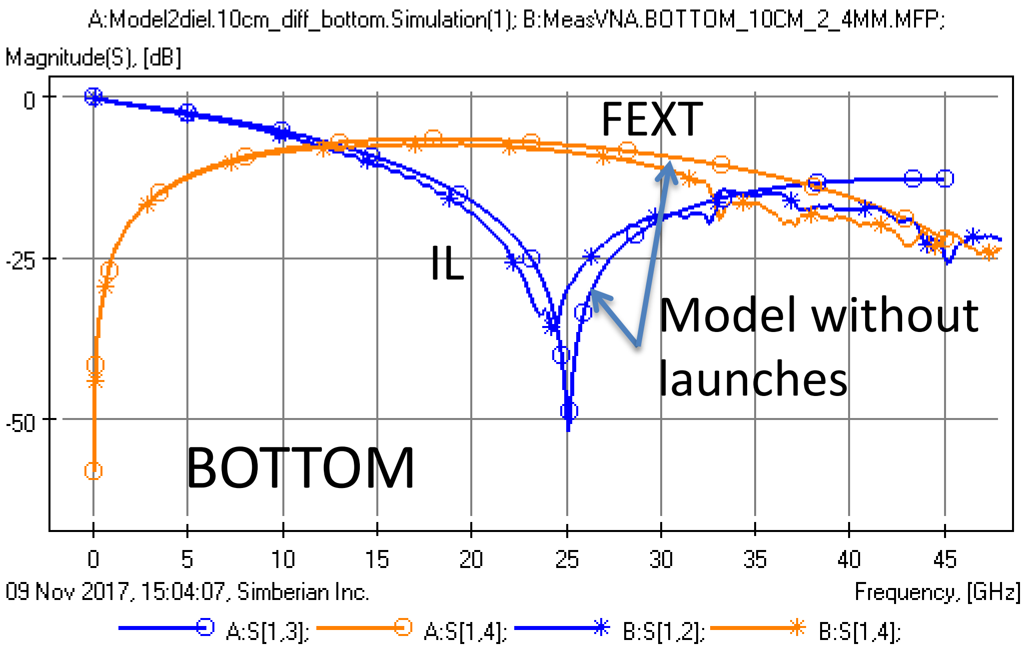


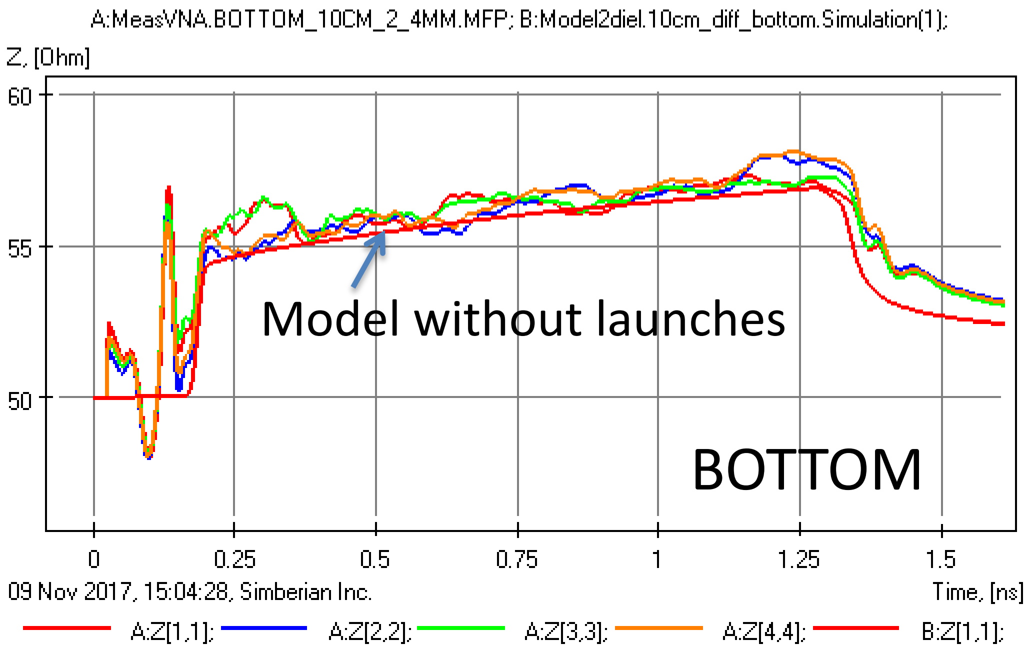


Good correlation in FEXT up to 30 GHz
About 1 Ohm impedance variation consistent with expectations

The result is acceptable – we can proceed with the post-layout analysis…

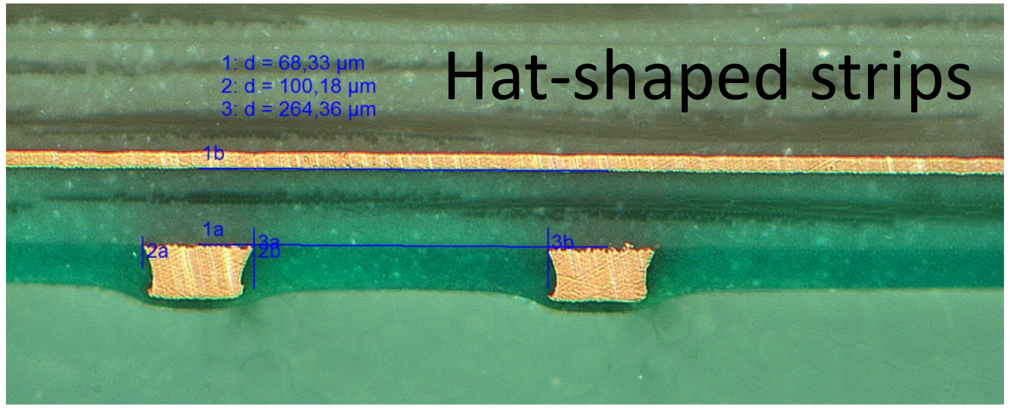
Preliminary checks for microstrips





Good correlation in FEXT up to 30 GHz
About 1.5 Ohm impedance variations – more than expected

The result is acceptable – we can proceed with the post-layout analysis…

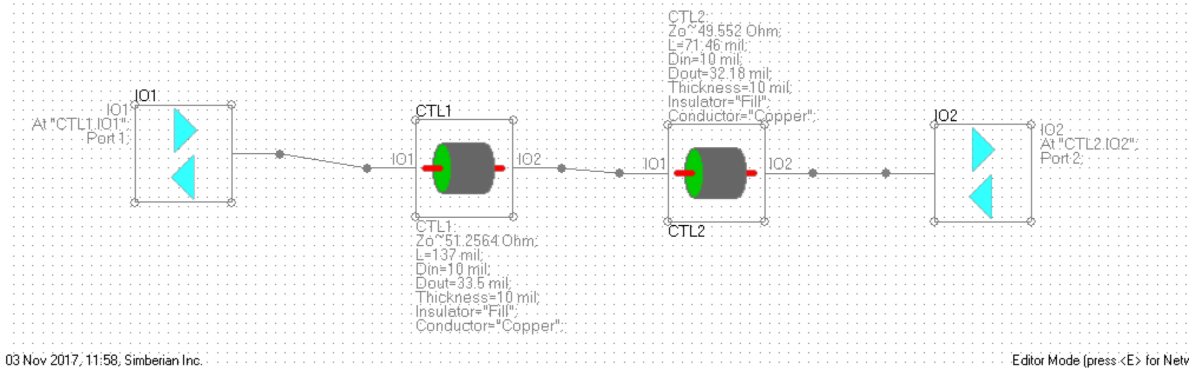


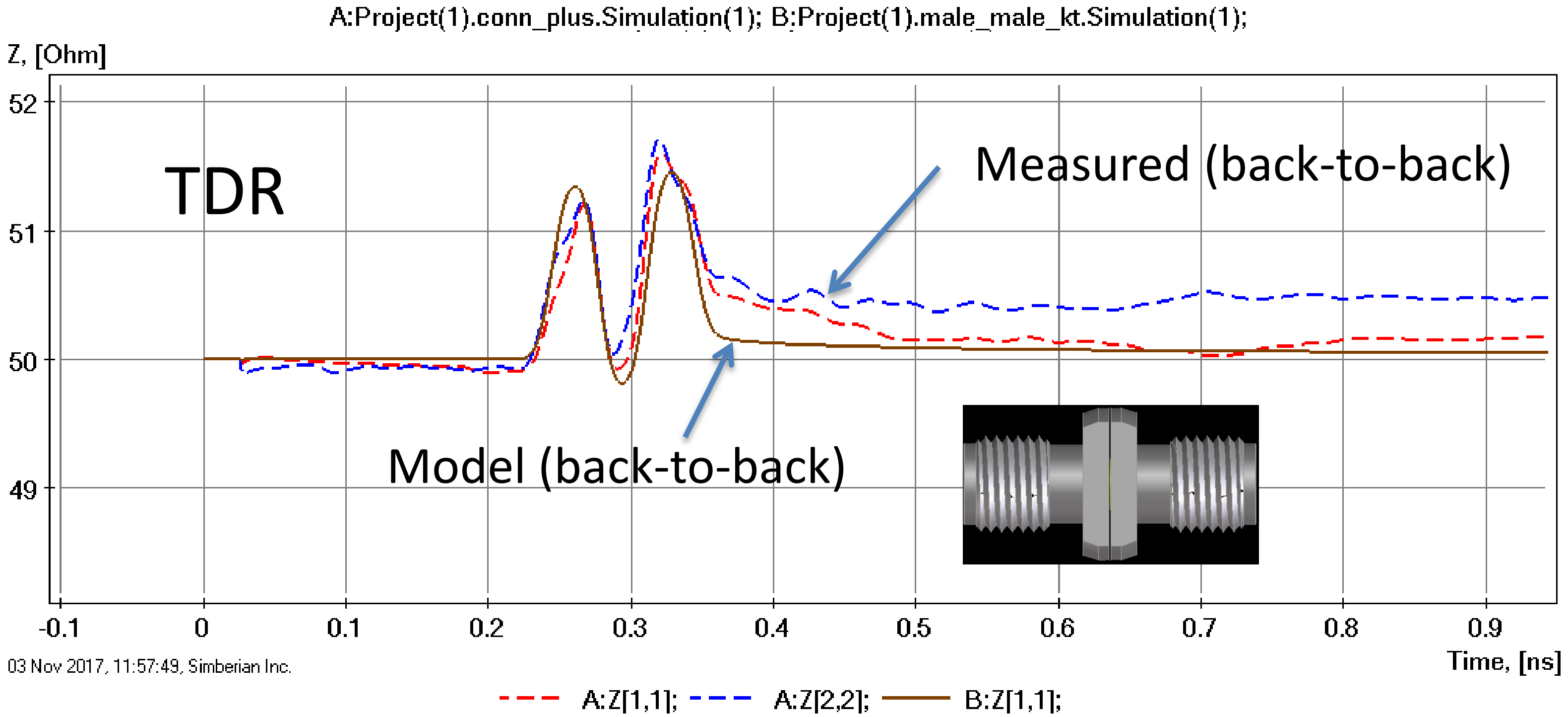
Validation: Expectations vs. Reality

Connector surrogate model

- We do not know the interior structure of the connector
- Simulation data or model provided by connector vendor usually gives perfect 50 Ohm result
- One option is to put two connectors back-to-back, measure S-parameters and construct surrogate model by matching S-parameters and TDR

Single connector surrogate model

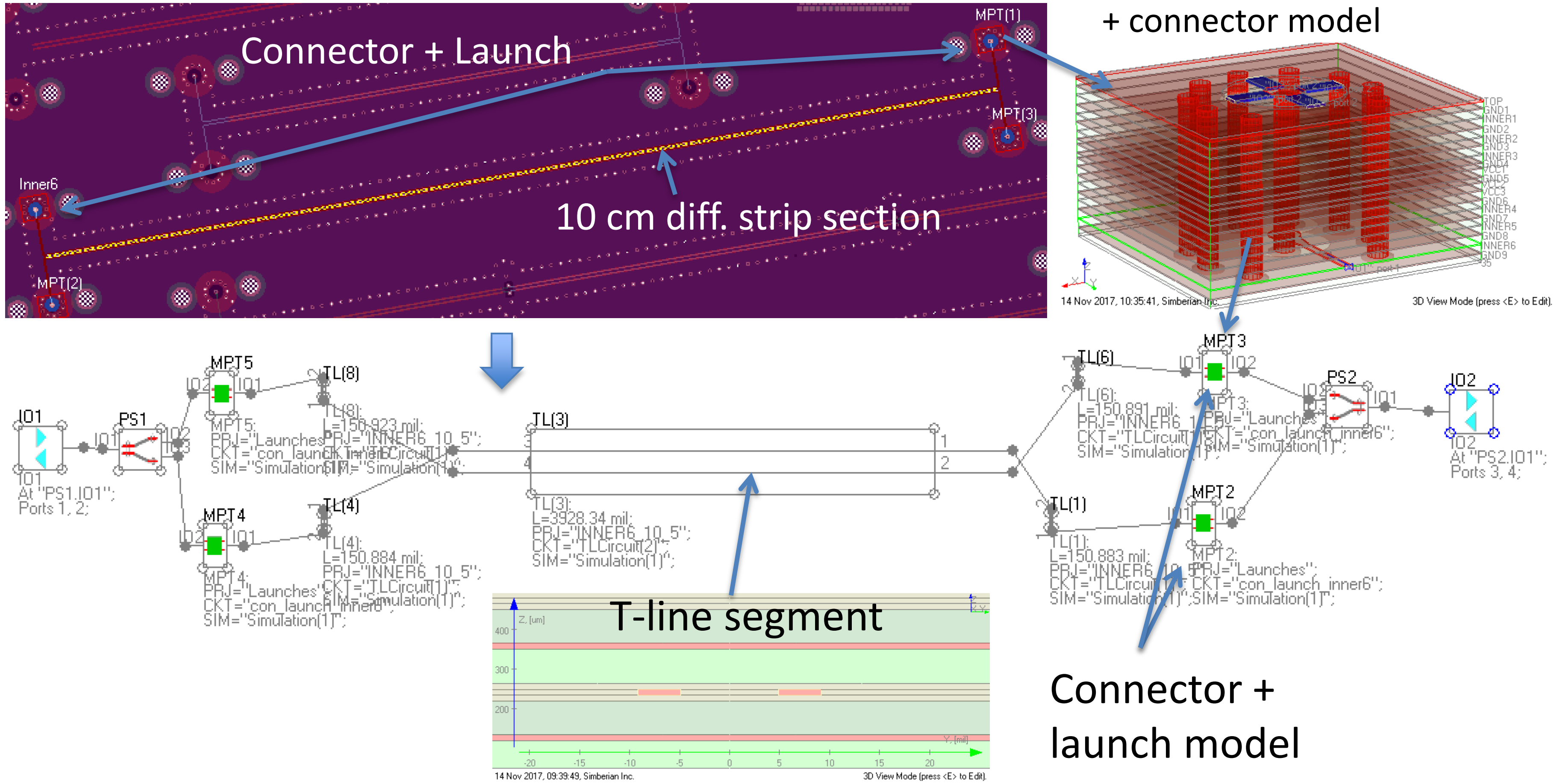




Can be further refined with 75 GHz bandwidth…

De-compositional electromagnetic analysis

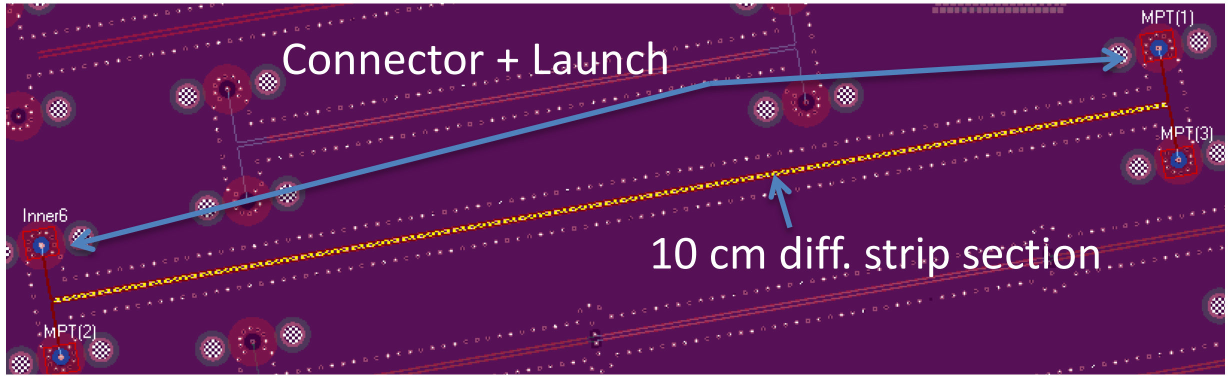
Example of model for 10 cm diff. link in INNER6



INNER6: 10 cm diff. strip link

Firsts attempt

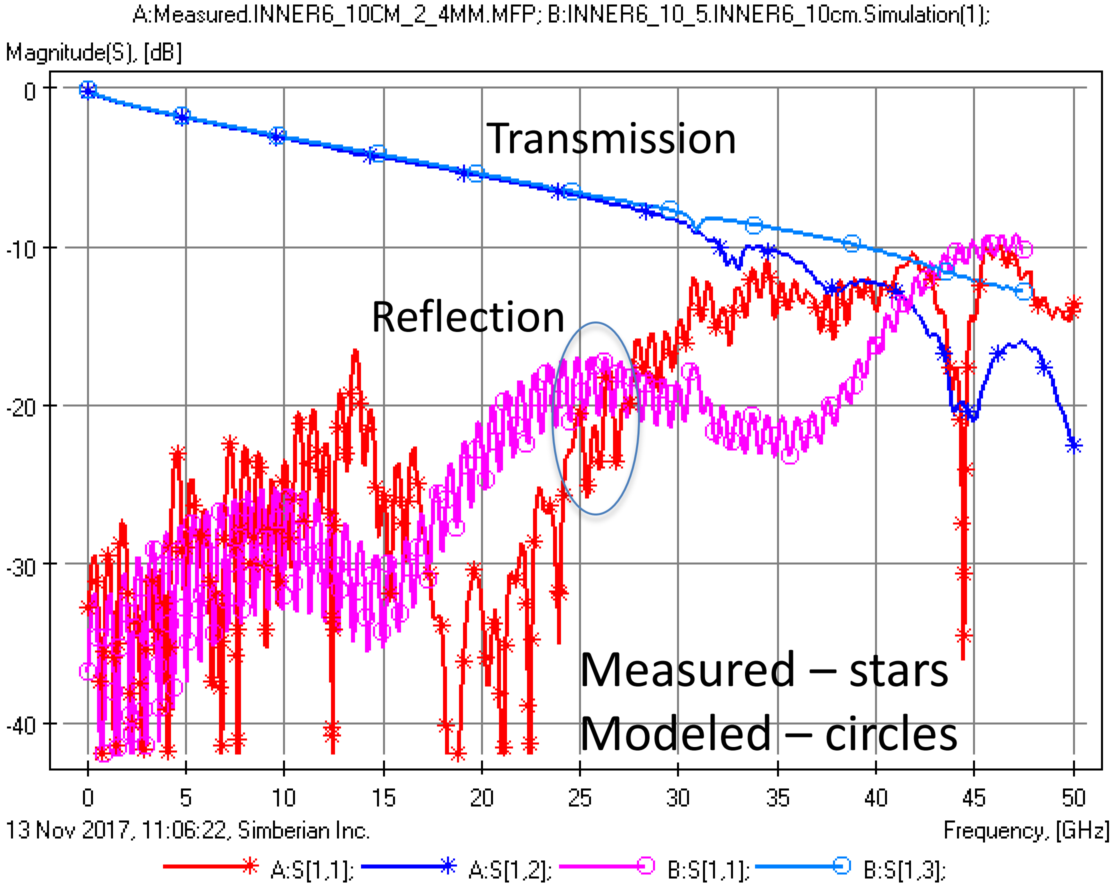
Single-ended S-parameters

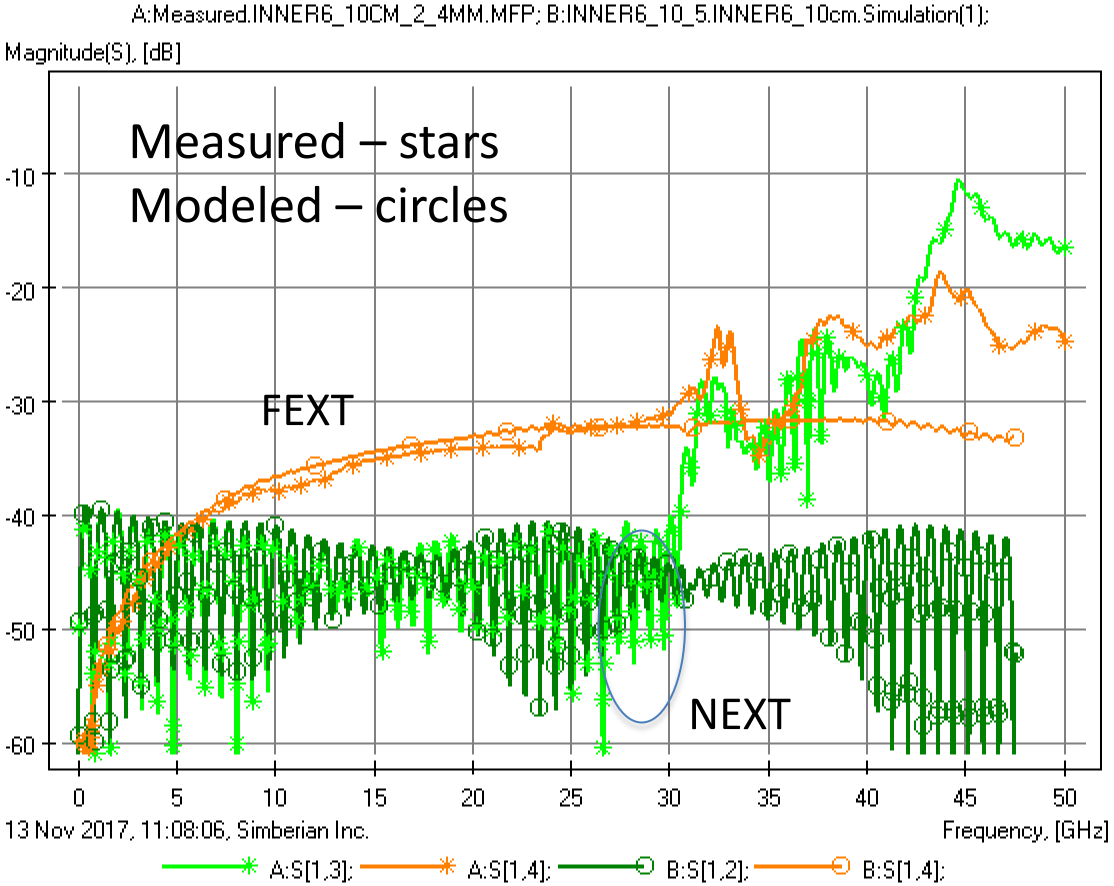


De-compositional EM analysis
All trace widths and shapes are adjusted

Reality: Large difference in reflection from 10 to 30 GHz (investigate), above 30 GHz – see reality above 30 GHz…

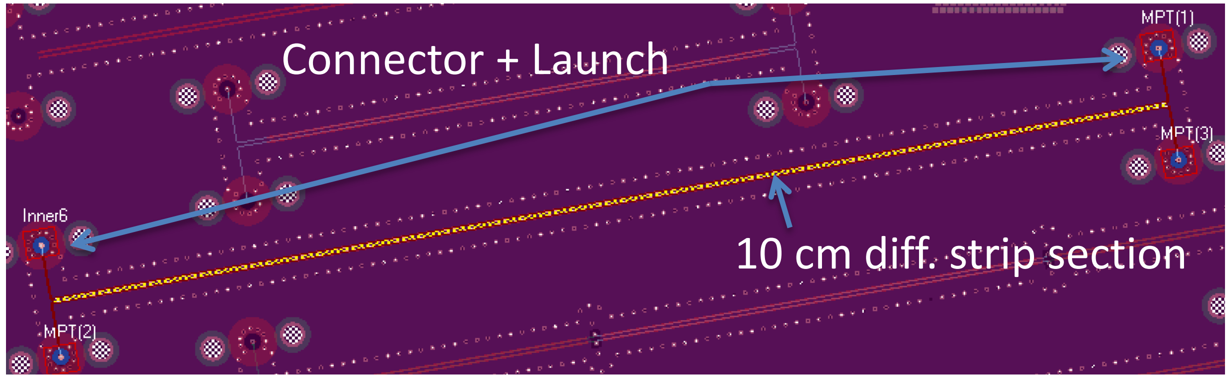
Acceptable correspondence up to 30 GHz





INNER6: 10 cm diff. strip link

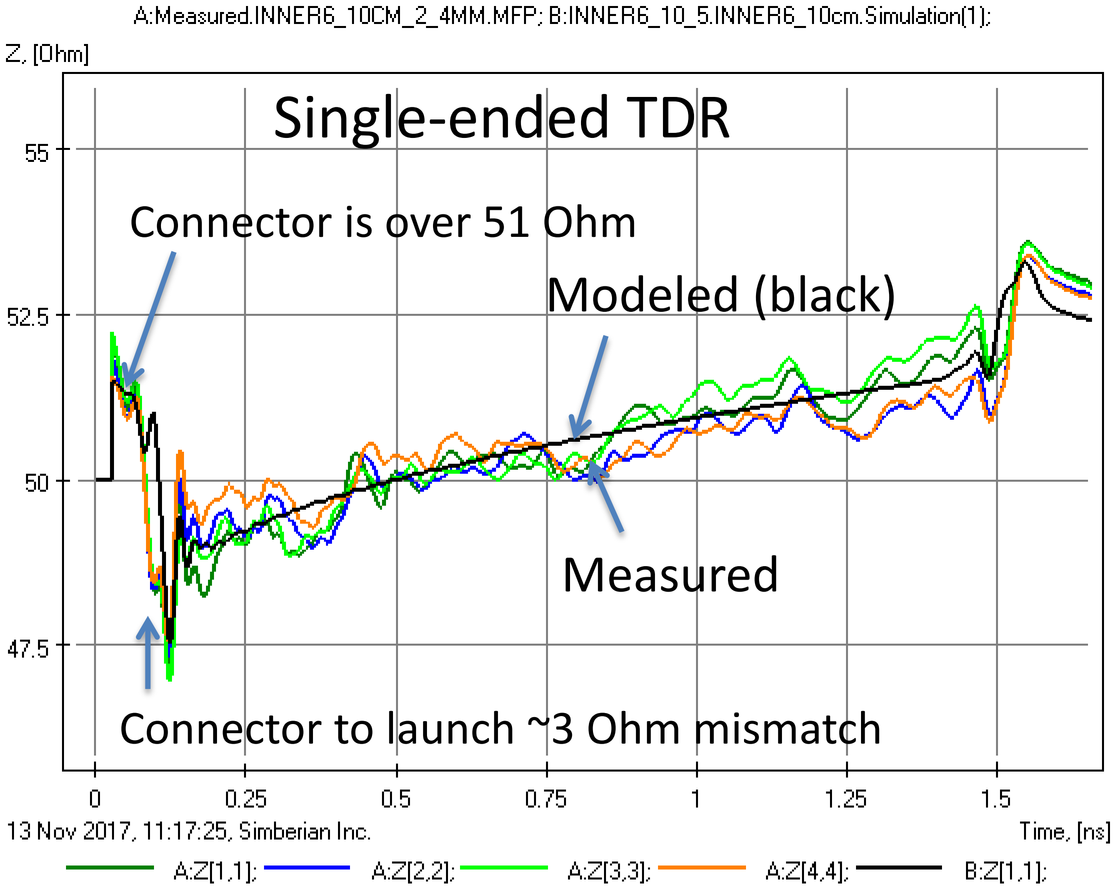
Firsts attempt

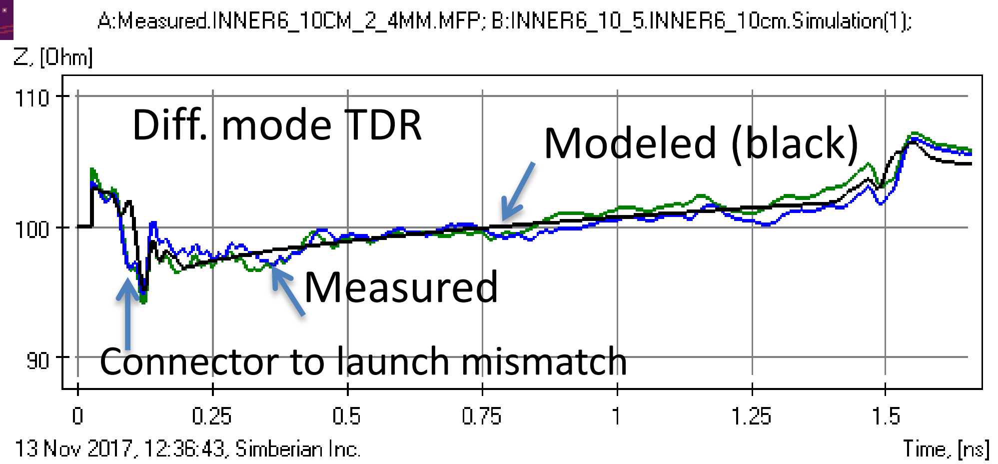


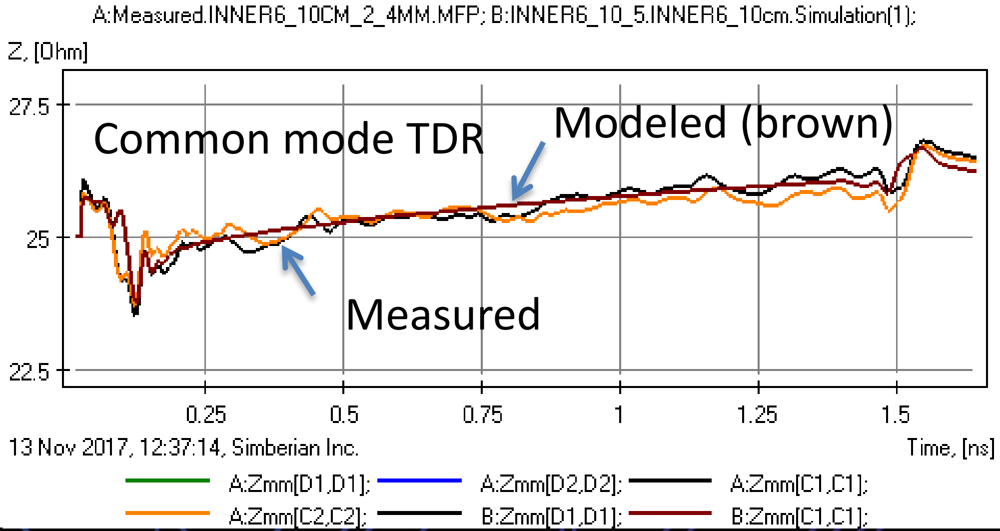
De-compositional EM analysis
All trace widths and shapes are adjusted

Reality: Large difference at the connector to launch transition (investigate), variation of impedance along the traces (expected)

Acceptable correspondence

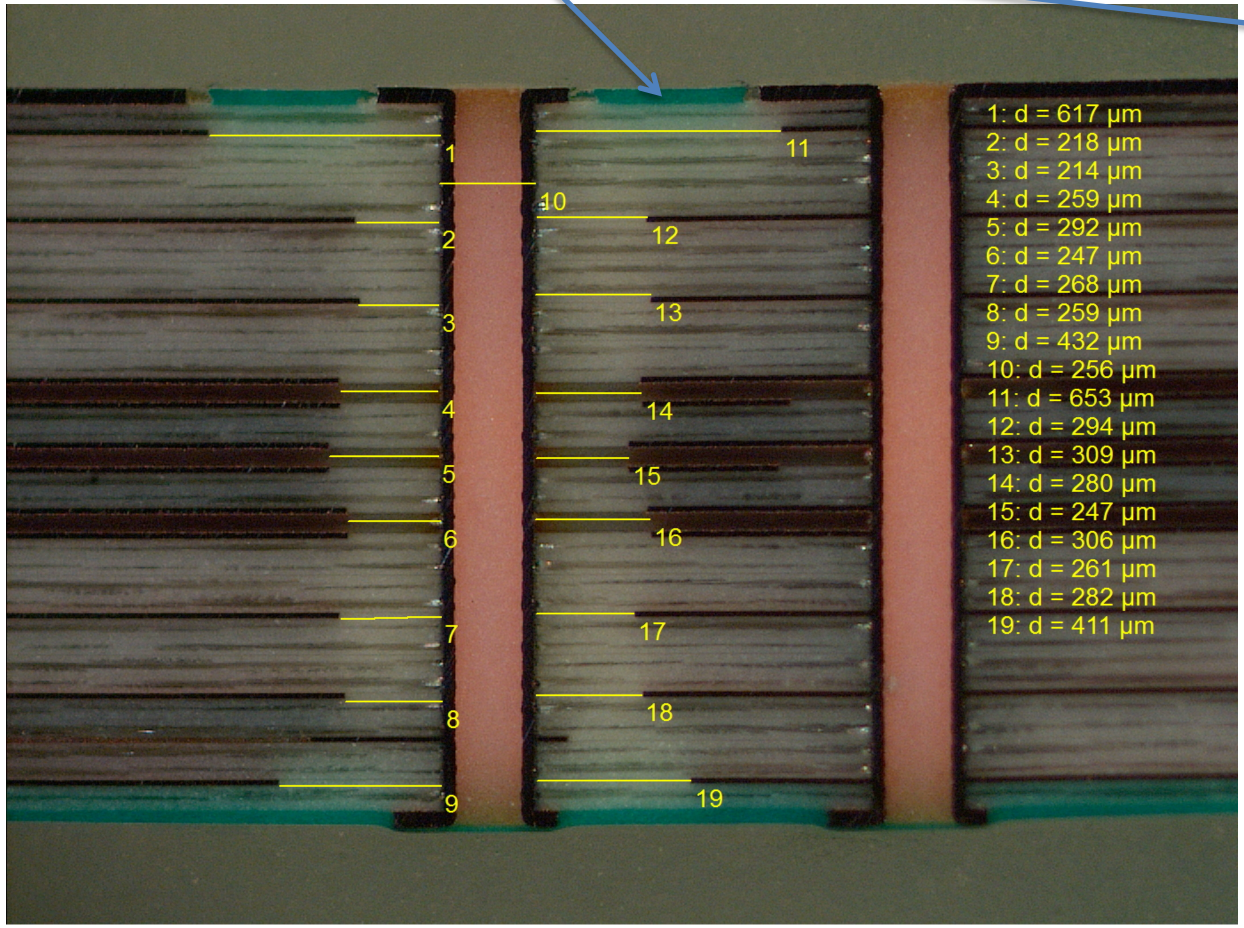


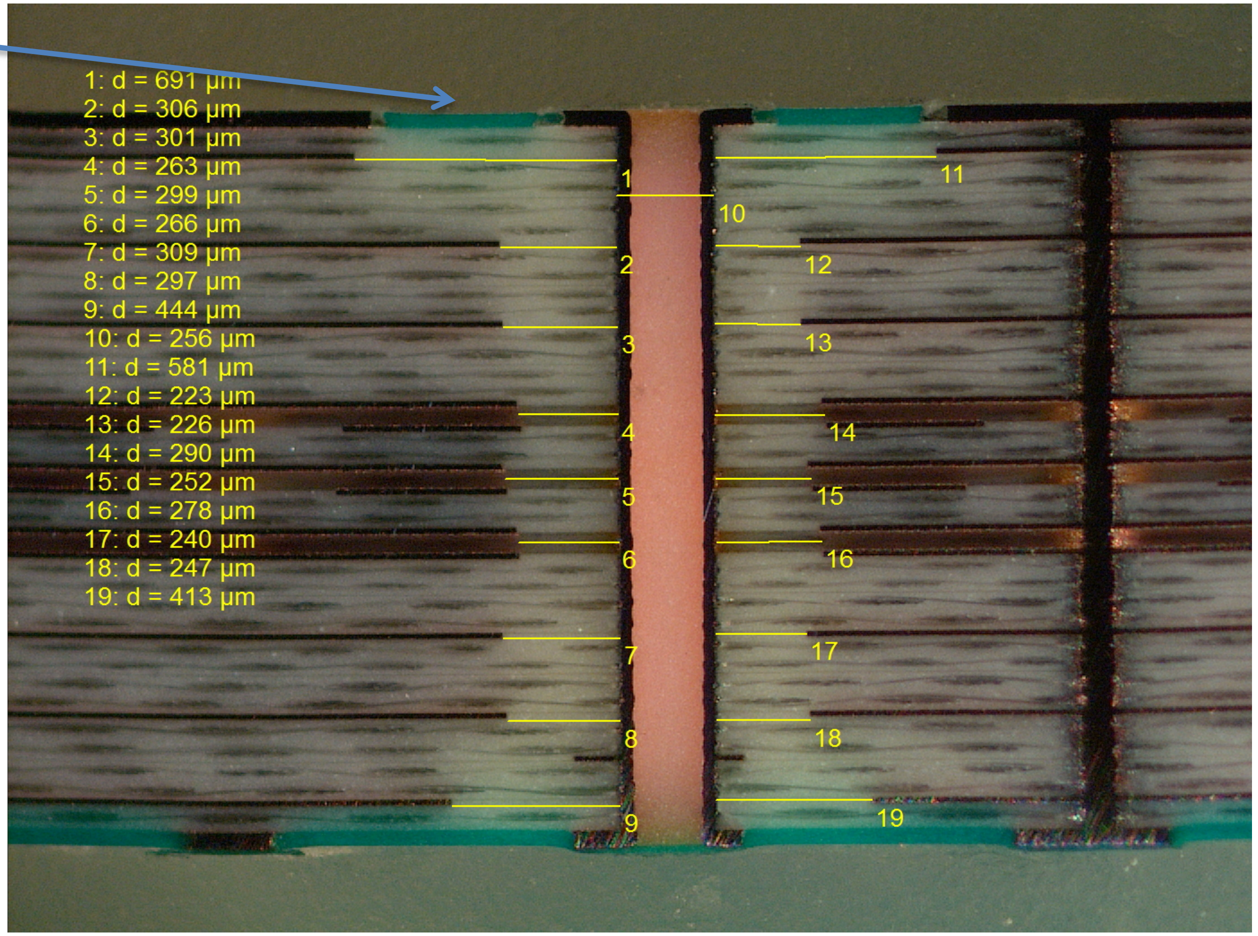




Launch investigation

- Solder mask under connector is not accounted in model (not expected)



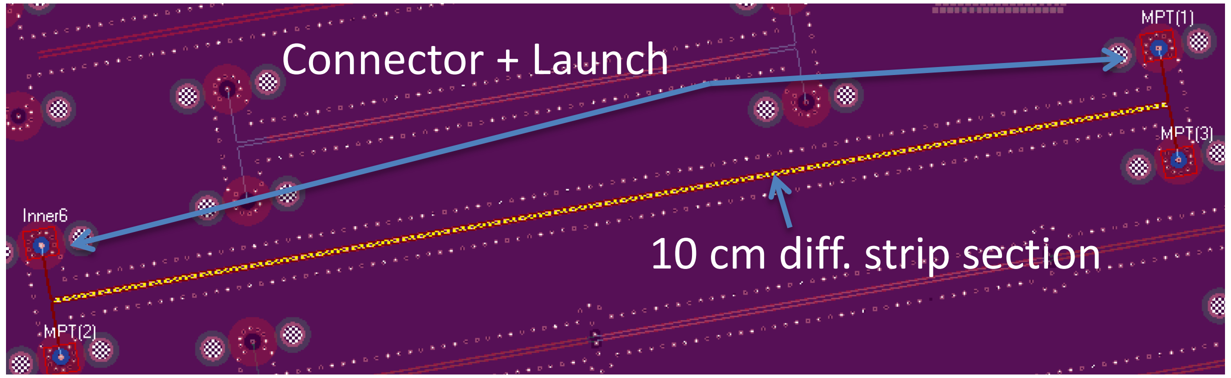


Also, offsets in pads and anti-pads – we cannot expect ideal correlation…

INNER6: 10 cm diff. strip link

With solder mask under connector

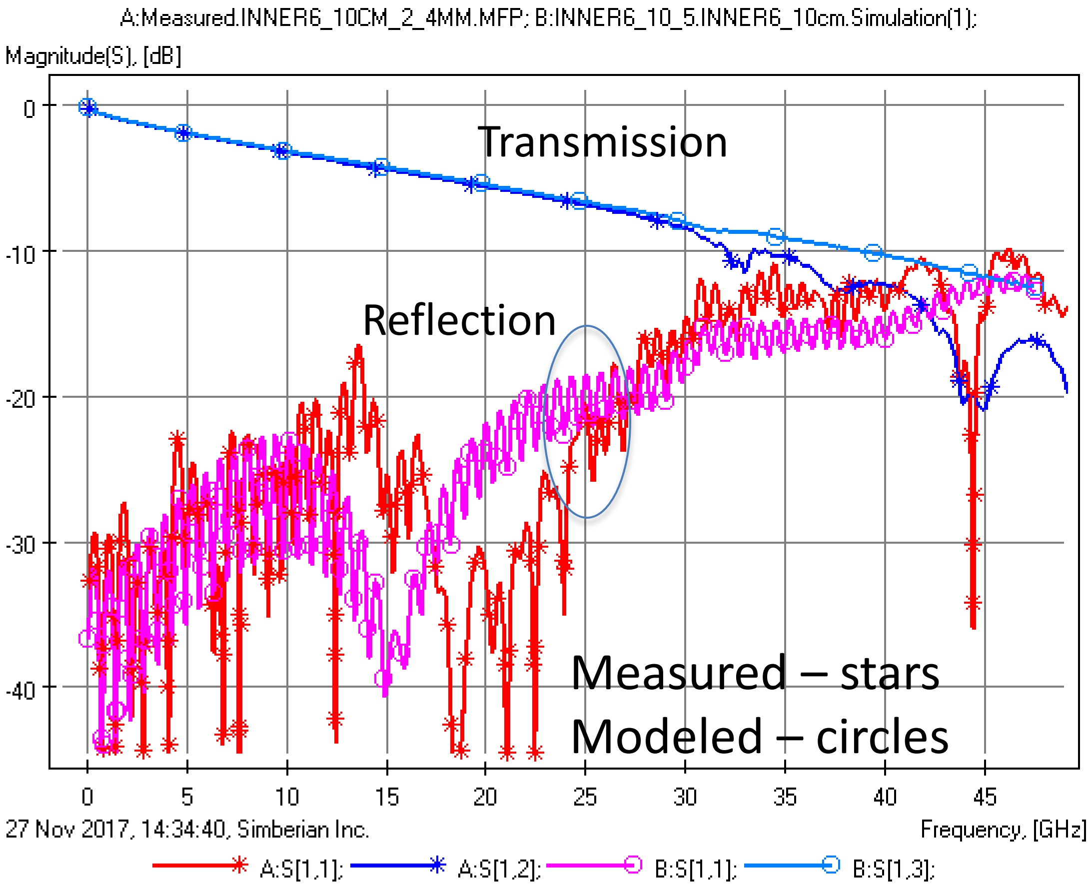
Single-ended S-parameters

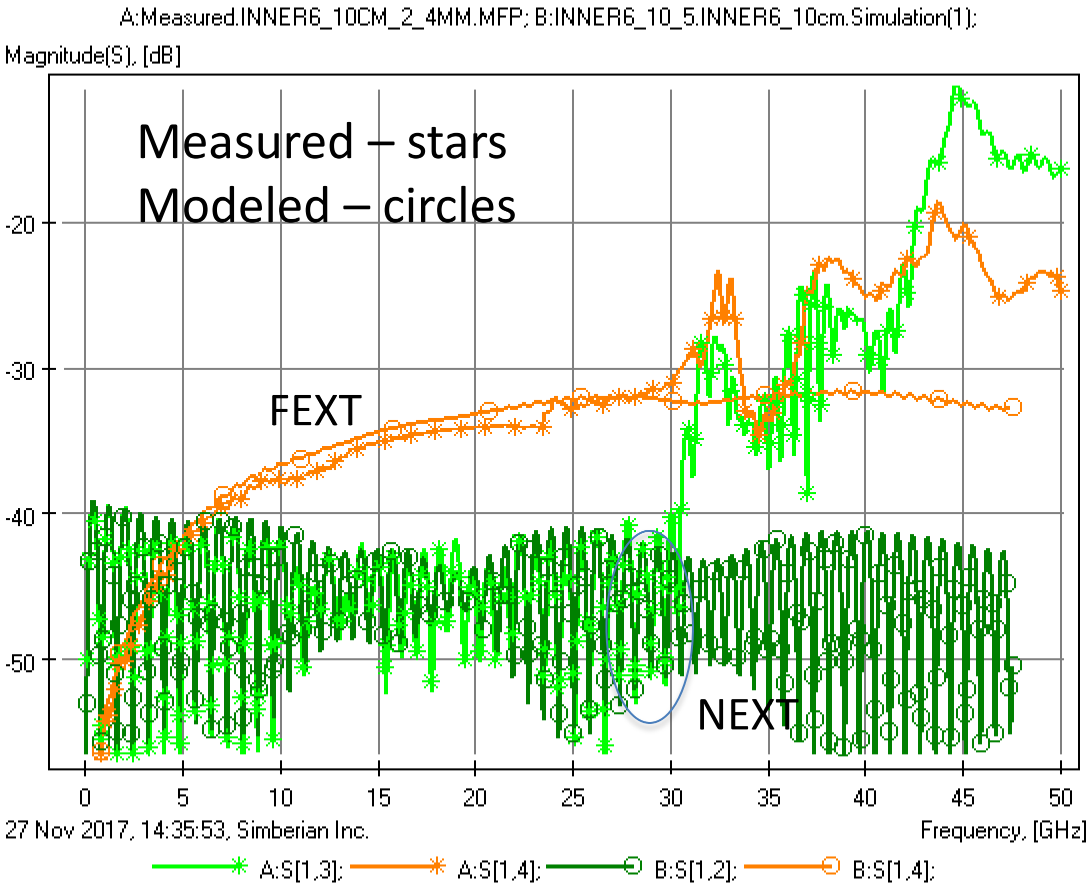


De-compositional EM analysis
All trace widths and shapes are adjusted

Reality: Large difference above 30 GHz – see reality above 30 GHz…

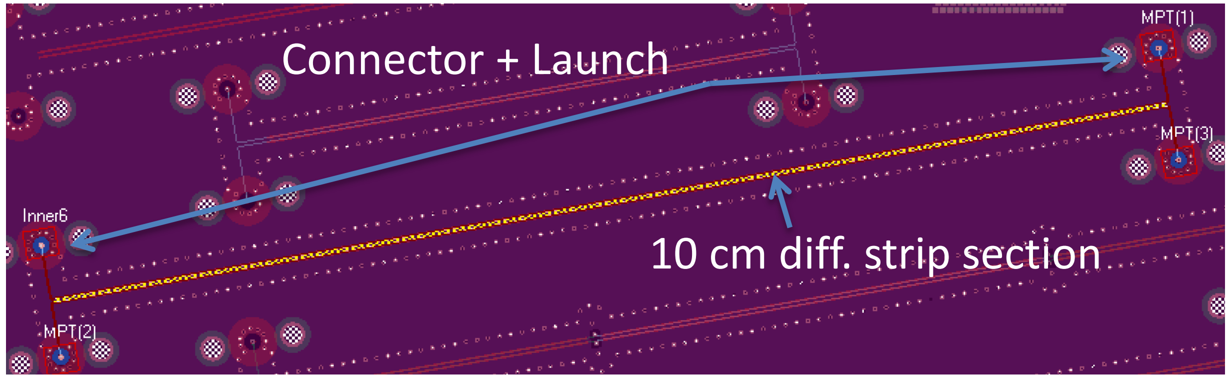
Acceptable correspondence up to 30 GHz





INNER6: 10 cm diff. strip link

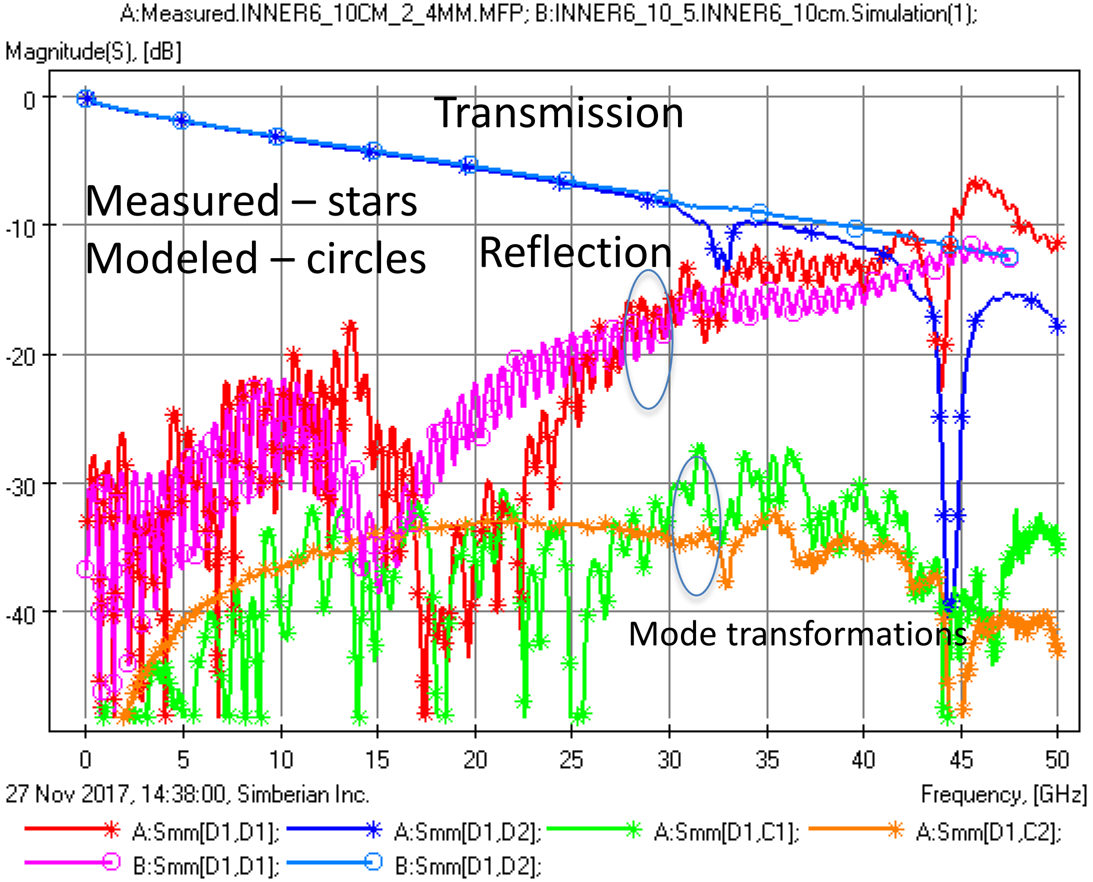
Mixed-mode S-parameters

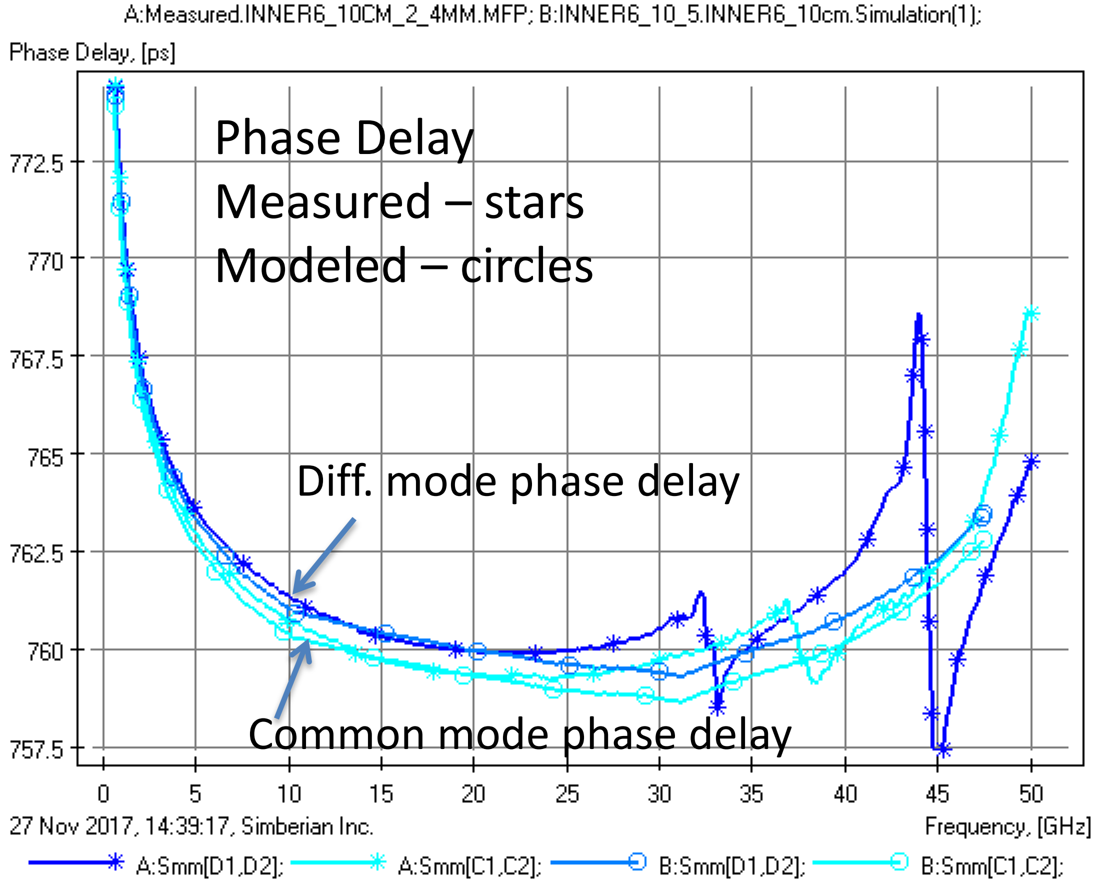


De-compositional EM analysis
All trace widths and shapes are adjusted

Reality: Difference in reflection between 10 to 30 GHz (now expected due to geometry differences), above 30 GHz – see reality above 30 GHz…

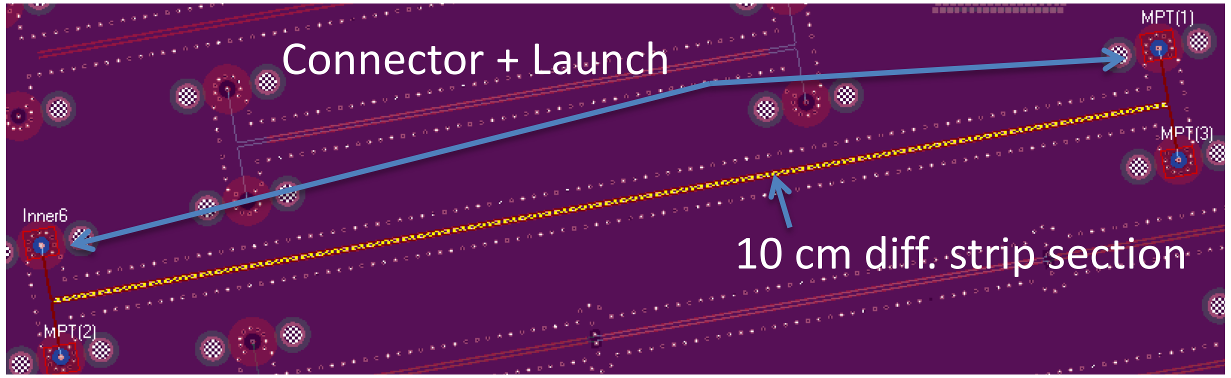
Acceptable correspondence up to 30 GHz





INNER6: 10 cm diff. strip link

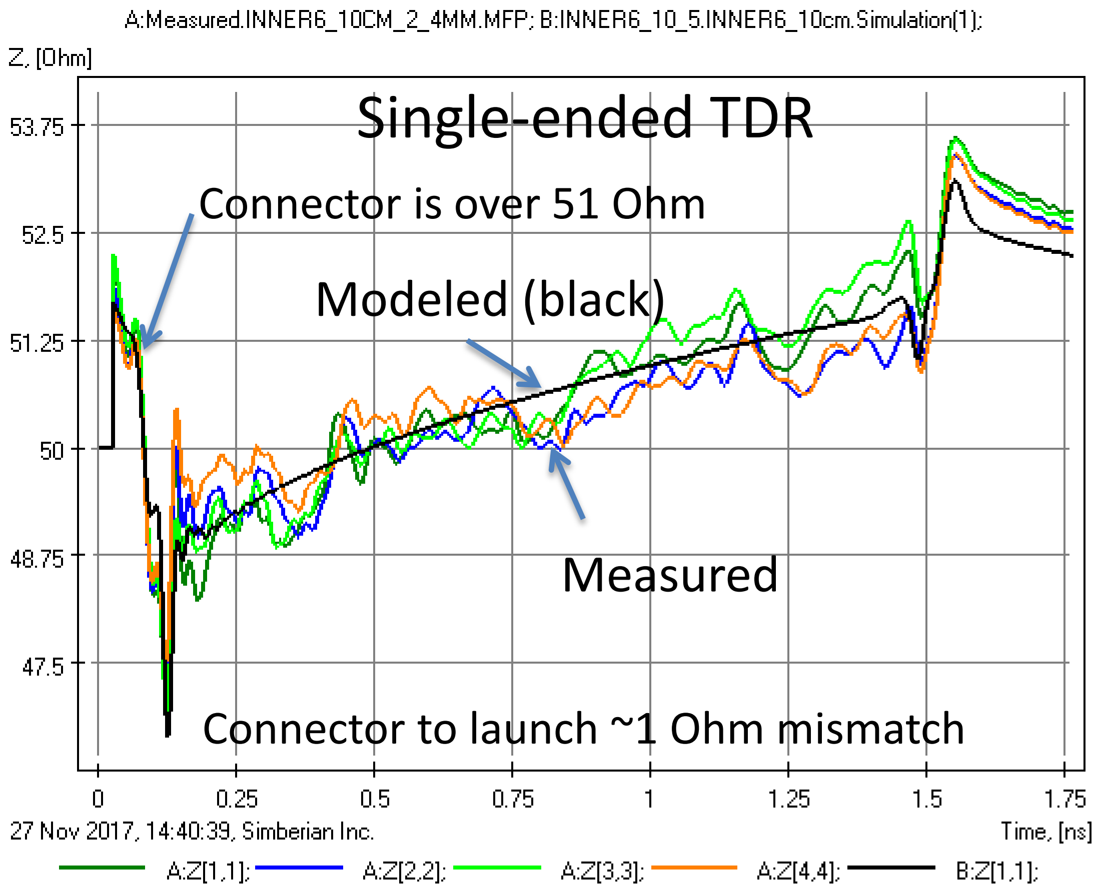
With solder mask under connector

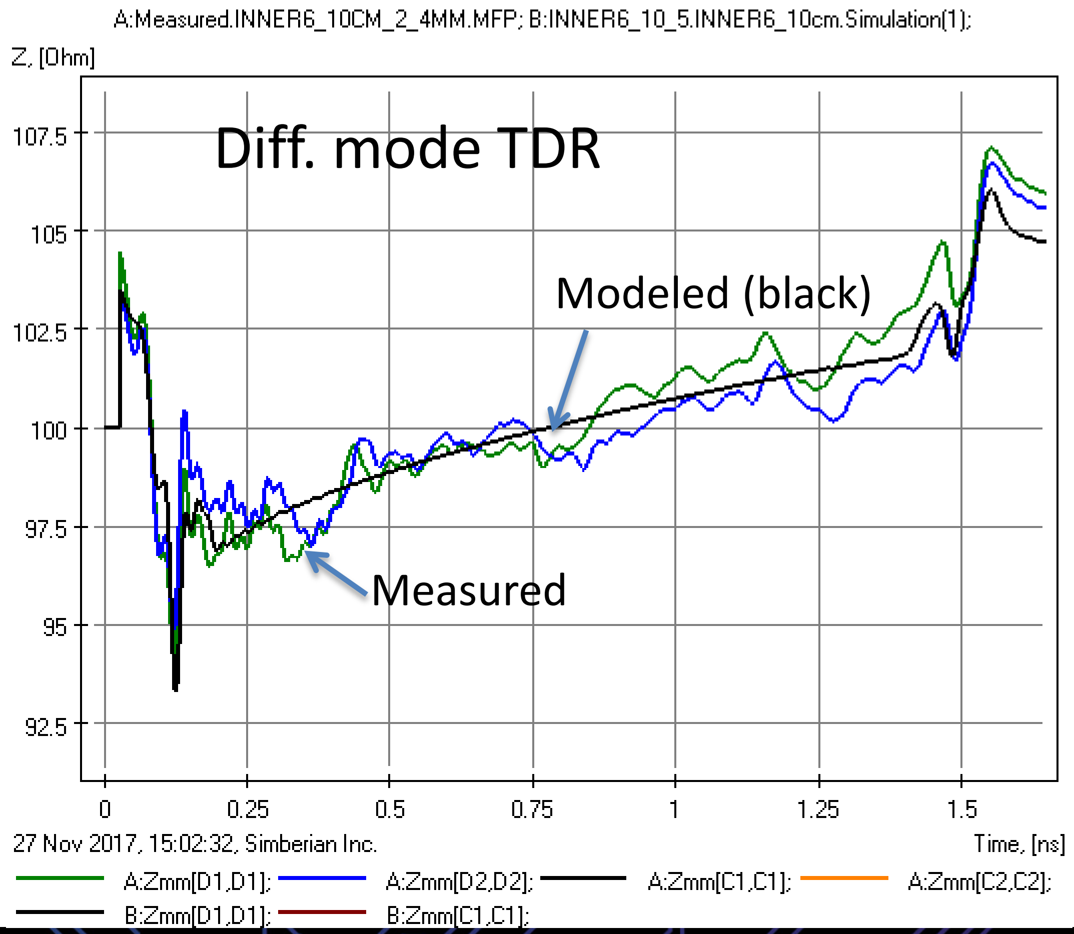


De-compositional EM analysis
All trace widths and shapes are adjusted

Reality: Variation of impedance along the traces (expected)

Acceptable correspondence





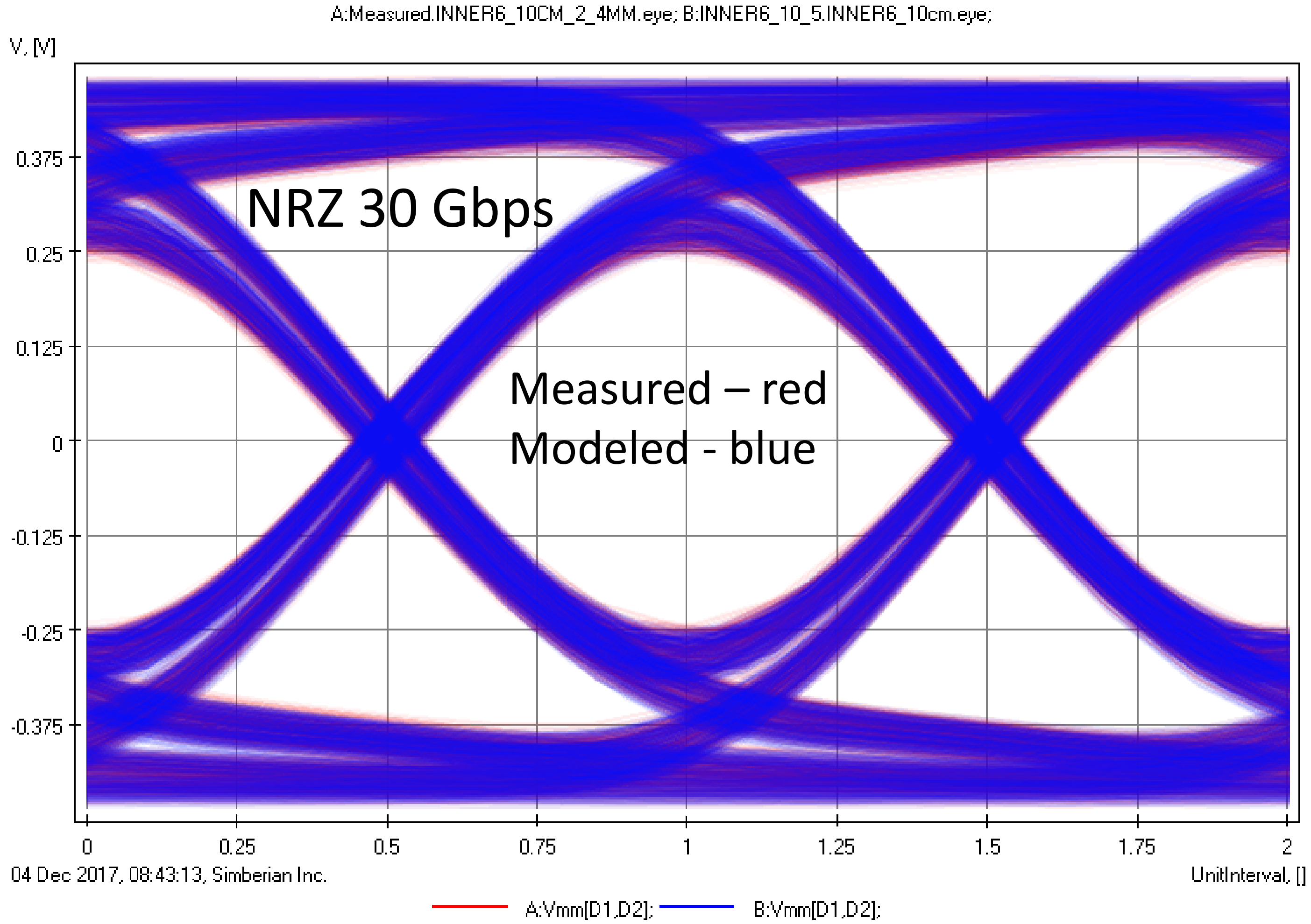
INNER6: 10 cm diff. strip link

- Eye diagrams comparison

Eye Analyzer

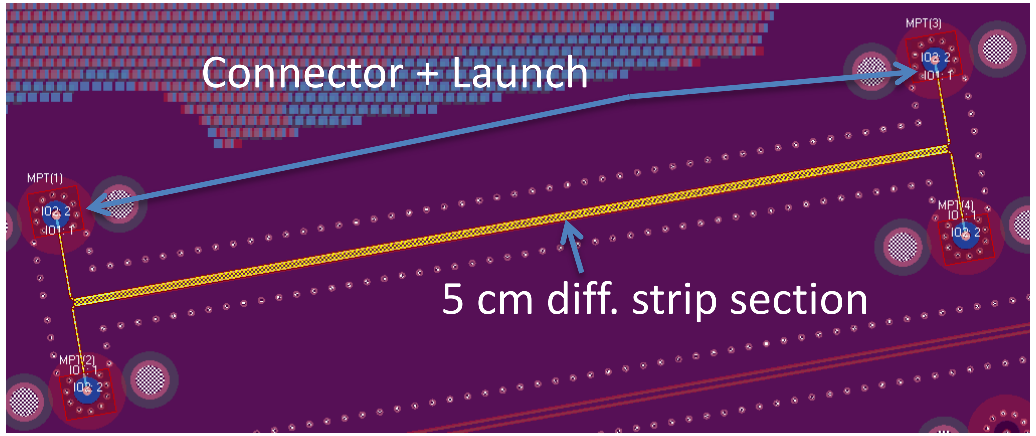
Show Eye Metrics: Selected ☑ Auto-open

Parameter	Measured.INNER6...	INNER6_10_5.IN...
Eye Level Zero (V)	-0.358943	-0.357034
Eye Level One (V)	0.358254	0.36771
Eye Level Mean (V)	-0.00219978	-0.0024401
Eye Amplitude (V)	0.717197	0.724743
Eye Height (V)	0.47057	0.480019
Eye Width (UI)	0.86031	0.869623
Eye Opening Factor	0.656123	0.66233
Eye Signal to Noise	5.51347	5.56869
Eye Rise Time (20-80) (UI)	0.518454	0.518457
Eye Fall Time (80-20) (UI)	0.517761	0.515182
Eye Jitter (PP) (UI)	0.13969	0.130377
Eye Jitter (RMS) (UI)	0.0318694	0.0320182



~2% difference in eye heights, close widths; Possible reason – impedance variations, launch mismatch and localization loss…

INNER6: 5 cm diff. strip link

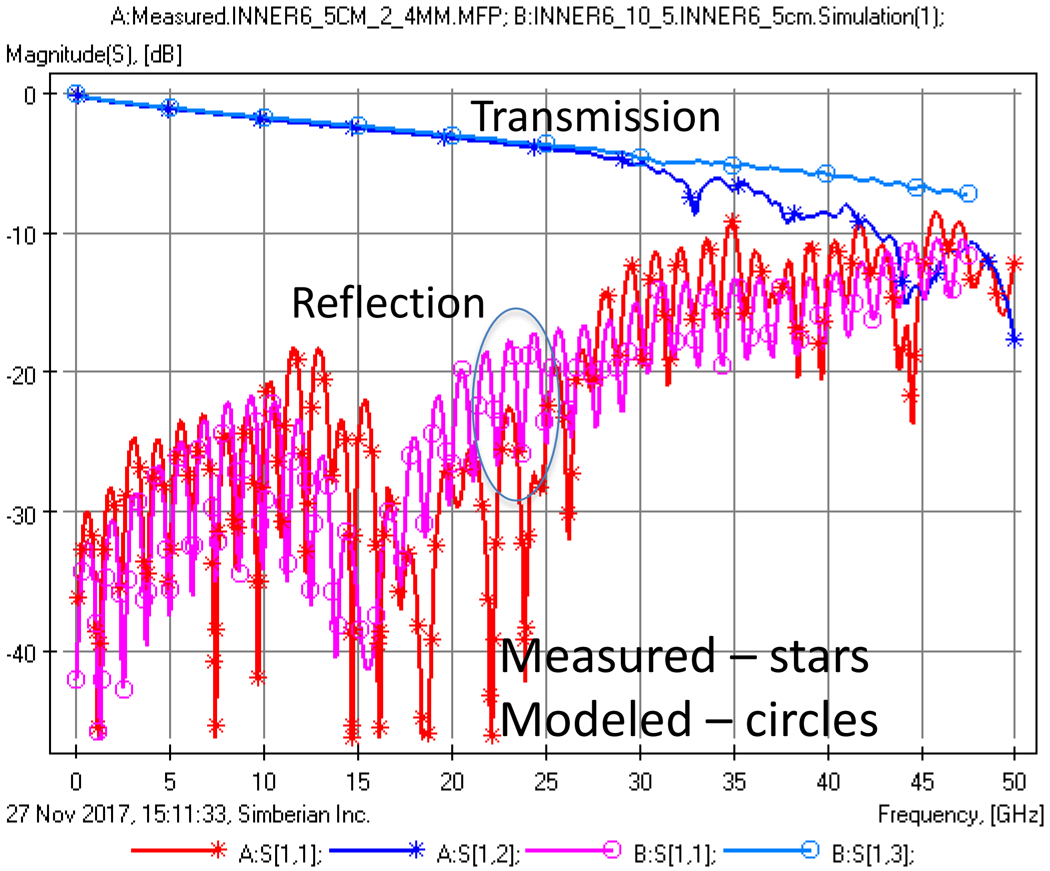


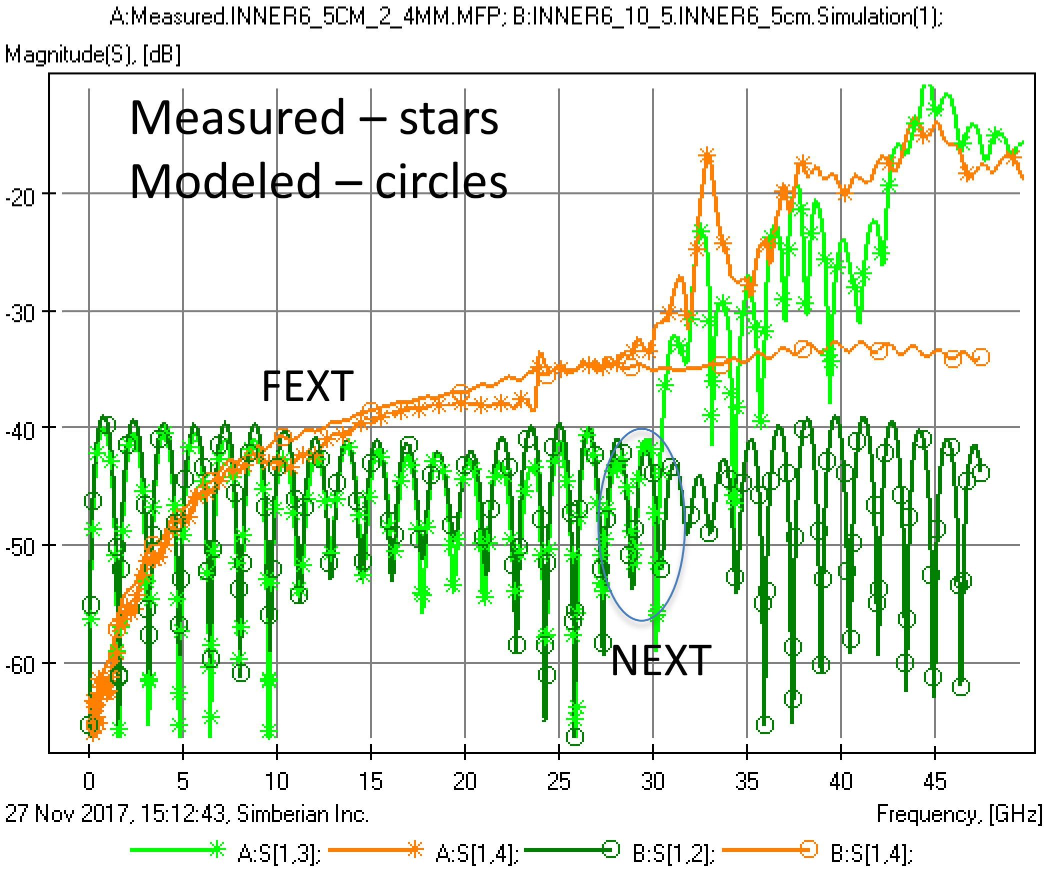
De-compositional EM analysis
All trace widths and shapes are adjusted

Single-ended S-parameters

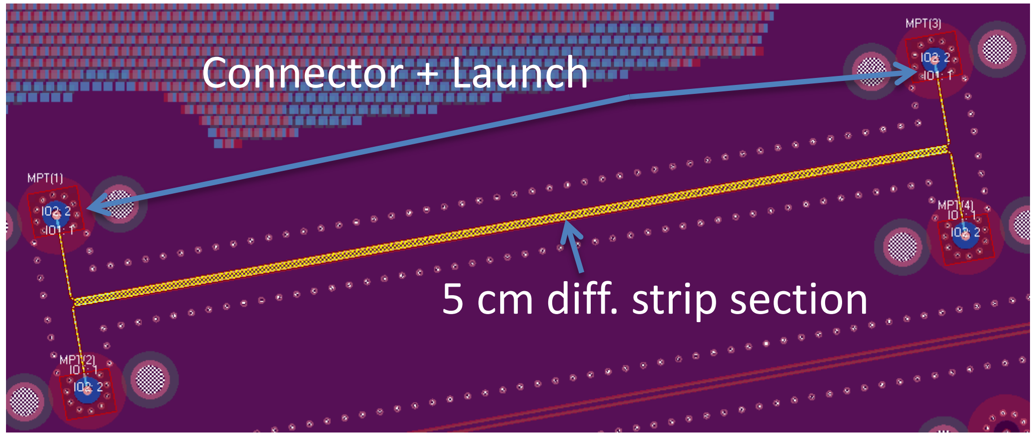
Reality: Difference above 30 GHz – see reality above 30 GHz…

Acceptable correspondence up to 30 GHz





INNER6: 5 cm diff. strip link

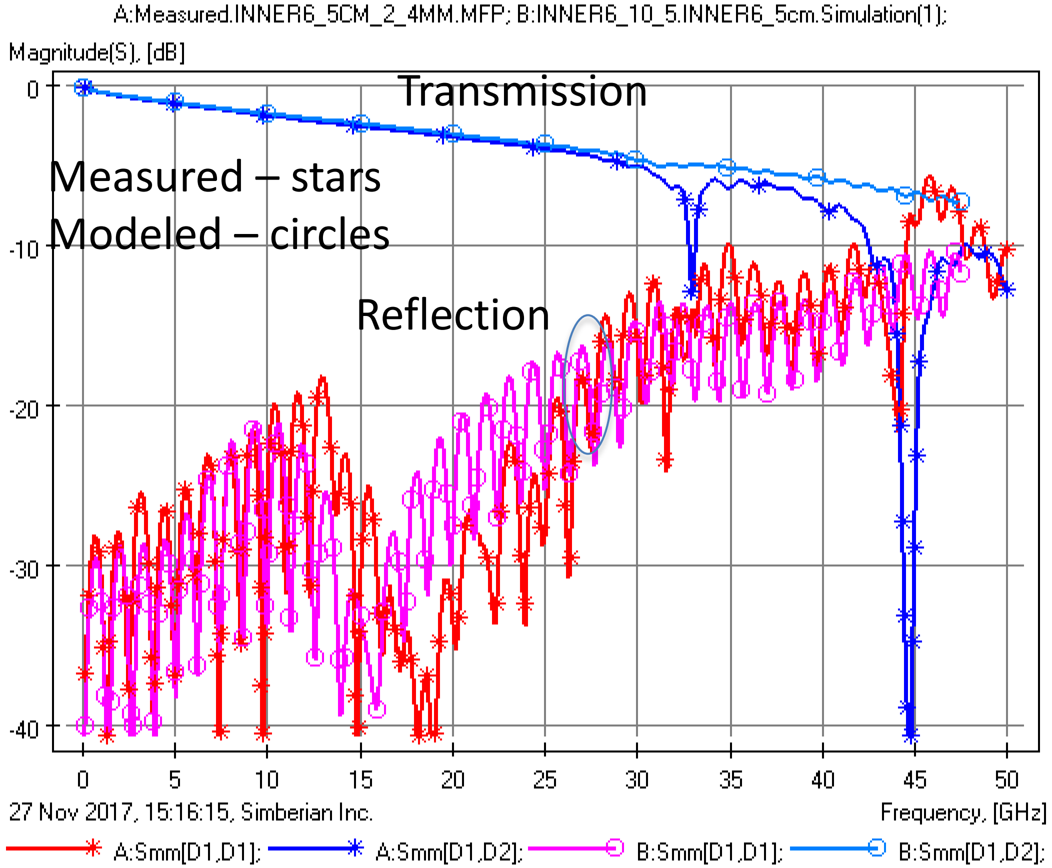


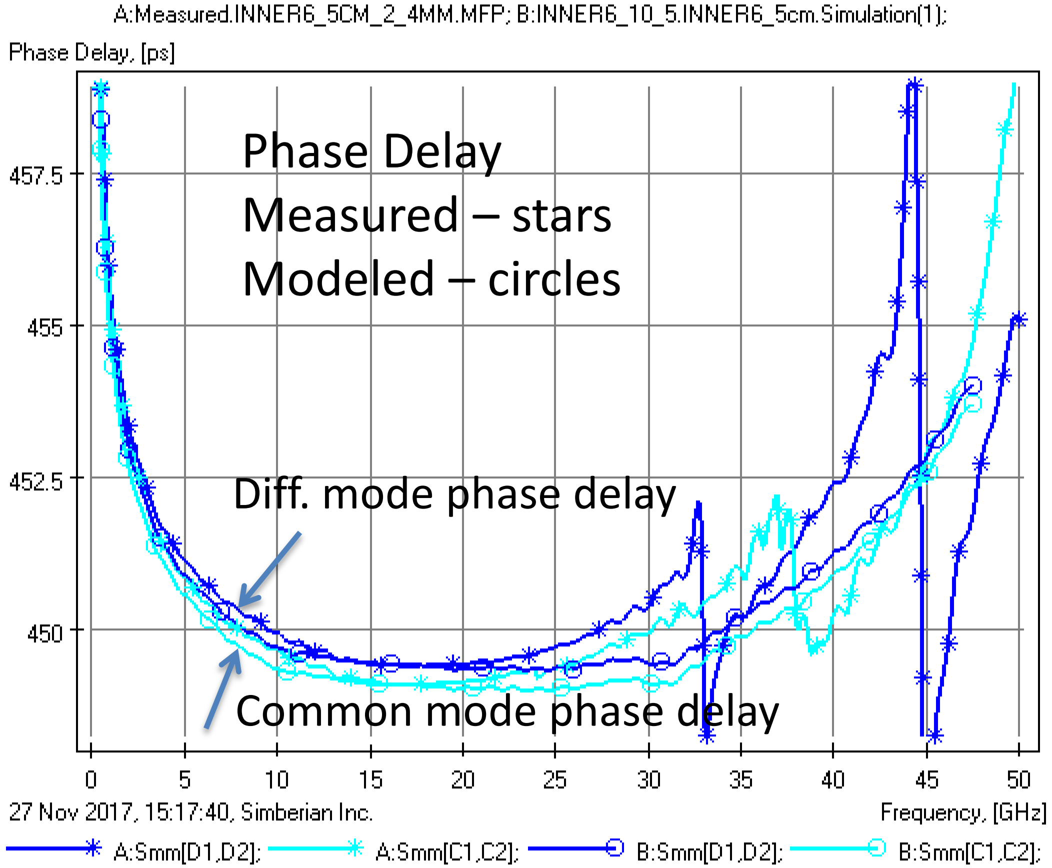
Mixed-mode S-parameters

De-compositional EM analysis
All trace widths and shapes are adjusted

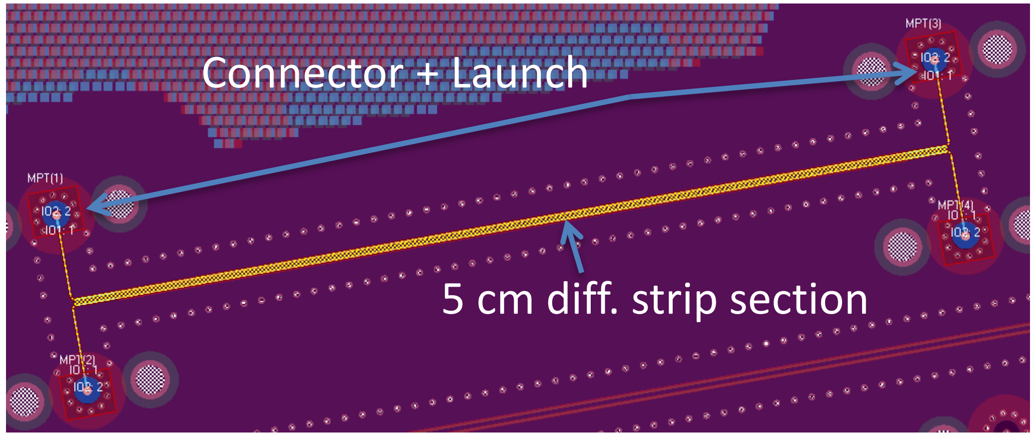
Reality: Difference in reflection between 10 to 30 GHz (now expected due to geometry differences), above 30 GHz – see reality above 30 GHz…

Acceptable correspondence up to 30 GHz





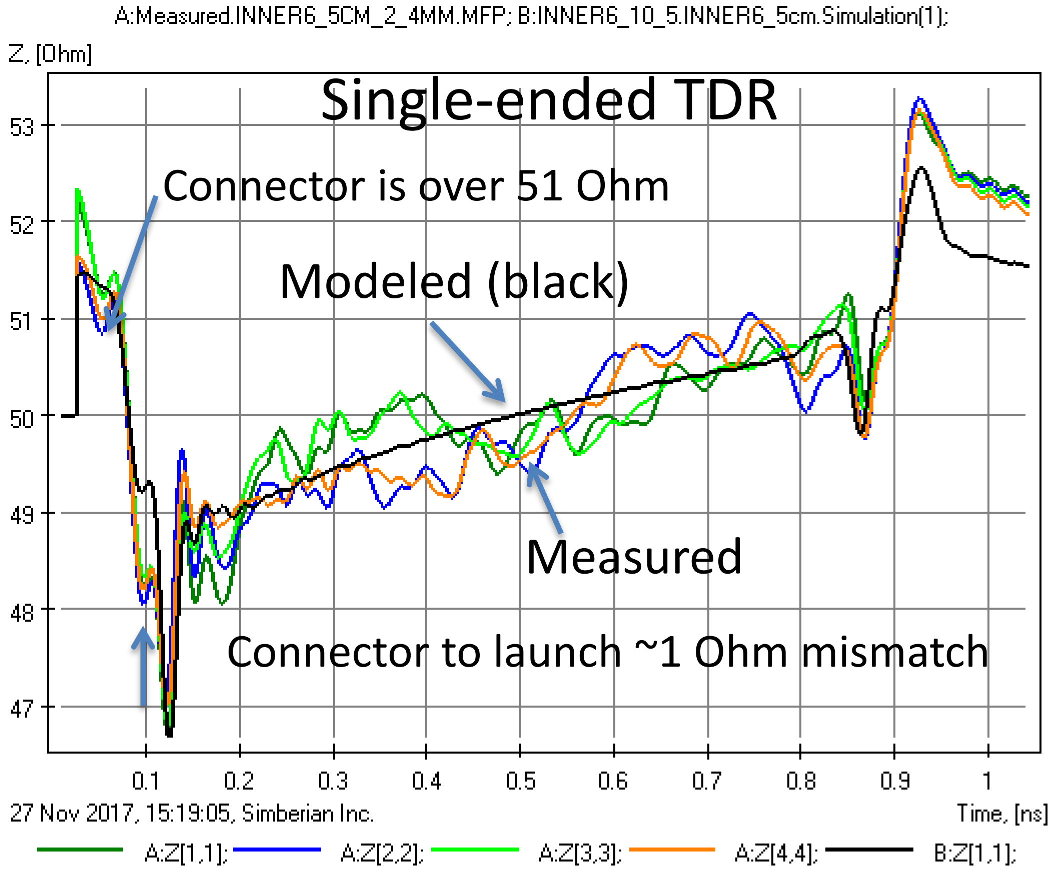
INNER6: 5 cm diff. strip link

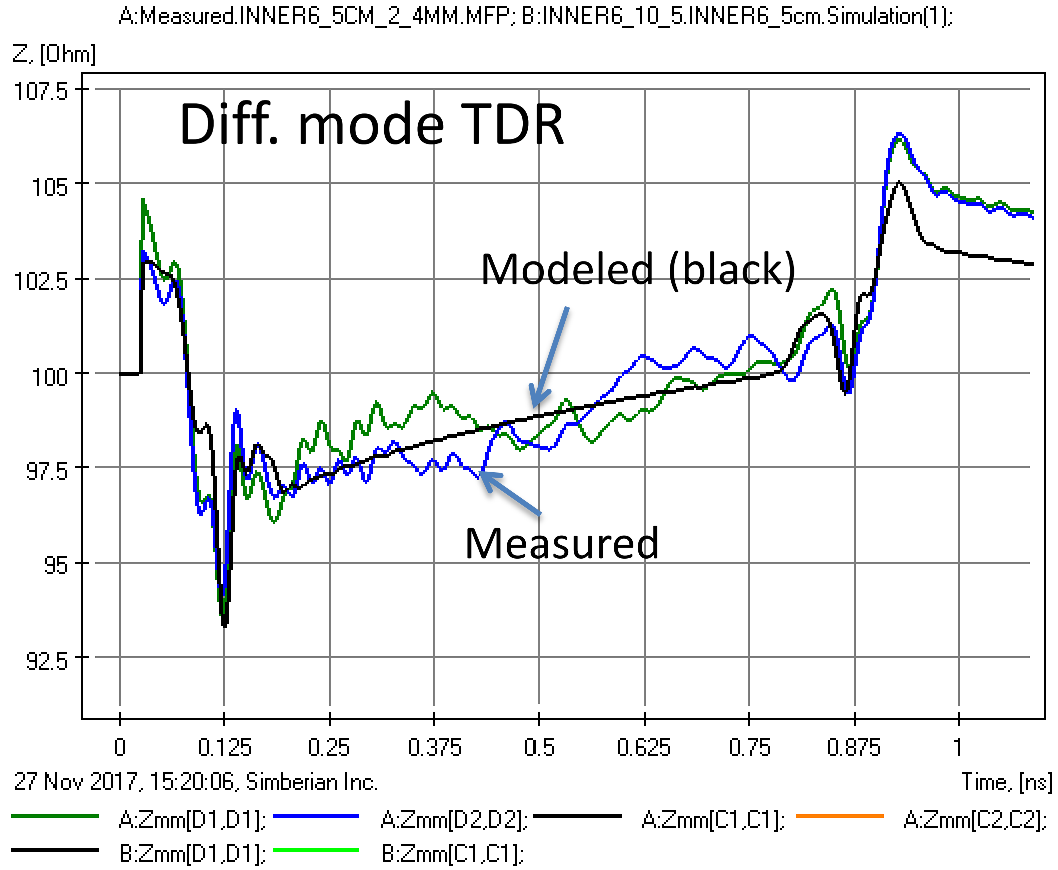


De-compositional EM analysis
All trace widths and shapes are adjusted

Reality: Variation of impedance along the traces (expected)

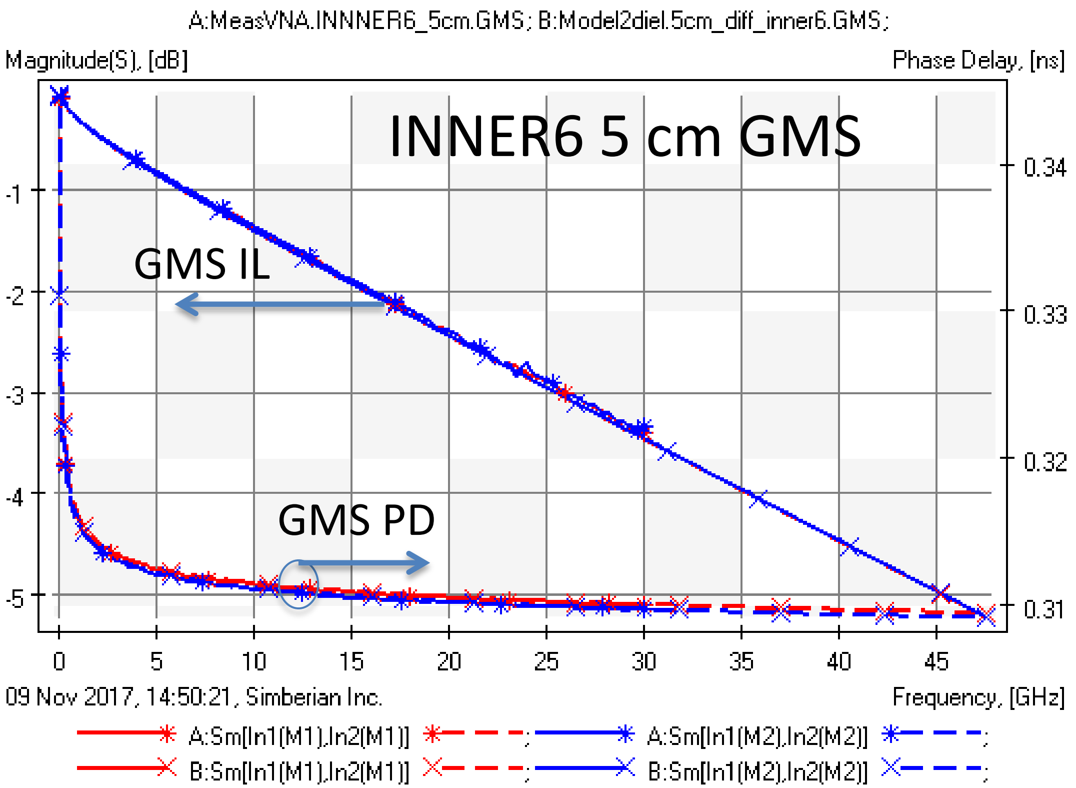
Acceptable correspondence

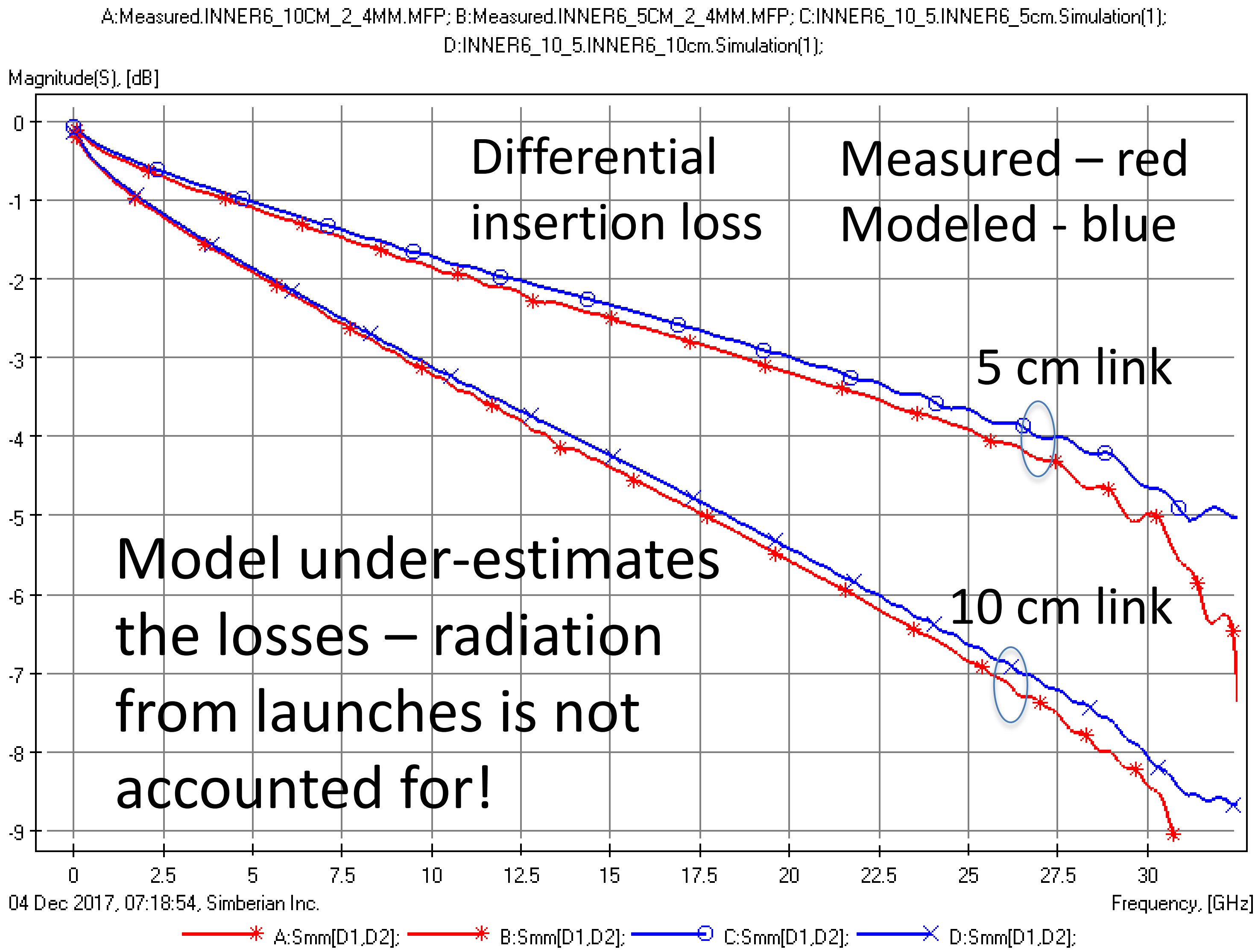




Insertion loss deviation analysis

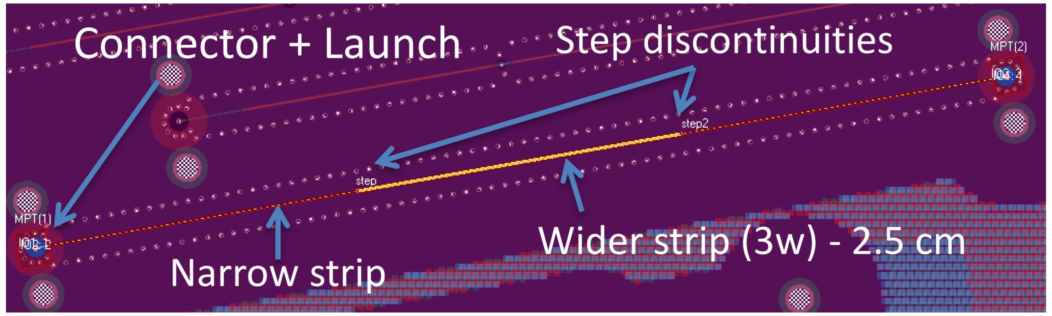
Nearly perfect match in GMS-parameters





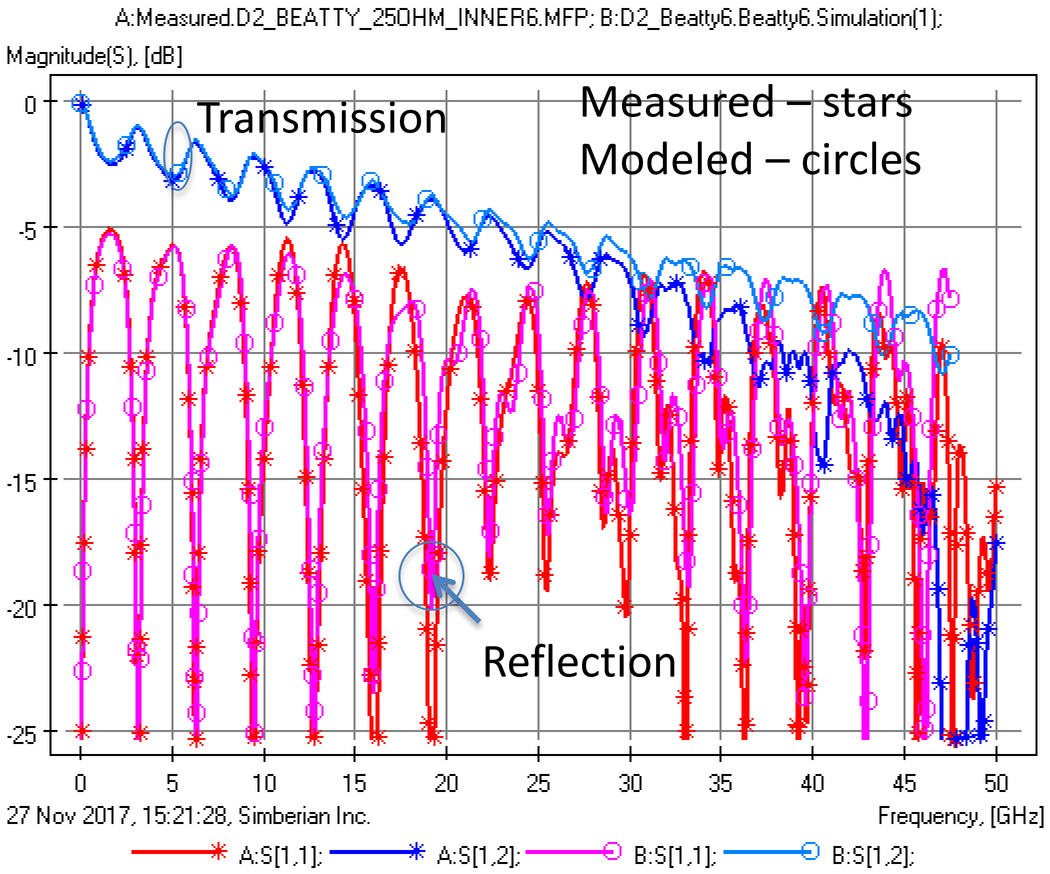
D2: Beatty strip standard in INNER6

S-parameters magnitudes

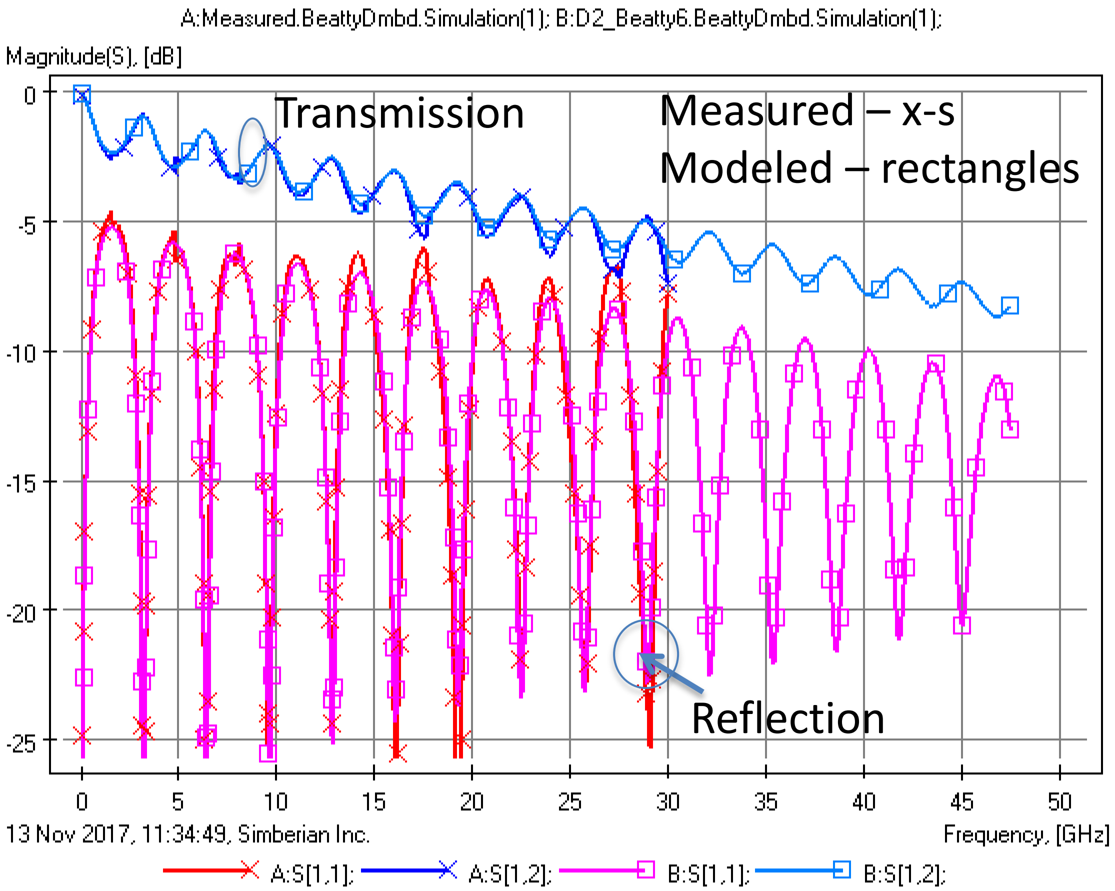


De-compositional EM analysis
Strip widths are adjusted

Complete

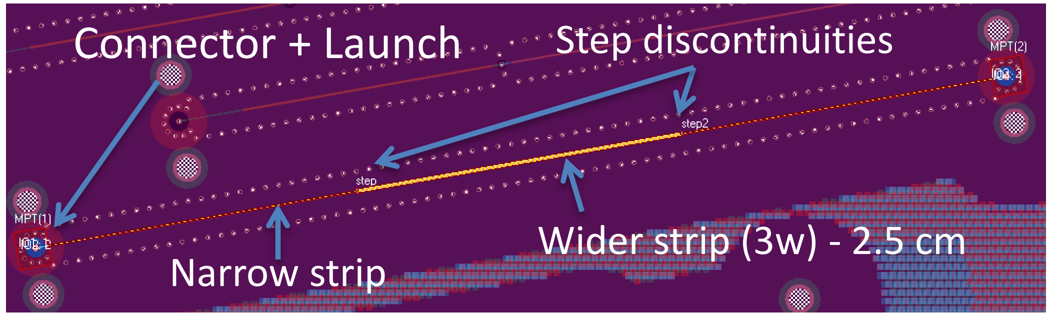


De-embedded connectors and launches

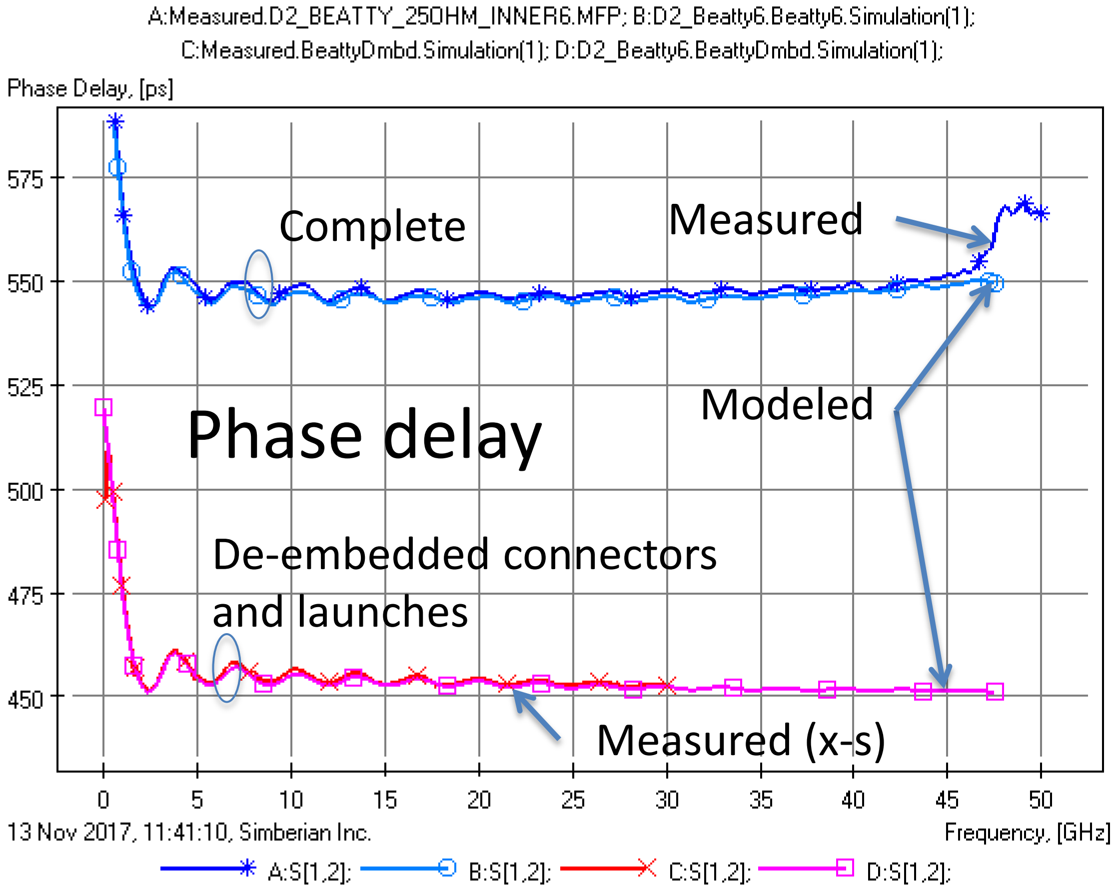


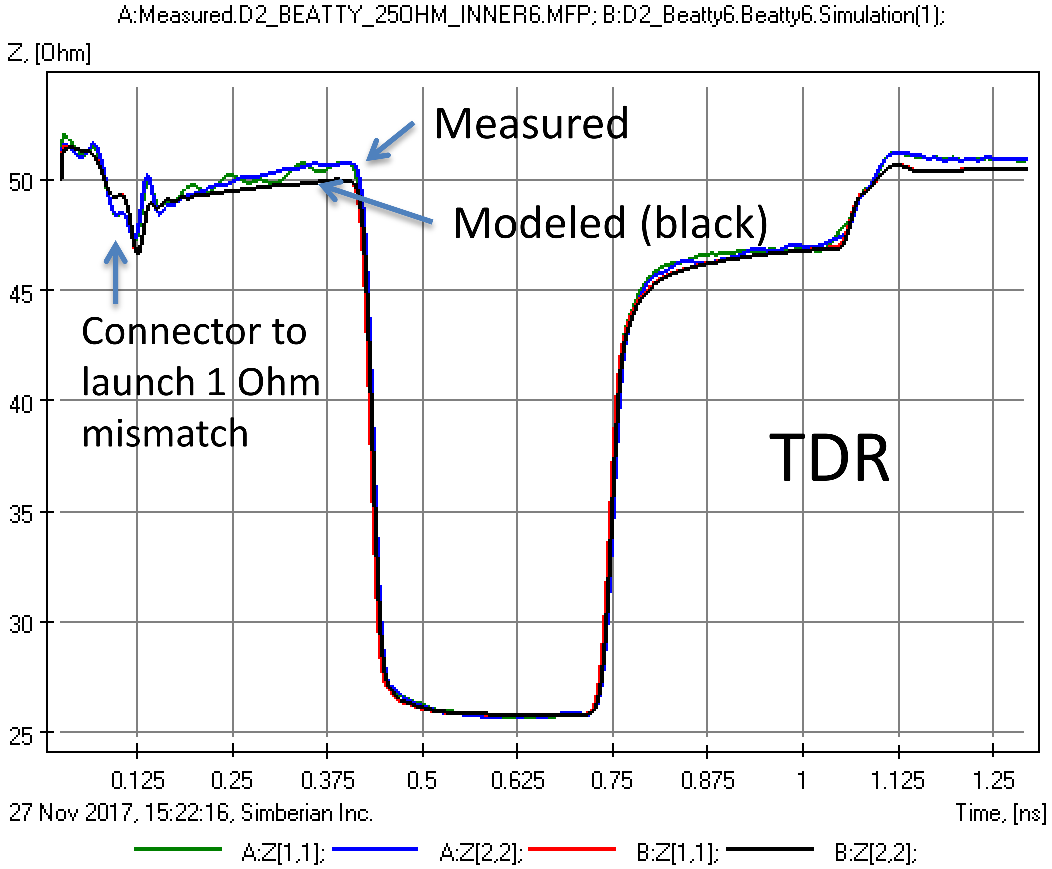
Loss and dispersion models work for much wider strips!

D2: Beatty strip standard in INNER6



De-compositional EM analysis
Strip widths are adjuted

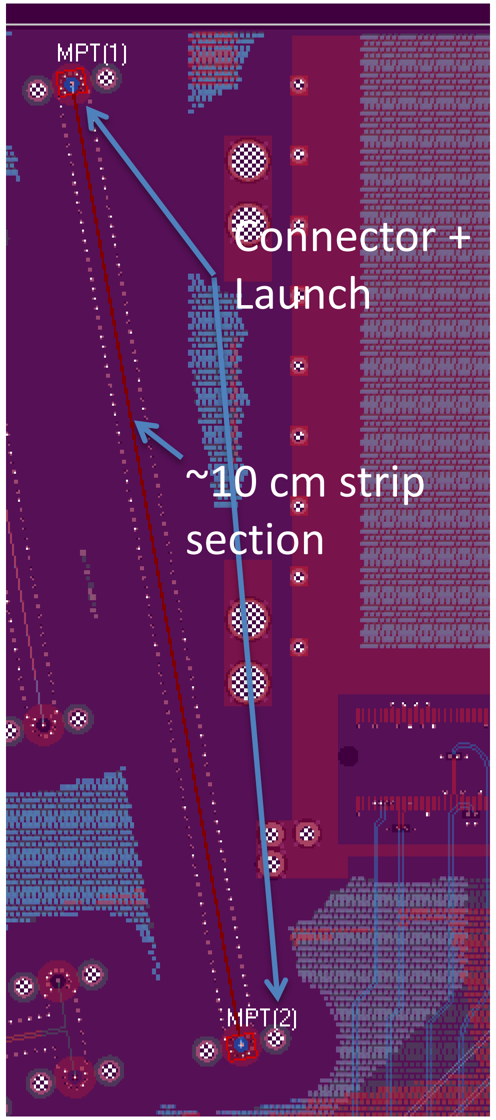


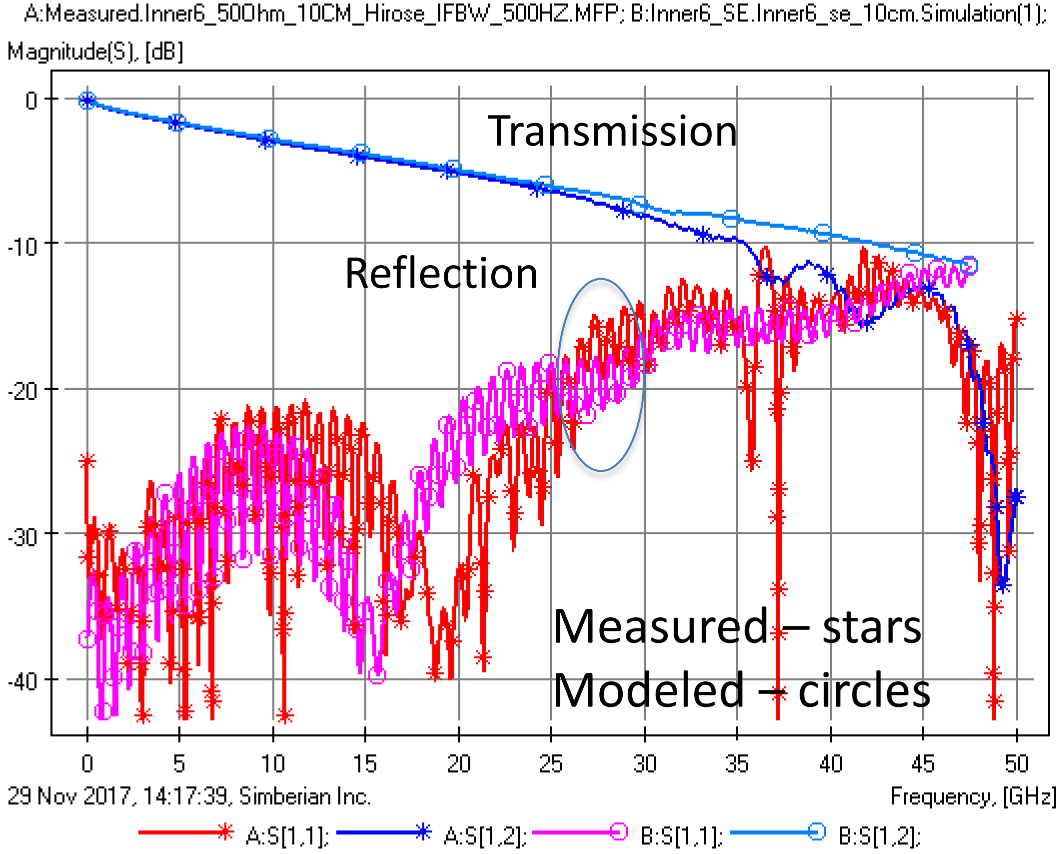


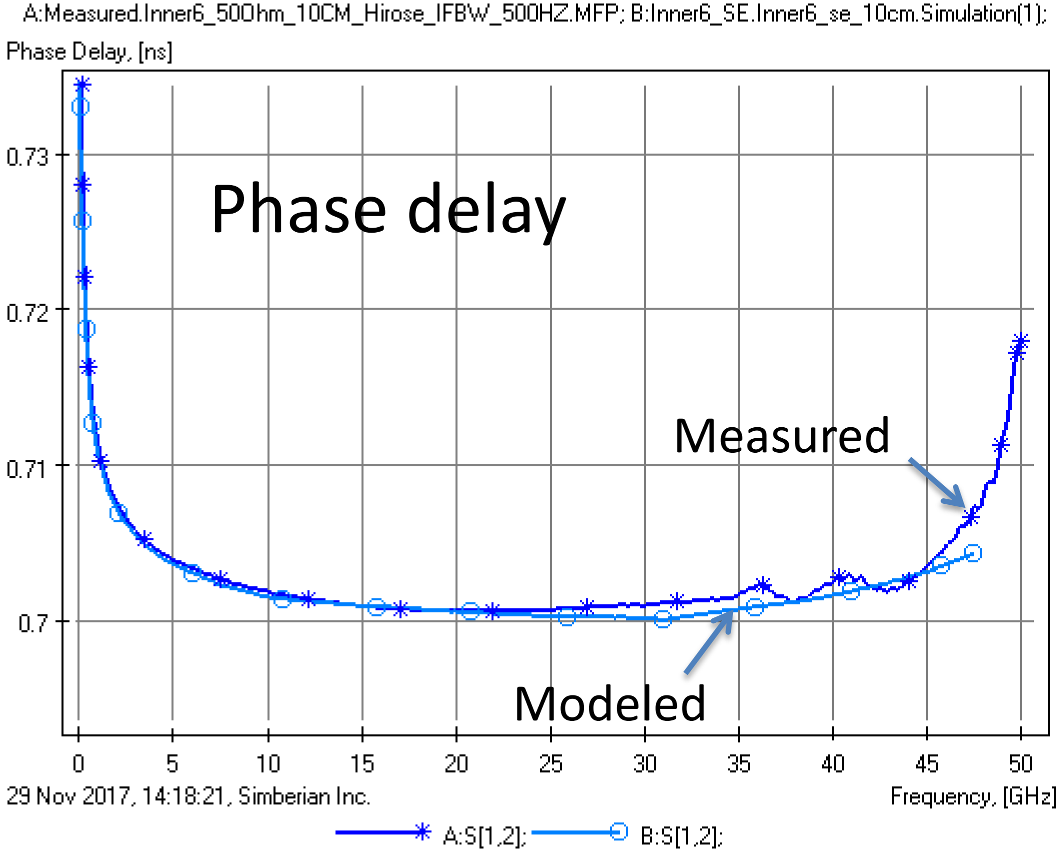
Good correspondence

INNER6 10 cm SE strip link

De-compositional EM analysis
All trace widths and shapes are adjusted





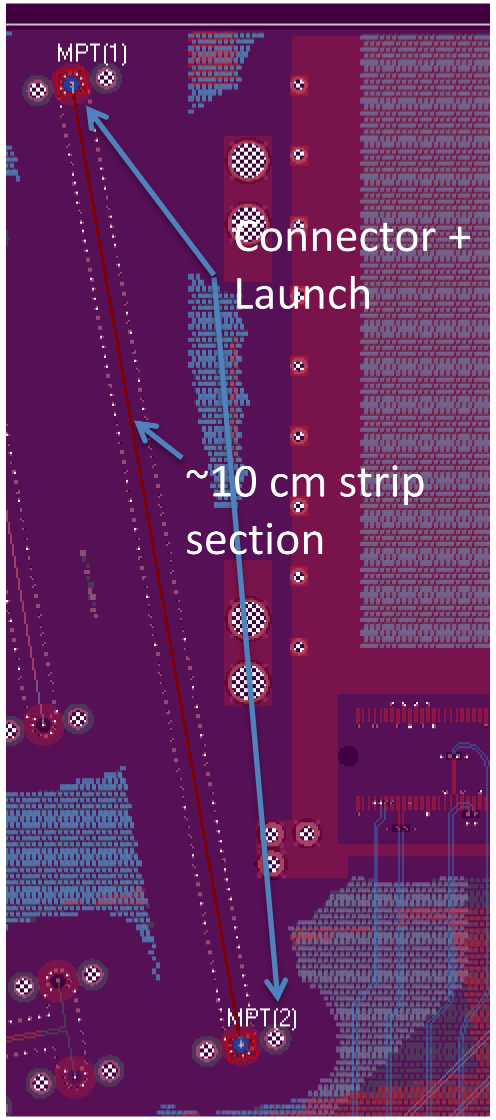


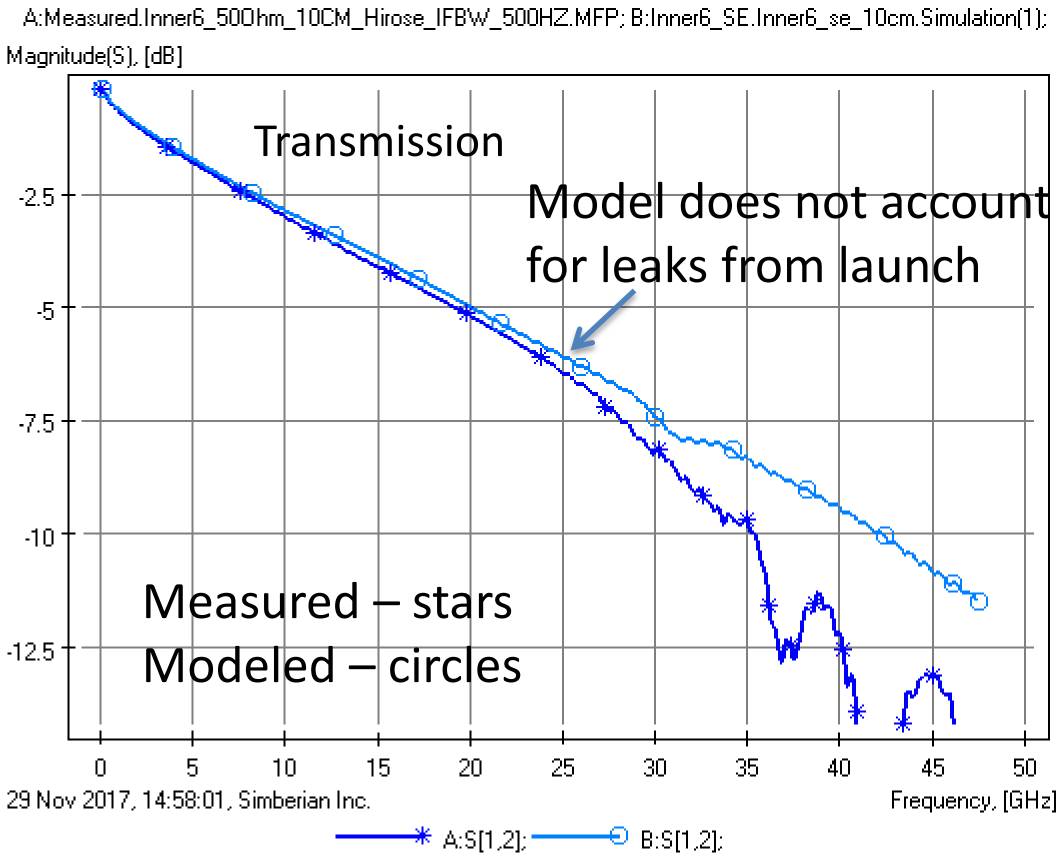
Reality: Large difference in transmission above 25 GHz – see reality above 30 GHz…

Acceptable correspondence up to 25 GHz…

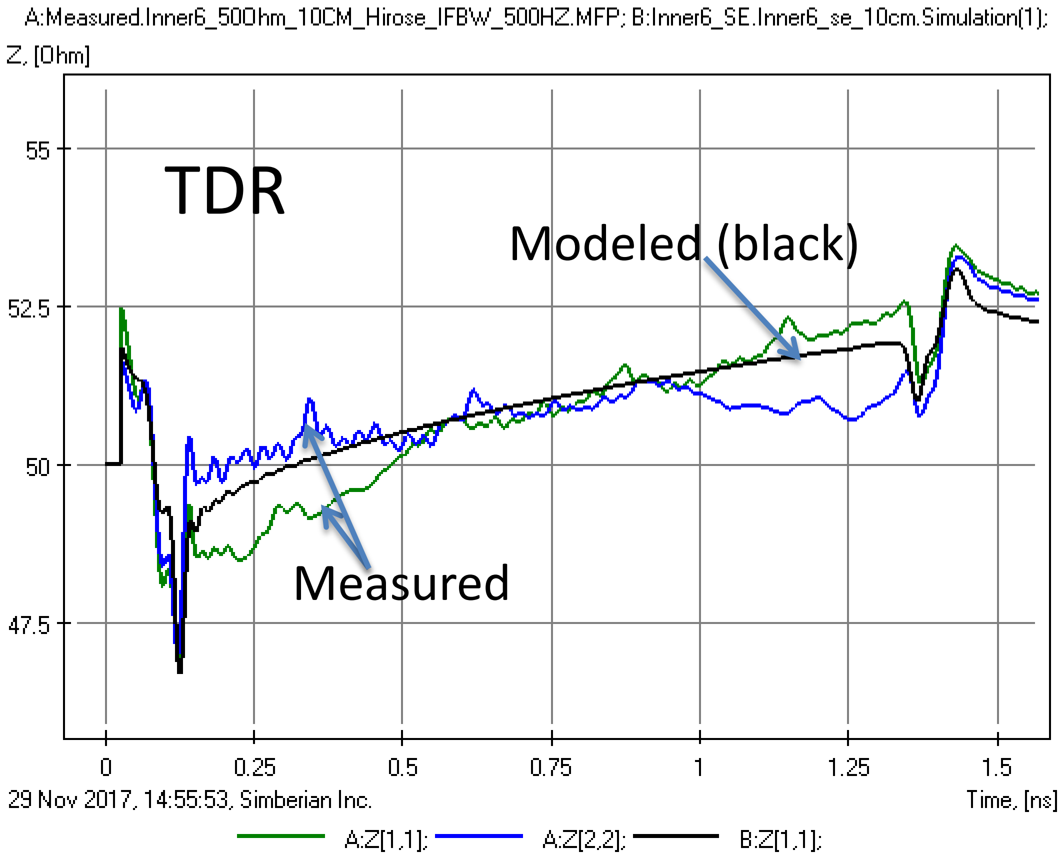
INNER6 10 cm SE strip link

De-compositional EM analysis
All trace widths and shapes are adjusted





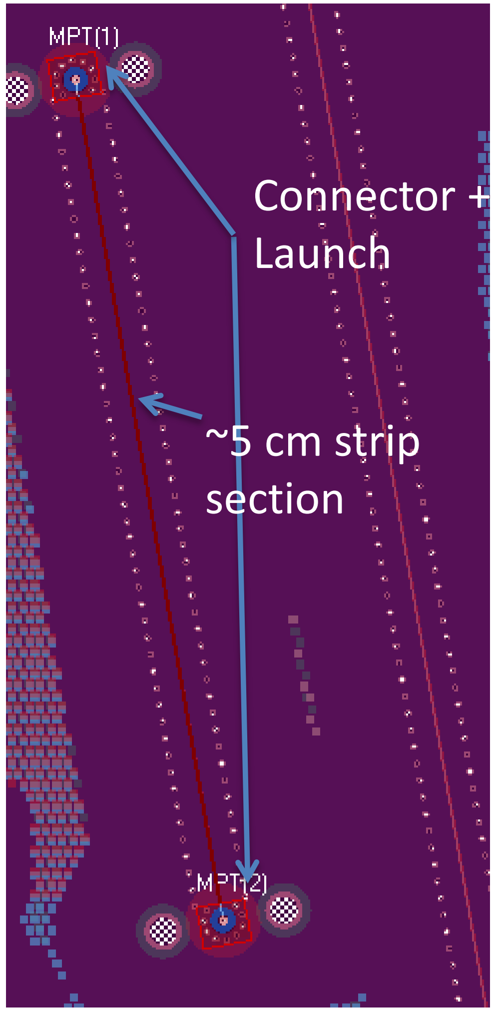
Reality: Larger insertion losses due to leaky launch? – see reality above 30 GHz

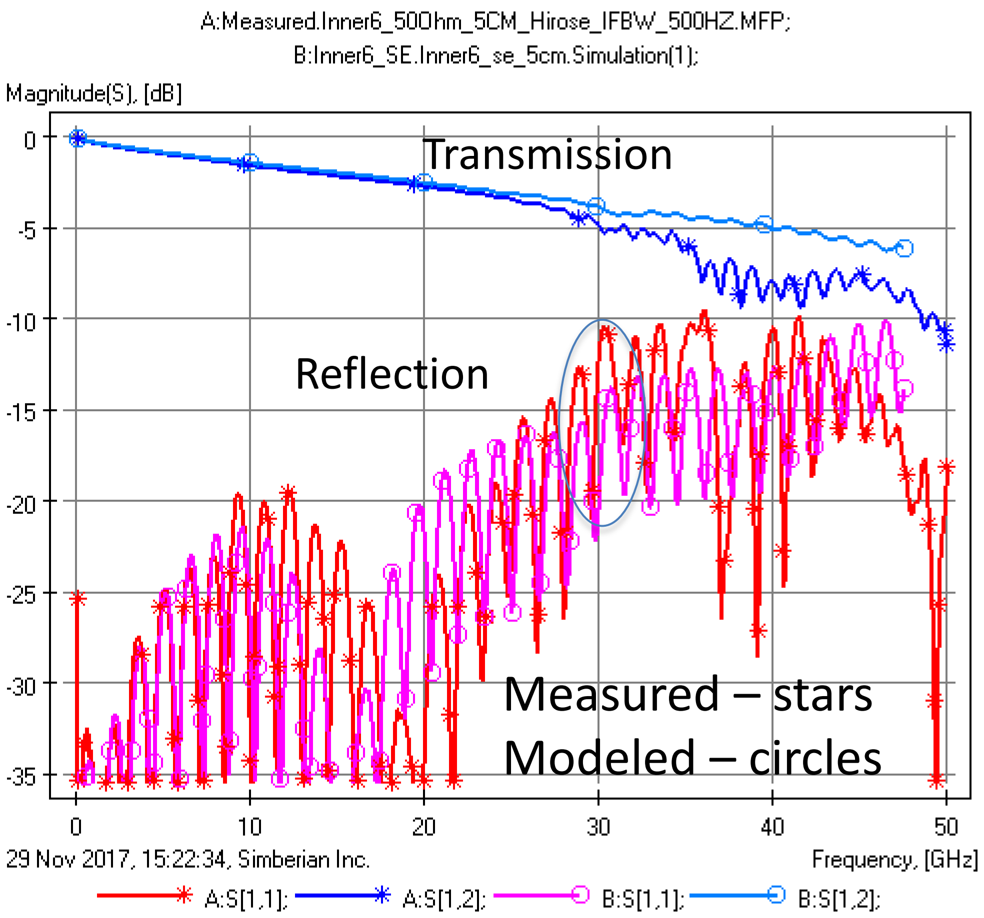


Reality: Variation of impedance along the traces (more than expected)

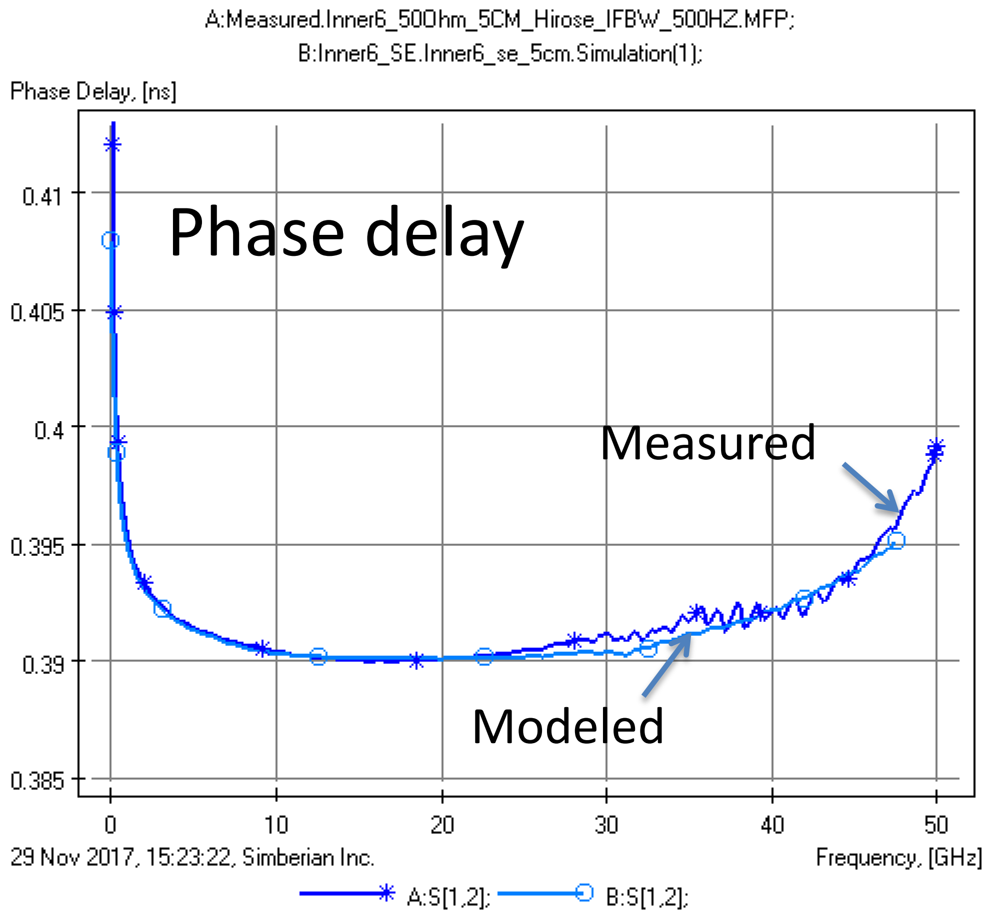
INNER6 5 cm SE strip link

De-compositional EM analysis
All trace widths and shapes are adjusted





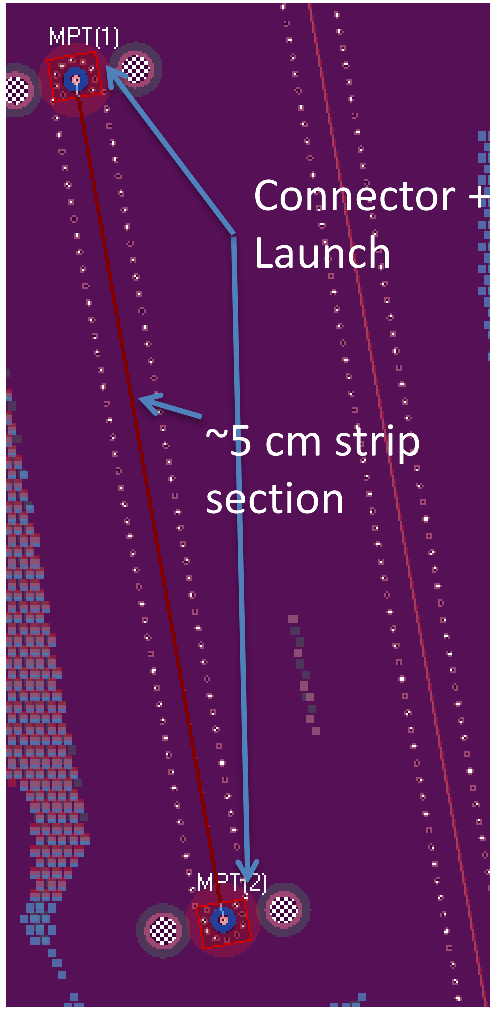
Reality: Large difference in transmission above 25 GHz – see reality above 30 GHz…

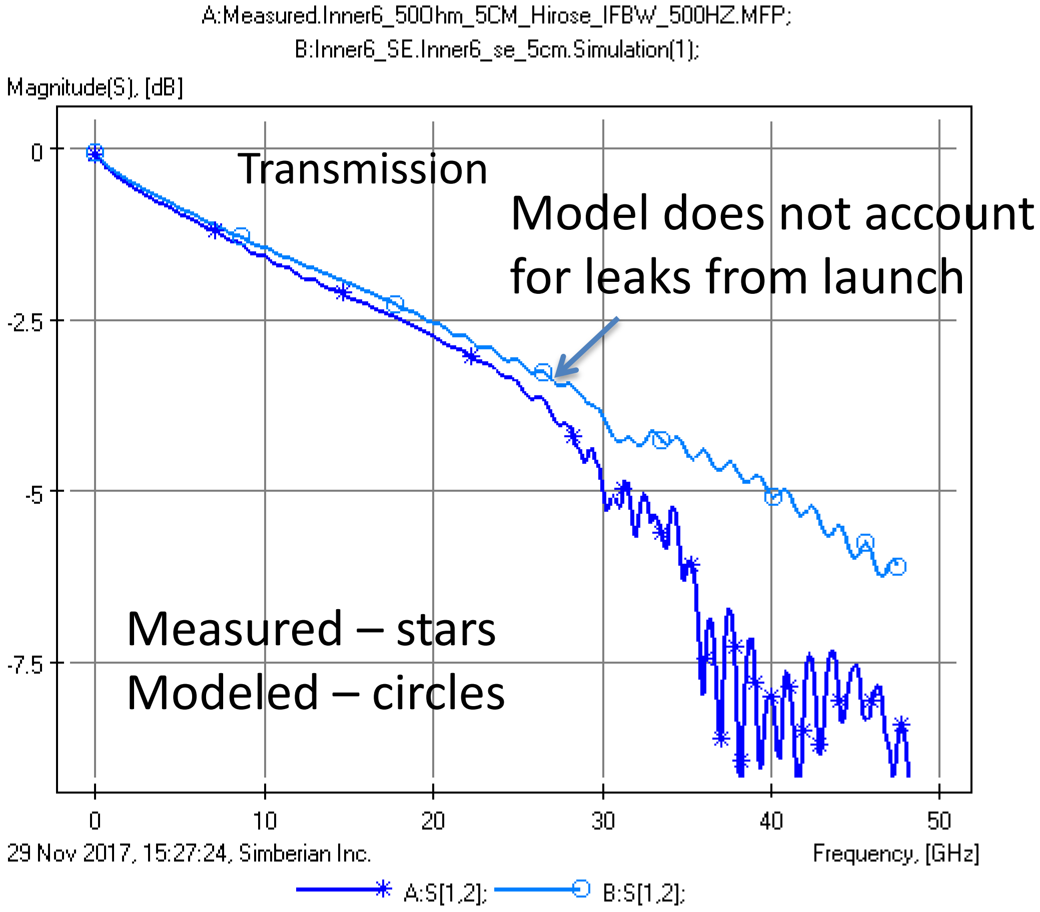


Acceptable correspondence up to 25 GHz…

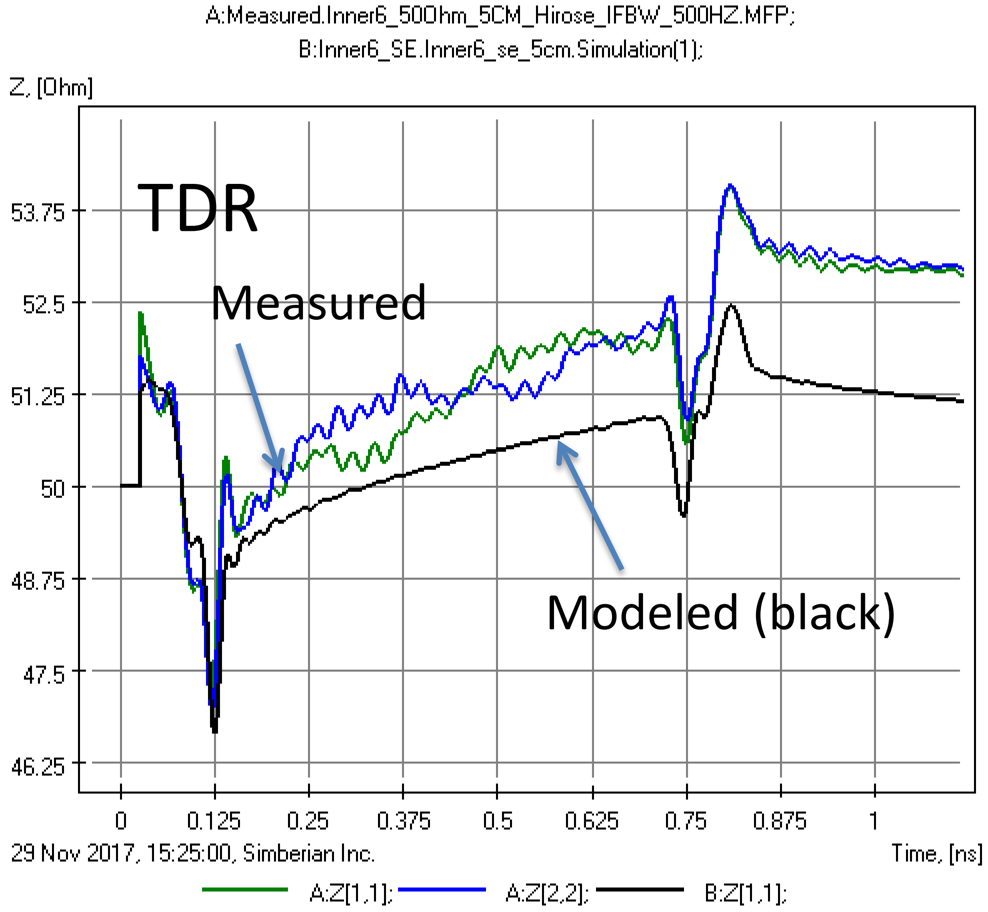
INNER6 5 cm SE strip link

De-compositional EM analysis
All trace widths and shapes are adjusted





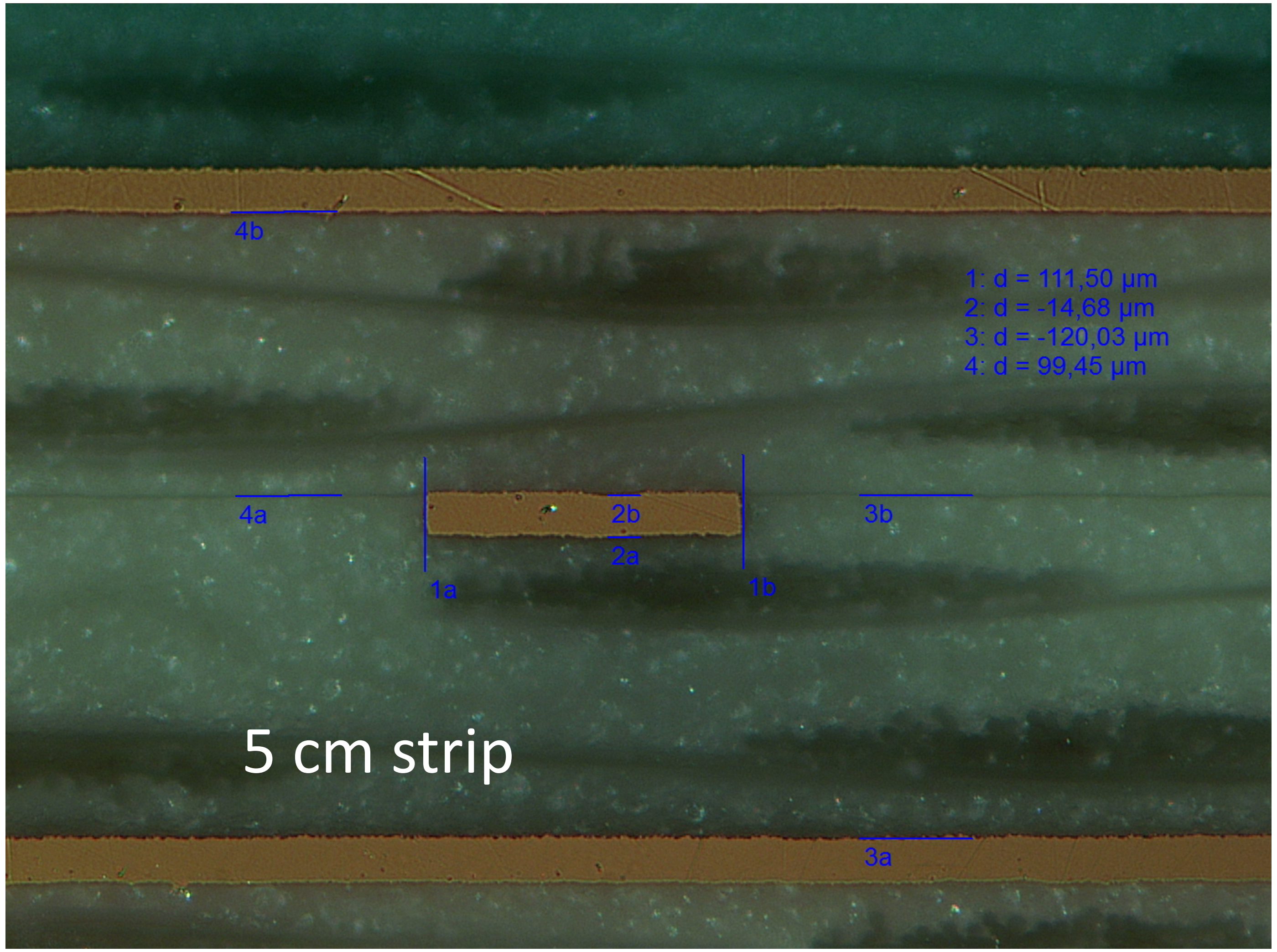
Reality: Larger insertion losses due to leaky launch? – see reality above 30 GHz

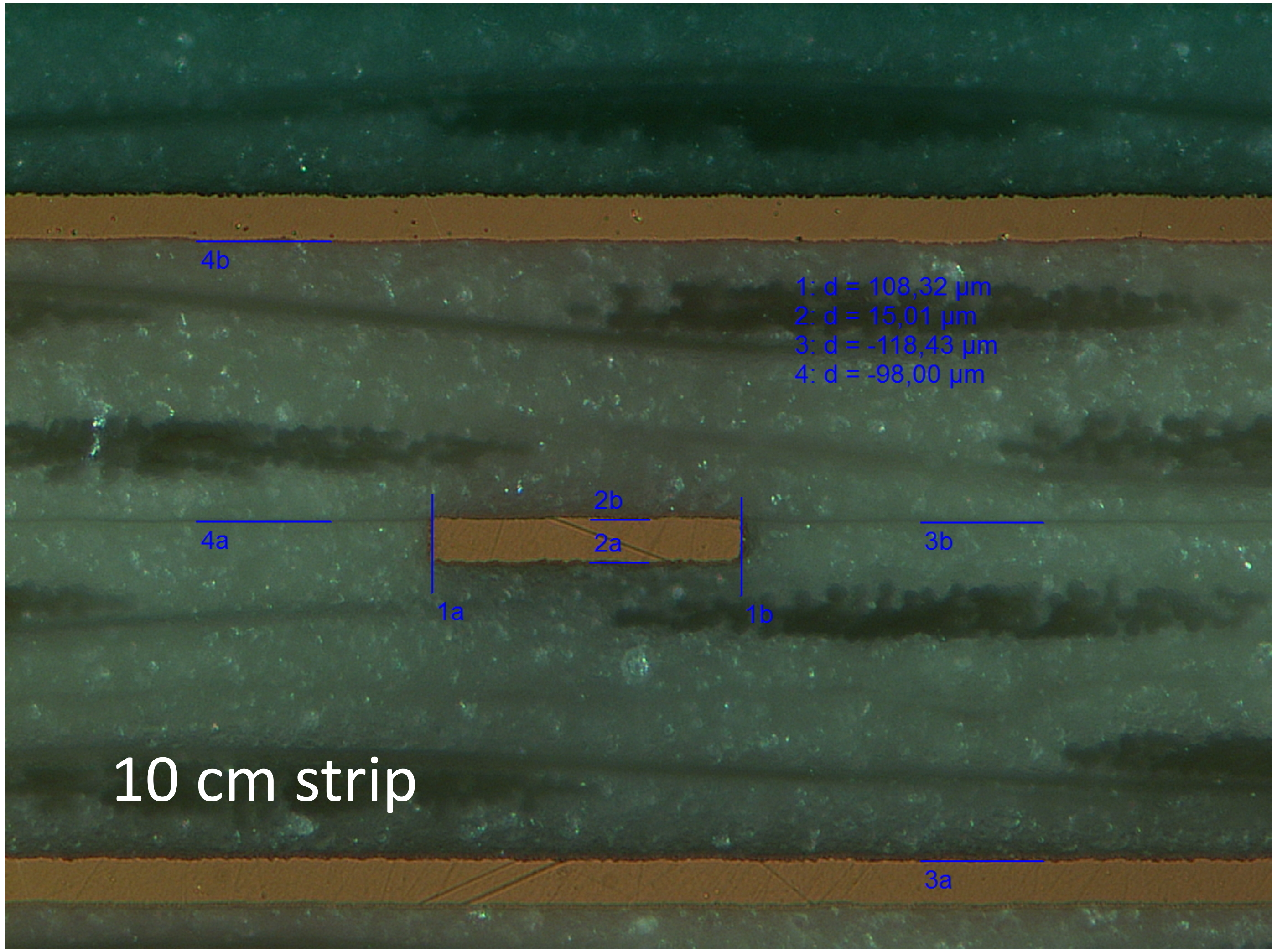


Reality: Larger impedance; Variation of impedance along the traces (more than expected)

INNER6 – SE strips cross-sections

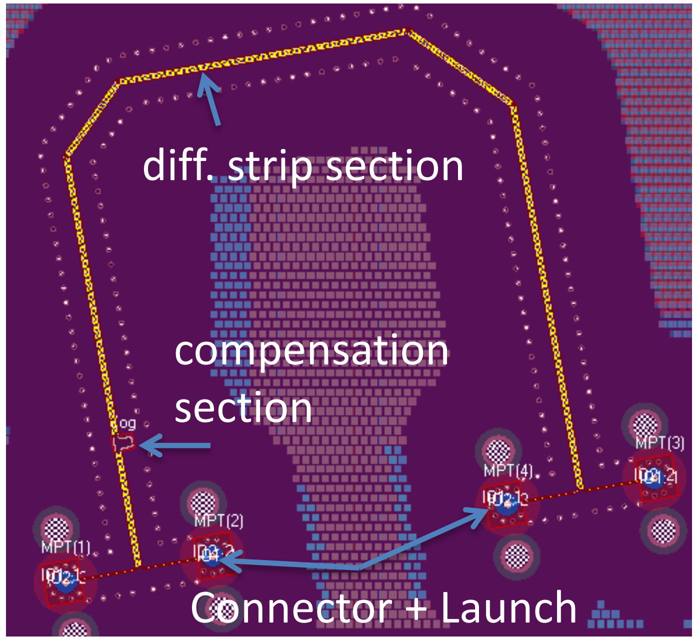
- Looks normal – close to expected





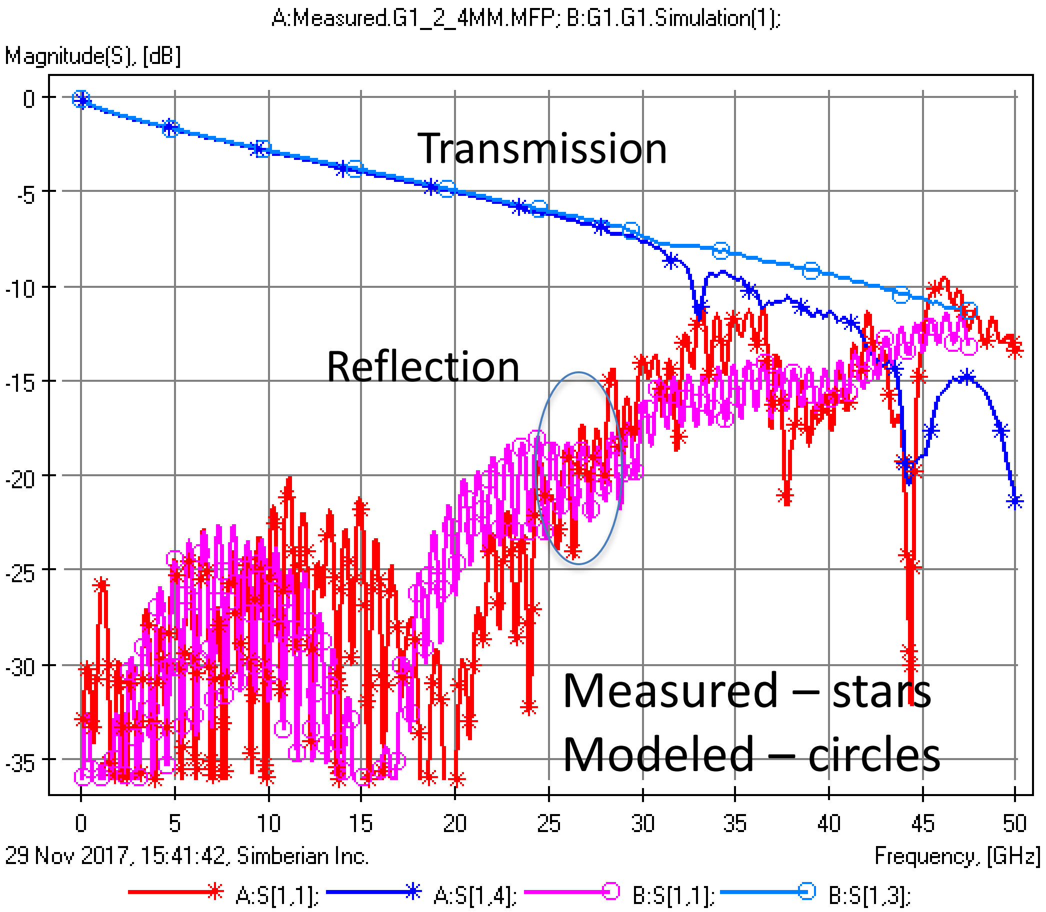
G1: Diff. length compensation structure in INNER6

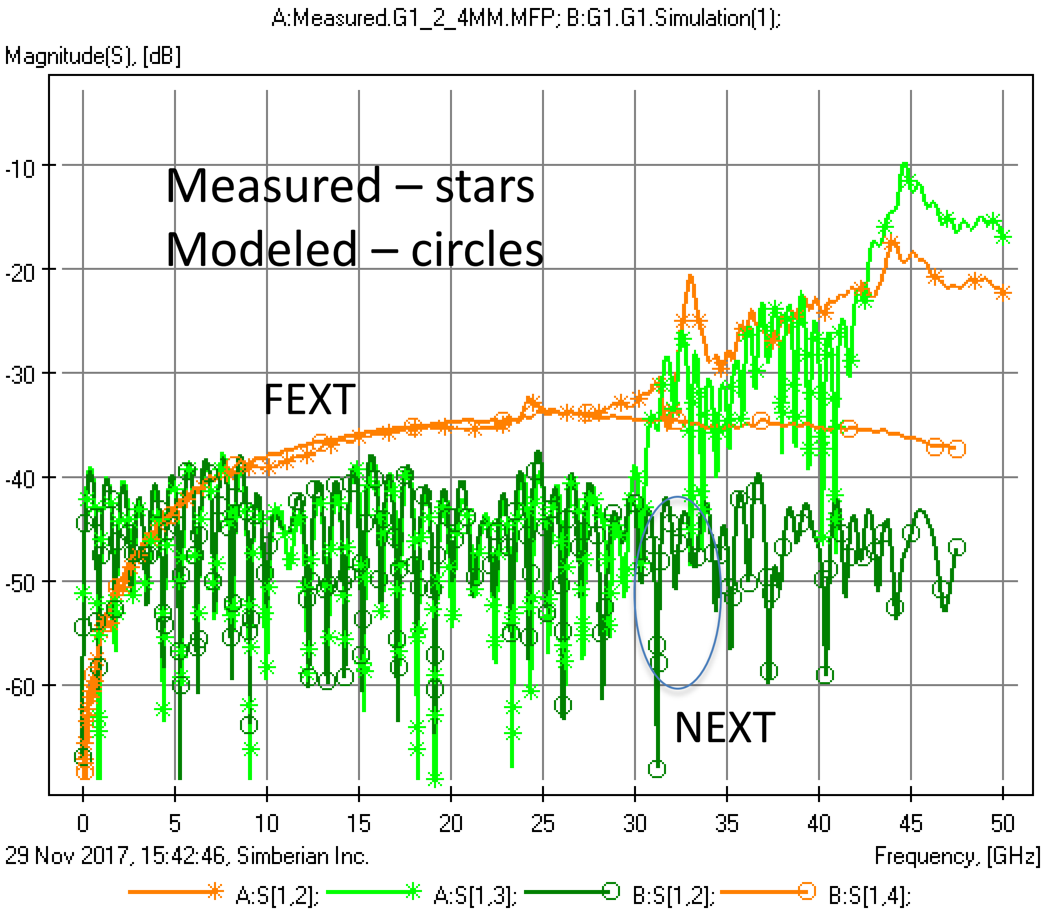
De-compositional EM analysis
All trace widths and shapes are adjusted



Analysis with t-line segment models only…

Single-ended S-parameters



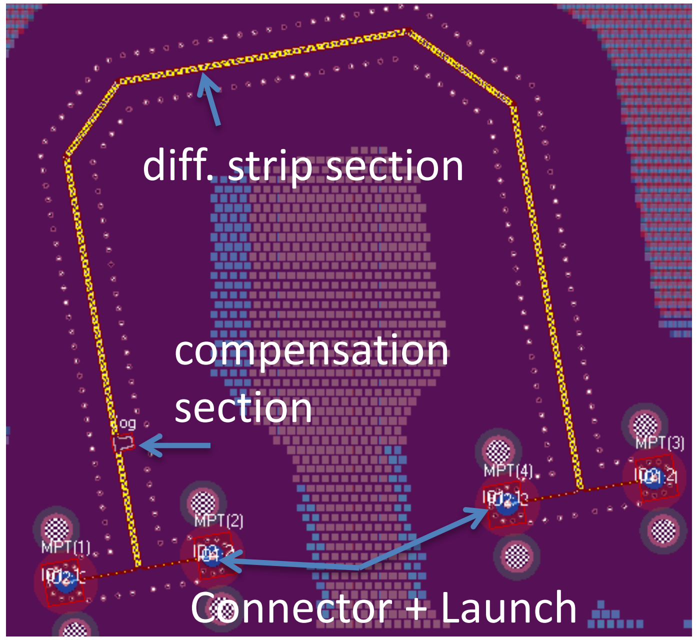


Reality: Difference above 30 GHz – see reality above 30 GHz…

Acceptable correspondence up to 30 GHz

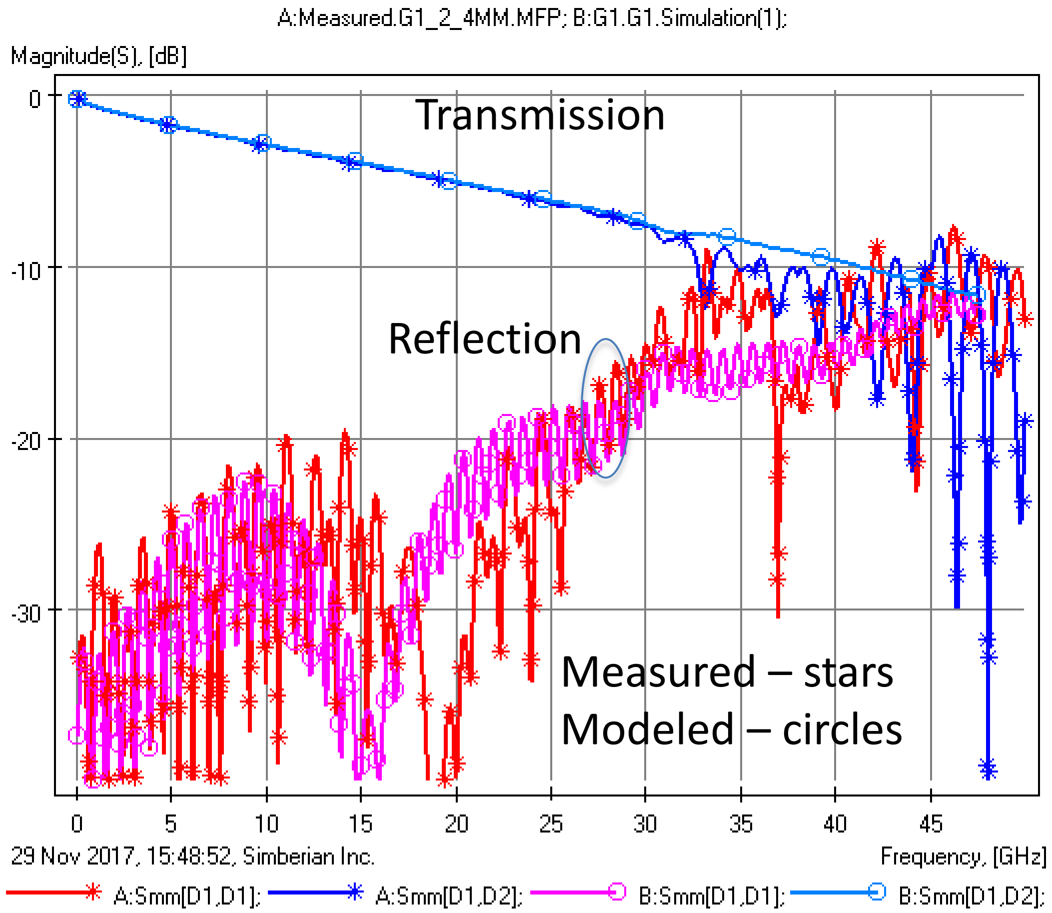
G1: Diff. length compensation structure in INNER6

De-compositional EM analysis
All trace widths and shapes are adjusted

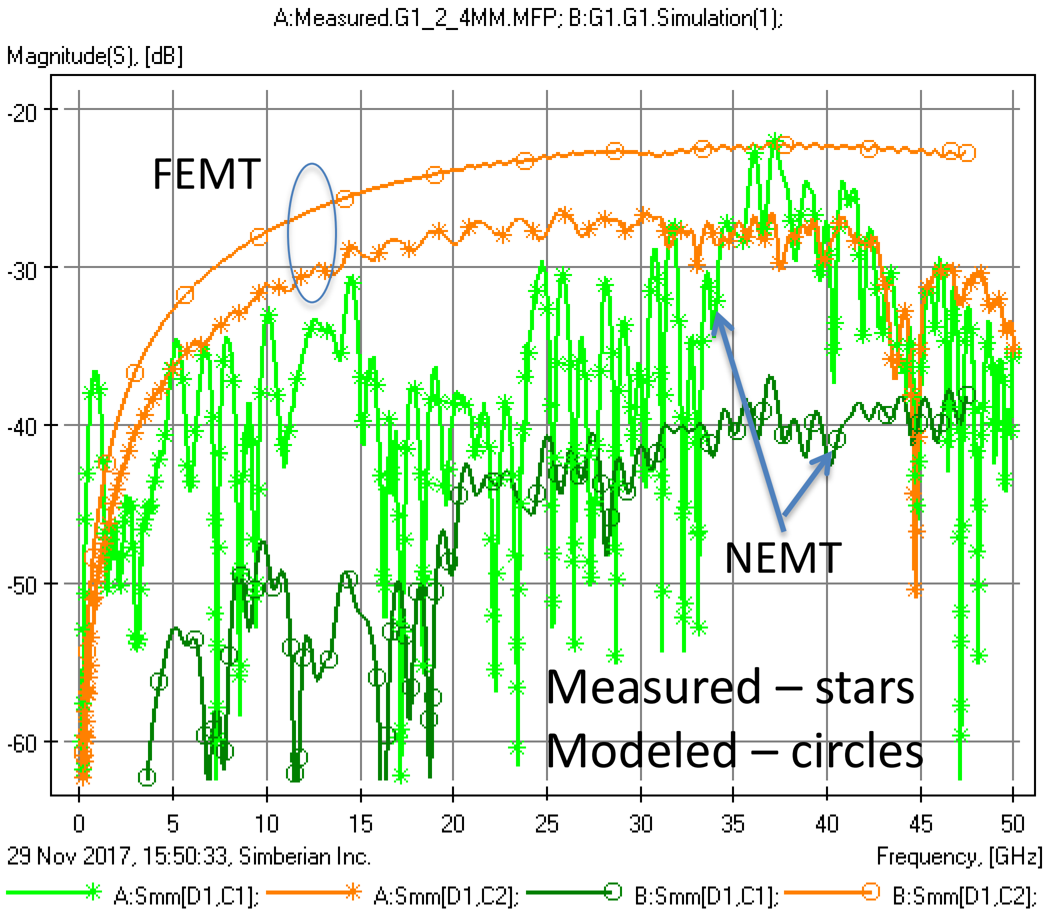


Analysis with t-line segment models only…

Mixed-mode S-parameters



Acceptable correspondence up to 30 GHz

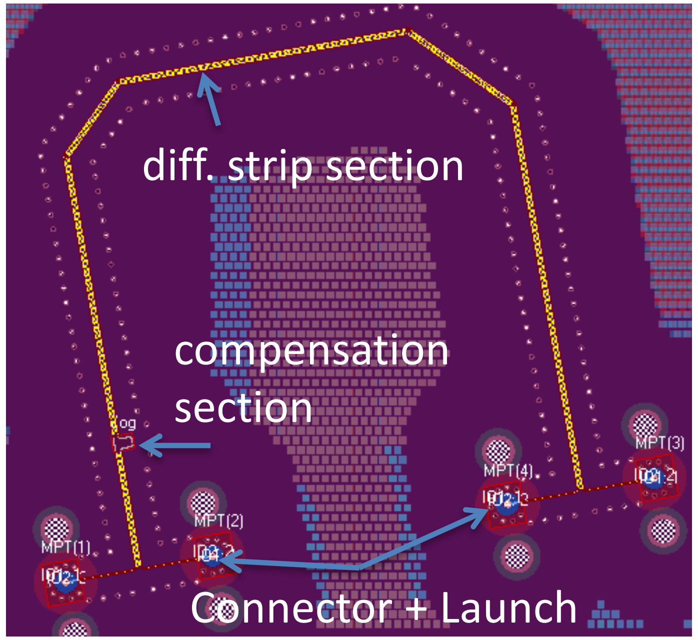


FEMT/NEMT – Far/Near End Mode Transformation

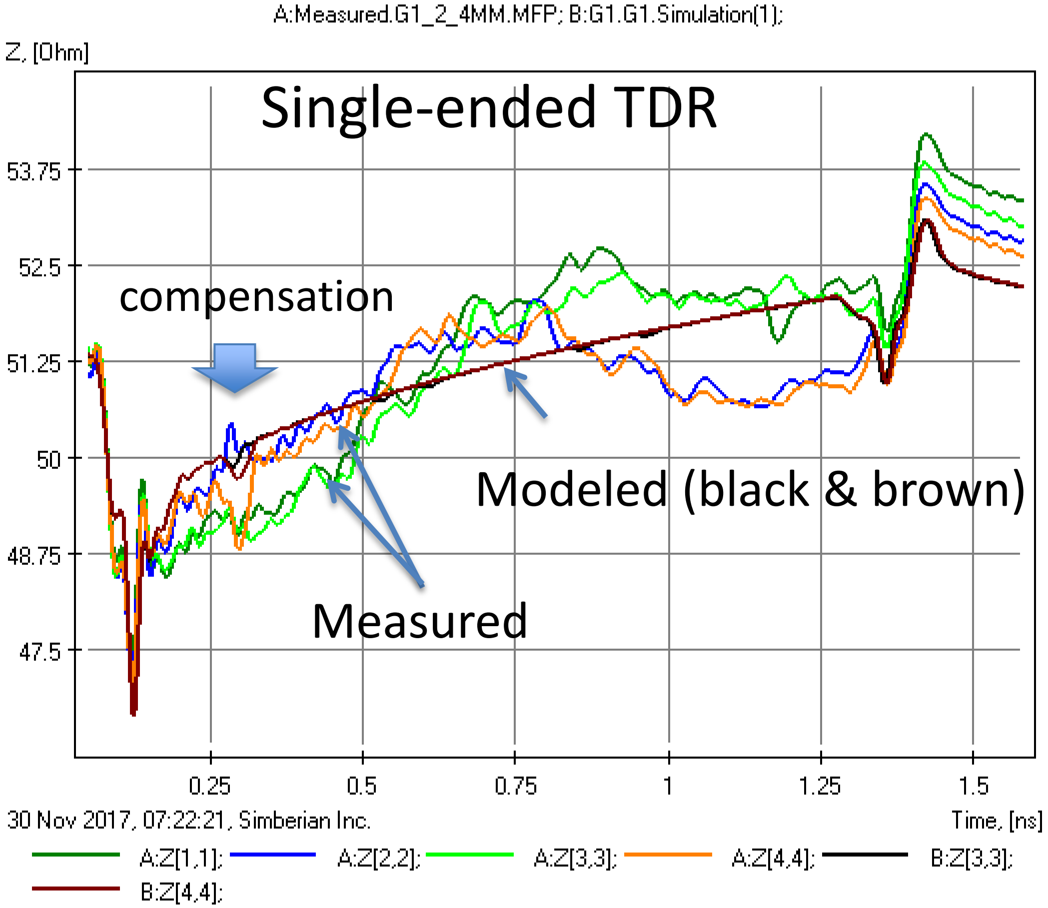
Reality: Large difference in mode transformation – investigate the model…

G1: Diff. length compensation structure in INNER6

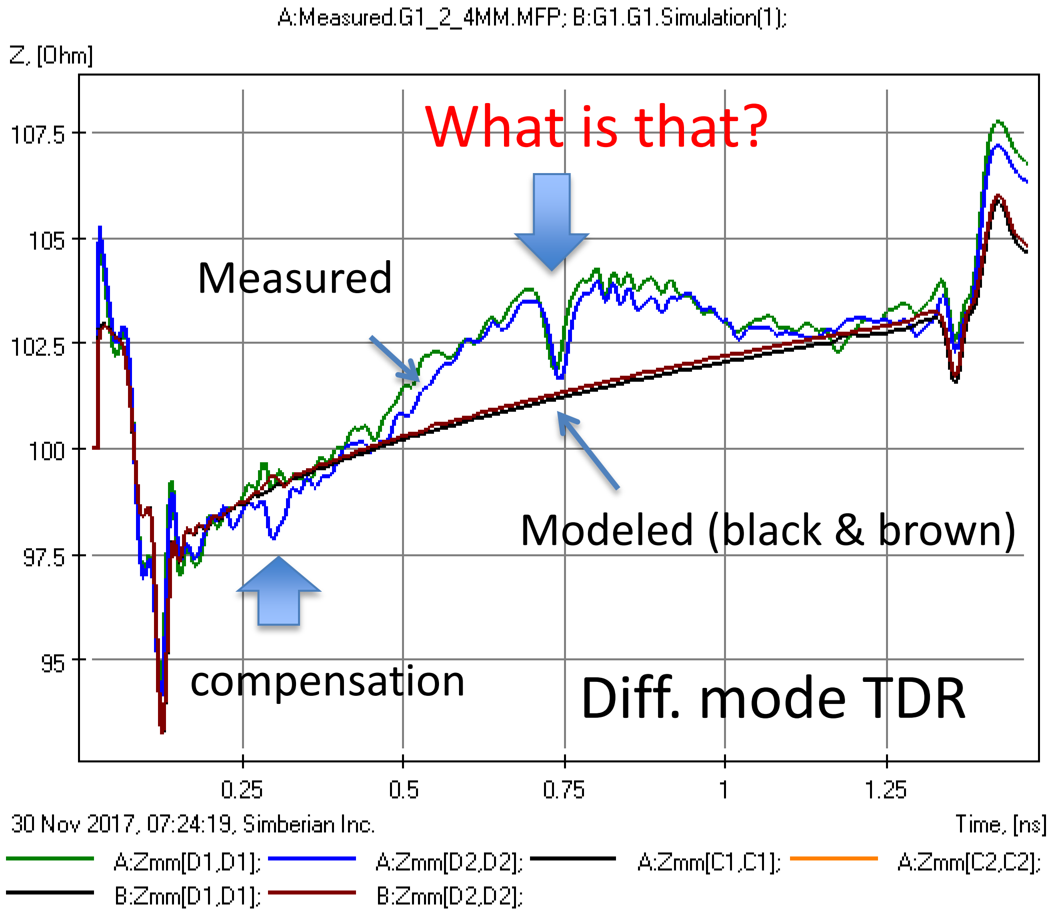
De-compositional EM analysis
All trace widths and shapes are adjusted



Analysis with t-line segment models only…



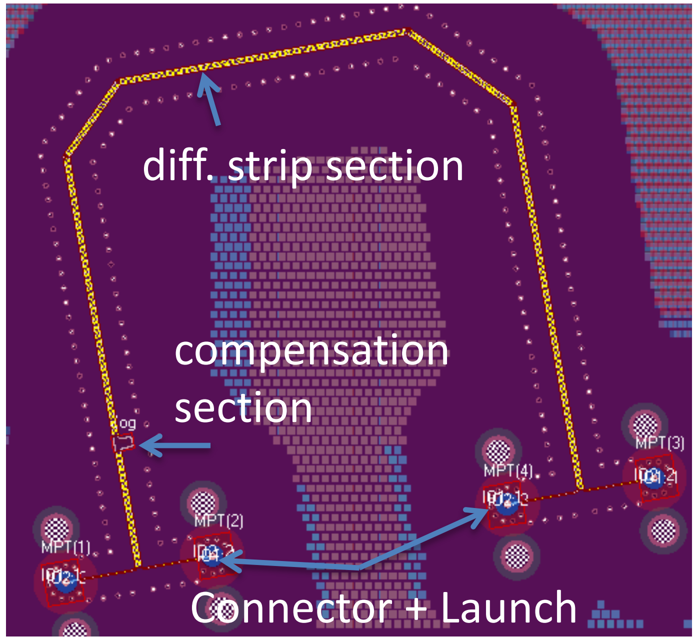
Reality: Variation of impedance along the traces (more than expected)



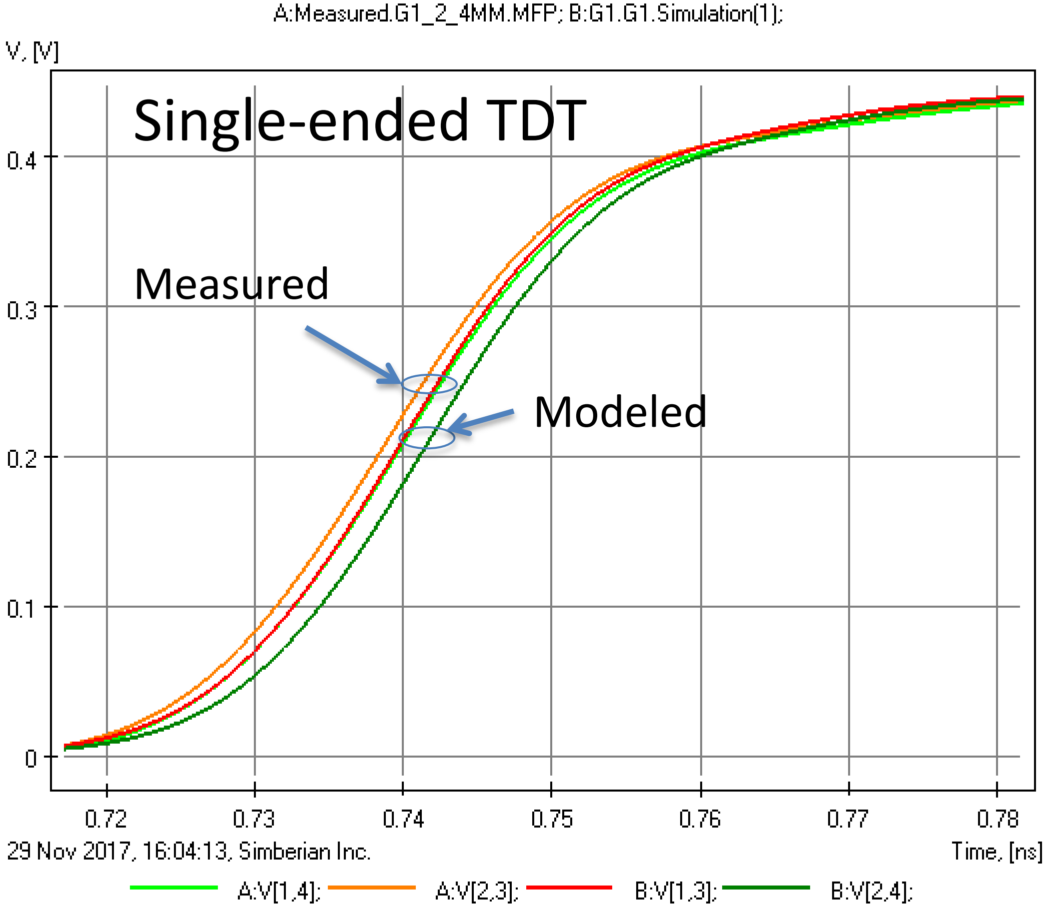
Questionable correspondence (something in the middle)

G1: Diff. length compensation structure in INNER6

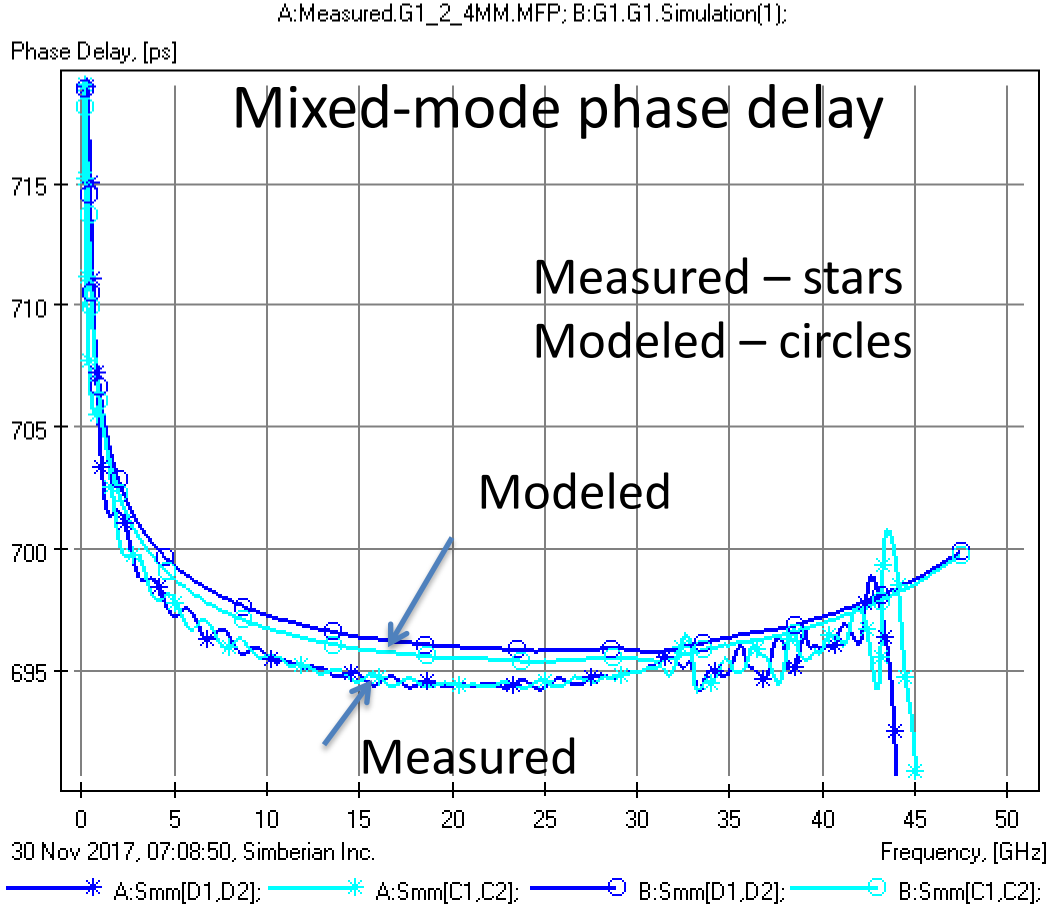
De-compositional EM analysis
All trace widths and shapes are adjusted



Analysis with t-line segment models only…



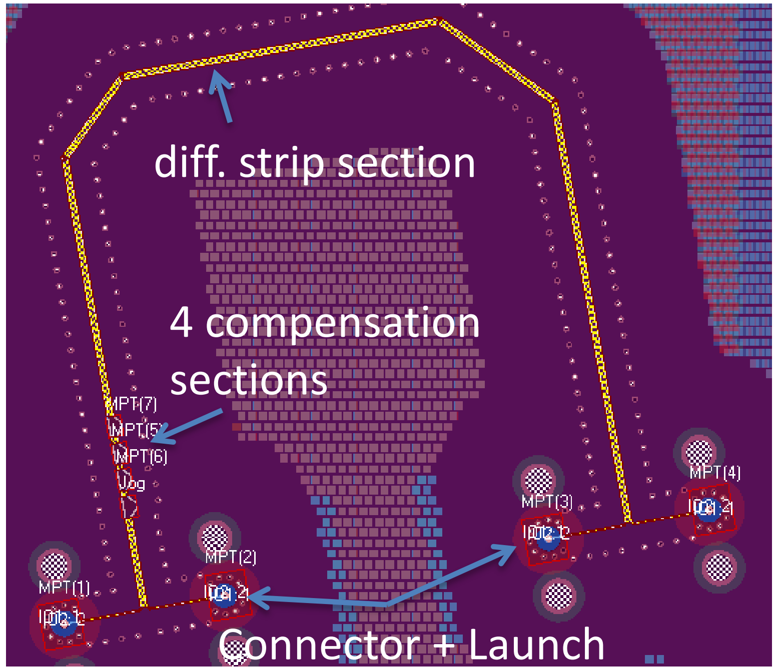
Acceptable correspondence…



Reality: Slightly smaller delay and delay difference…

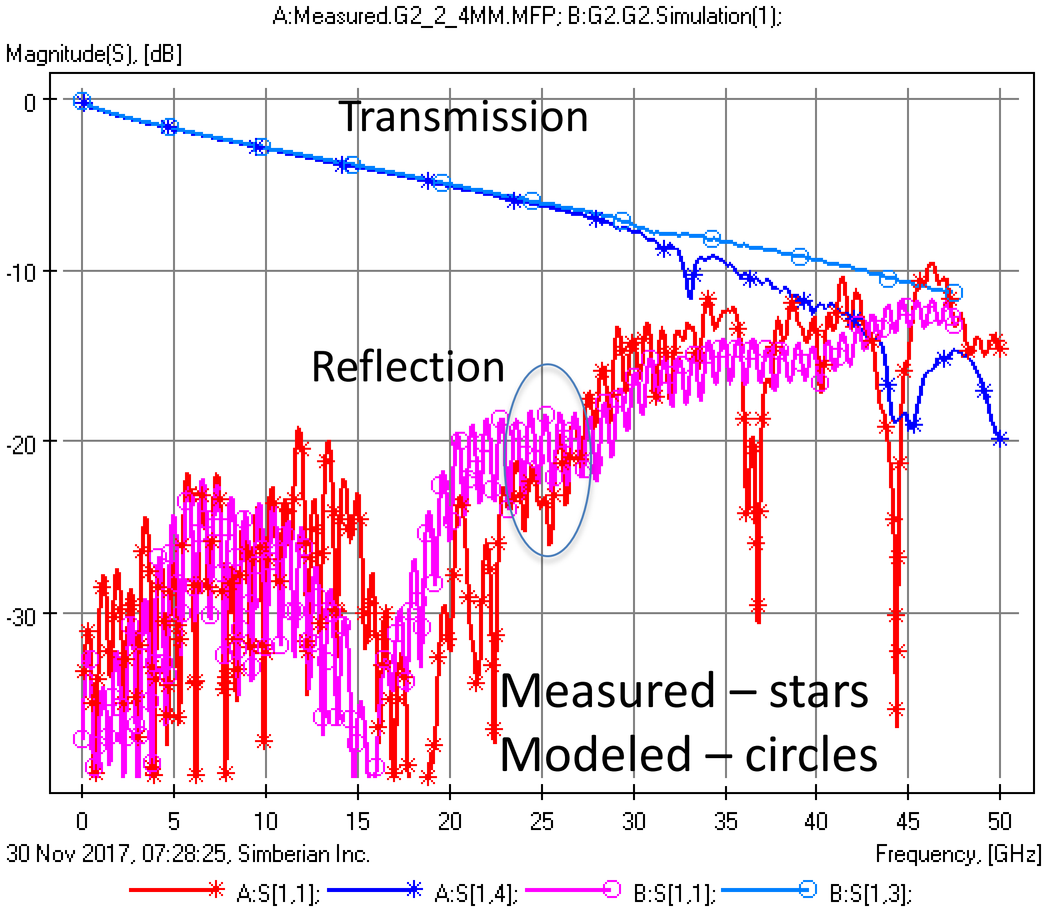
G2: Diff. length compensation structure in INNER6

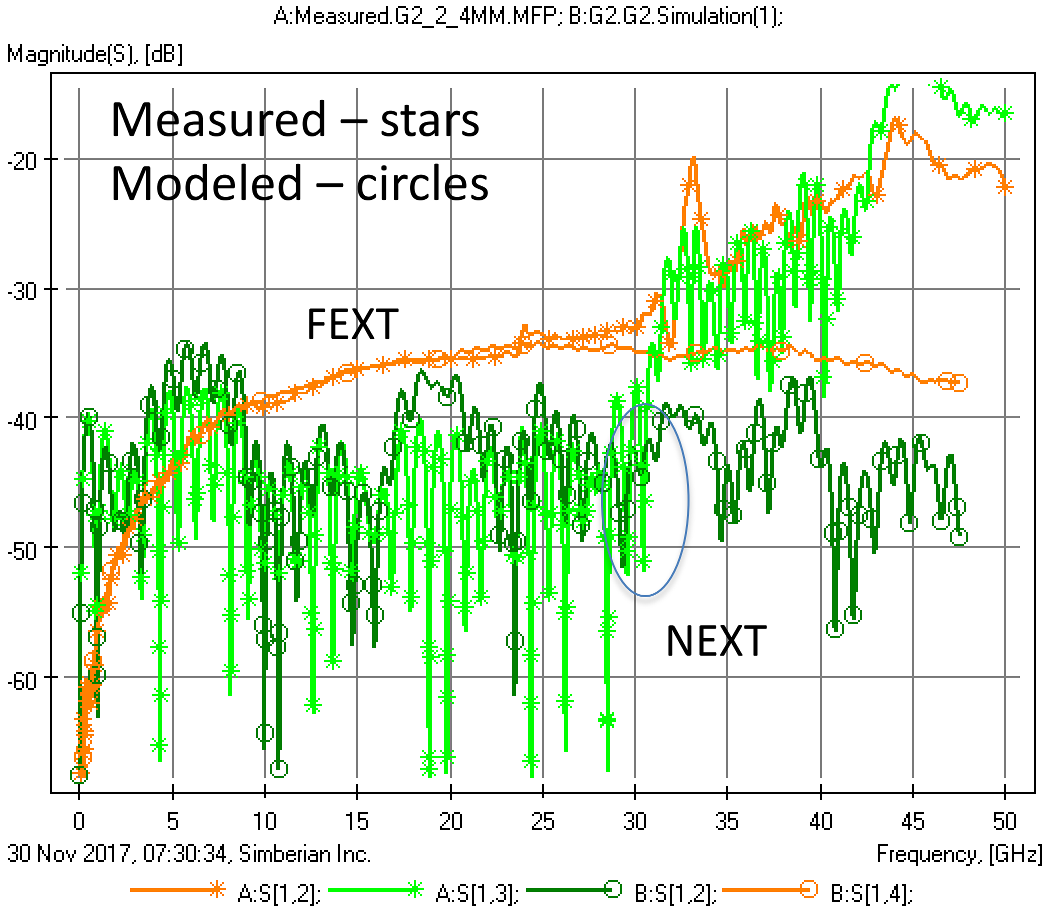
De-compositional EM analysis
All trace widths and shapes are adjusted



Analysis with t-line segment models only…

Single-ended S-parameters



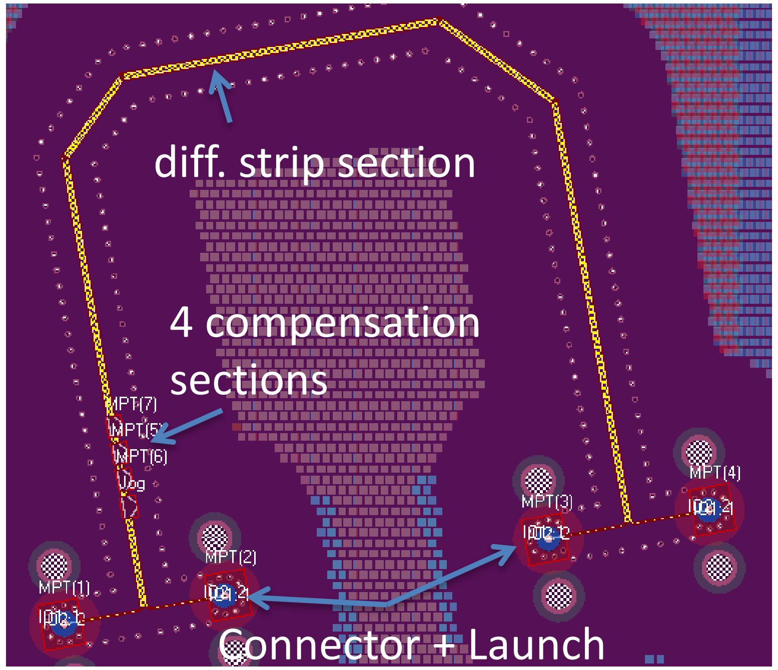


Acceptable correspondence up to 30 GHz

Reality: Difference above 30 GHz – see reality above 30 GHz…

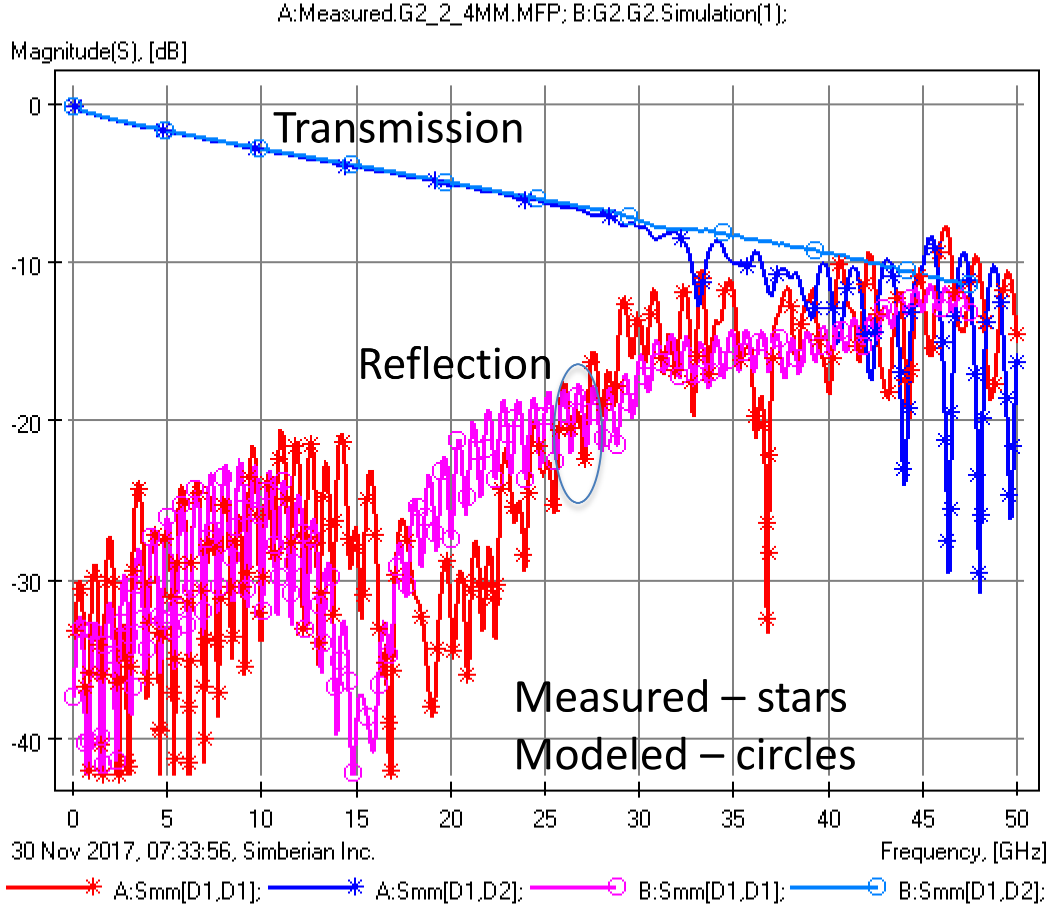
G2: Diff. length compensation structure in INNER6

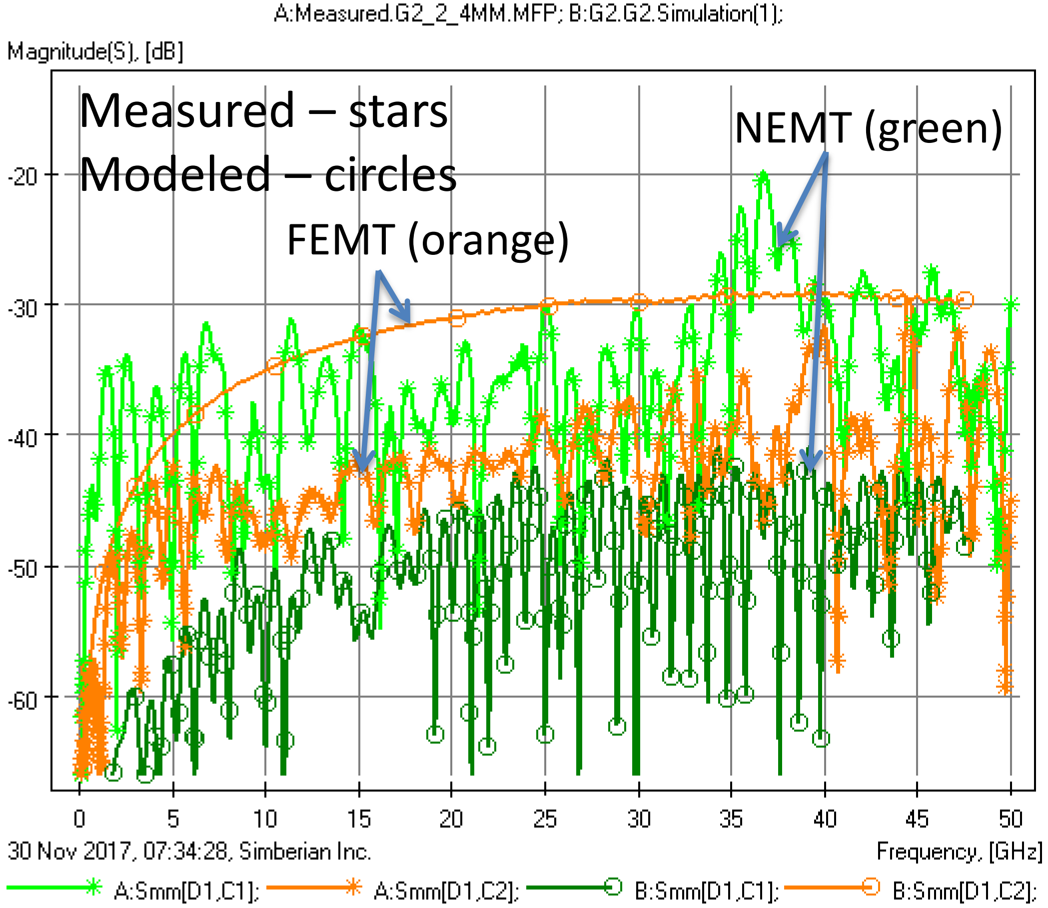
De-compositional EM analysis
All trace widths and shapes are adjusted



Analysis with t-line segment models only…

Mixed-mode S-parameters





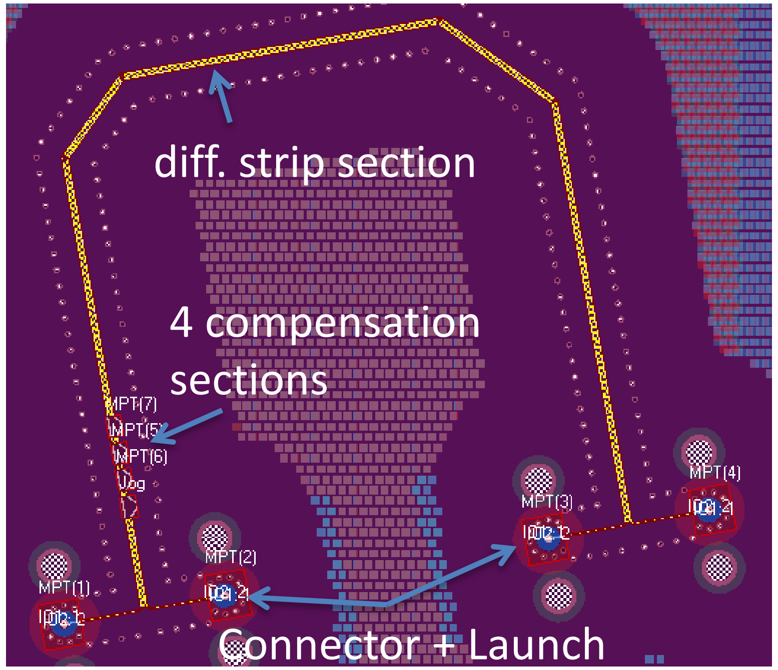
FEMT/NEMT – Far/Near End Mode Transformation

Acceptable correspondence up to 30 GHz

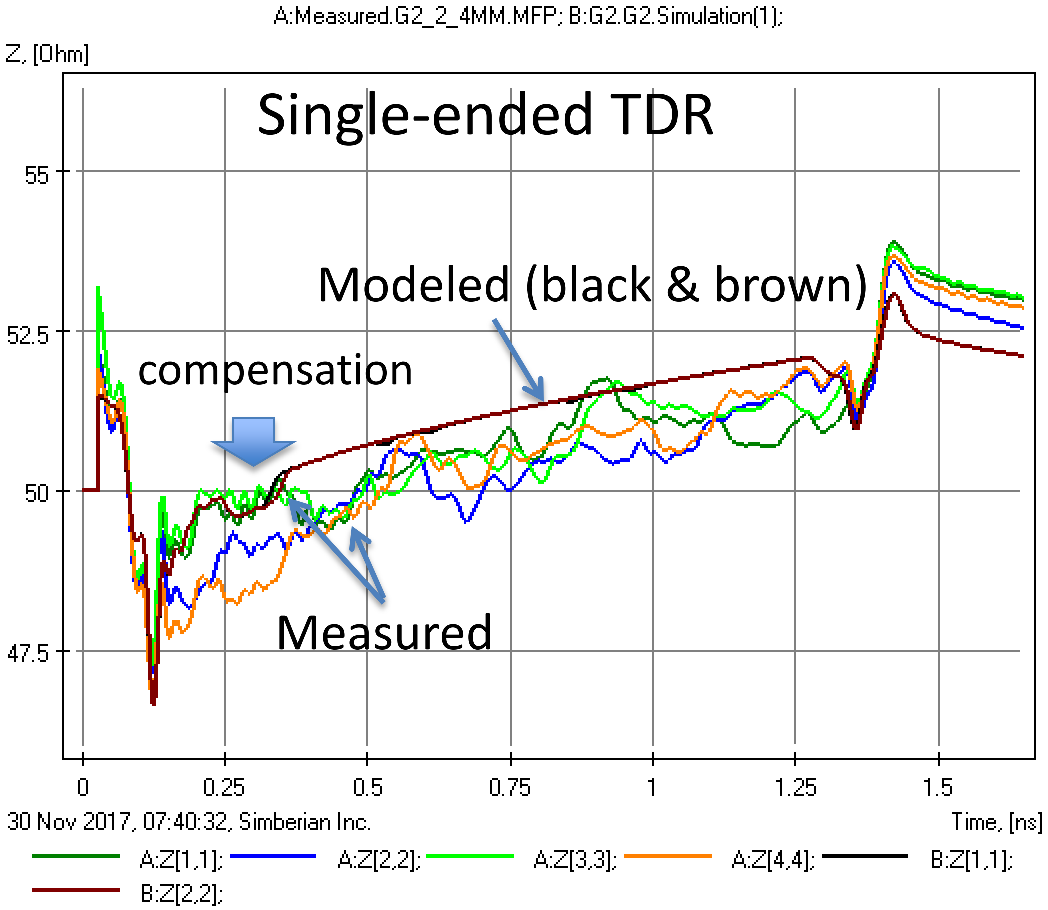
Reality: Large difference in mode transformation – investigate what causes it…

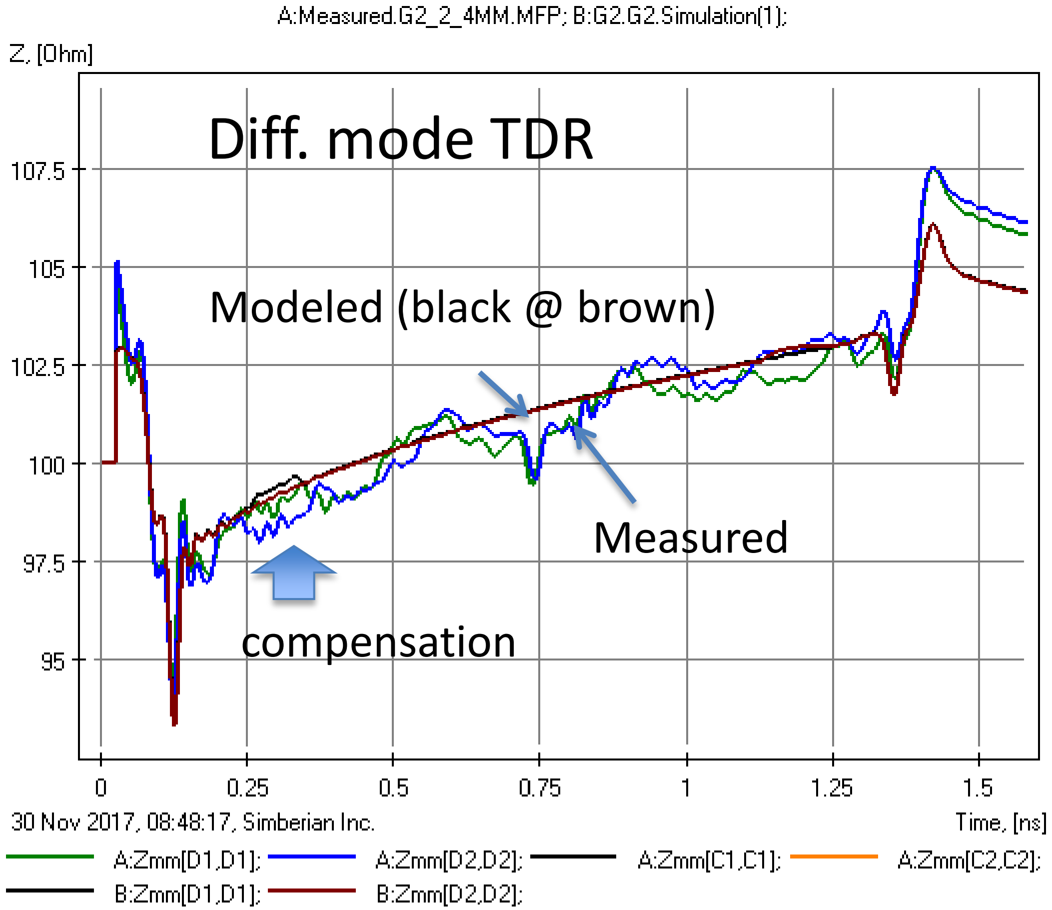
G2: Diff. length compensation structure in INNER6

De-compositional EM analysis
All trace widths and shapes are adjusted



Analysis with t-line segment models only…



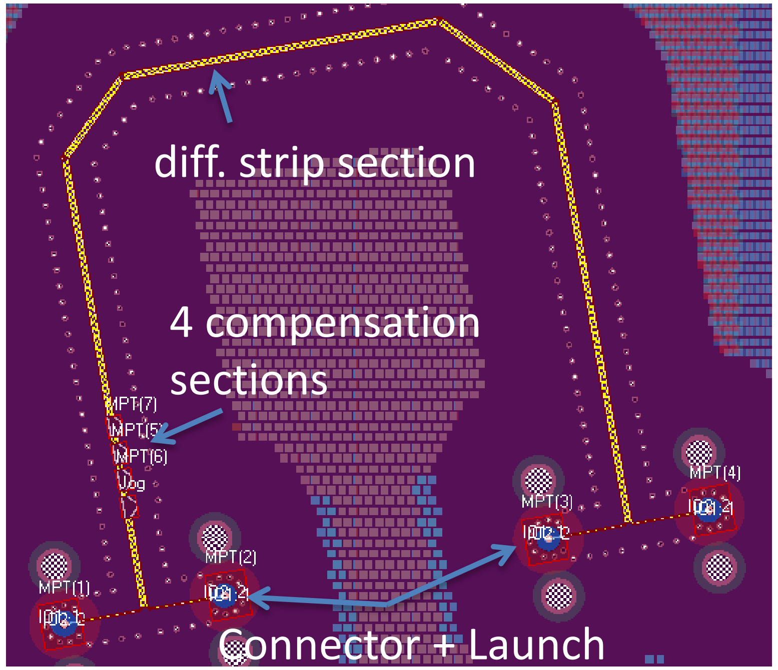


Reality: Variation of impedance along the traces (expected)

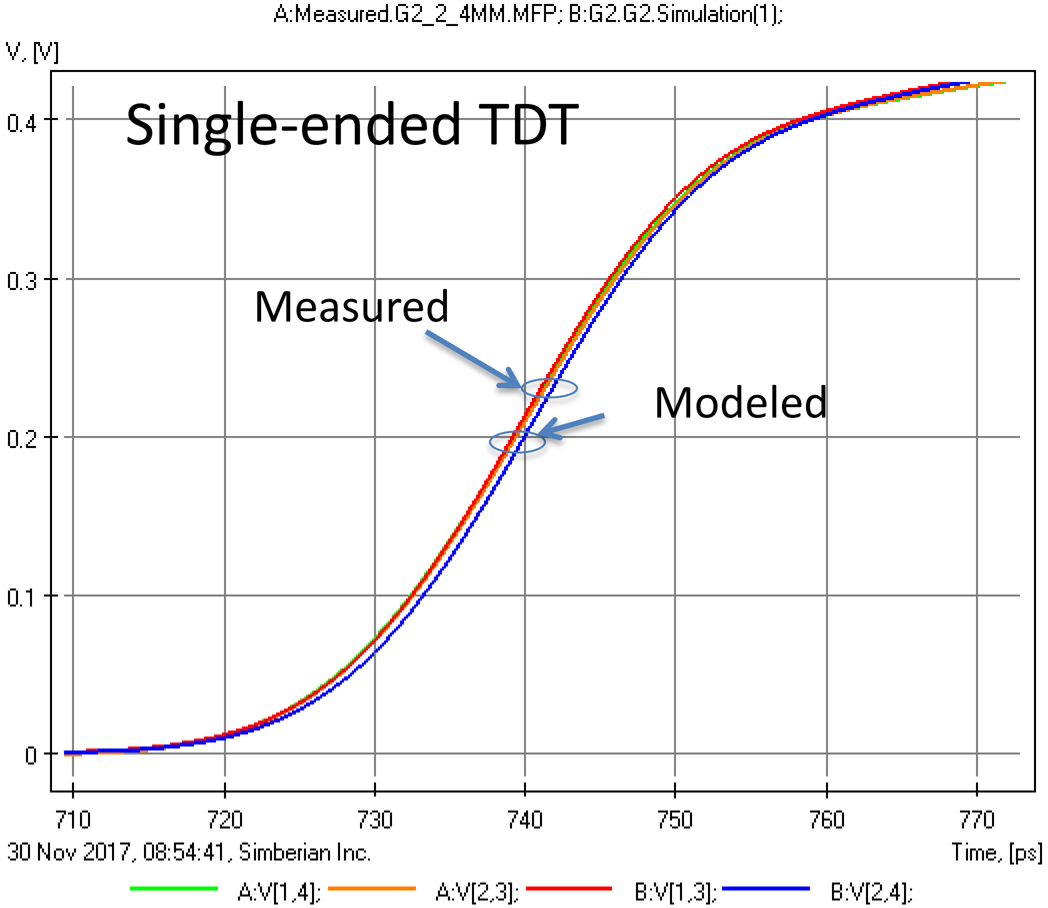
Acceptable correspondence

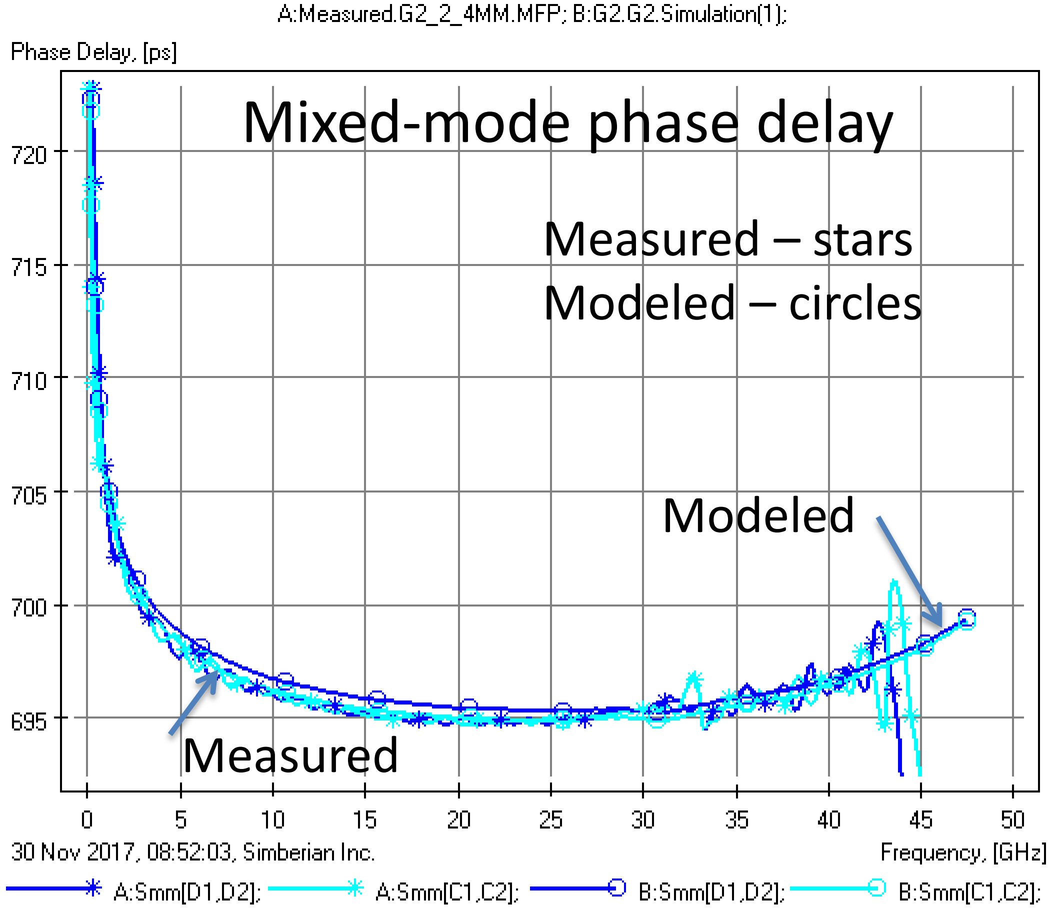
G2: Diff. length compensation structure in INNER6

De-compositional EM analysis
All trace widths and shapes are adjusted



Analysis with t-line segment models only…





Acceptable correspondence…

Note: t-line analysis with adaptivity tolerance 0.01

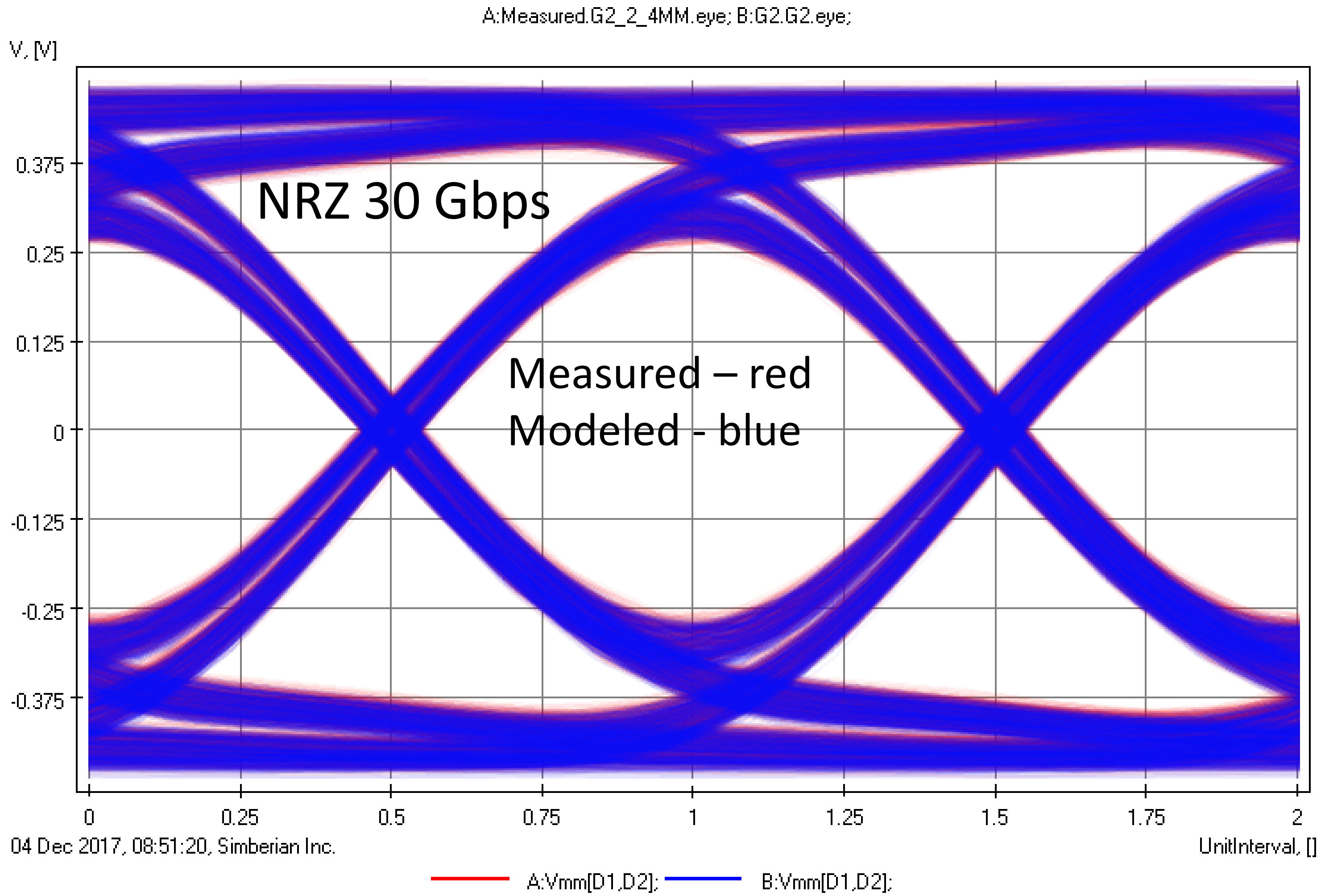
G2: Diff. length compensation structure in INNER6

- Eye diagrams comparison

Eye Analyzer

Show Eye Metrics: Selected ☑ Auto-open

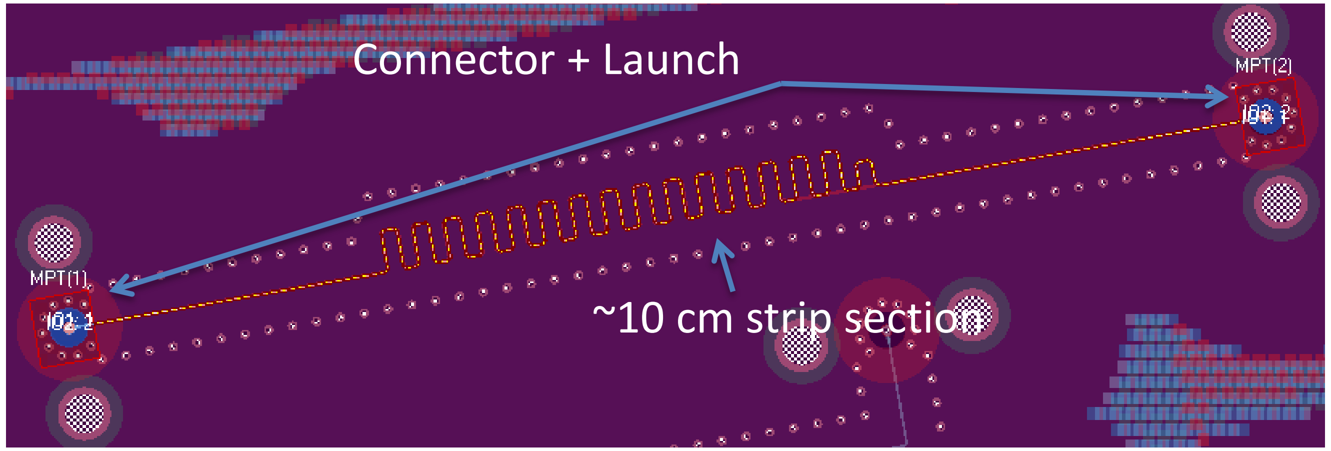
Parameter	Measured.G2_2_4MM....	G2.G2.eye: ...
Eye Level Zero (V)	-0.366796	-0.373366
Eye Level One (V)	0.368903	0.370287
Eye Level Mean (V)	0.00307387	-0.00268303
Eye Amplitude (V)	0.735699	0.743652
Eye Height (V)	0.505731	0.514399
Eye Width (UI)	0.878936	0.885588
Eye Opening Factor	0.687417	0.69172
Eye Signal to Noise	5.96404	5.97982
Eye Rise Time (20-80) (UI)	0.506565	0.507008
Eye Fall Time (80-20) (UI)	0.506913	0.508176
Eye Jitter (PP) (UI)	0.121064	0.114412
Eye Jitter (RMS) (UI)	0.0295313	0.0286911



~2% difference in eye heights, ~1% in widths; Possible reason – impedance variations, launch mismatch and localization loss…

E1: Meander in INNER6

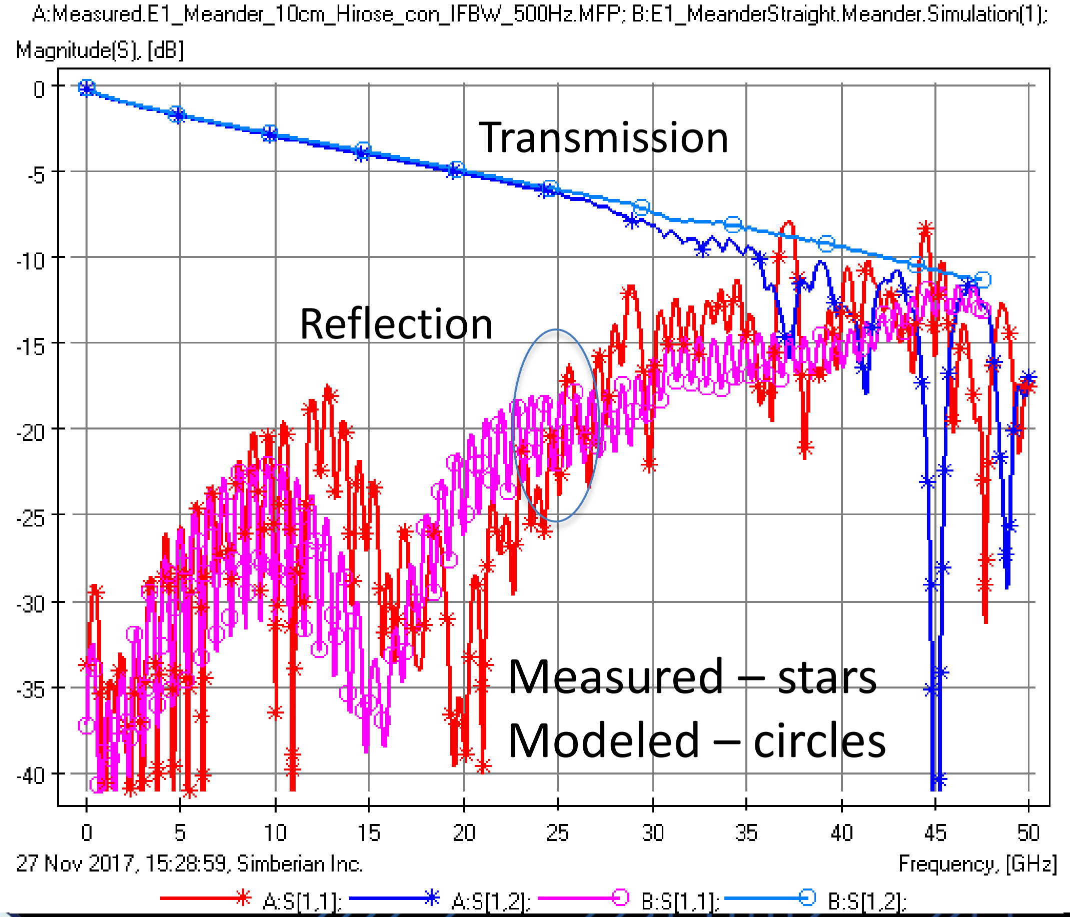
S-parameters

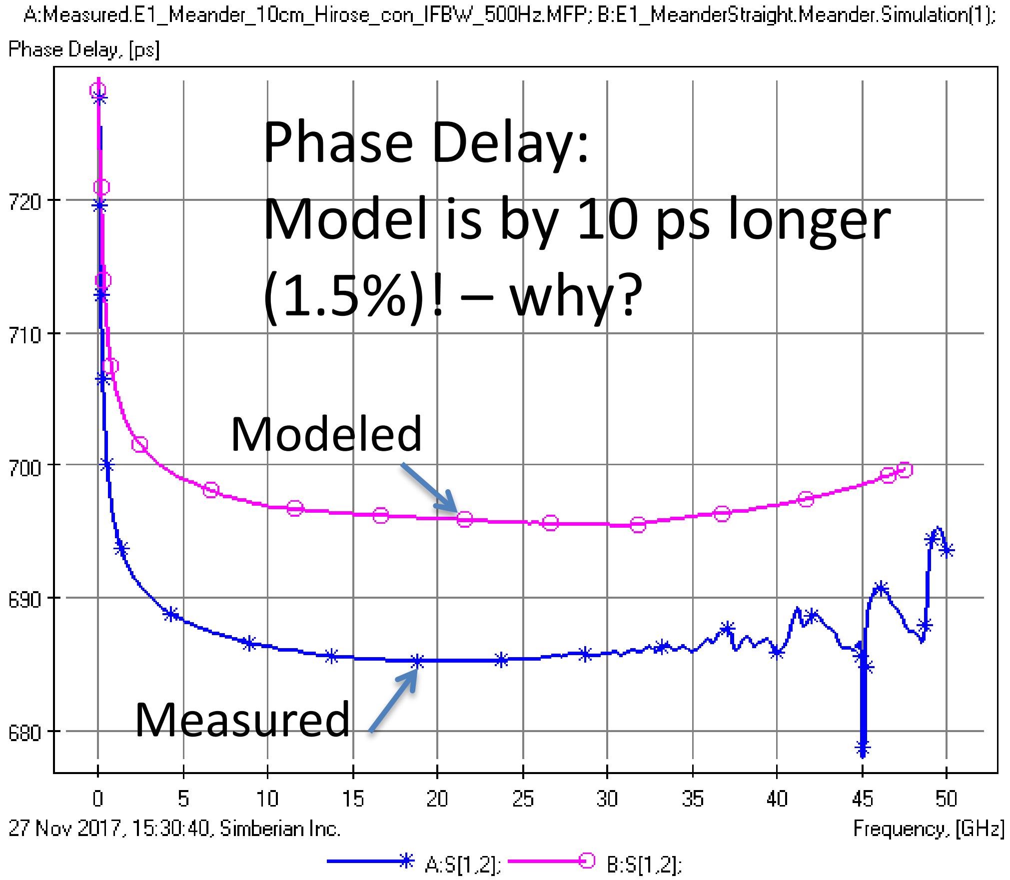


De-compositional EM analysis
All trace widths and shapes are adjusted
Analyses with un-coupled t-line segments

Reality: Large difference in reflection above 25 GHz – see reality above 30 GHz…

Acceptable correspondence up to 25 GHz, systematic delay problem…

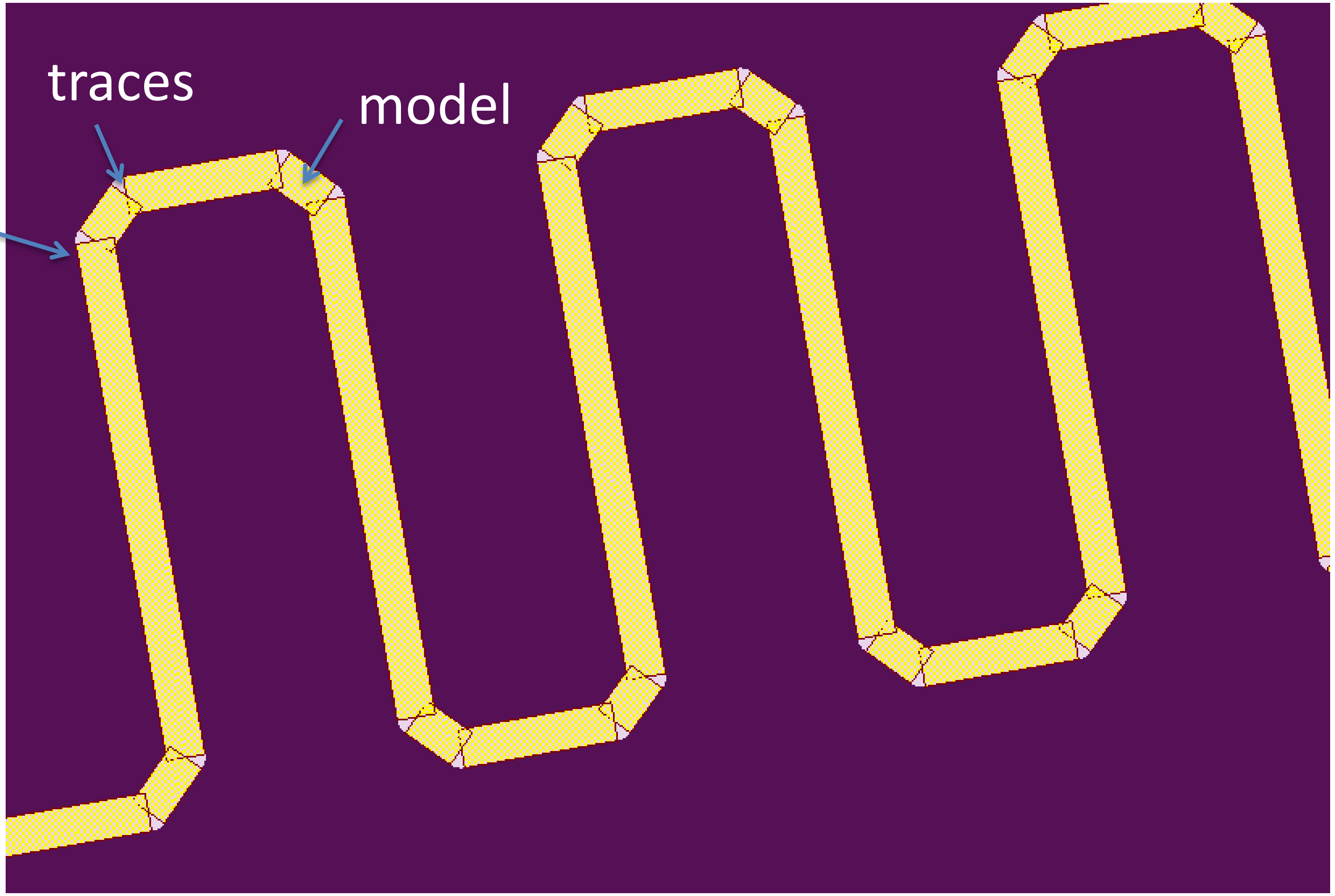




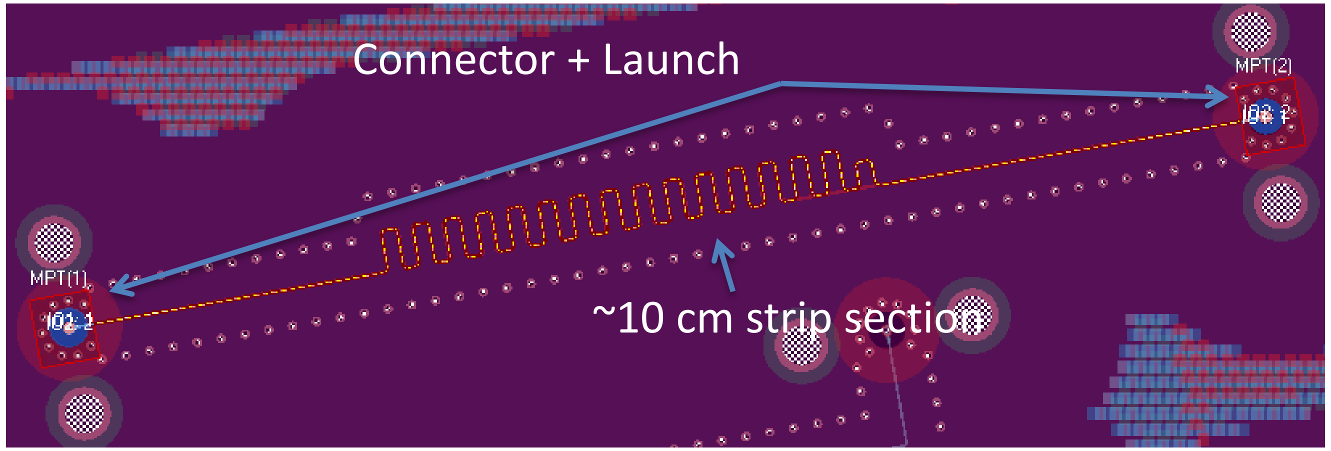
E1: Meander in INNER6

Simplified model does not account for the bends – the lengths of the t-line segments are set to the middle line – this is the problem
Bends should be properly simulated…

Coupling is weak and not accounted either – the impact is expected above 30 GHz…



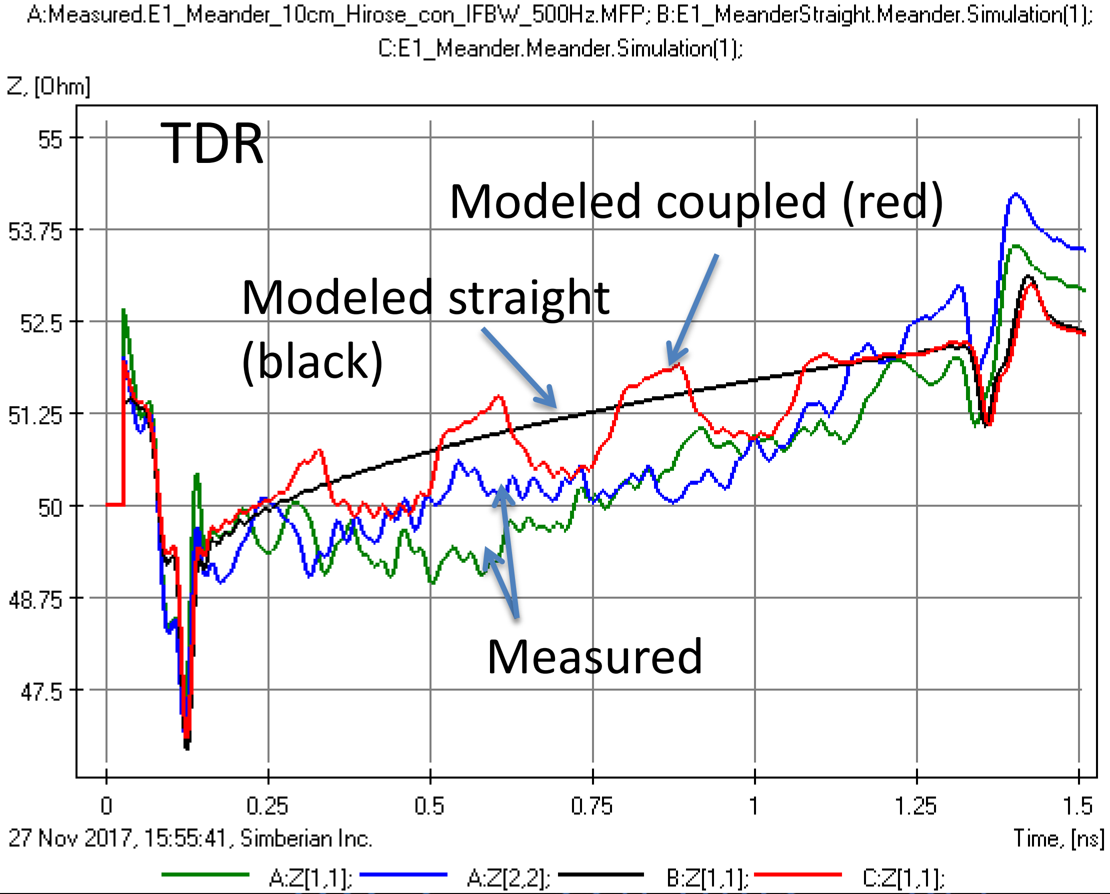
E1: Meander in INNER6

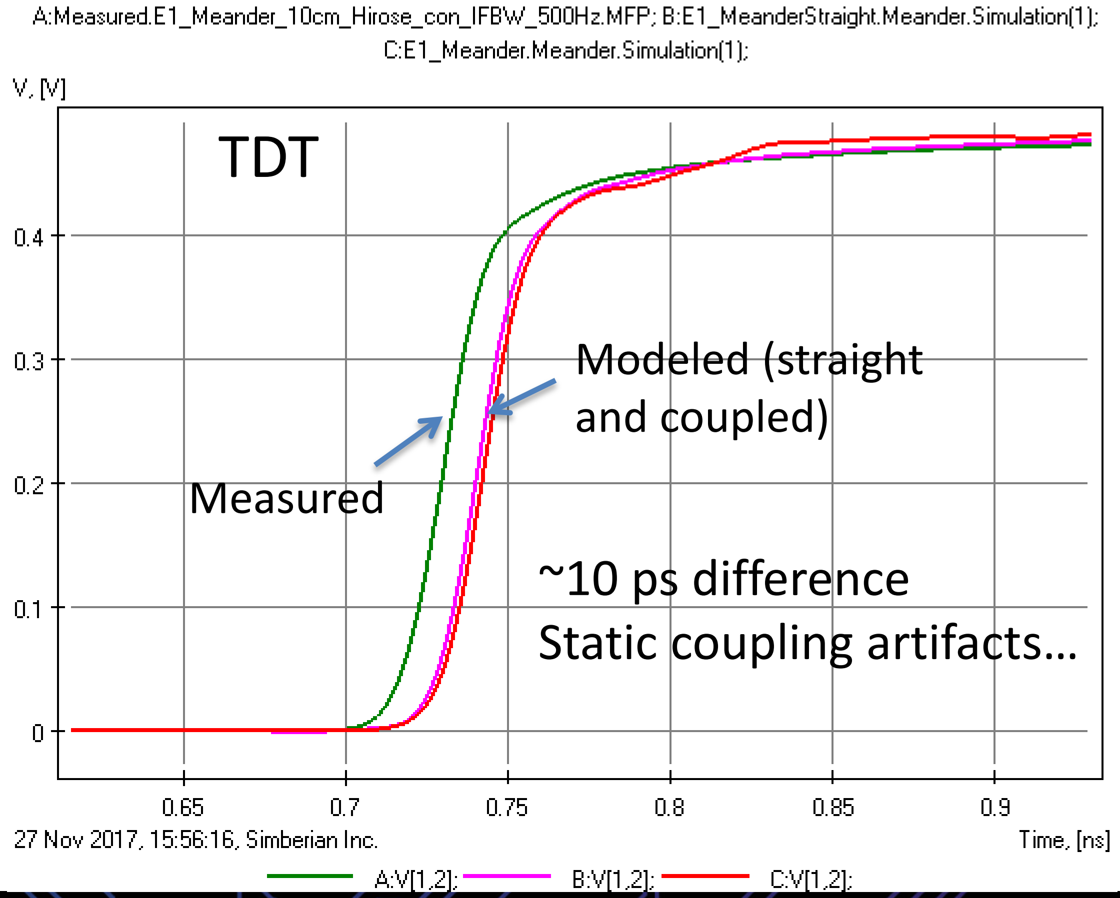


De-compositional EM analysis
All trace widths and shapes are adjusted
Analyses with un-coupled and coupled t-line segments

Reality: Smaller delay (bends); Variation of impedance along the traces (more than expected)

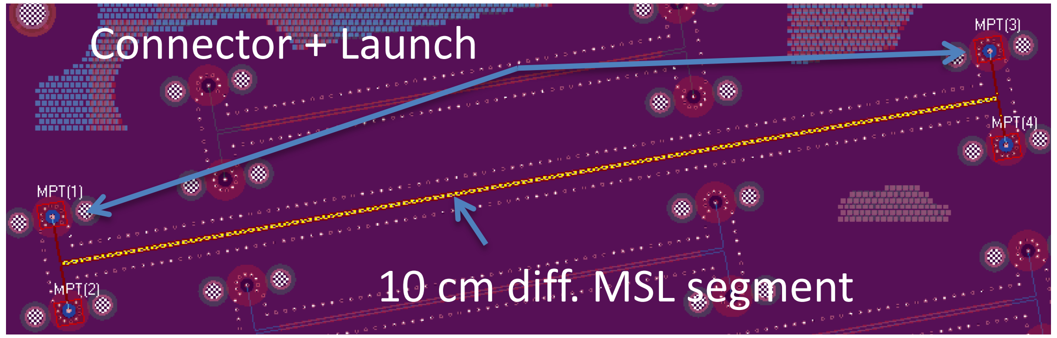
Not so good correspondence





BOTTOM: 10 cm diff. microstrip link

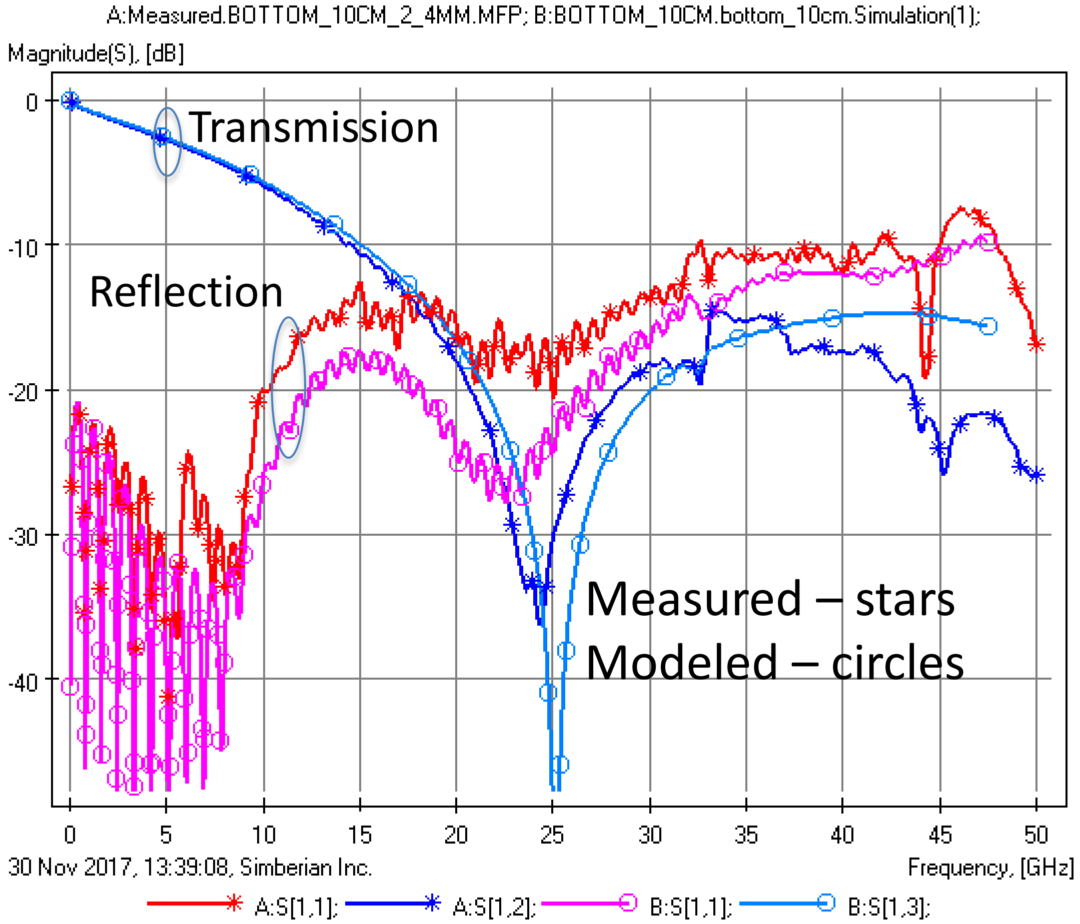
Single-ended S-parameters

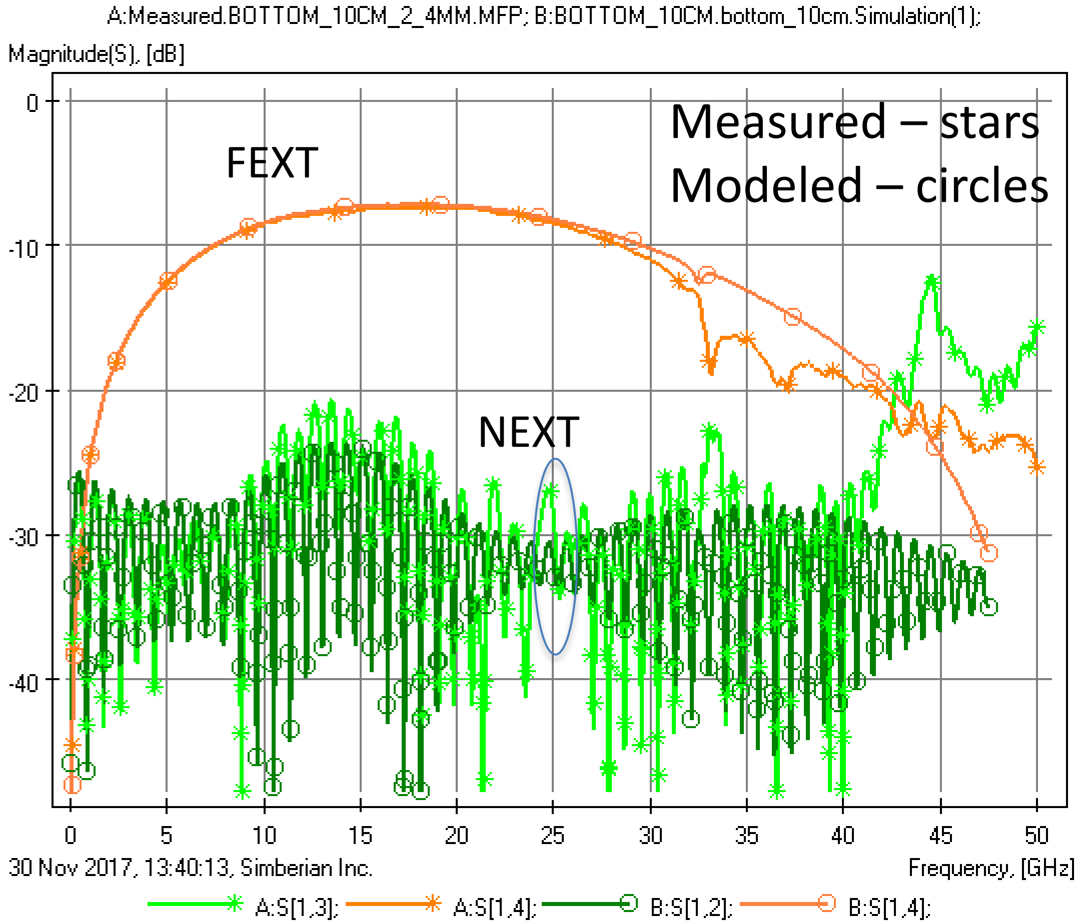


De-compositional EM analysis
Shape and size of all MSL sections are adjusted…

Reality: more reflection at from 10 to 30 GHz (investigate)…

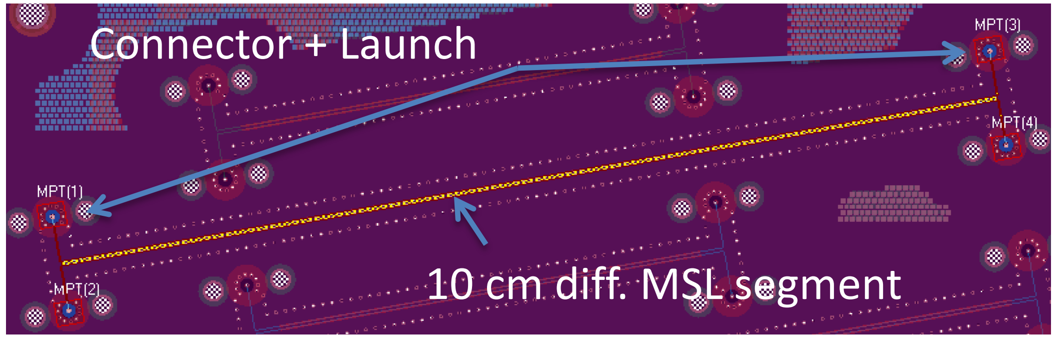
Acceptable correspondence up to 30 GHz





BOTTOM: 10 cm diff. microstrip link

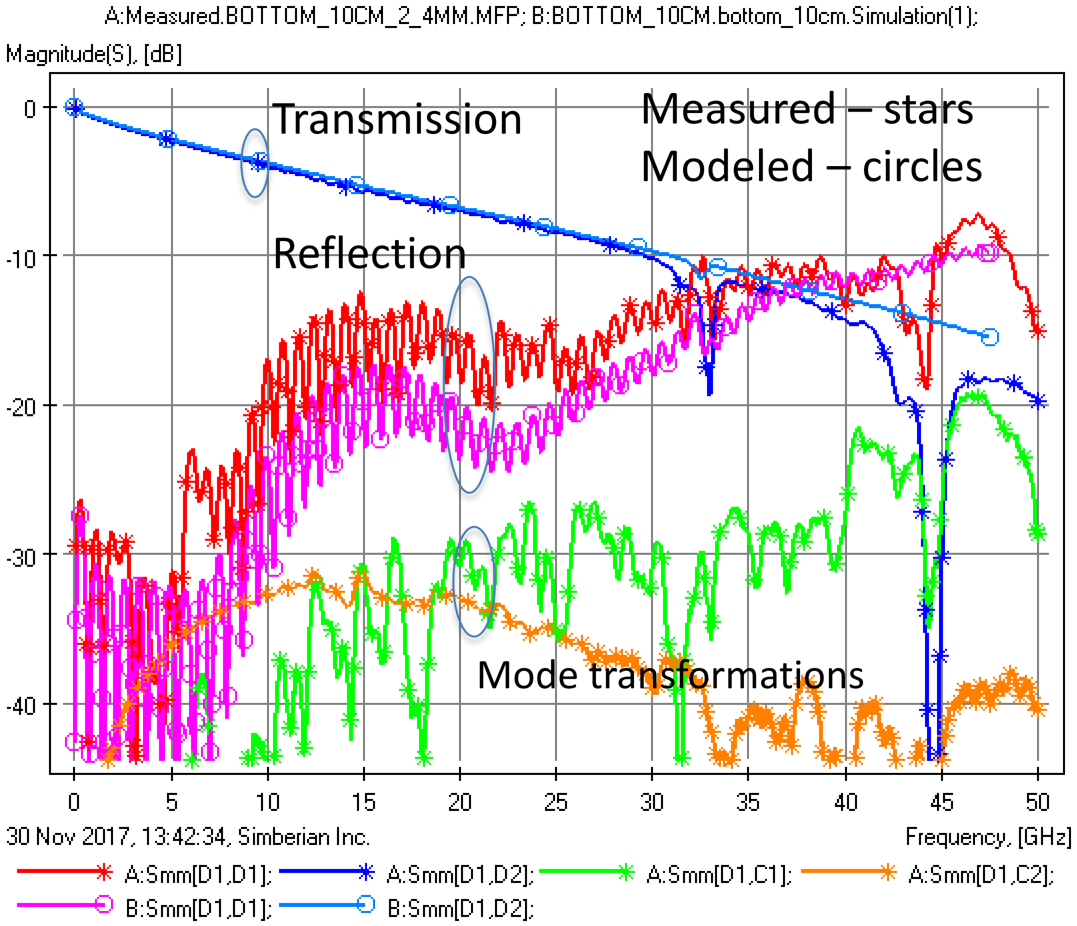
Mixed-mode S-parameters

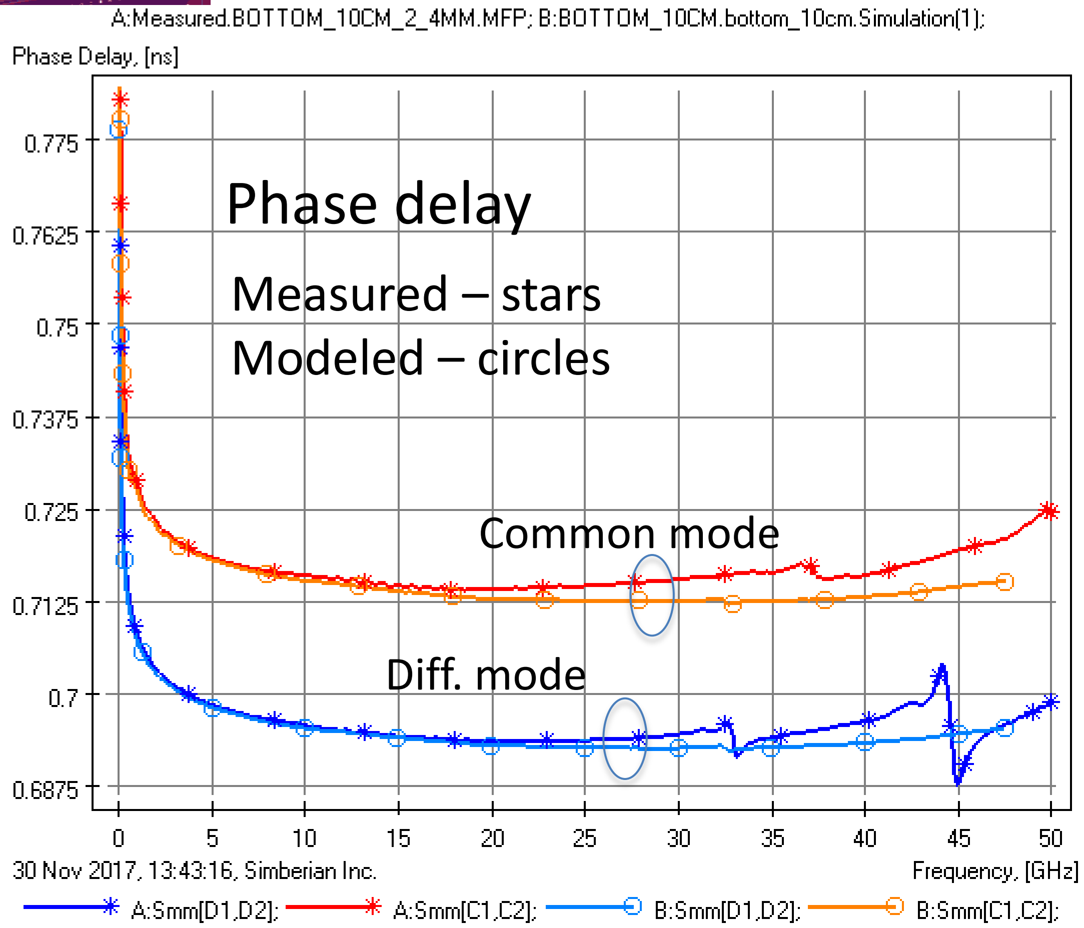


De-compositional EM analysis
Shape and size of all MSL sections are adjusted…

Reality: more reflections from 10 to 30 GHz (investigate)…

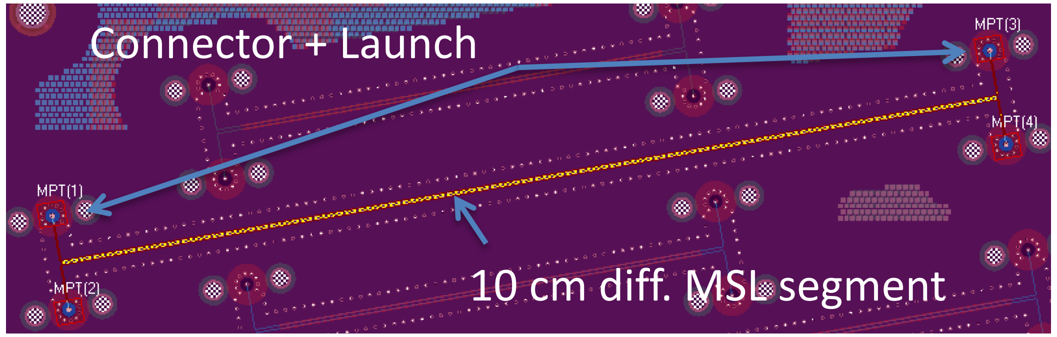
Acceptable correspondence up to 30 GHz





BOTTOM: 10 cm diff. microstrip link

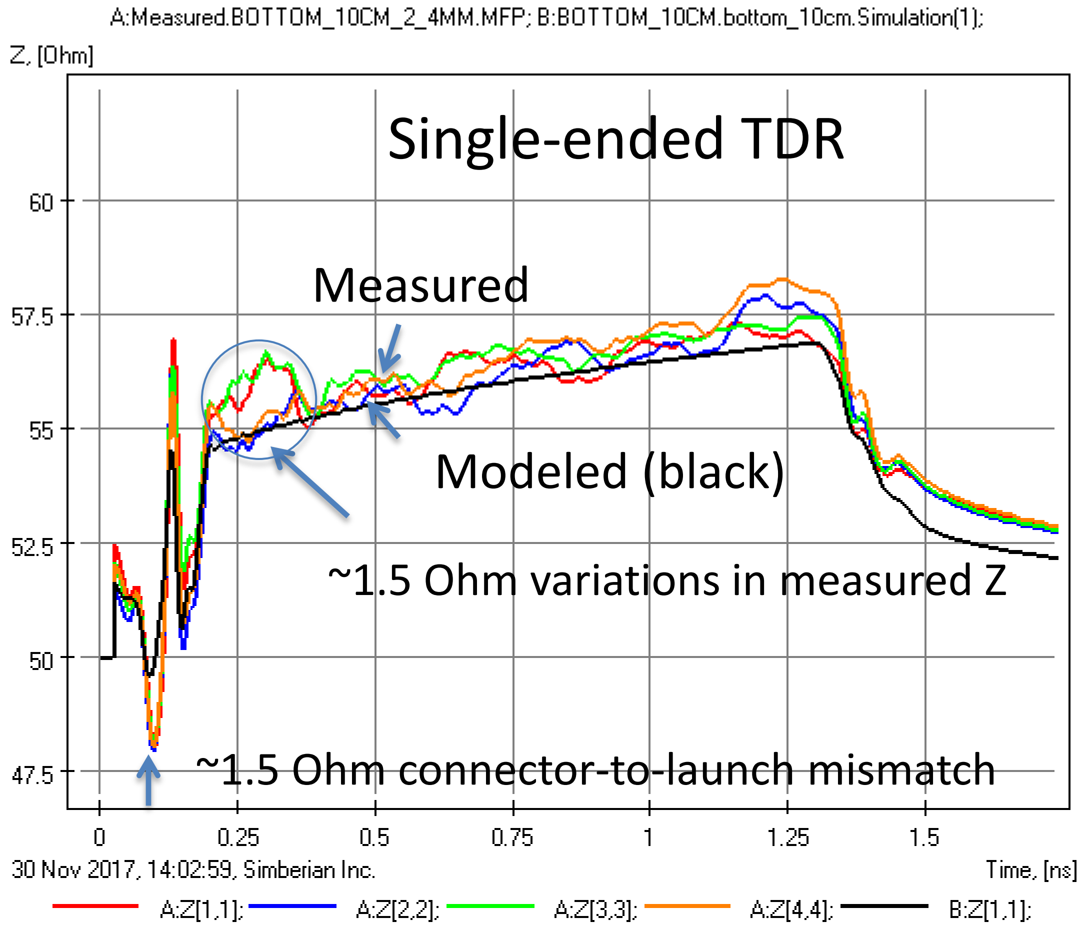
With solder mask under connector…

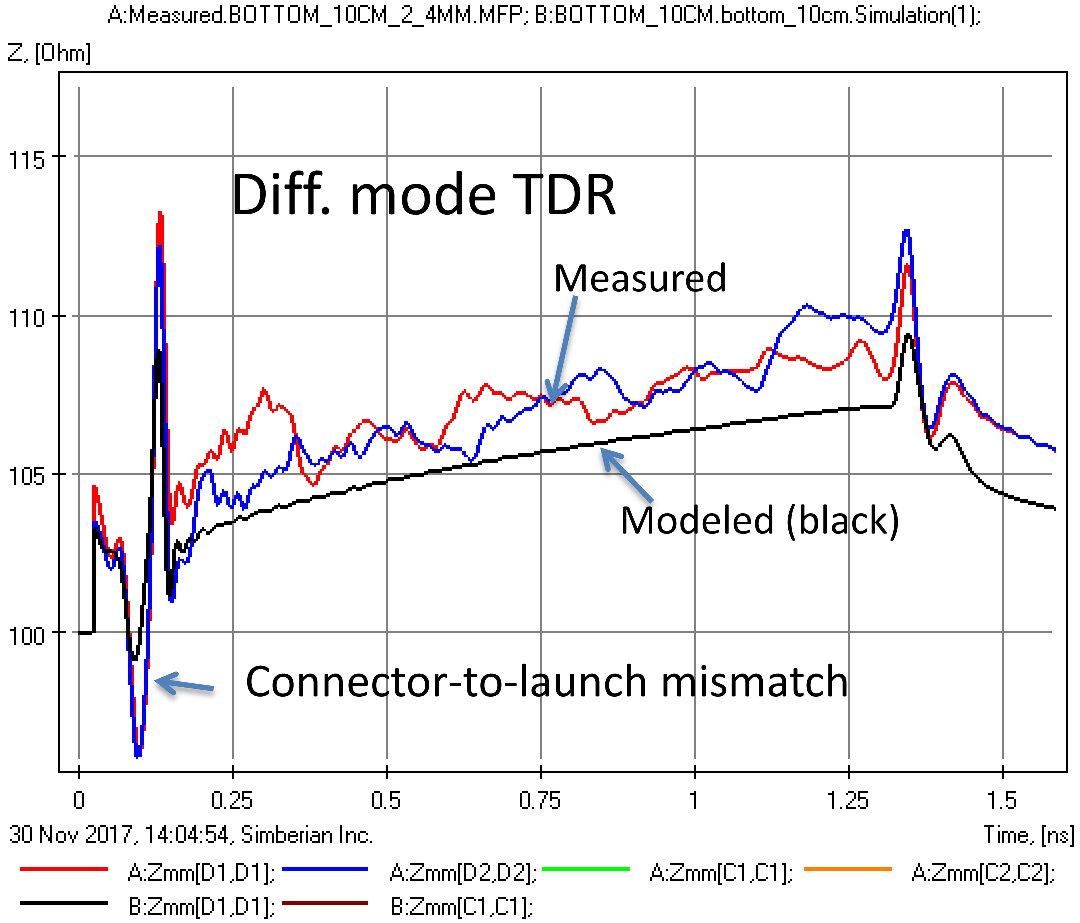


De-compositional EM analysis
Shape and size of all MSL sections are adjusted…

Reality: more reflection at the microstrip launch (investigate)…
Large variations of impedance along the traces (investigate)…

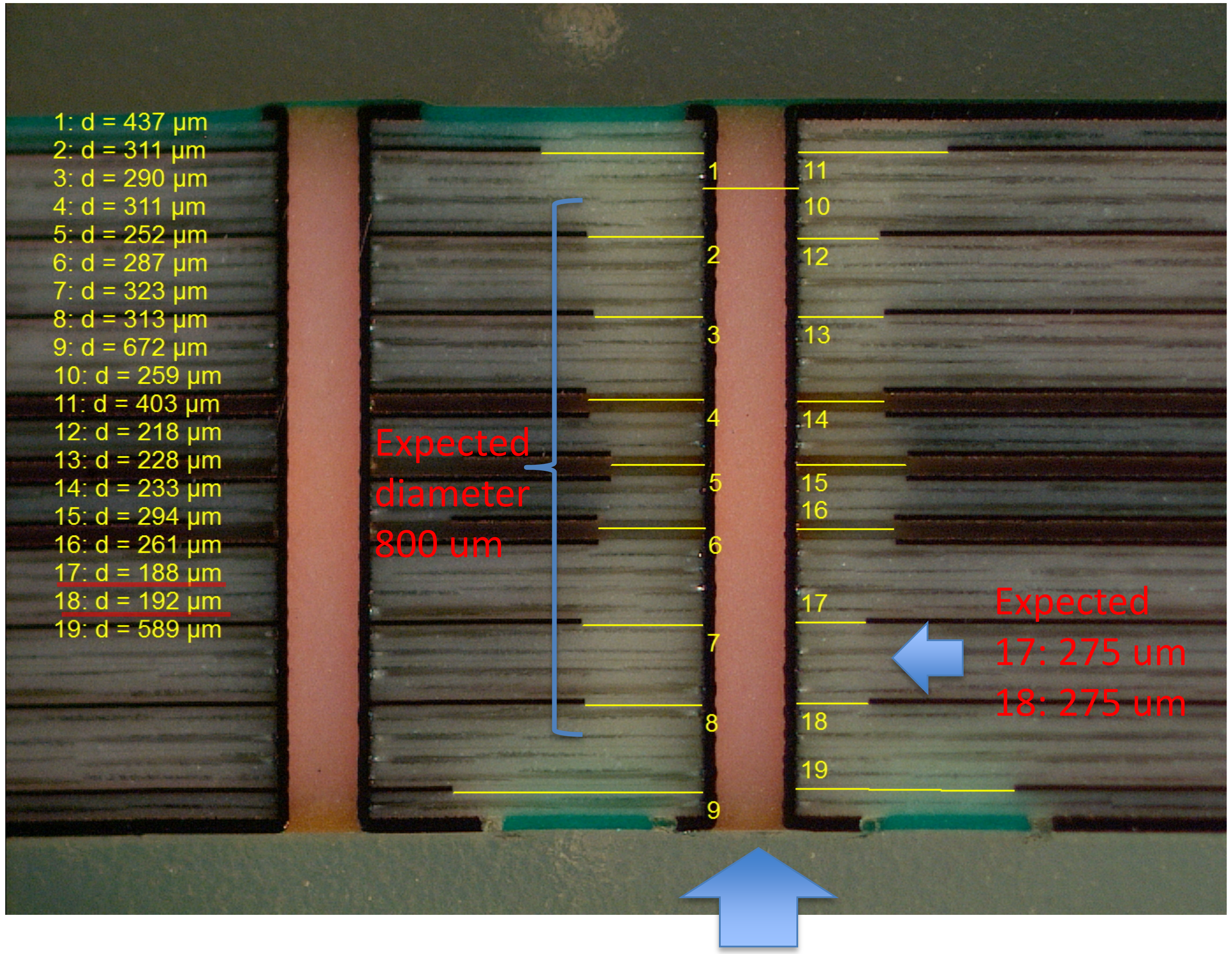
Acceptable correspondence;



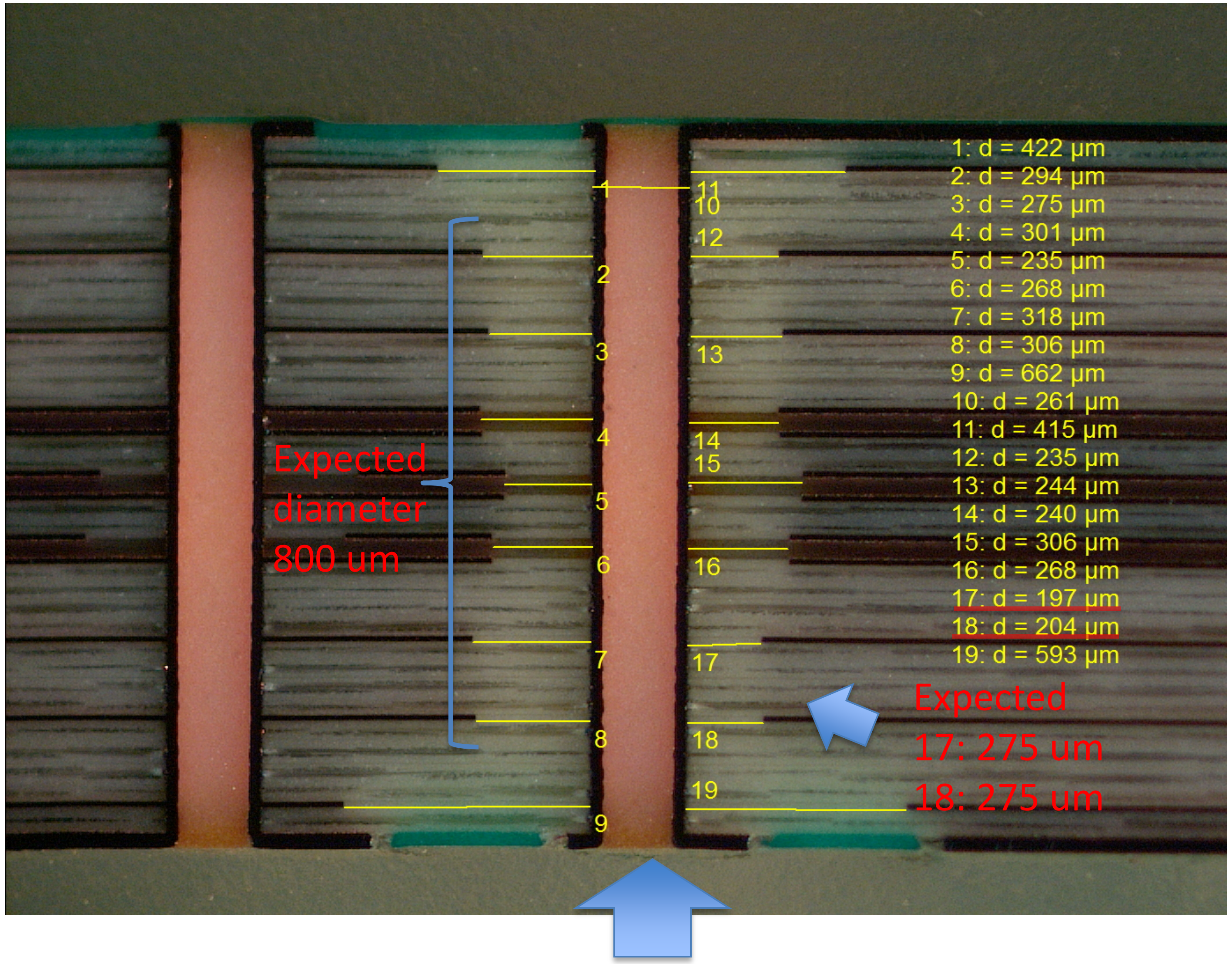


Launch mismatch

Smaller and offset antipads right below the connector, in addition to the solder mask



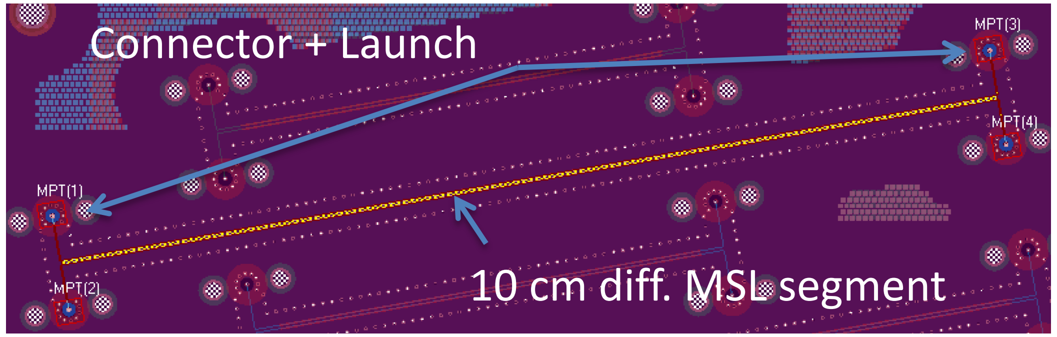
Connector side



Connector side

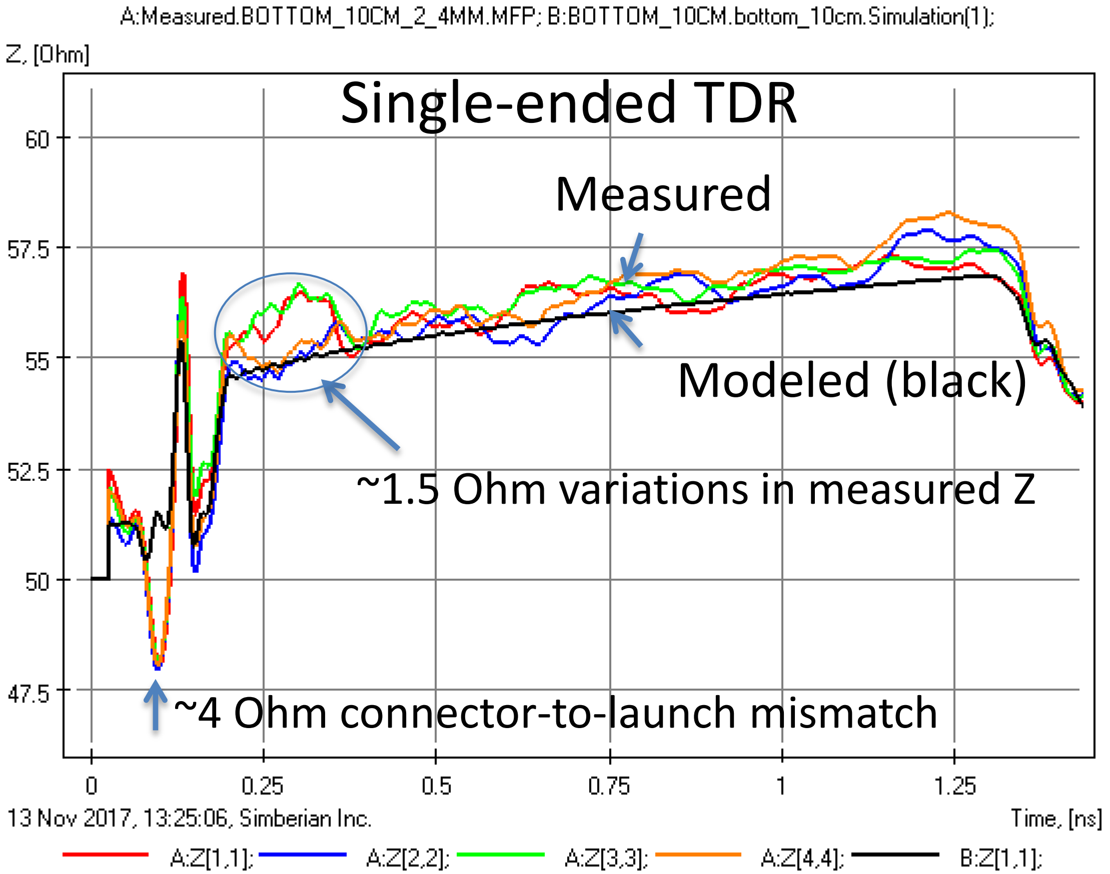
BOTTOM: 10 cm diff. microstrip link

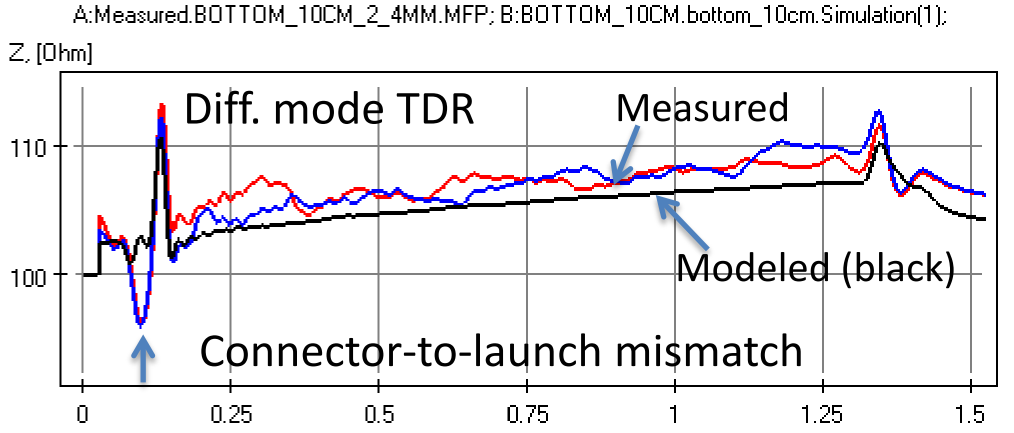
Without solder mask under connector…

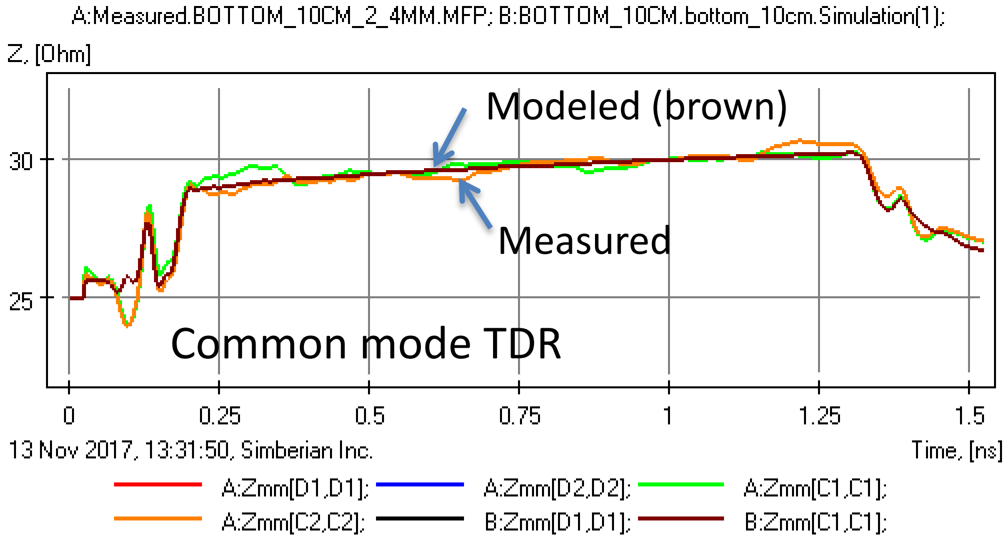


De-compositional EM analysis
Shape and size of all MSL sections are adjusted…

Reality: solder mask is under the connector…







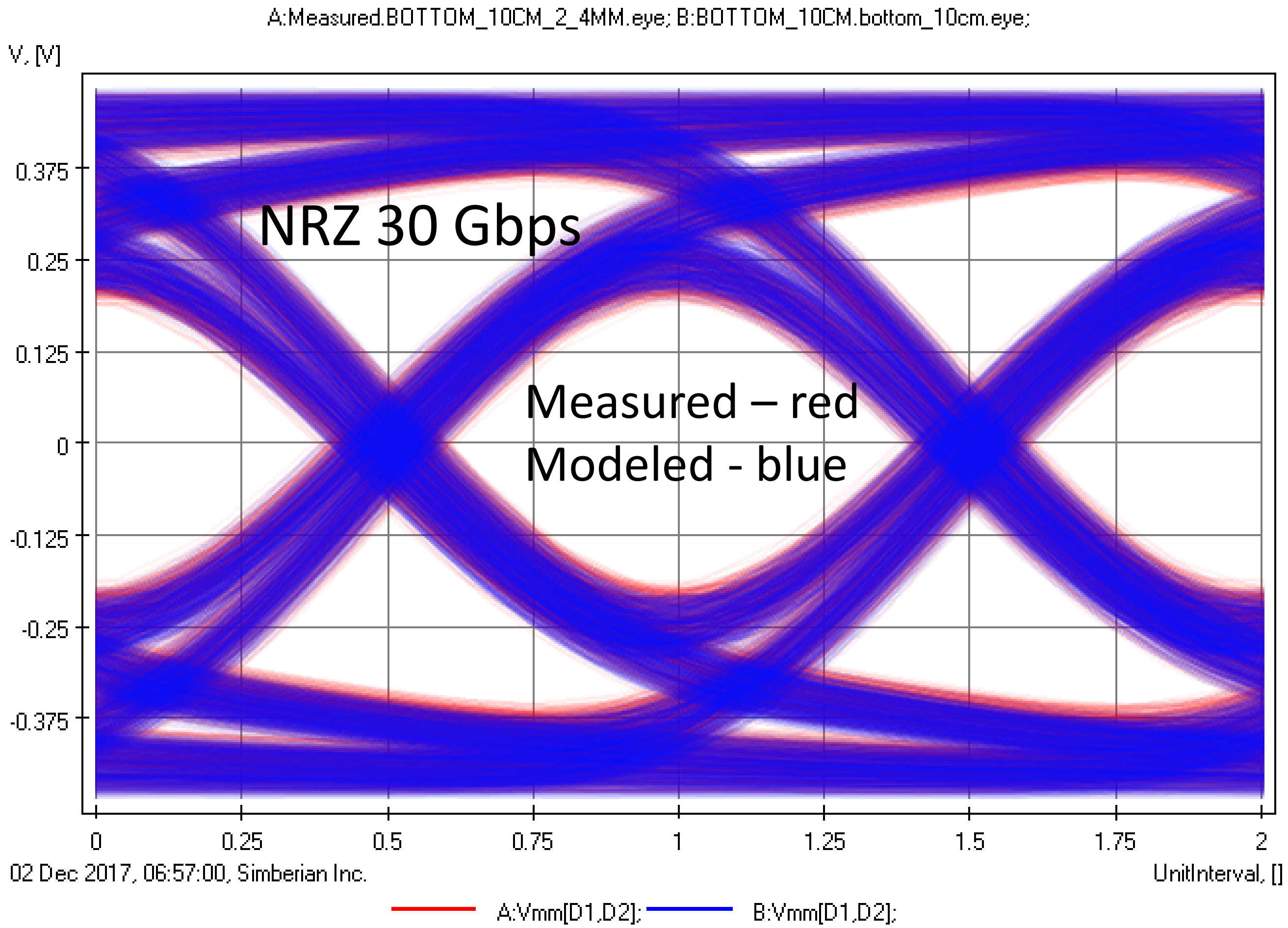
BOTTOM: 10 cm diff. microstrip link

- Eye diagrams comparison

Eye Analyzer

Show Eye Metrics: Selected ☑ Auto-open

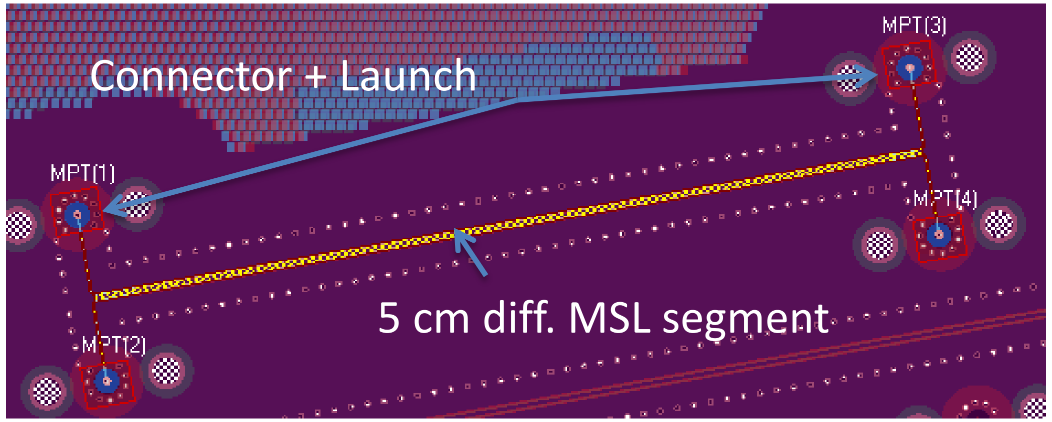
Parameter	Measured.BOTTO...	BOTTOM_10CM....
Eye Level Zero (V)	-0.334196	-0.343371
Eye Level One (V)	0.33443	0.339881
Eye Level Mean (V)	-0.000438433	1.49821e-005
Eye Amplitude (V)	0.668627	0.683252
Eye Height (V)	0.368693	0.38681
Eye Width (UI)	0.757871	0.769845
Eye Opening Factor	0.551418	0.56613
Eye Signal to Noise	4.19297	4.34656
Eye Rise Time (20-80) (UI)	0.565492	0.559771
Eye Fall Time (80-20) (UI)	0.565037	0.561818
Eye Jitter (PP) (UI)	0.242129	0.230155
Eye Jitter (RMS) (UI)	0.0494993	0.0478879



~6% difference in eye heights, close widths; Possible reason – large impedance variations, launch mismatch and localization loss…

BOTTOM: 5 cm diff. microstrip link

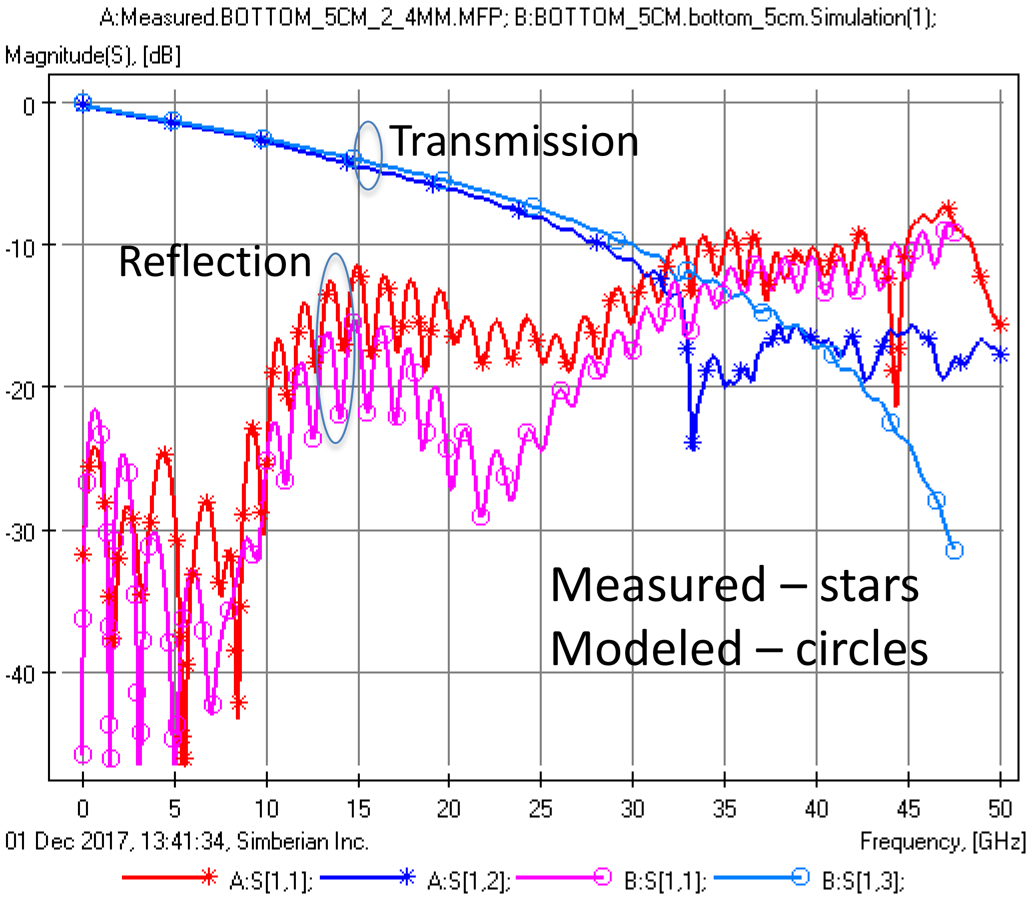
Single-ended S-parameters

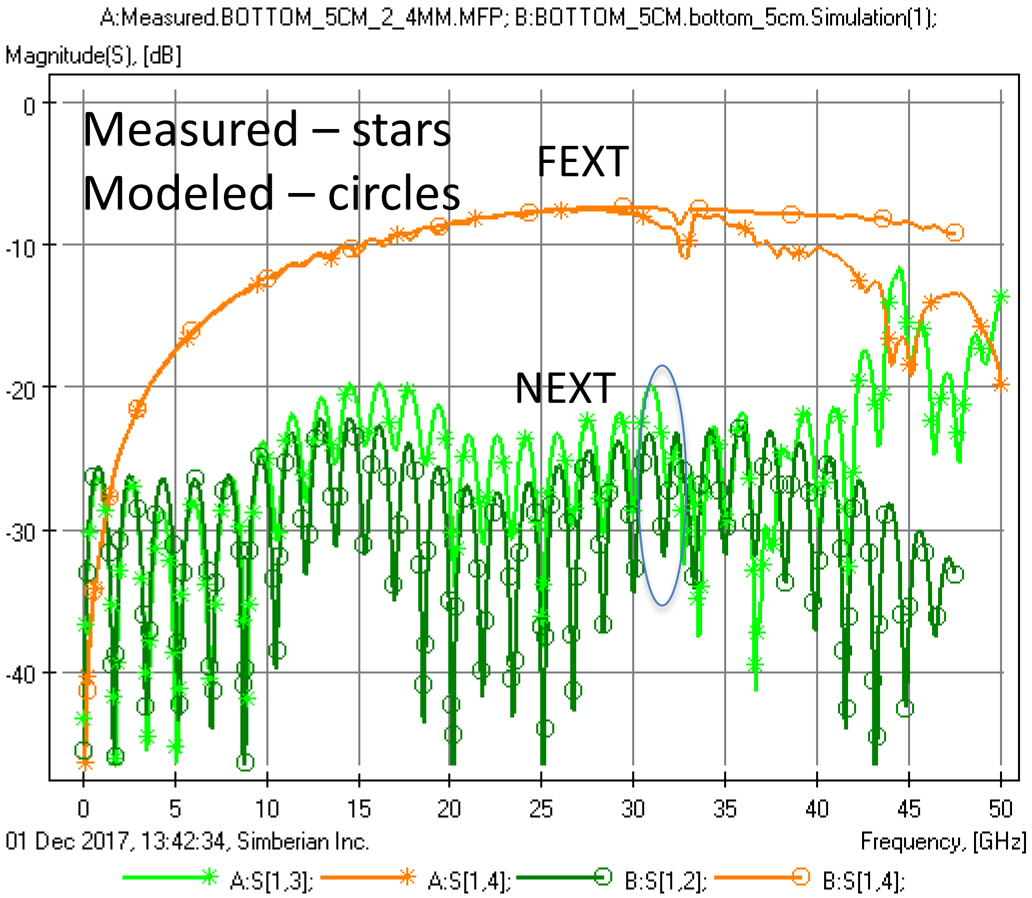


De-compositional EM analysis
Shape and size of all MSL sections are adjusted…

Reality: more reflections from 10 to 30 GHz (launch problem?)…

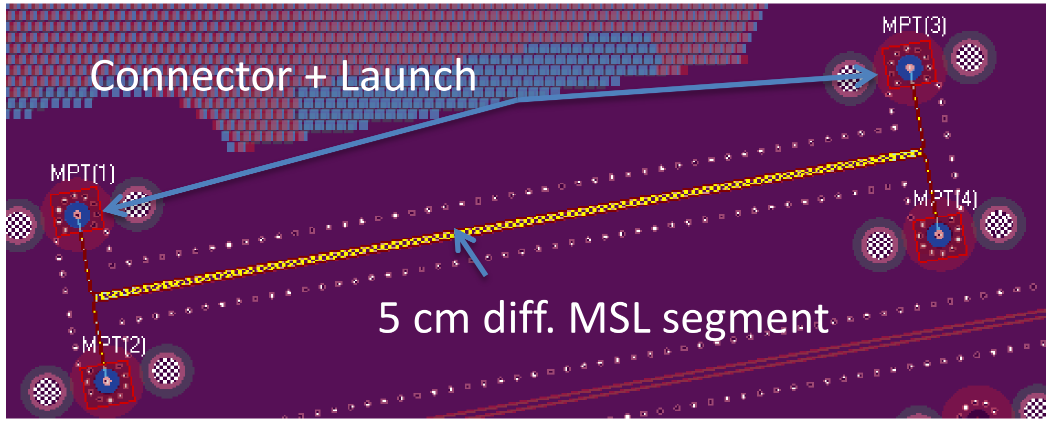
Acceptable correspondence up to 30 GHz





BOTTOM: 5 cm diff. microstrip link

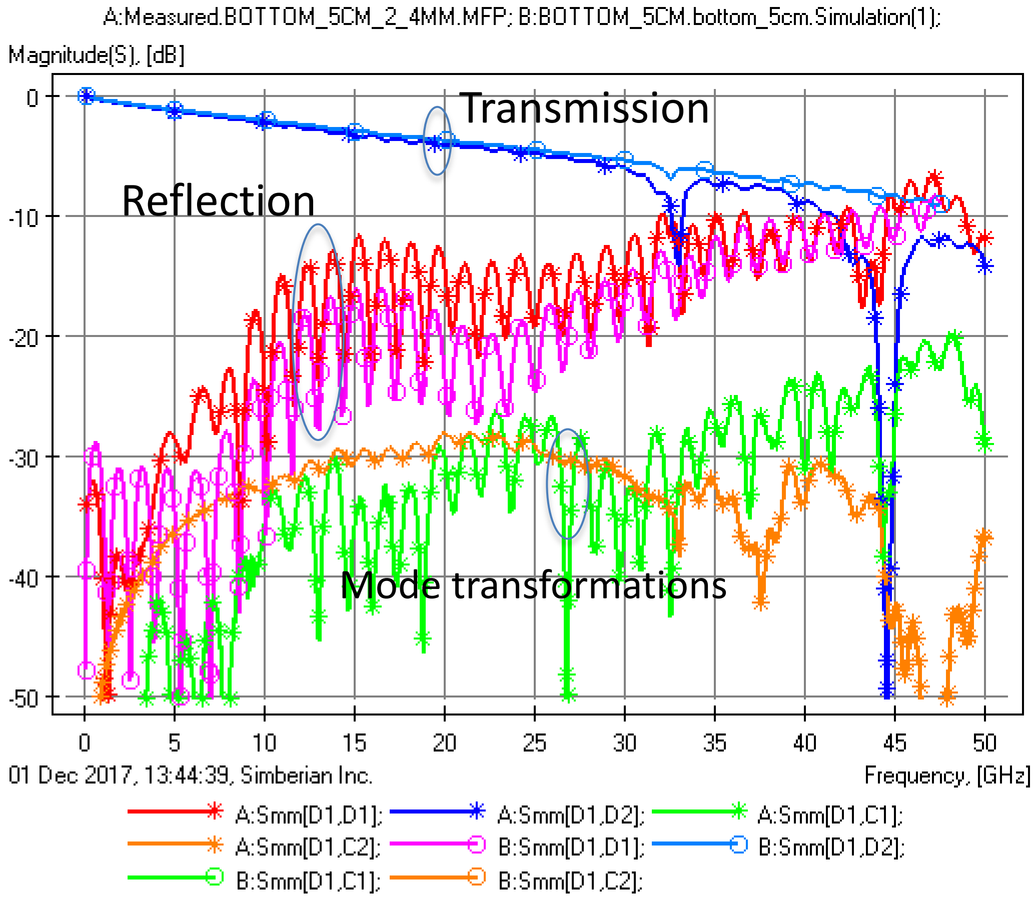
Mixed-mode S-parameters

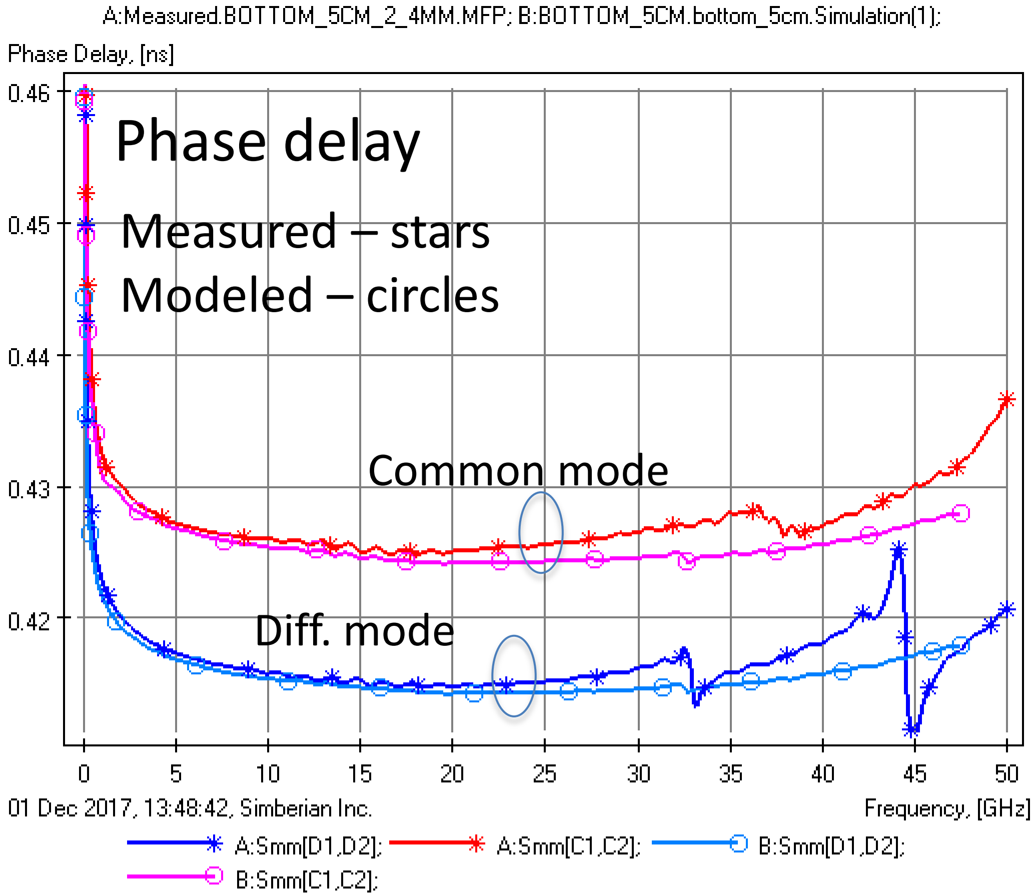


De-compositional EM analysis
Shape and size of all MSL sections are adjusted…

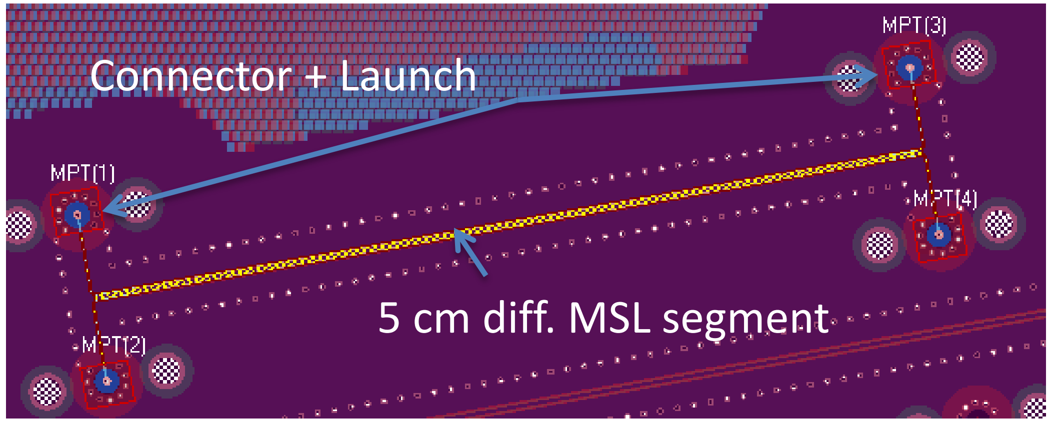
Reality: more reflection from 10 to 30 GHz (launch problem?)…

Acceptable correspondence up to 30 GHz





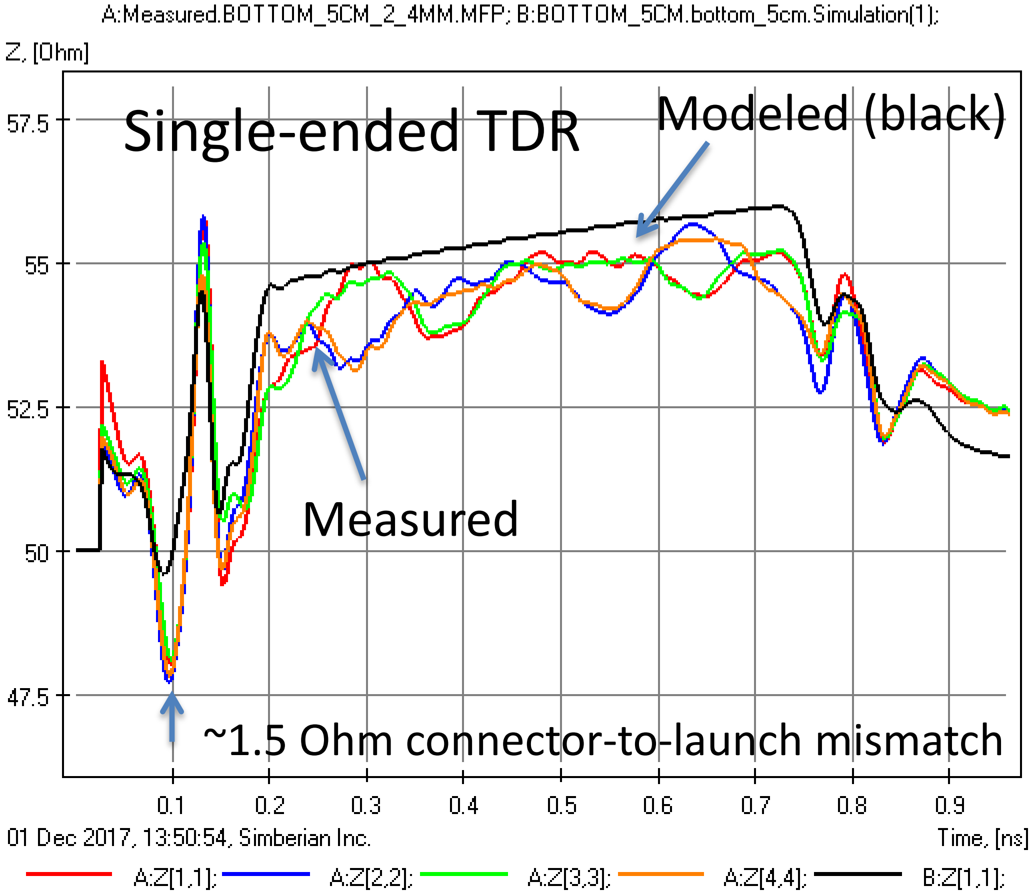
BOTTOM: 5 cm diff. microstrip link

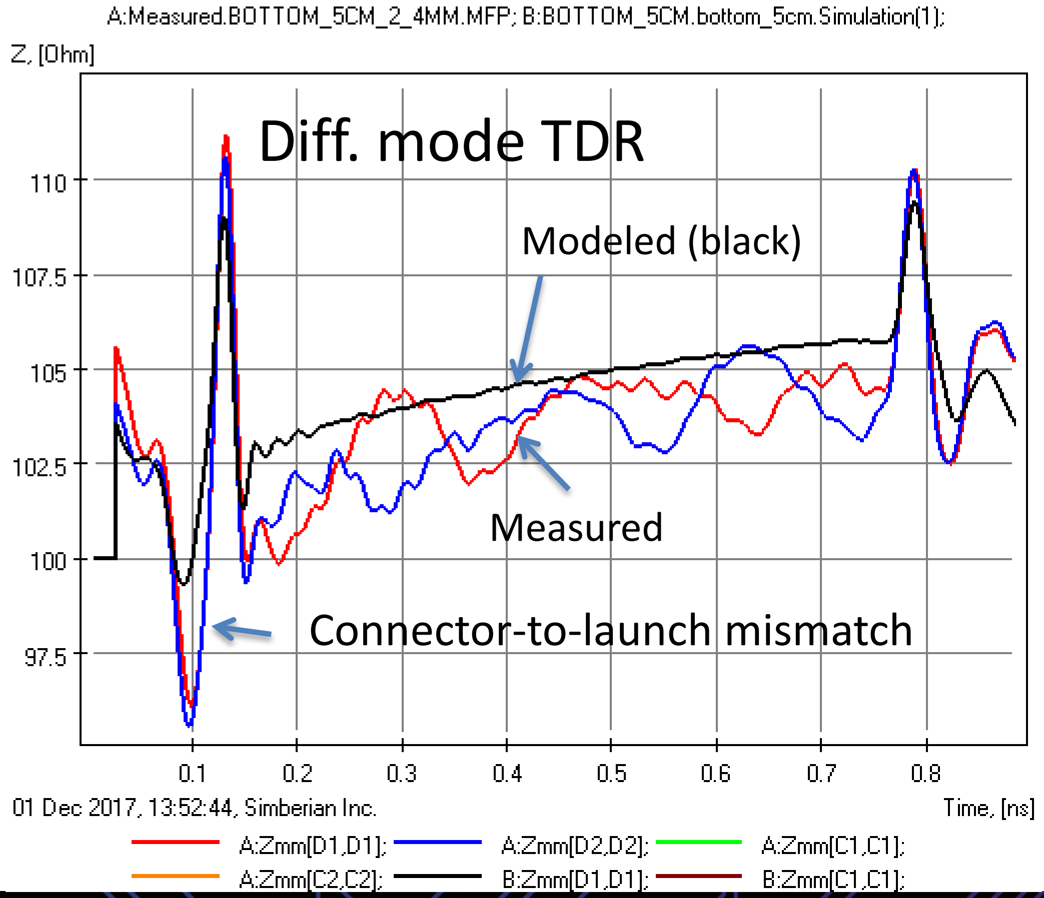


De-compositional EM analysis
Shape and size of all MSL sections are adjusted…

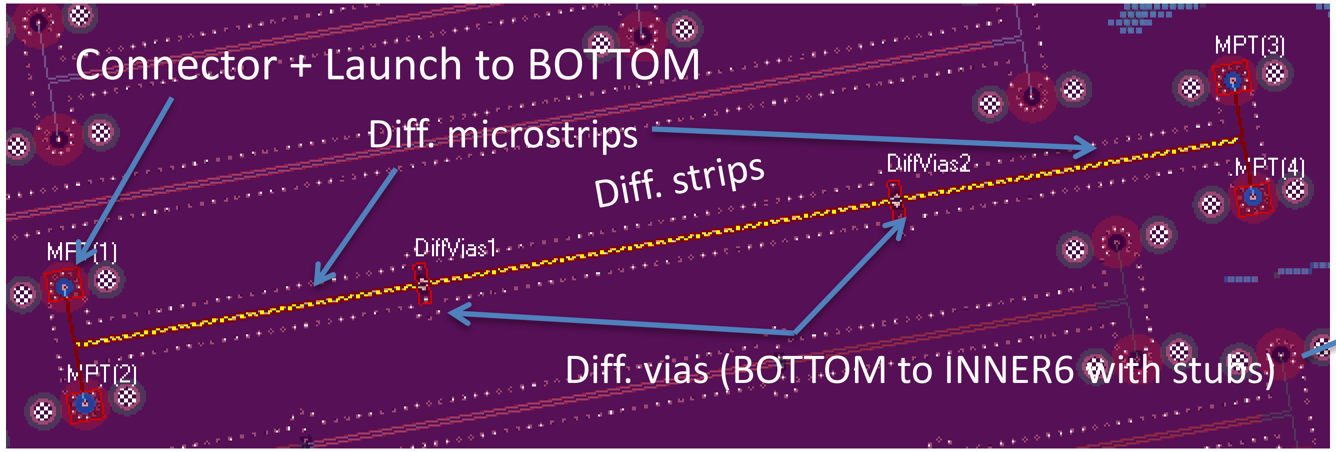
Reality: more reflection at the microstrip launch (offset)…
Large variations of impedance along the traces (investigate)…

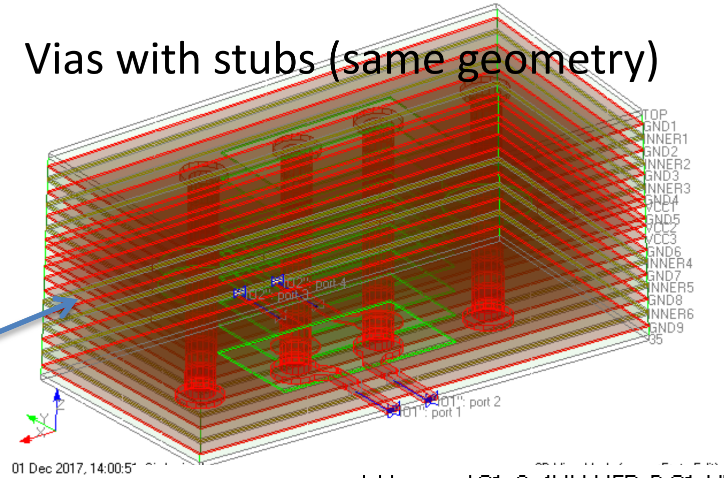
Acceptable correspondence;





C1: Diff. link with 2 vias from BOTTOM to INNTER6



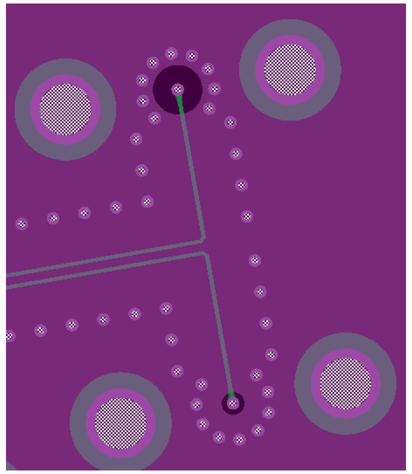


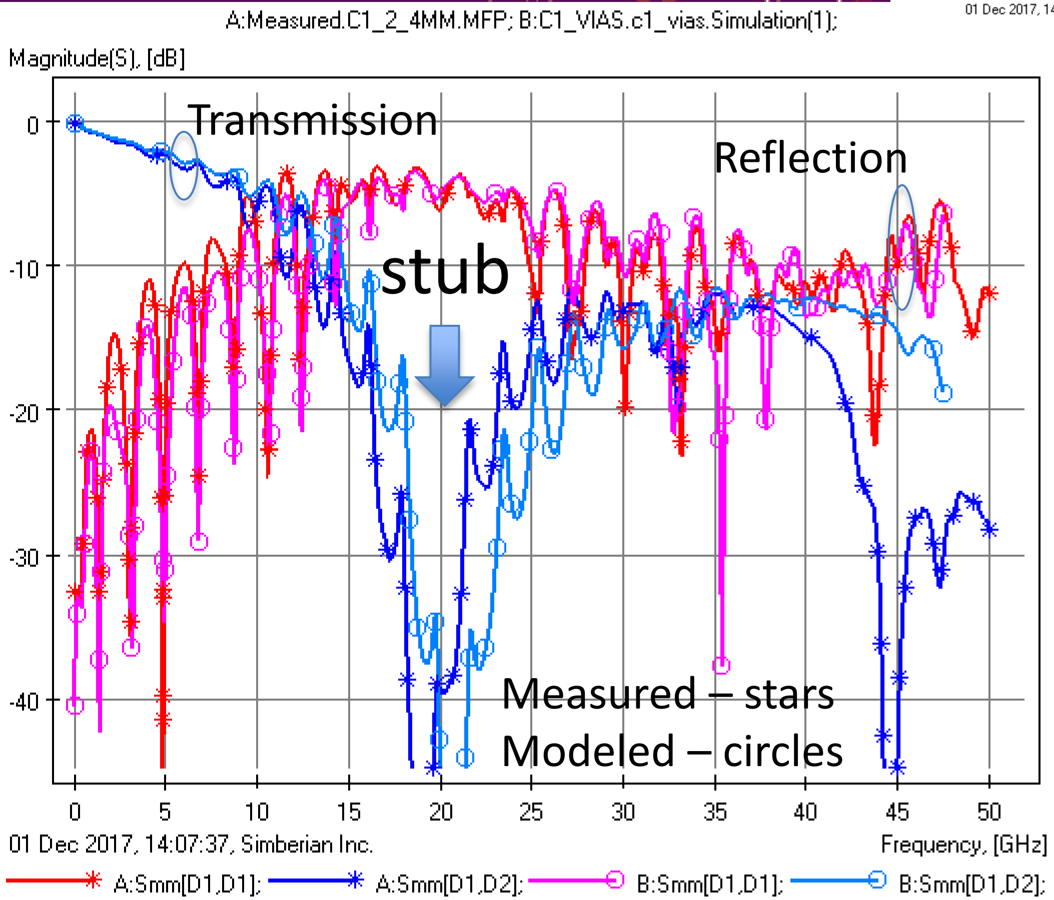
De-compositional EM analysis
Shape and size of all traces and backdrilling position are adjusted…

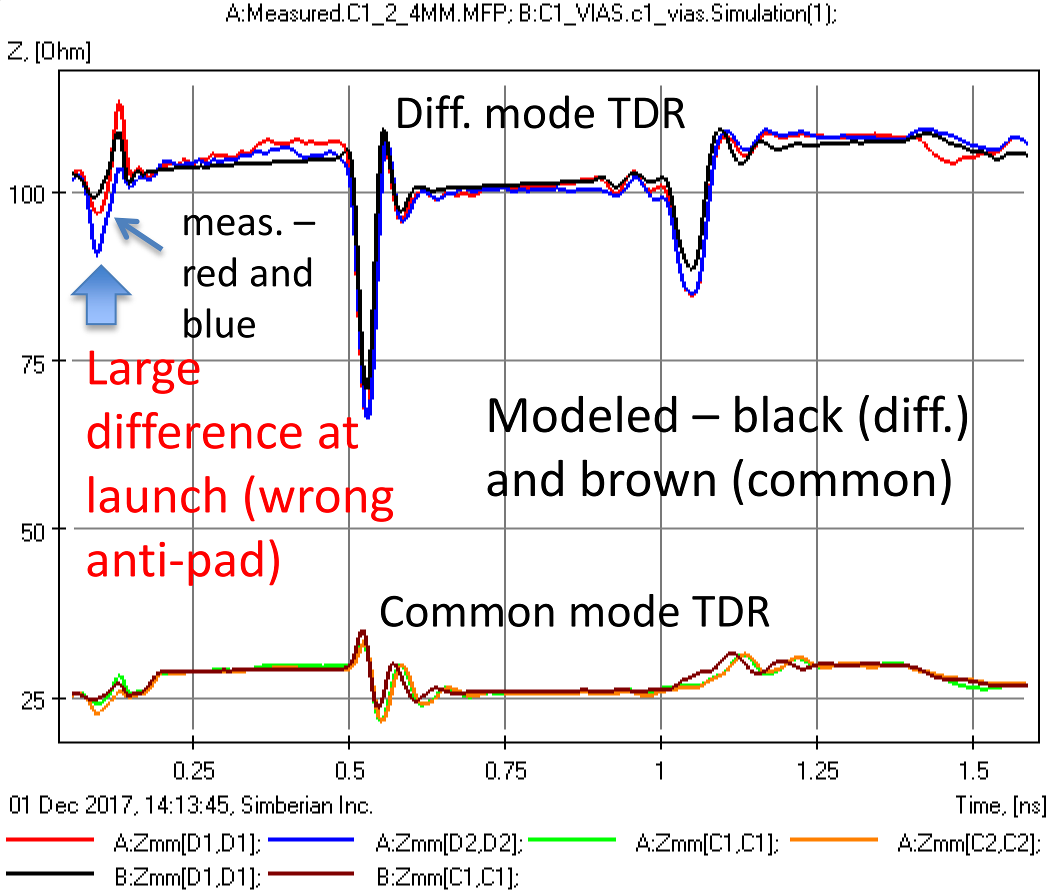
Vias simulated with “collapsed” metal option

Mixed-mode S-parameters & TDR

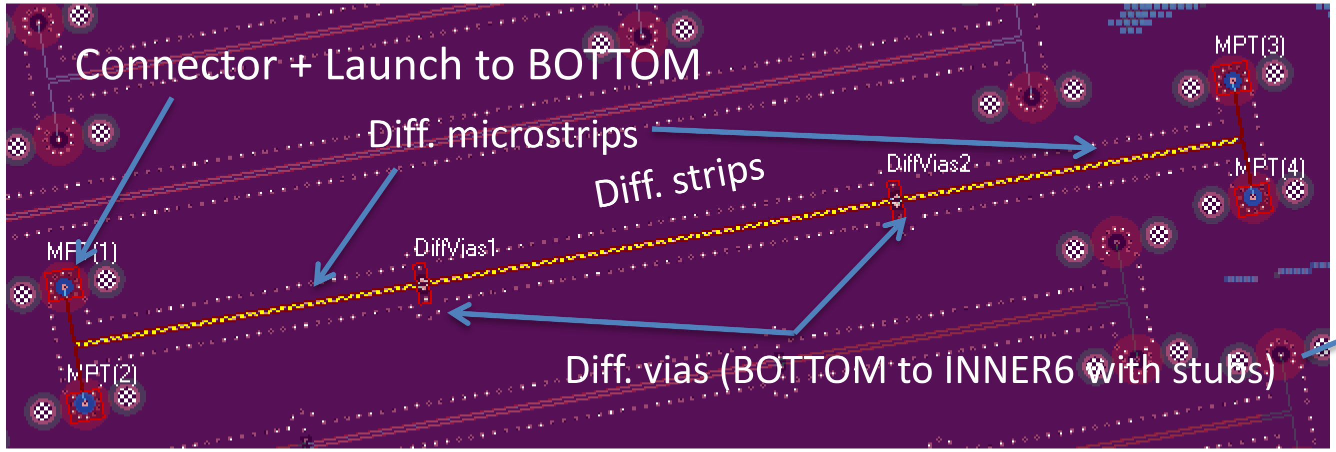
Reality: single-ended via response differences, launch differences (smaller anti-pad on port 4 – layout mistake)

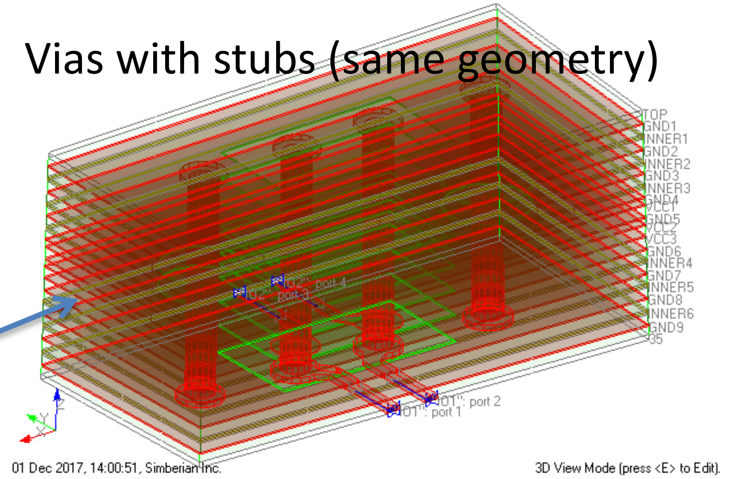






C1: Diff. link with 2 vias from BOTTOM to INNTER6



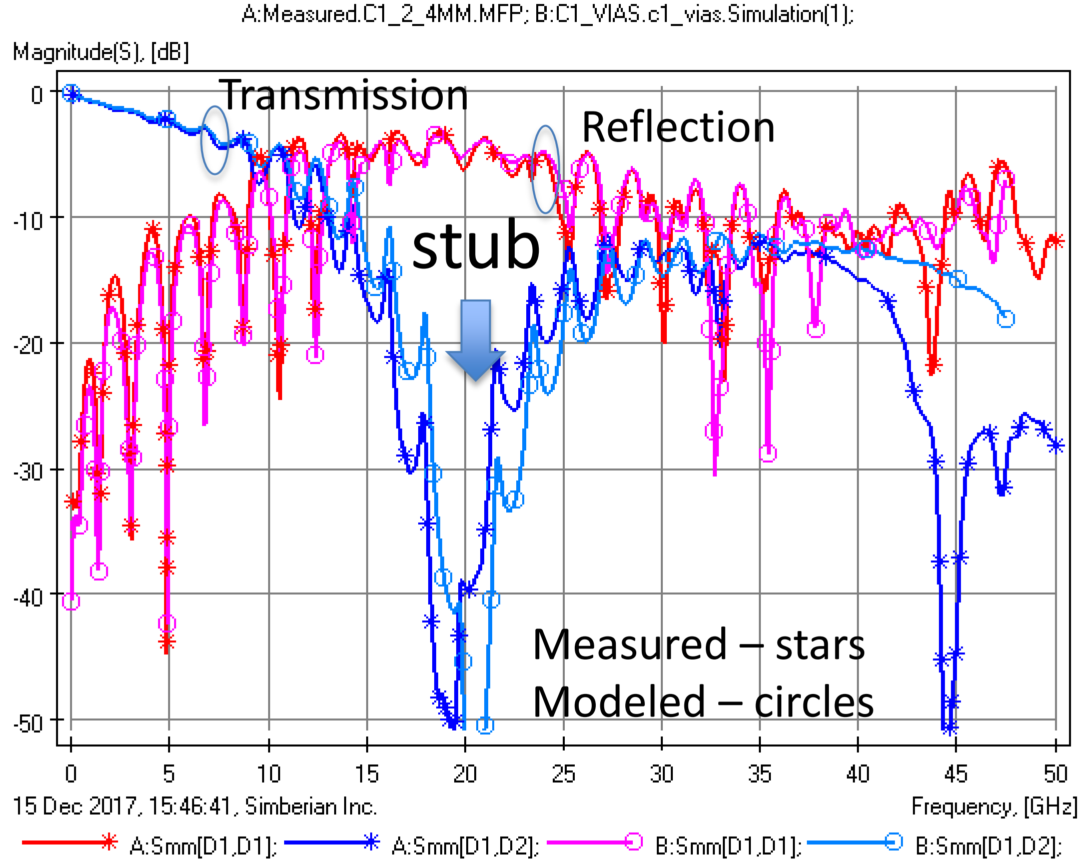


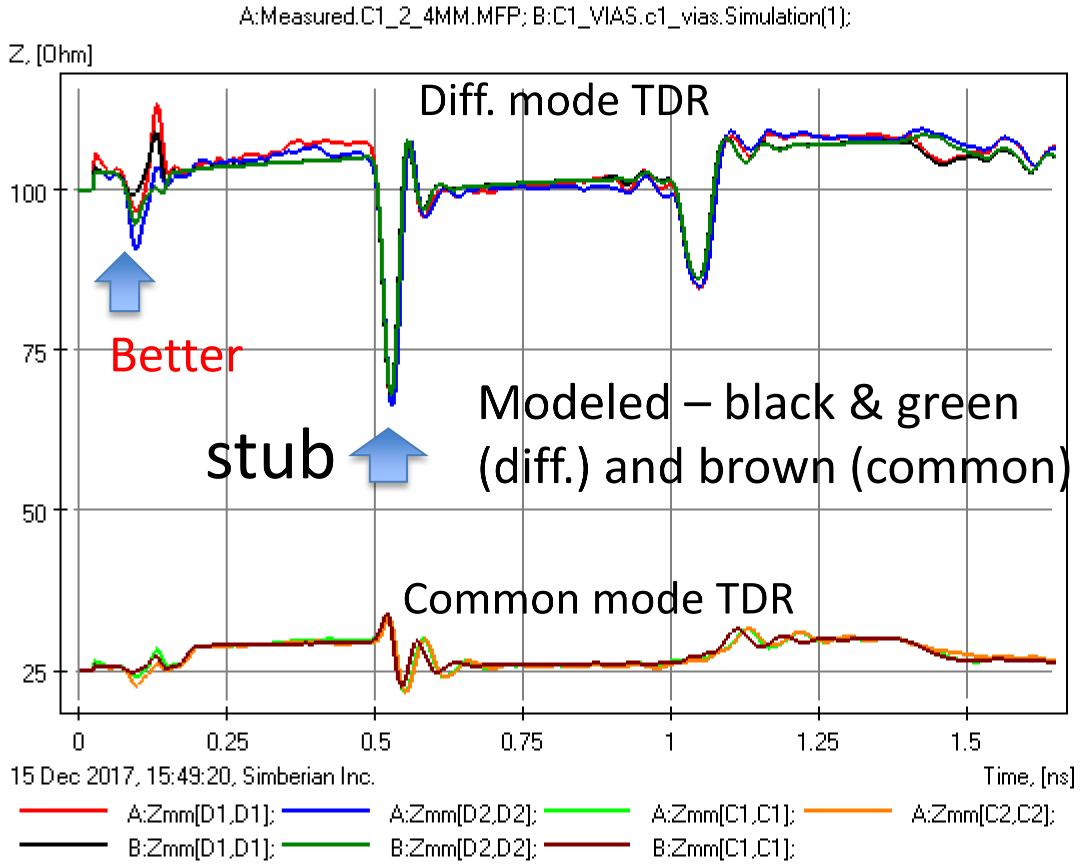
De-compositional EM analysis
Shape and size of all traces and backdrilling position are adjusted…

Vias simulated with "thick" metal option

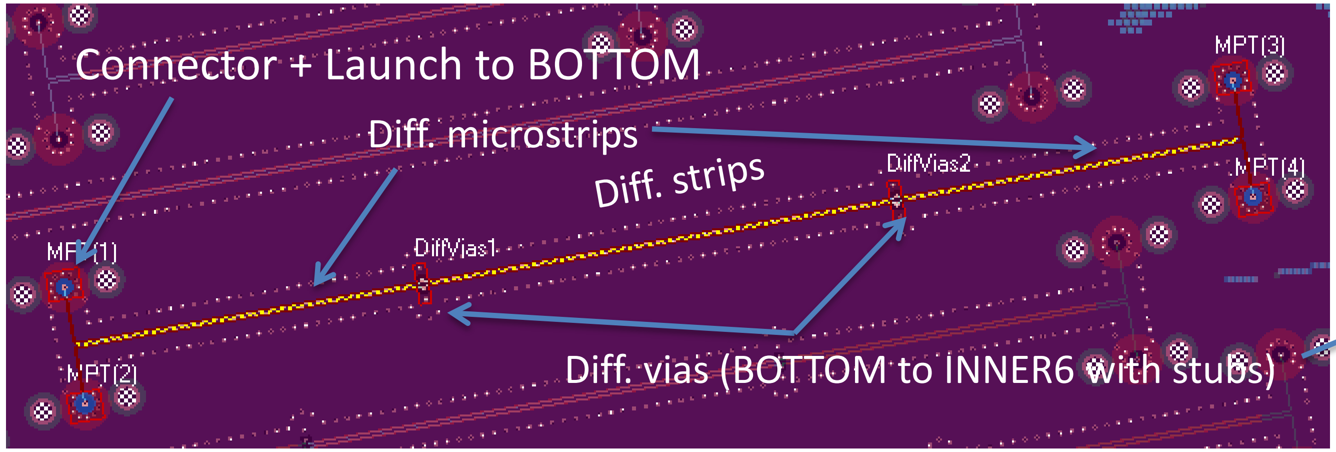
Mixed-mode S-parameters & TDR

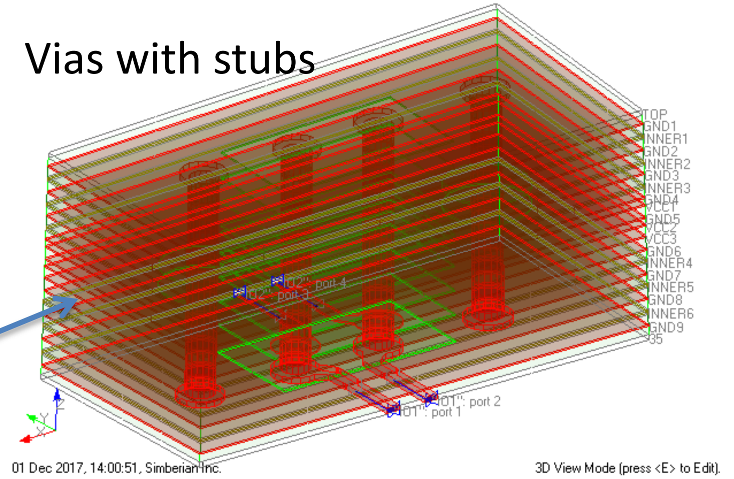
Reality: Better correlation after correction of geometry, large discrepancies in transmission around the stub resonance…





C1: Diff. link with 2 vias from BOTTOM to INNTER6



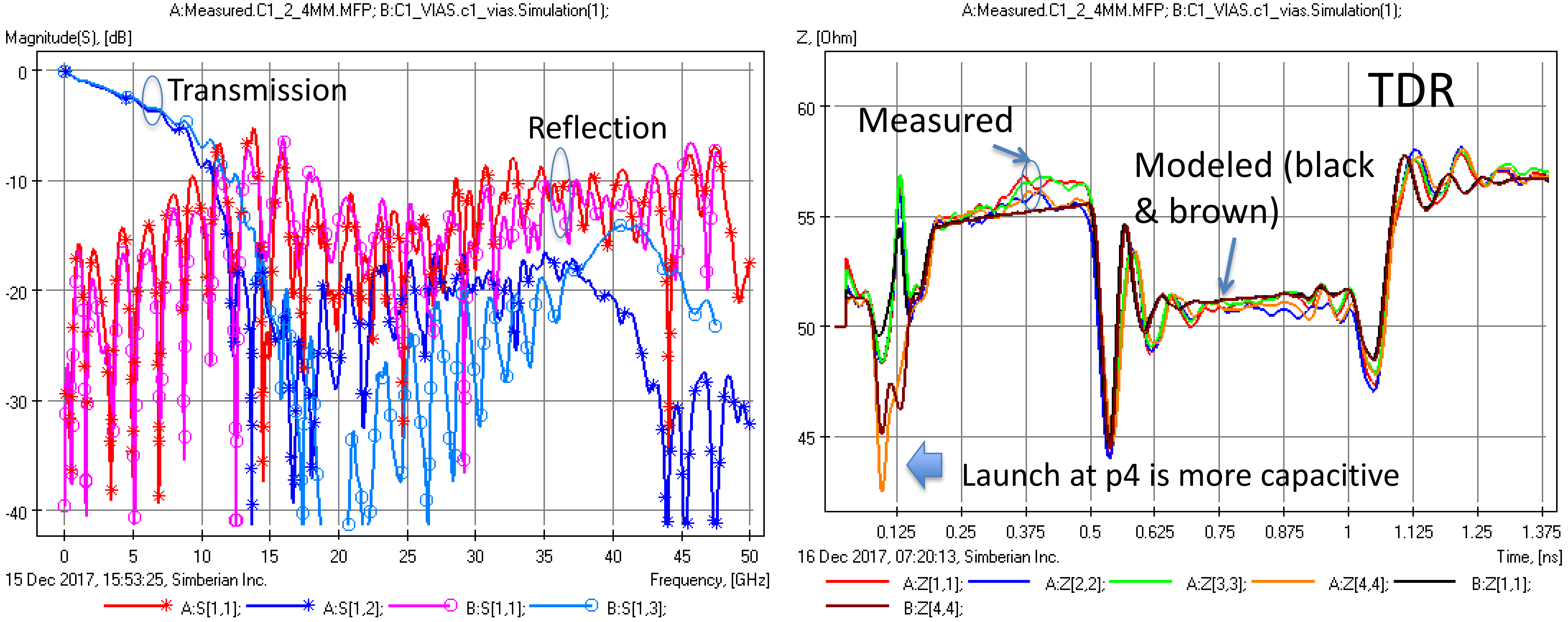


De-compositional EM analysis
Shape and size of all traces and backdrilling position are adjusted…

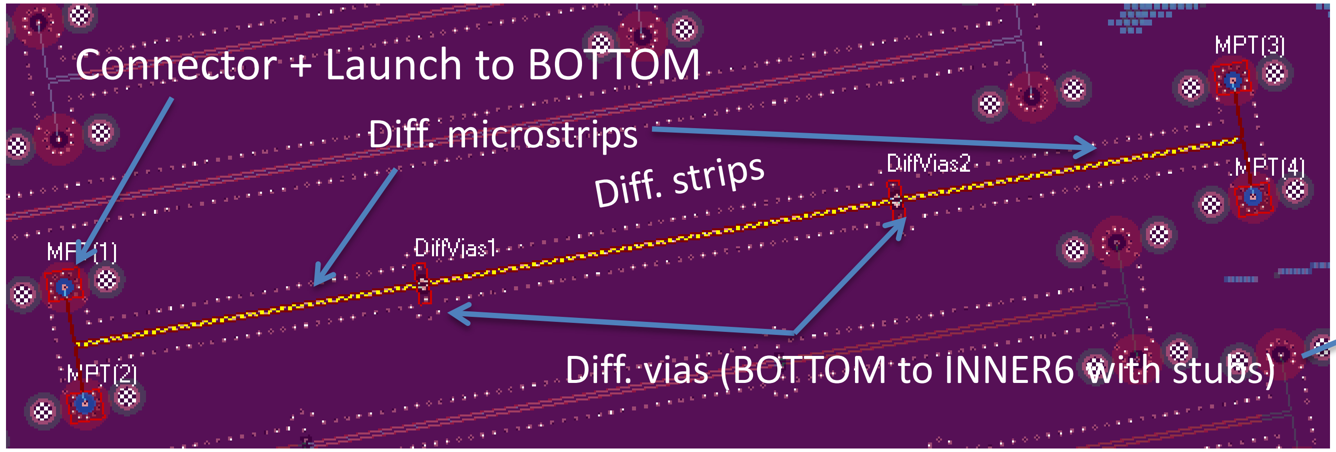
Single-ended S-parameters & TDR

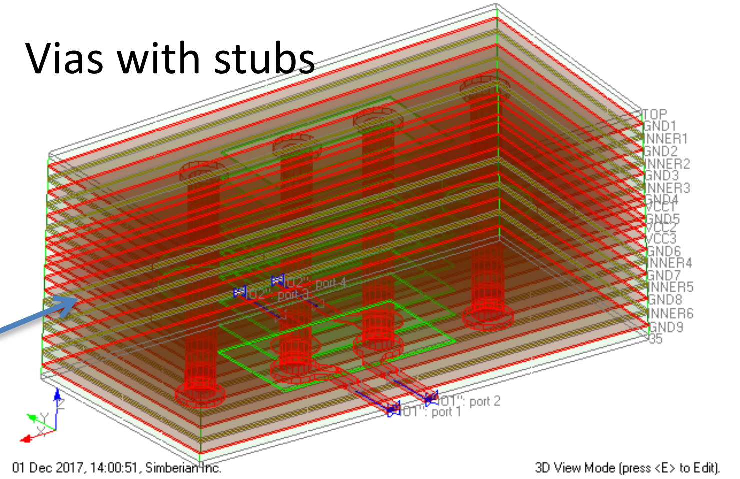
Reality: Differences in reflection and in transmission above 10-15 GHz (loss of localization or geometry?)

Acceptable correspondence only up to 10-15 GHz



C1: Diff. link with 2 vias from BOTTOM to INNTER6



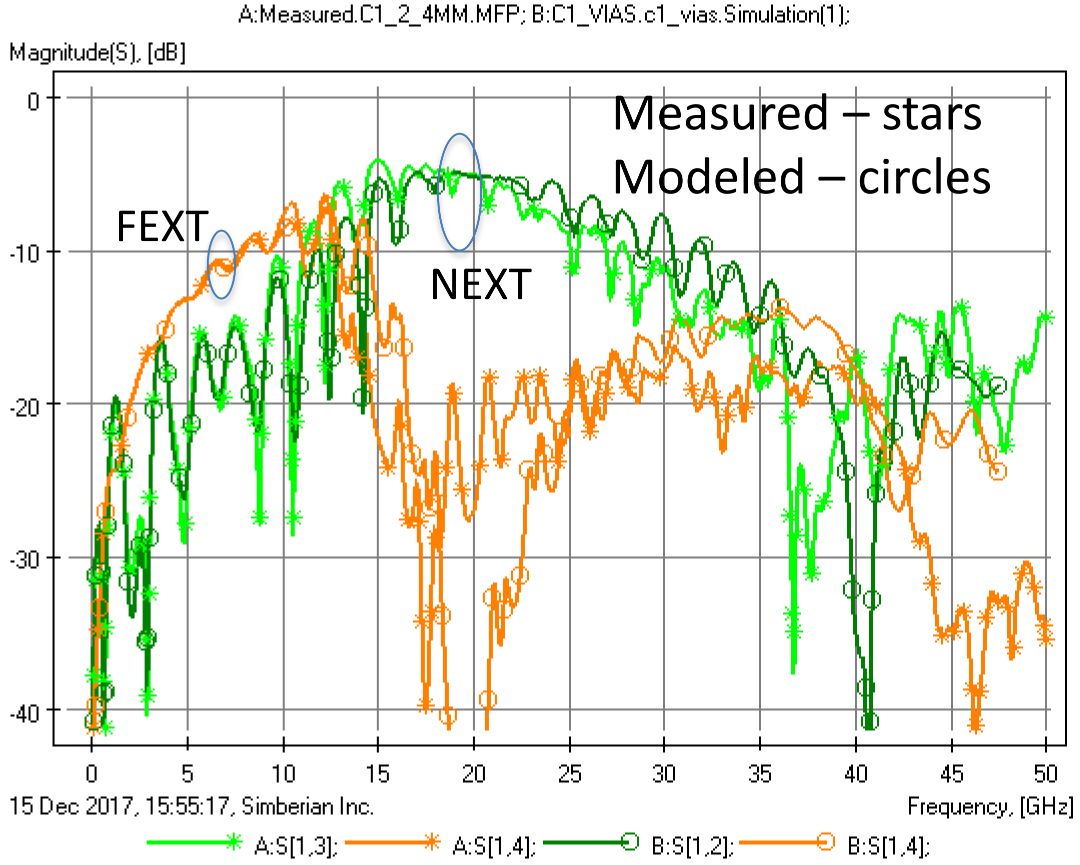


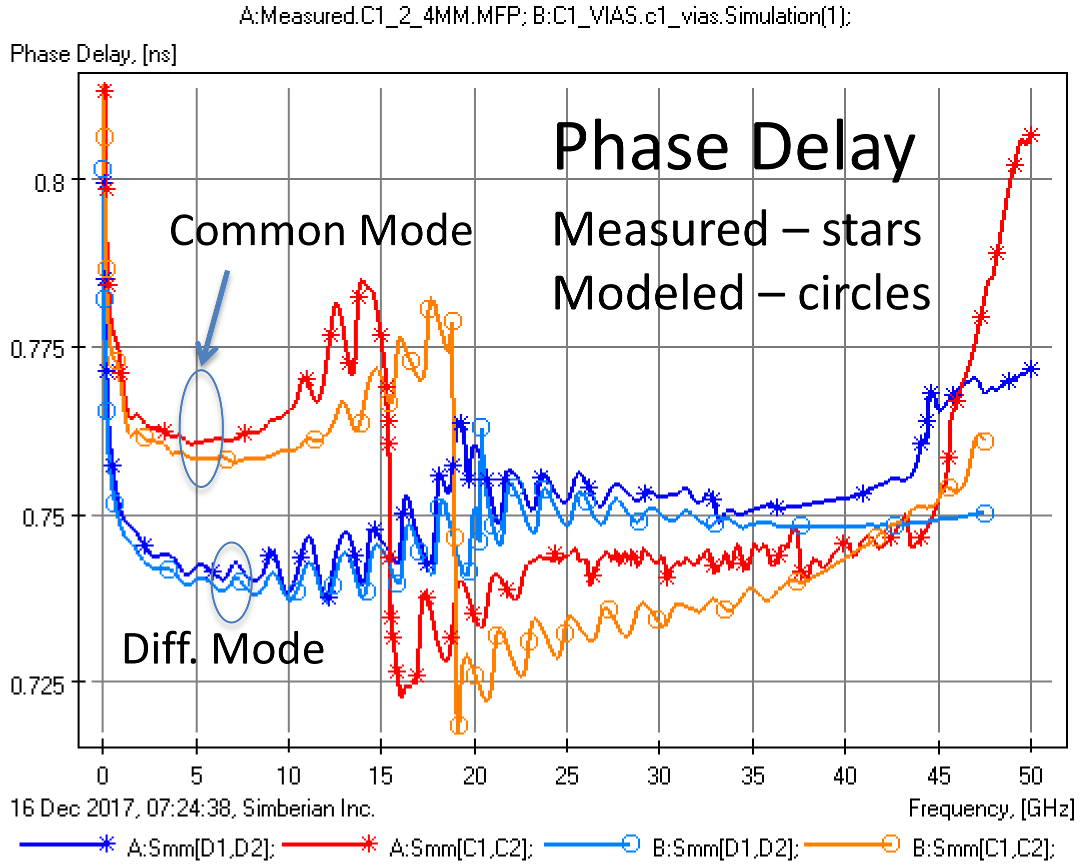
De-compositional EM analysis
Shape and size of all traces and backdrilling position are adjusted…

S-parameters

Reality: Stub resonance is at lower frequency

Acceptable correspondence only up to 10-15 GHz





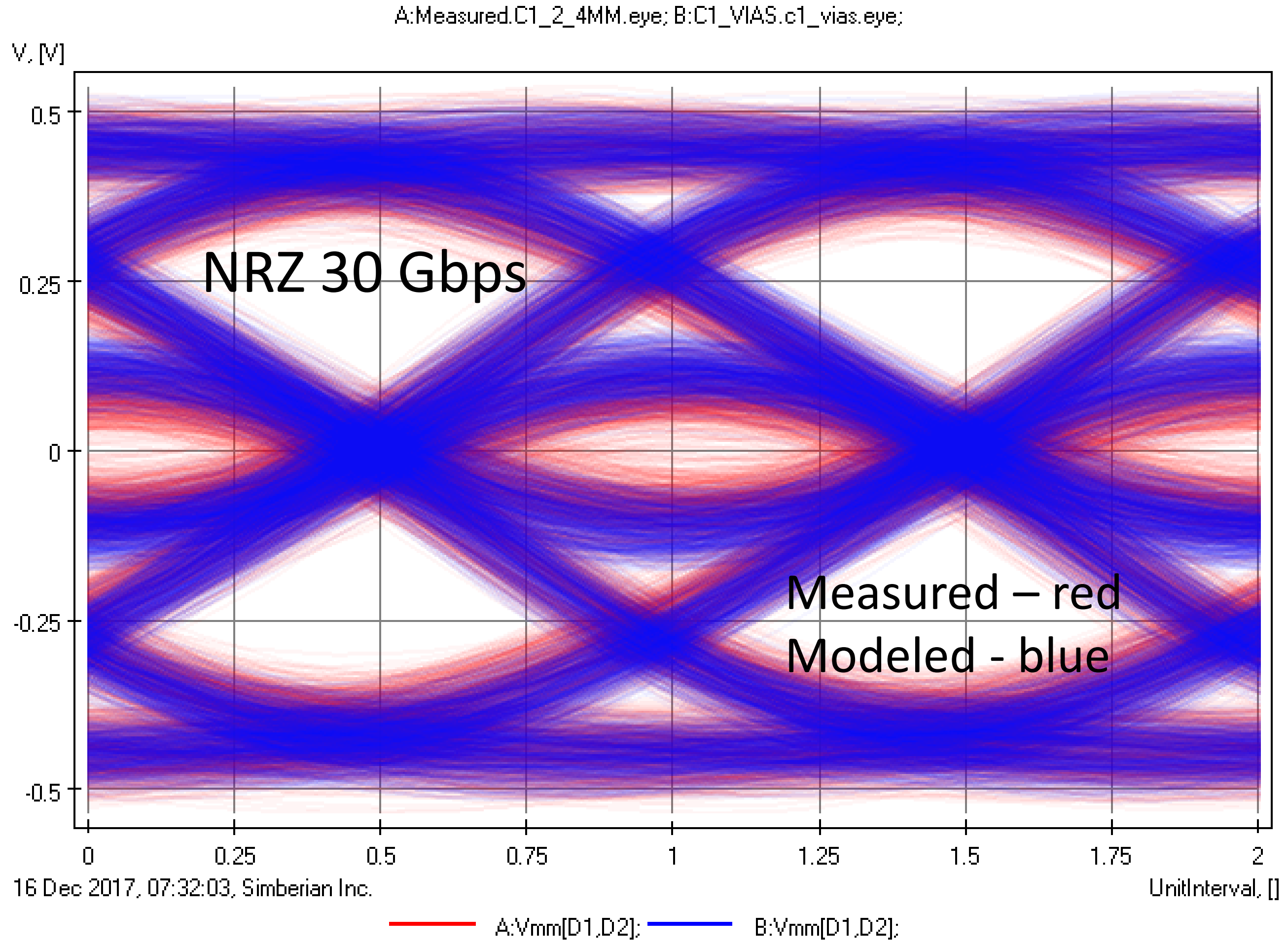
C1: Diff. link with 2 vias from BOTTOM to INNTER6

- Eye diagrams comparison

Eye Analyzer

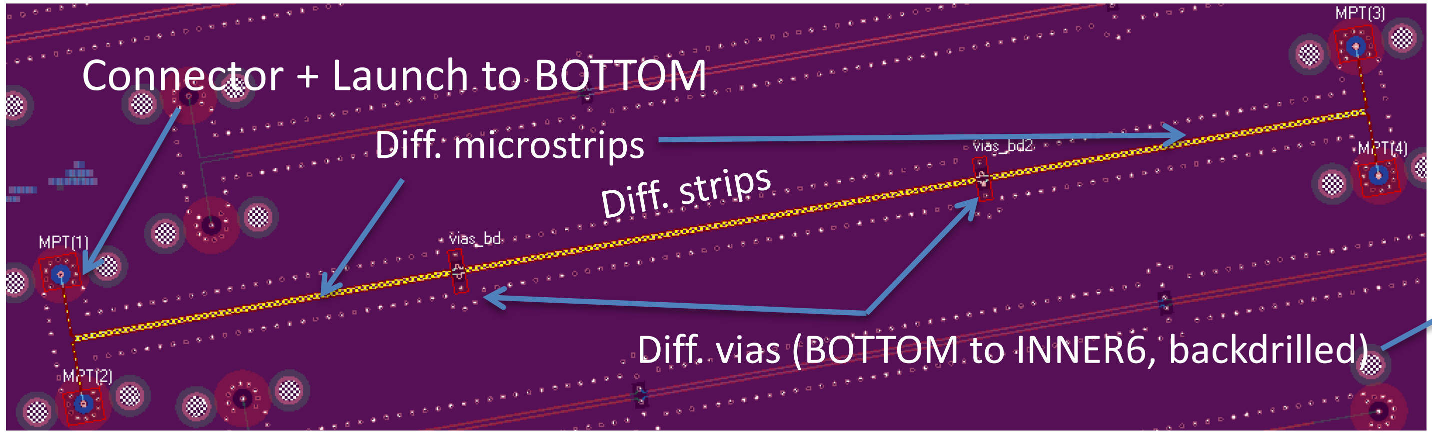
Show Eye Metrics: Selected ☑ Auto-open

Parameter	Measured.C1_2_4...	C1_VIAS.c1_vi...
Eye Level Zero (V)	-0.262759	-0.266934
Eye Level One (V)	0.26513	0.288451
Eye Level Mean (V)	0.00108081	0.00407434
Eye Amplitude (V)	0.527889	0.555385
Eye Height (V)	0.0167171	0.0913997
Eye Width (UI)	0.233259	0.455876
Eye Opening Factor	0.0316679	0.16457
Eye Signal to Noise	1.96447	2.24884
Eye Rise Time (20-80) (UI)	0.565194	0.567113
Eye Fall Time (80-20) (UI)	0.567233	0.574103
Eye Jitter (PP) (UI)	0.766741	0.544124
Eye Jitter (RMS) (UI)	0.131581	0.0810516

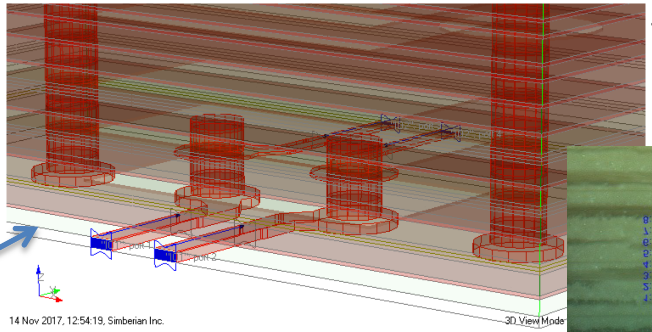


Large difference in eye width and height Reality: much larger ISI due to differences in stub behavior and launch with small anti-pads (sensitive to manufacturing variations)…

C2: Diff. link with 2 vias from BOTTOM to INNTER6

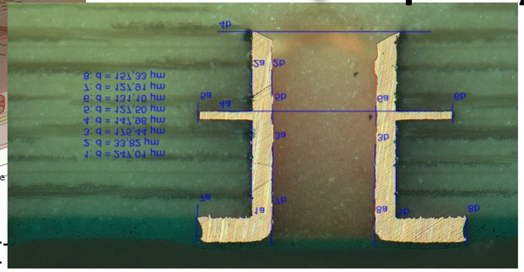


Backdrilled vias model

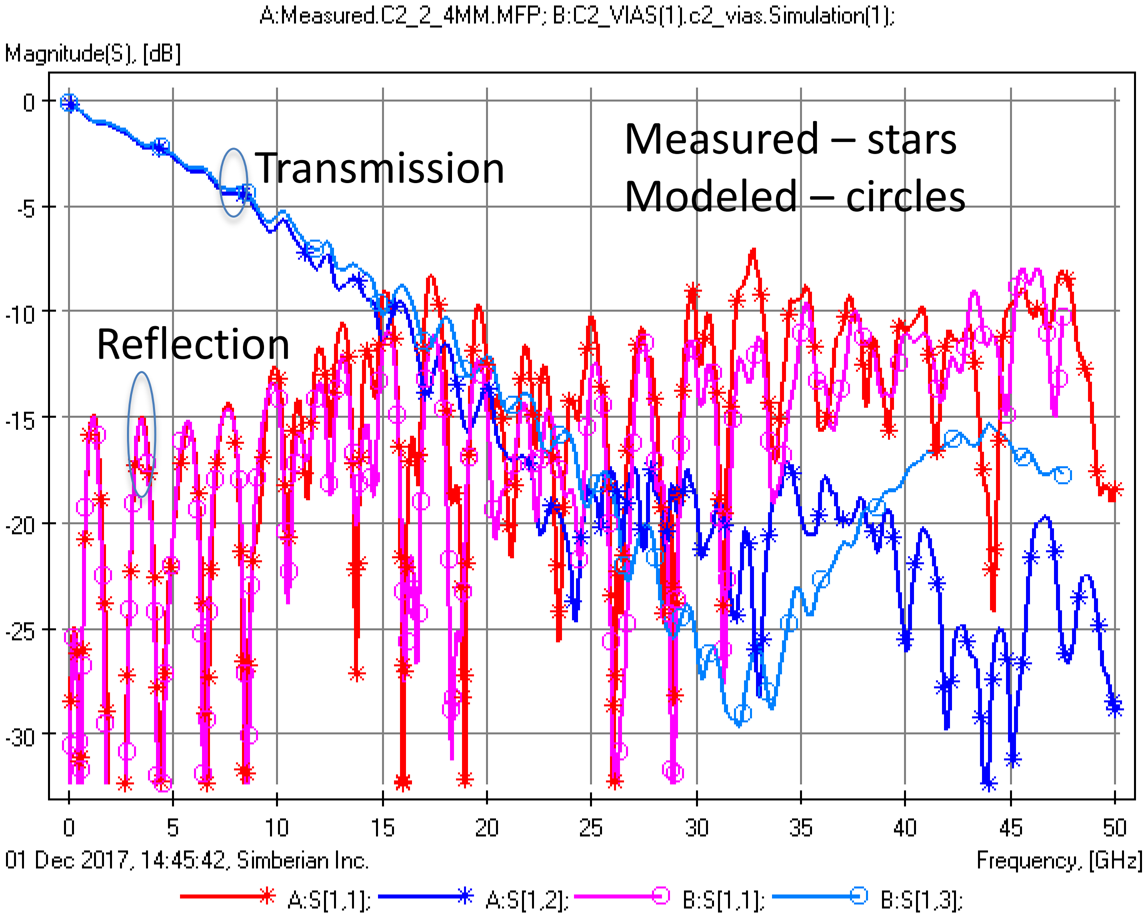


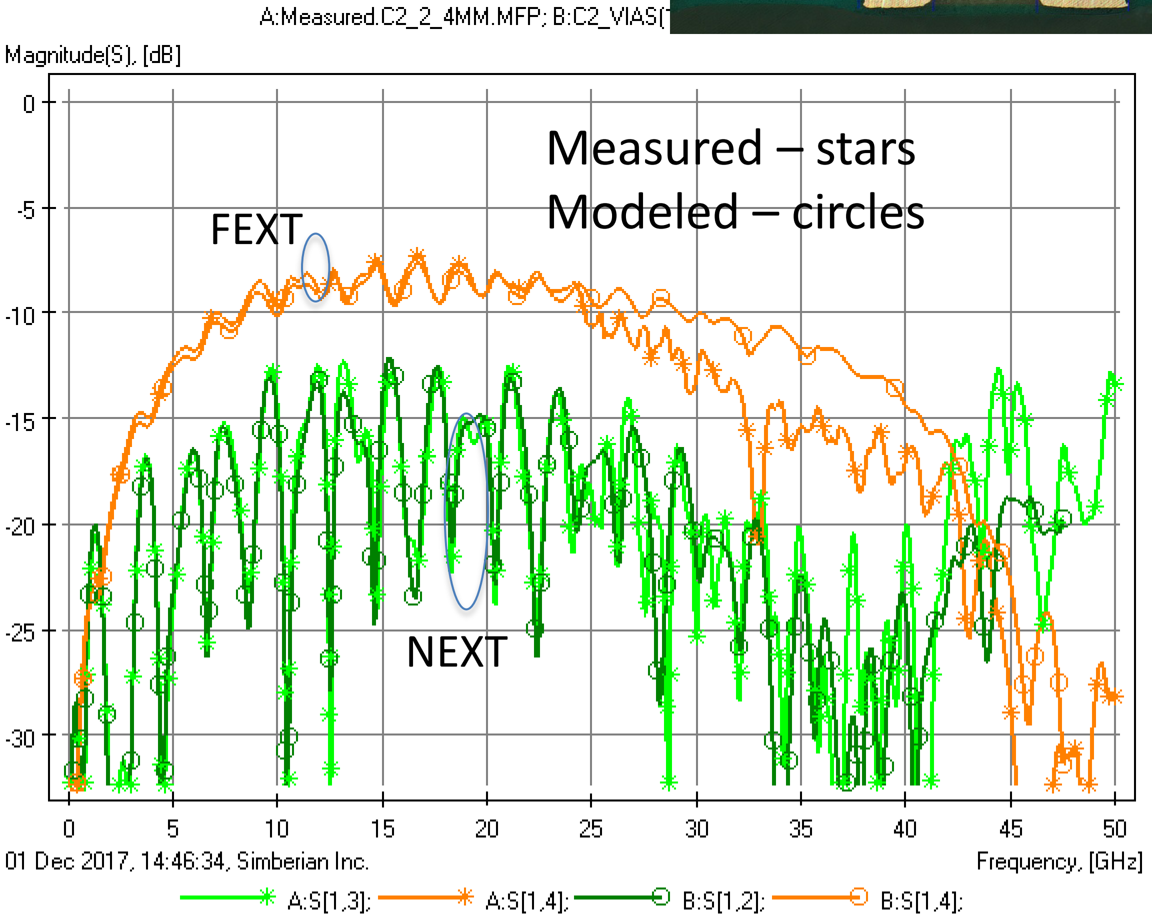
De-compositional EM analysis
Shape and size of all traces and backdrilling position are adjusted…

epoxy



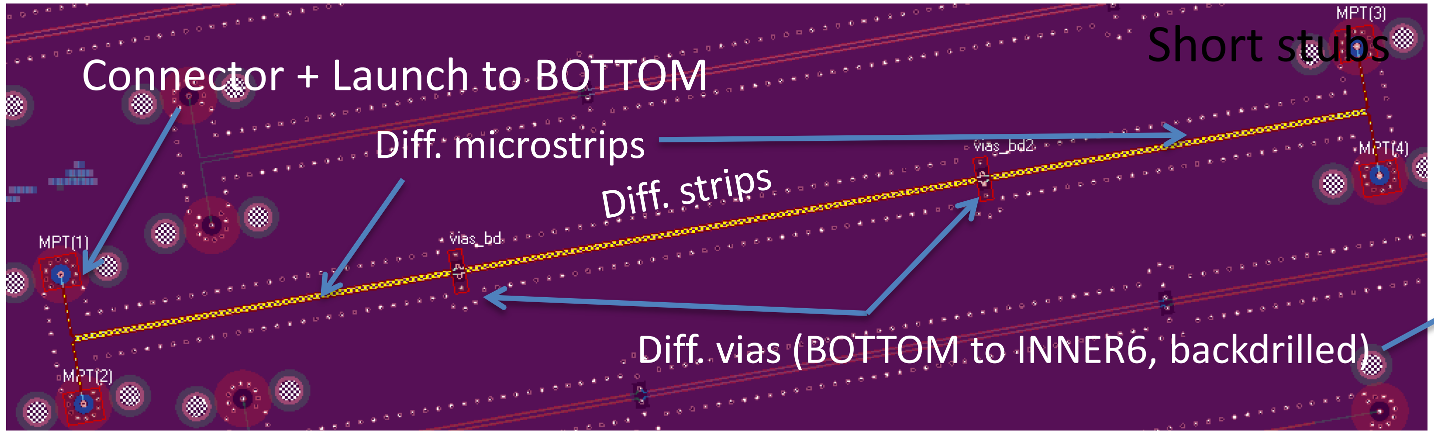
Single-ended S-parameters



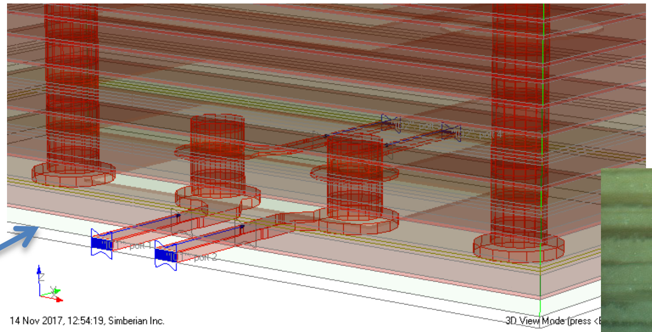


Acceptable correspondence up to 30 GHz

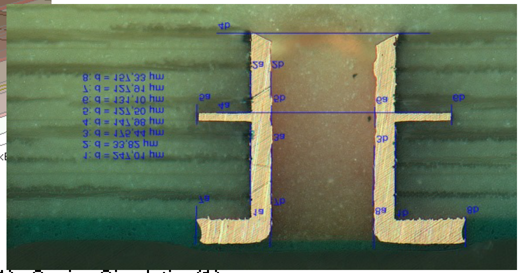
C2: Diff. link with 2 vias from BOTTOM to INNTER6



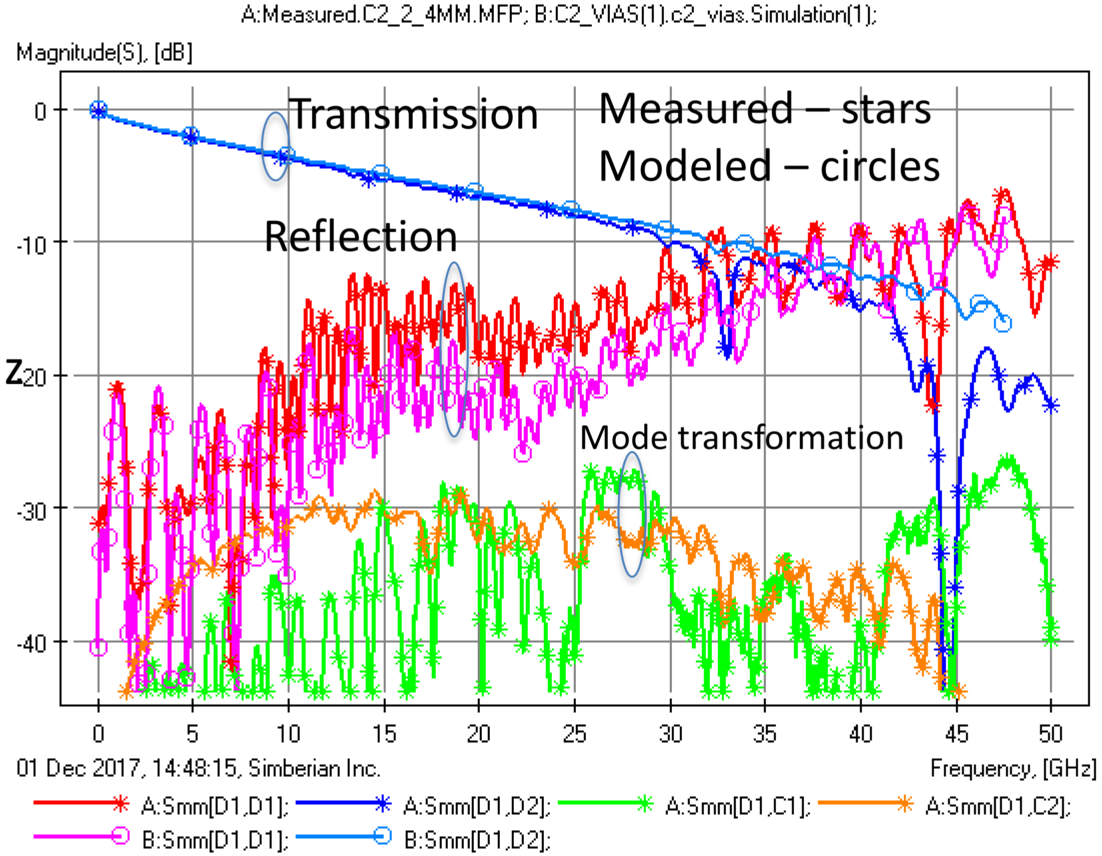
Backdrilled vias model

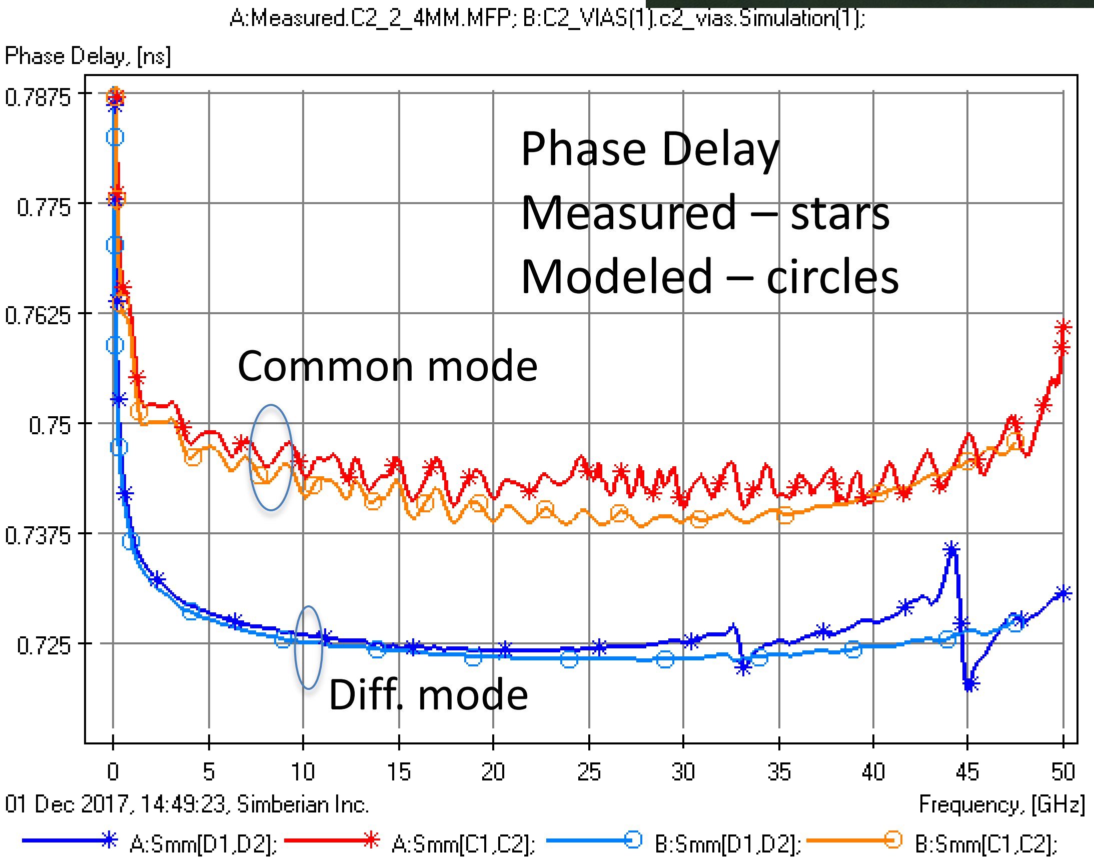


De-compositional EM analysis
Shape and size of all traces and backdrilling position are adjusted…



Mixed-mode S-parameters

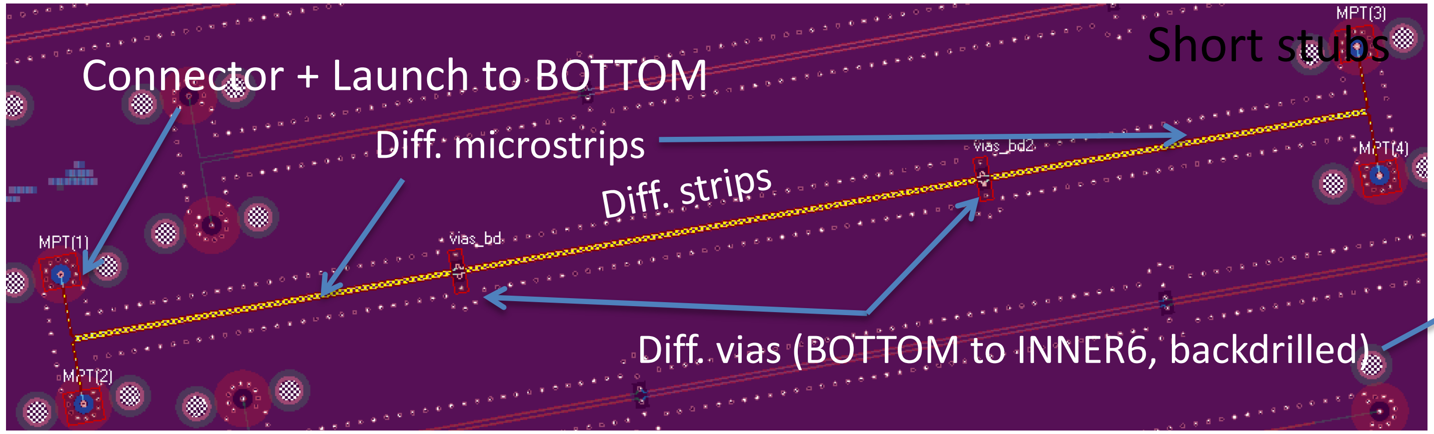




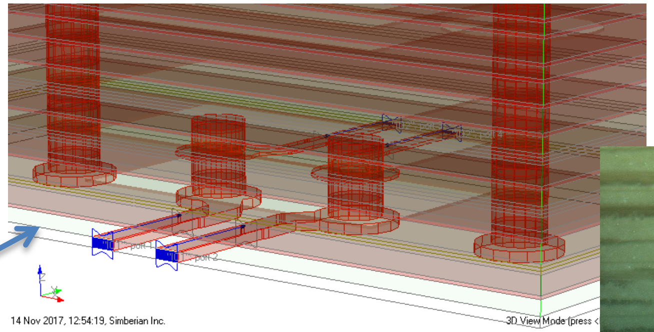
Reality: differences in diff. reflection from 10 to 25 GHz and in transmission above 30 GHz

Acceptable correspondence up to 30 GHz

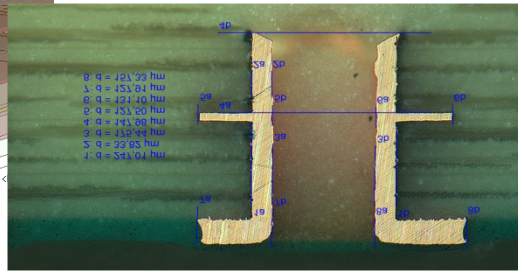
C2: Diff. link with 2 vias from BOTTOM to INNTER6



Backdrilled vias model

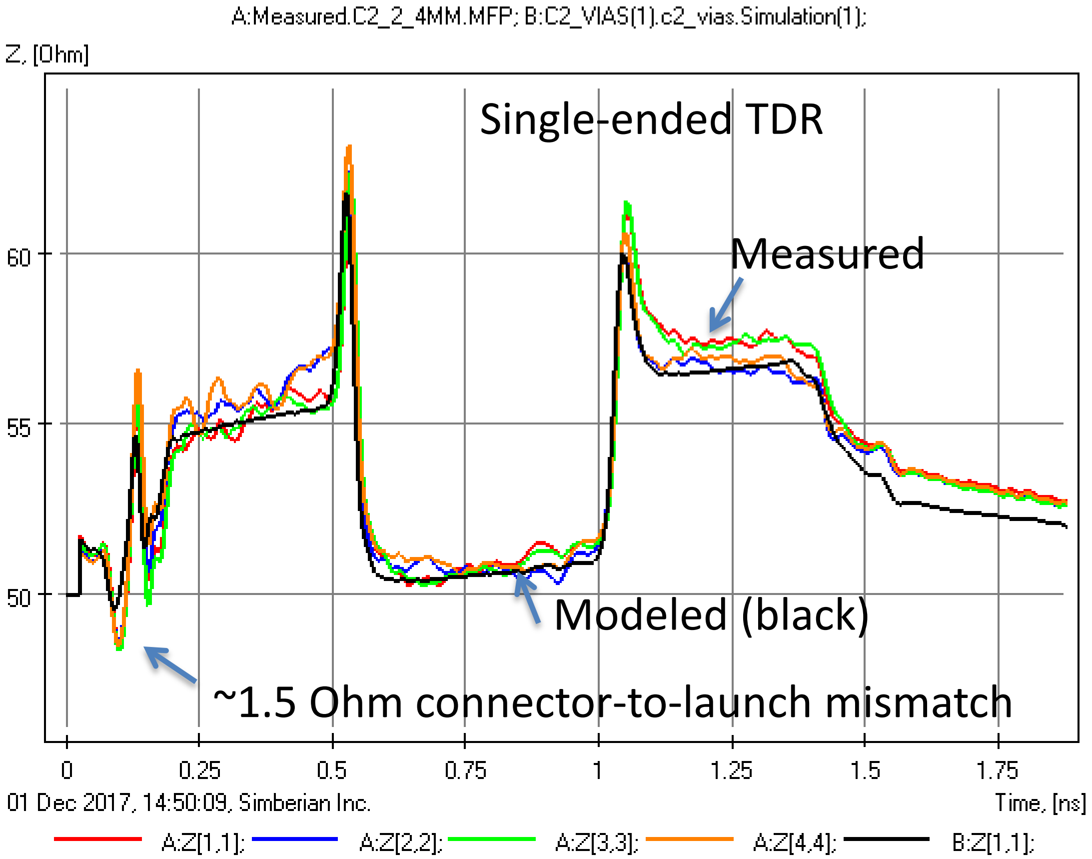


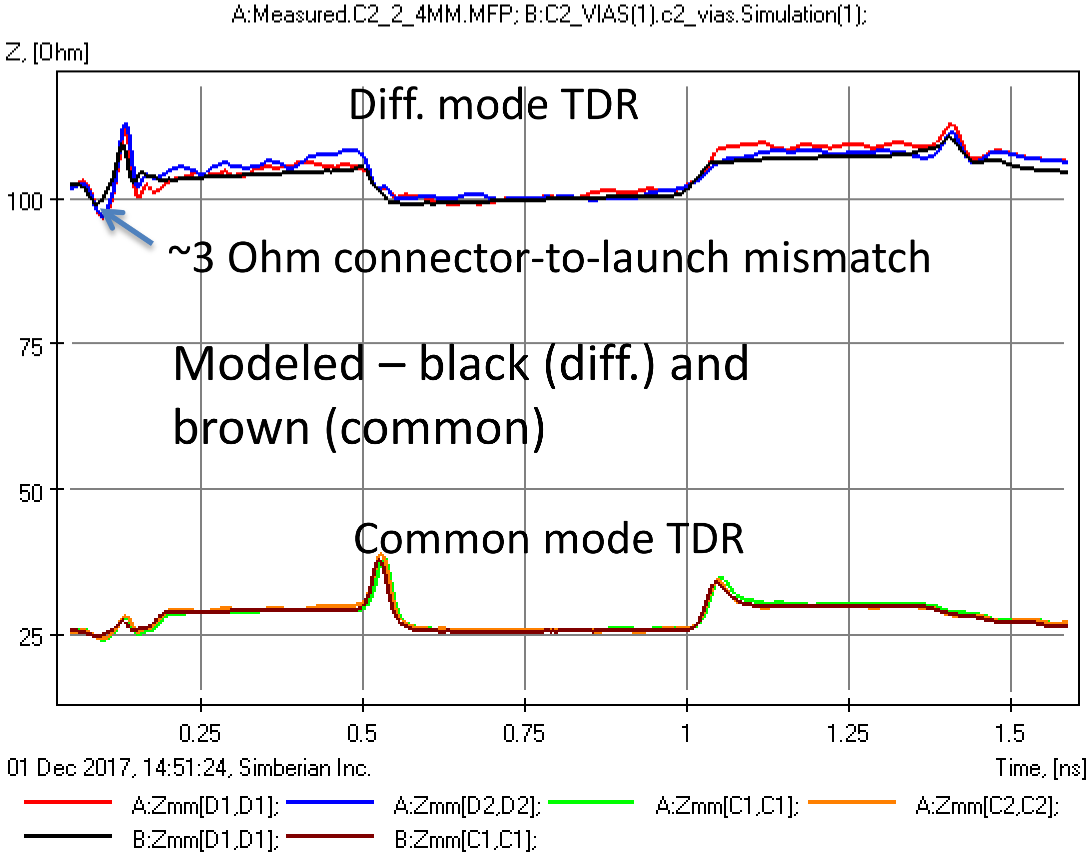
De-compositional EM analysis
Shape and size of all traces and backdrilling position are adjusted…



Reality: connector-to-launch discontinuity in measured data, vias are more inductive than expected

Acceptable correspondence





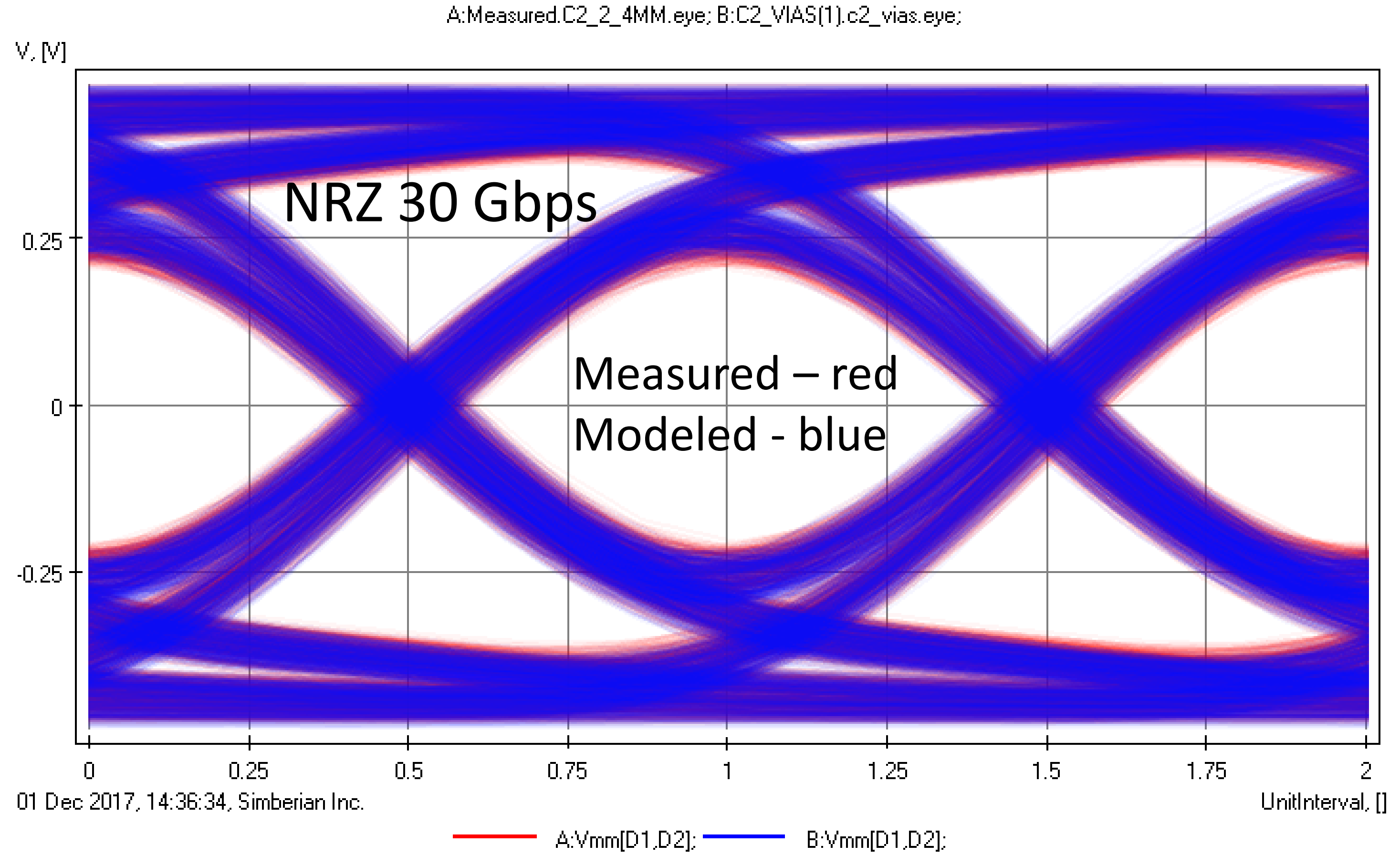
C2: Diff. link with 2 vias from BOTTOM to INNTER6

- Eye diagrams comparison

Eye Analyzer

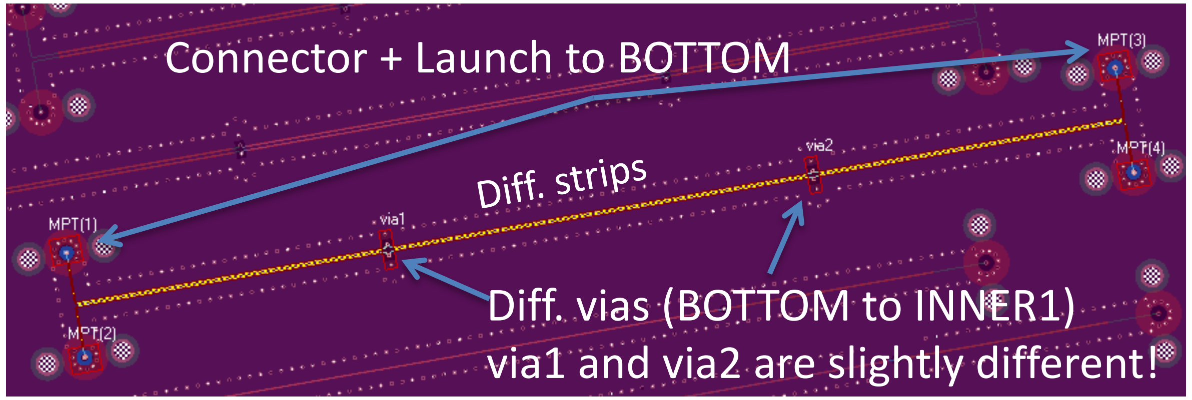
Show Eye Metrics: Selected   Auto-open

Parameter	Measured.C2_2_4...	C2_VIAS(1).c2_vi...
Eye Level Zero (V)	-0.345207	-0.345943
Eye Level One (V)	0.342614	0.349671
Eye Level Mean (V)	0.00174869	-0.00229624
Eye Amplitude (V)	0.687821	0.695614
Eye Height (V)	0.400463	0.423729
Eye Width (UI)	0.78714	0.780044
Eye Opening Factor	0.582219	0.609144
Eye Signal to Noise	4.56524	4.80348
Eye Rise Time (20-80) (UI)	0.552103	0.539368
Eye Fall Time (80-20) (UI)	0.552473	0.537425
Eye Jitter (PP) (UI)	0.21286	0.219956
Eye Jitter (RMS) (UI)	0.0456376	0.0438262

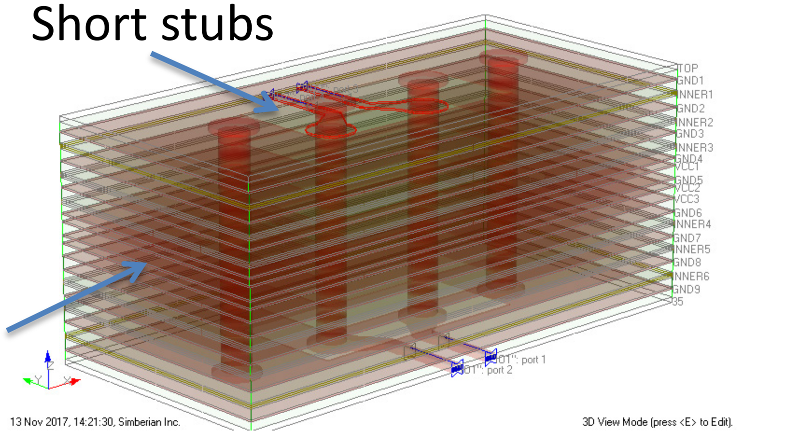


~5% difference in eye heights, same width; Possible reason – impedance and geometry variations, launch localization loss…

C3: Diff. link with 2 vias from BOTTOM to INNTER1



Short stubs

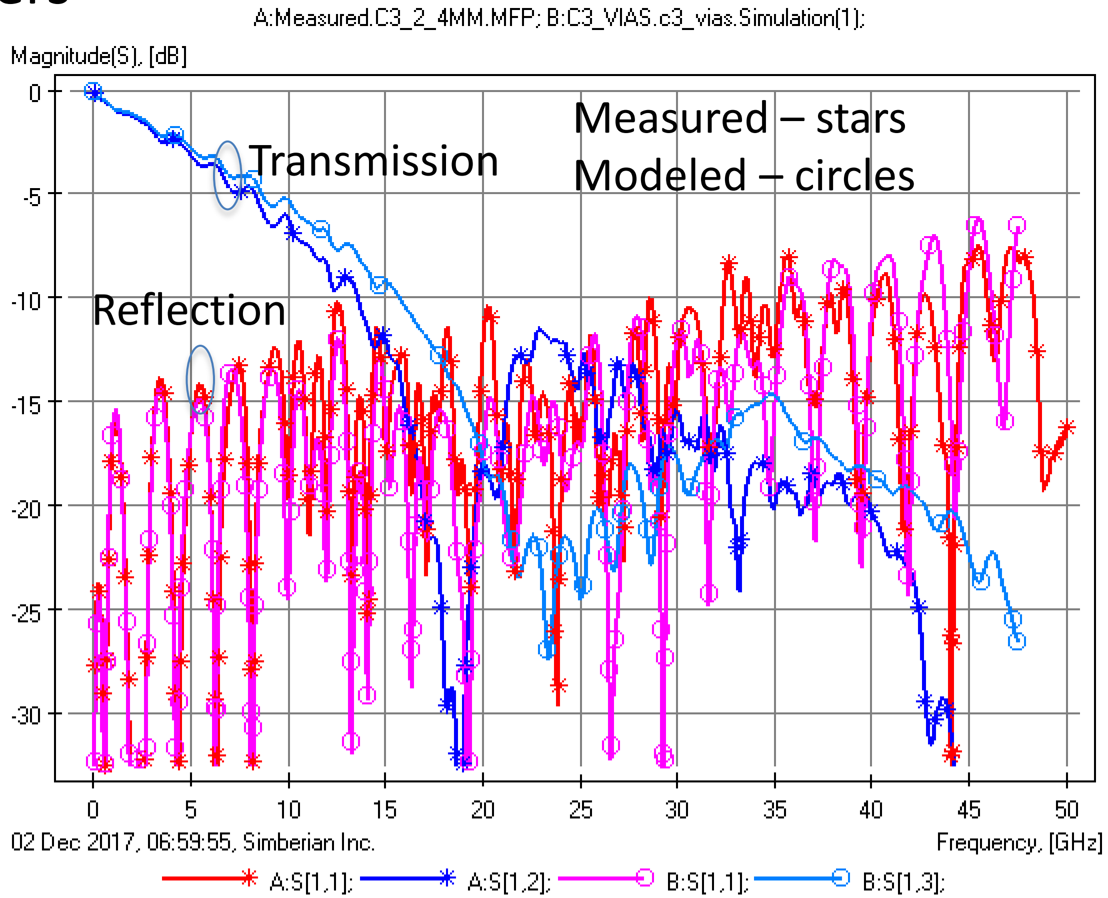


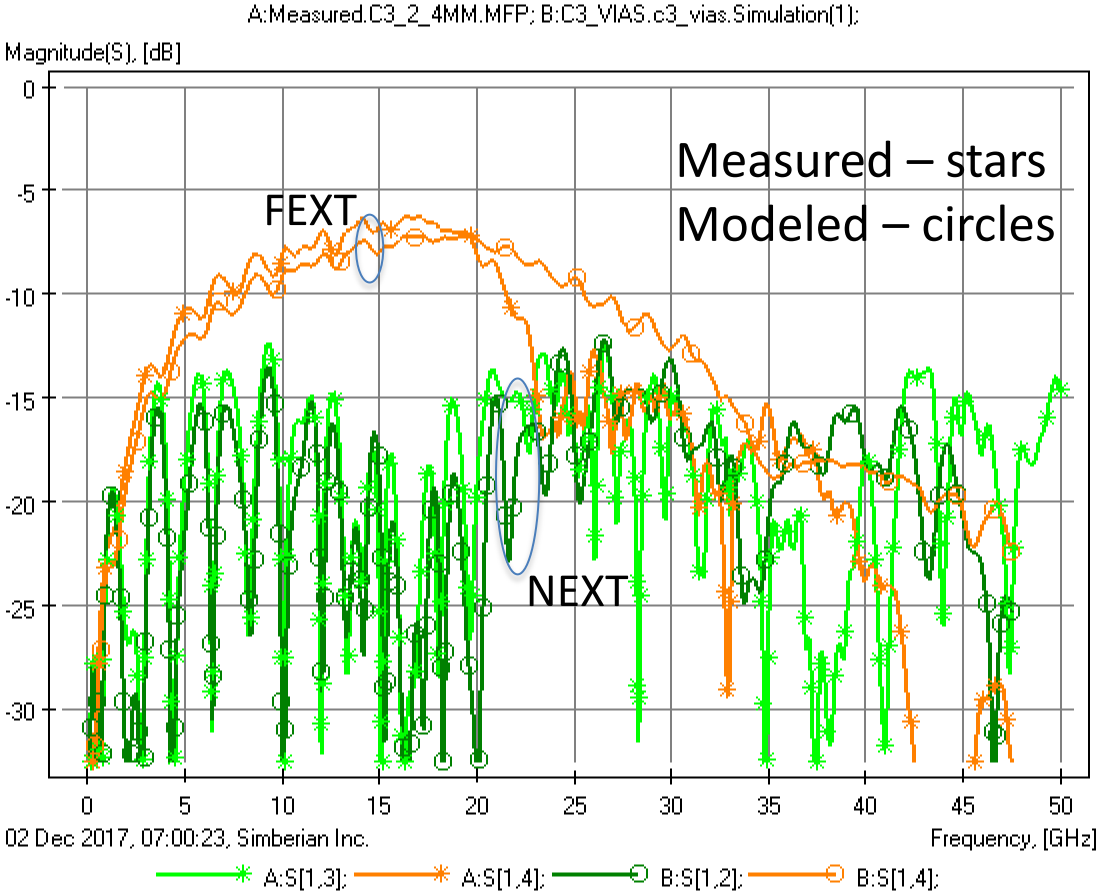
De-compositional EM analysis
Shape and size of all traces are adjusted…

Single-ended S-parameters

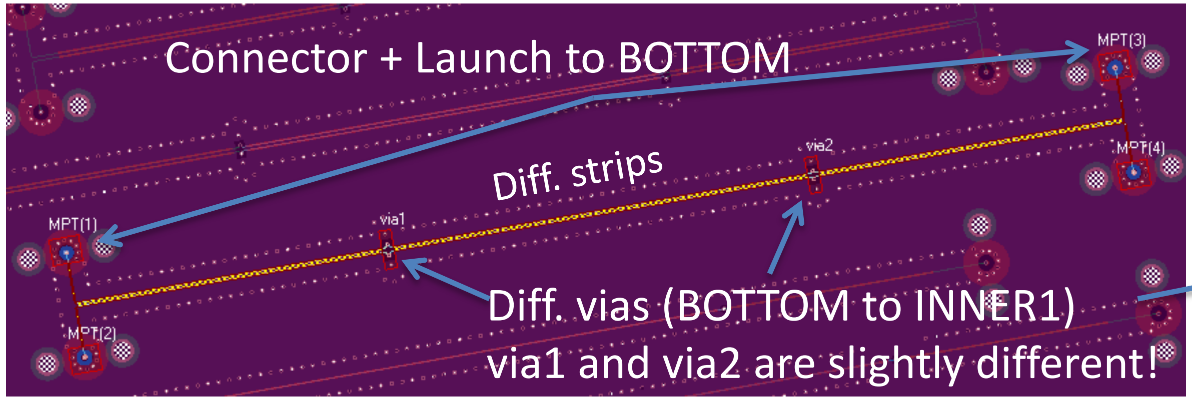
Reality: Single-ended localization breaks around 10-15 GHz (predictable)

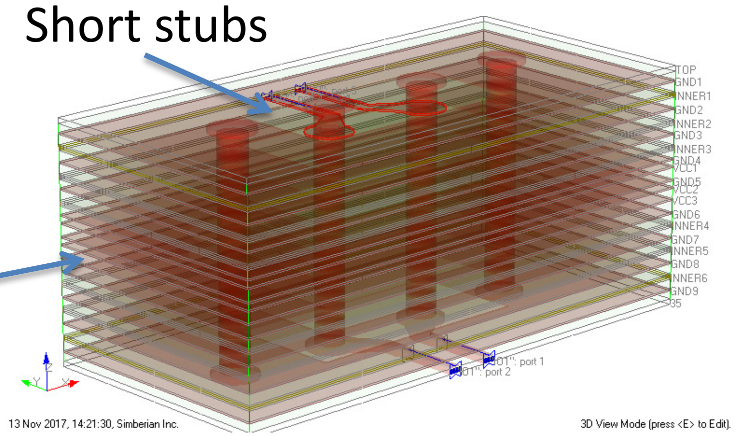
Acceptable correspondence up to 30 GHz





C3: Diff. link with 2 vias from BOTTOM to INNTER1



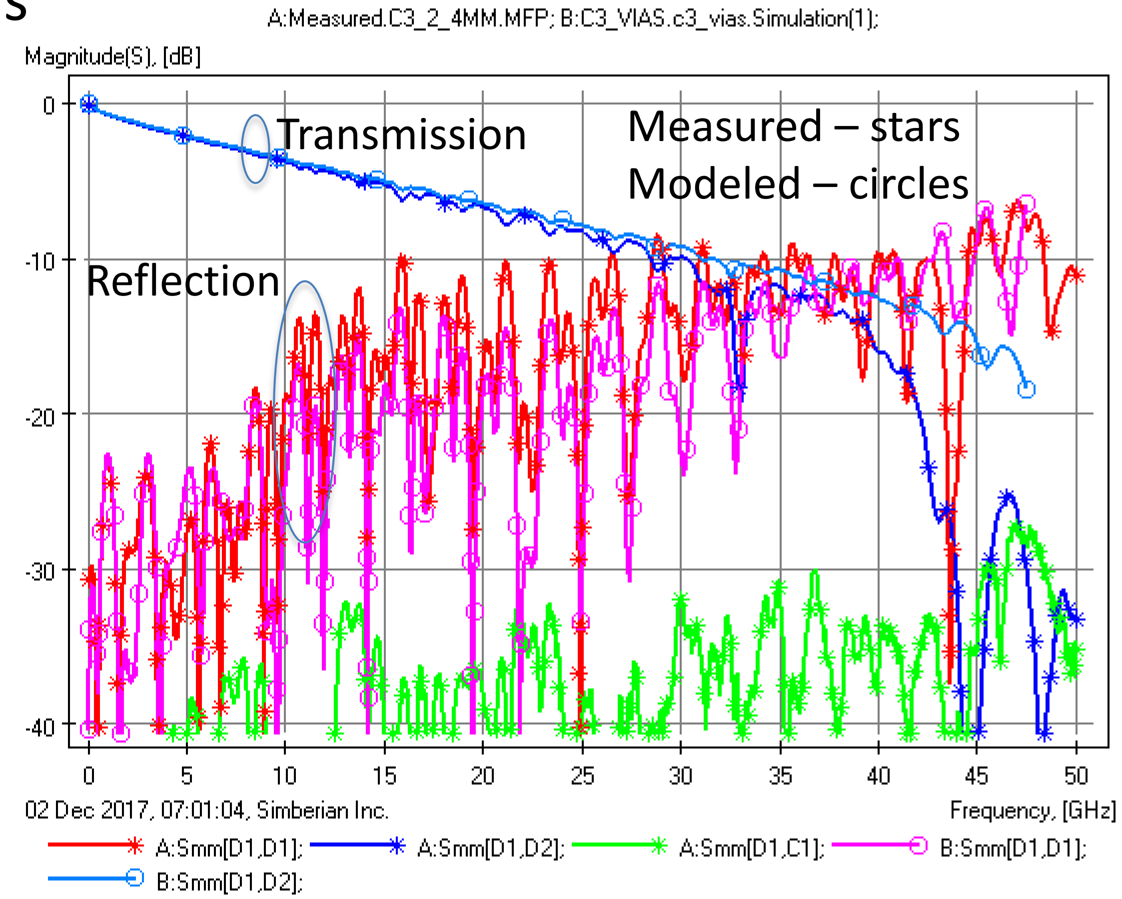


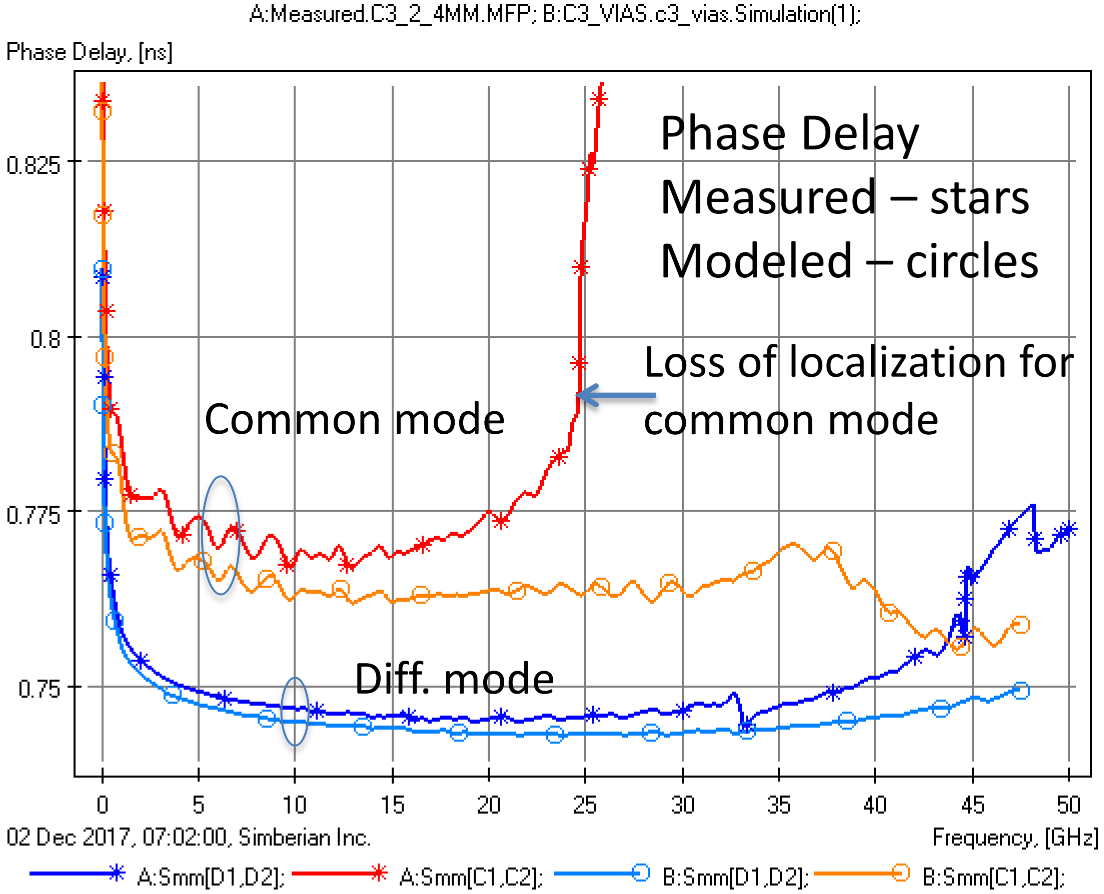
De-compositional EM analysis
Shape and size of all traces are adjusted…

Mixed-mode S-parameters

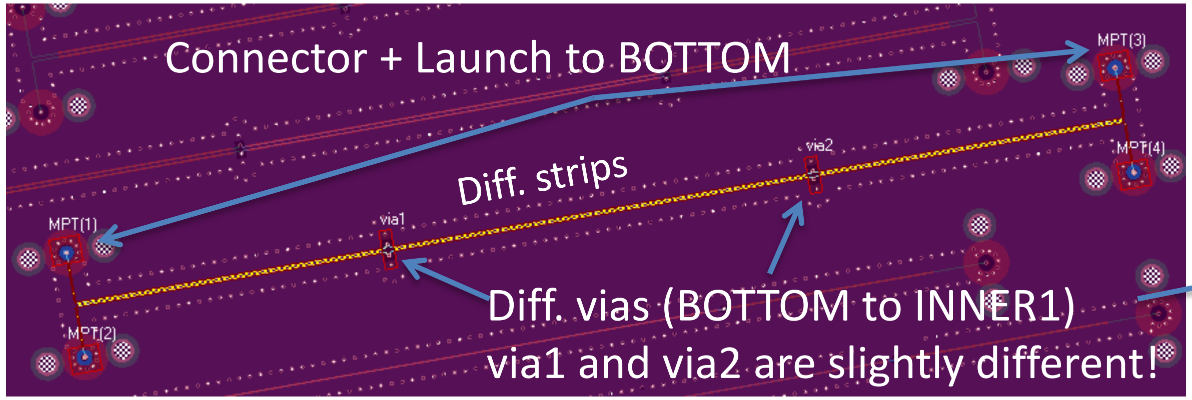
Reality: Common mode localization breaks around 20 GHz (predictable)

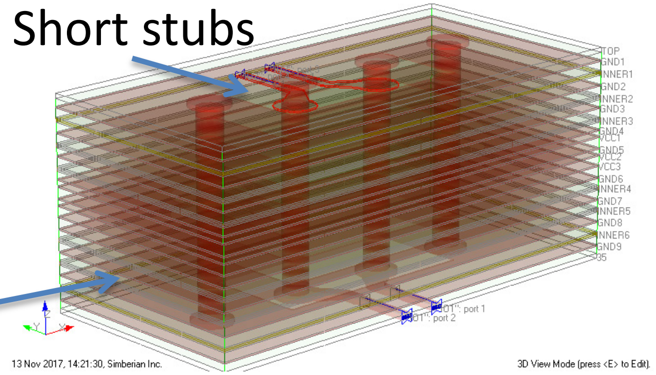
Acceptable correspondence up to 30 GHz





C3: Diff. link with 2 vias from BOTTOM to INNTER1

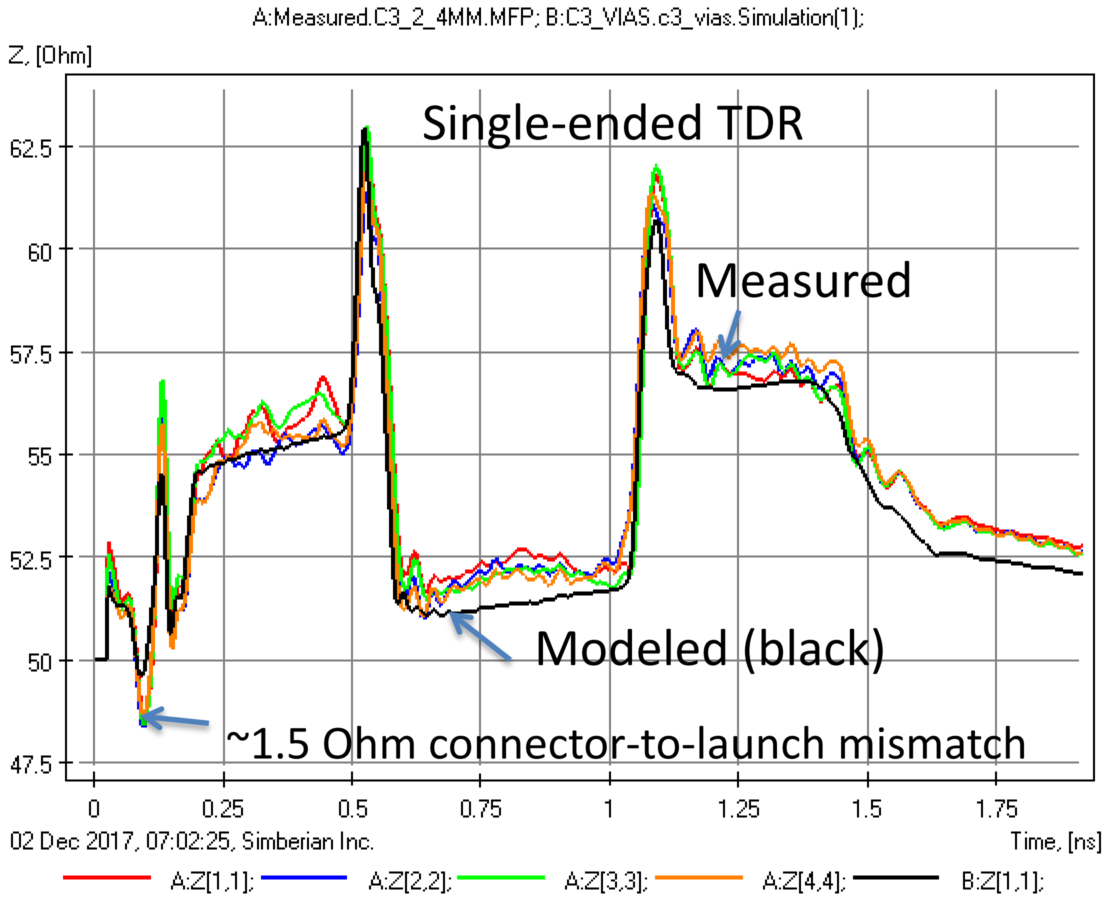


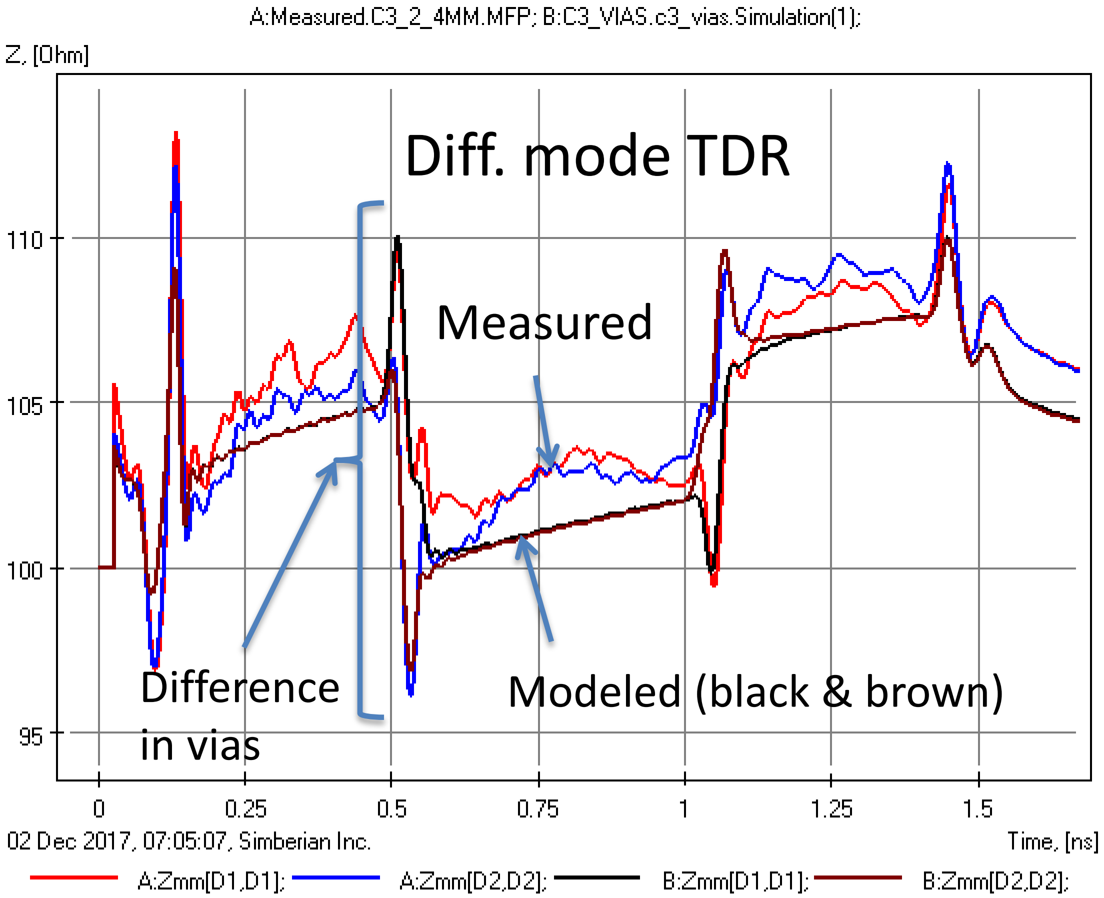


De-compositional EM analysis
Shape and size of all traces are adjusted…

VIAS ARE ACTUALLY DIFFERENT

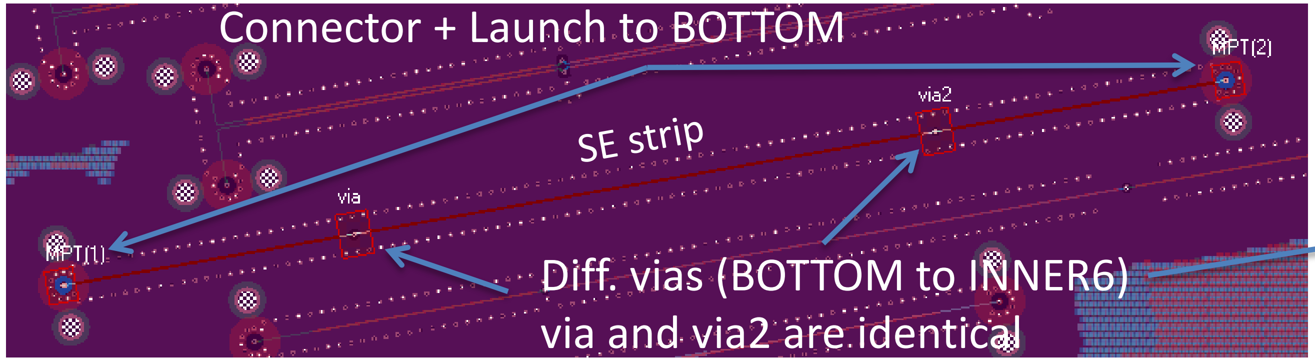
Reality: Small change in distance between vias turns via from inductive to capacitive…

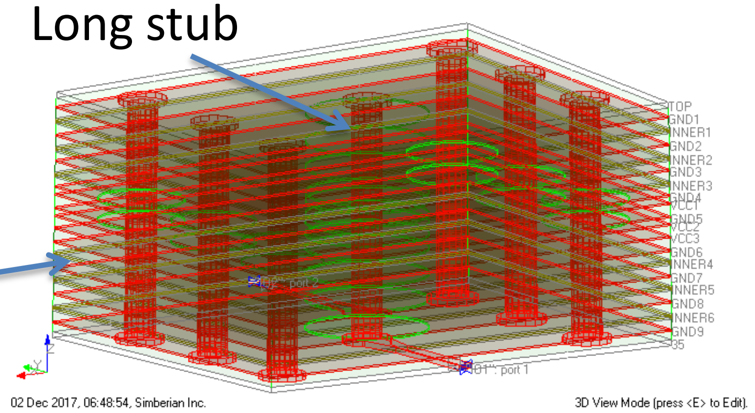




Acceptable correspondence

C4: SE link with 2 vias from BOTTOM to INNTER6



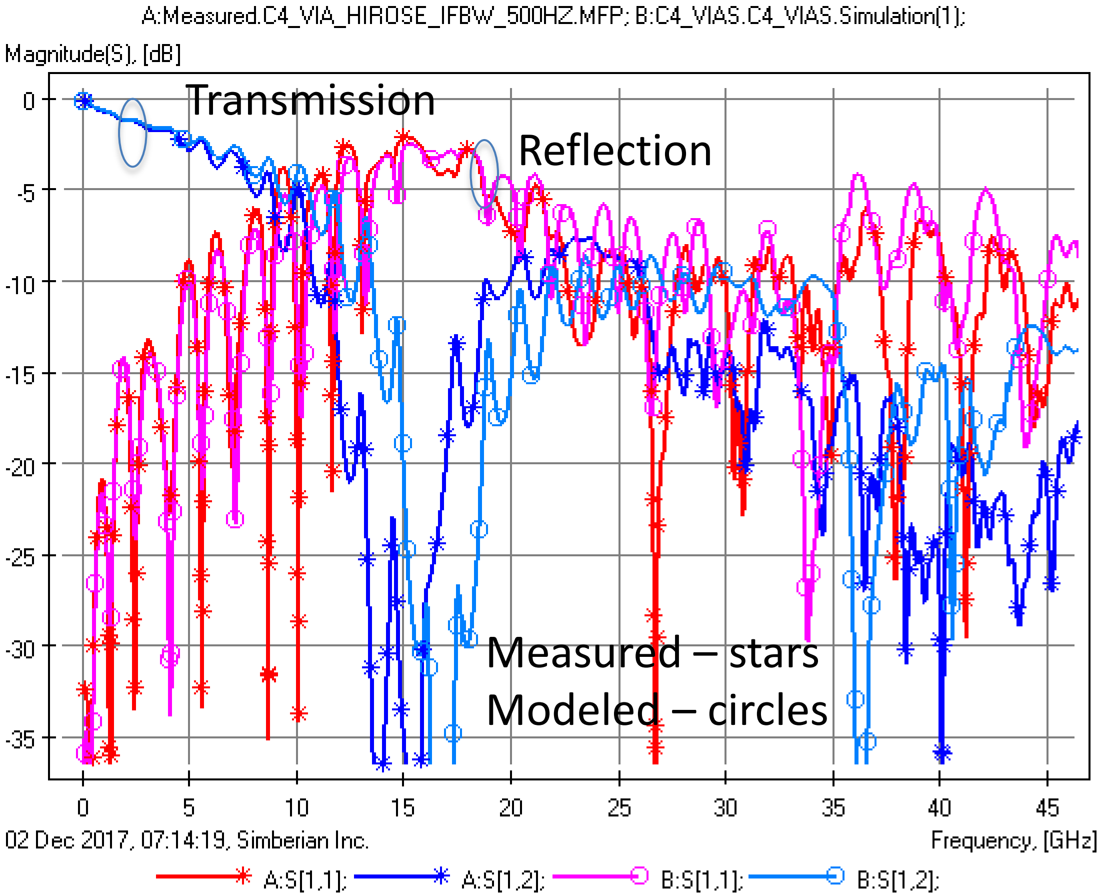


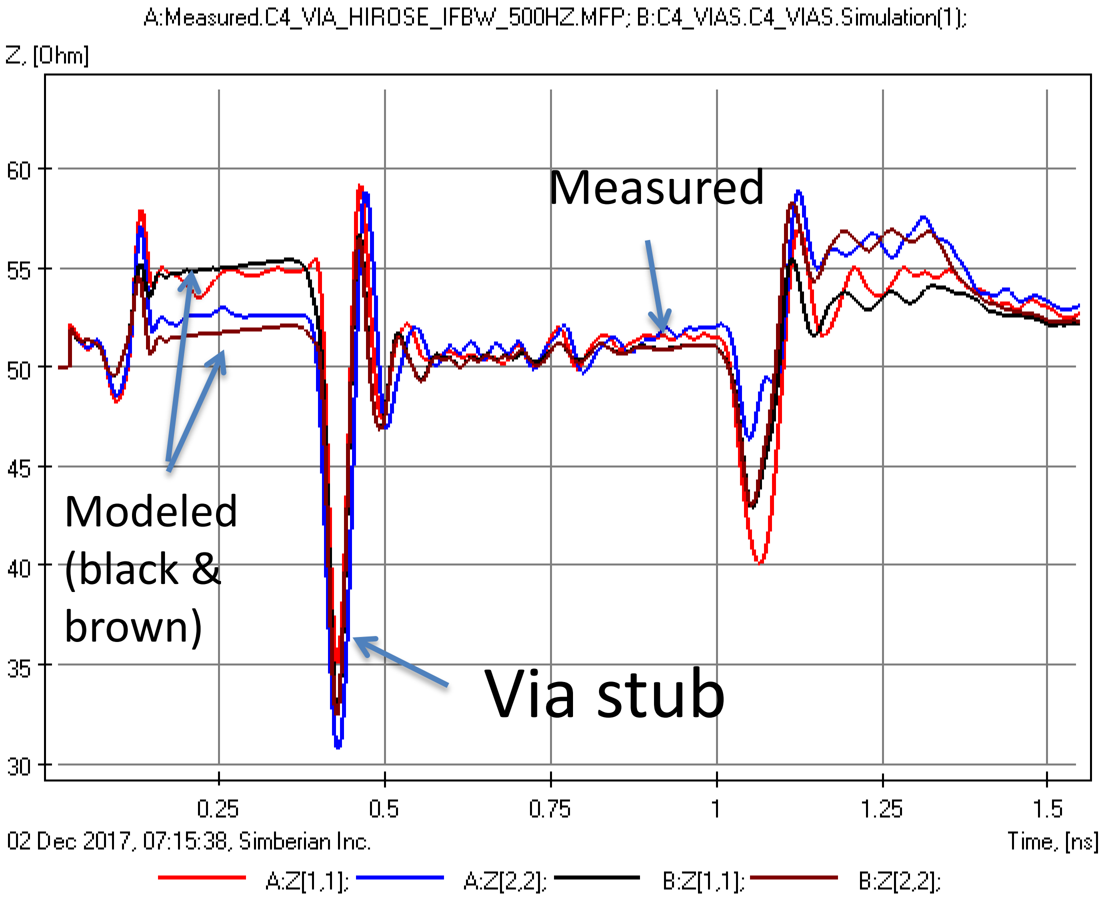
De-compositional EM analysis
Shape and size of all traces are adjusted…

S-parameters & TDR

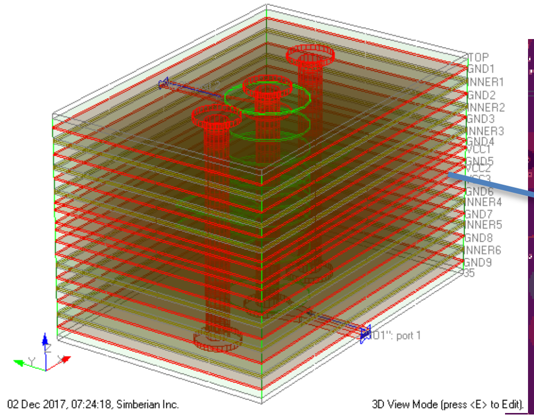
Reality: Localization breaks around 10-15 GHz (expected – stitching vias are too far…); Microstrip trace widths are different…

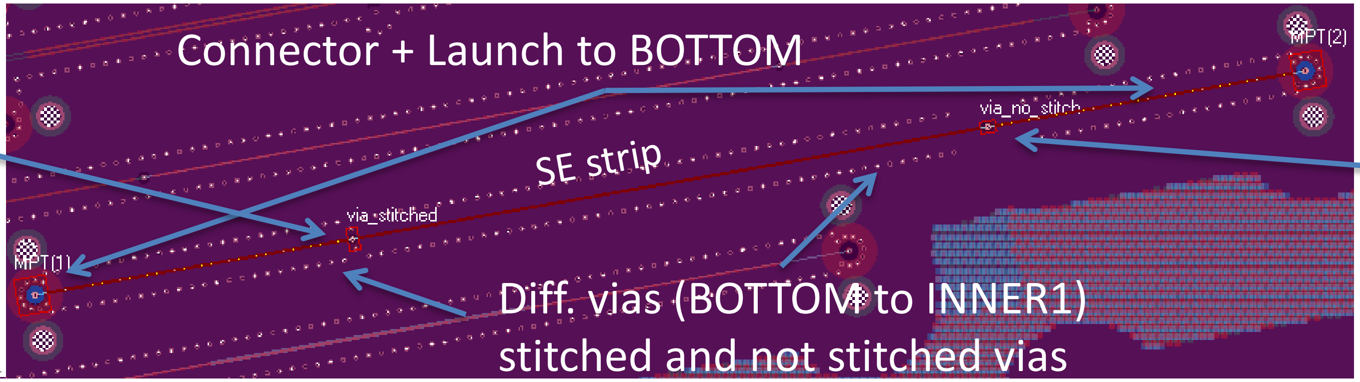
Acceptable correspondence only up to 10-15 GHz

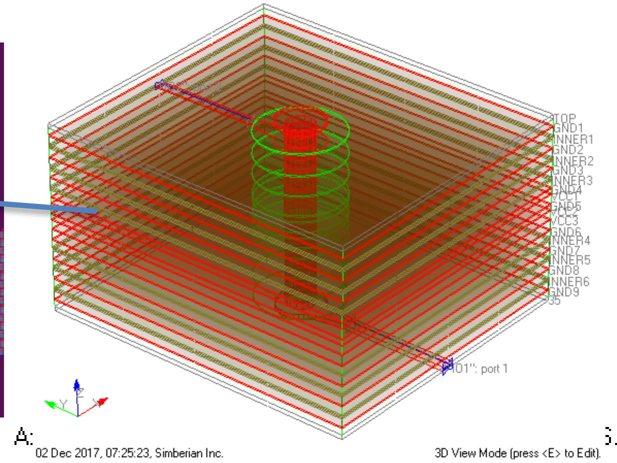




C5: SE link with 2 vias from BOTTOM to INNTER1







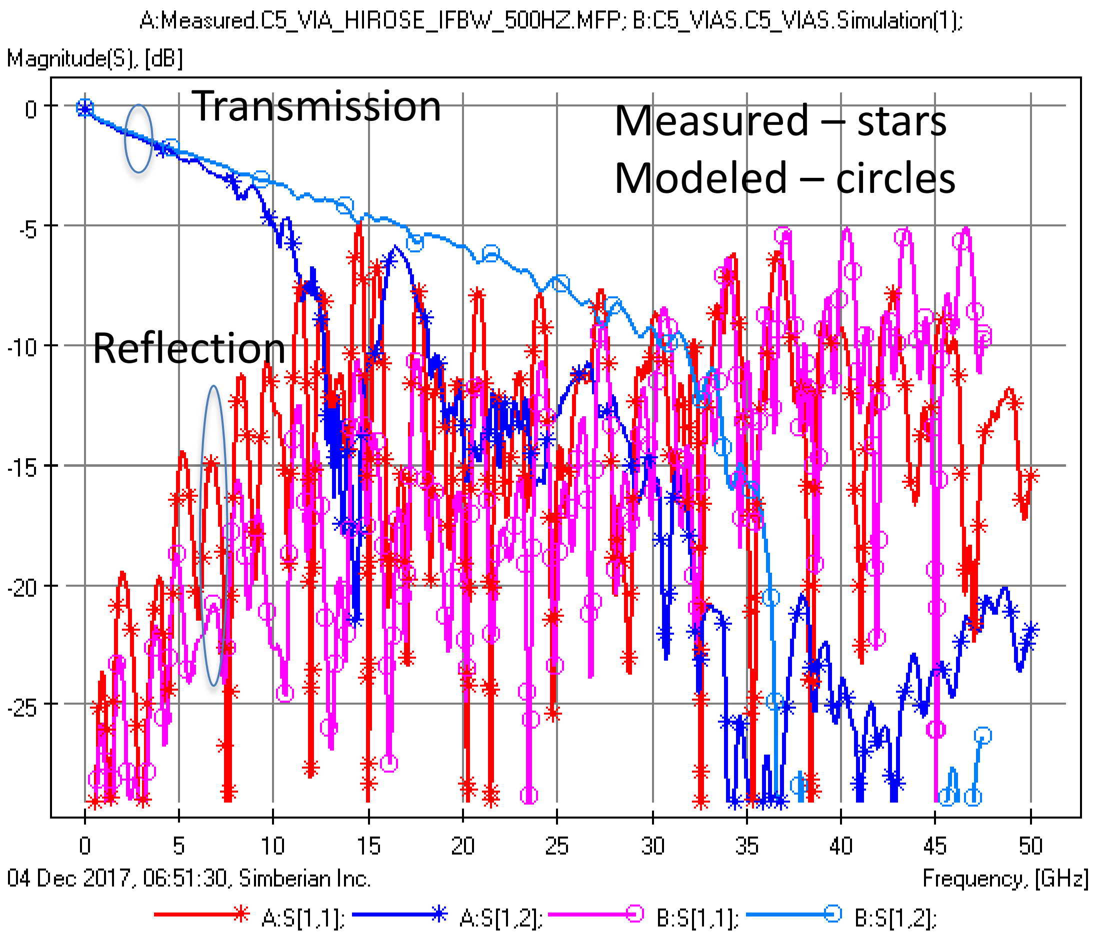
De-compositional EM analysis

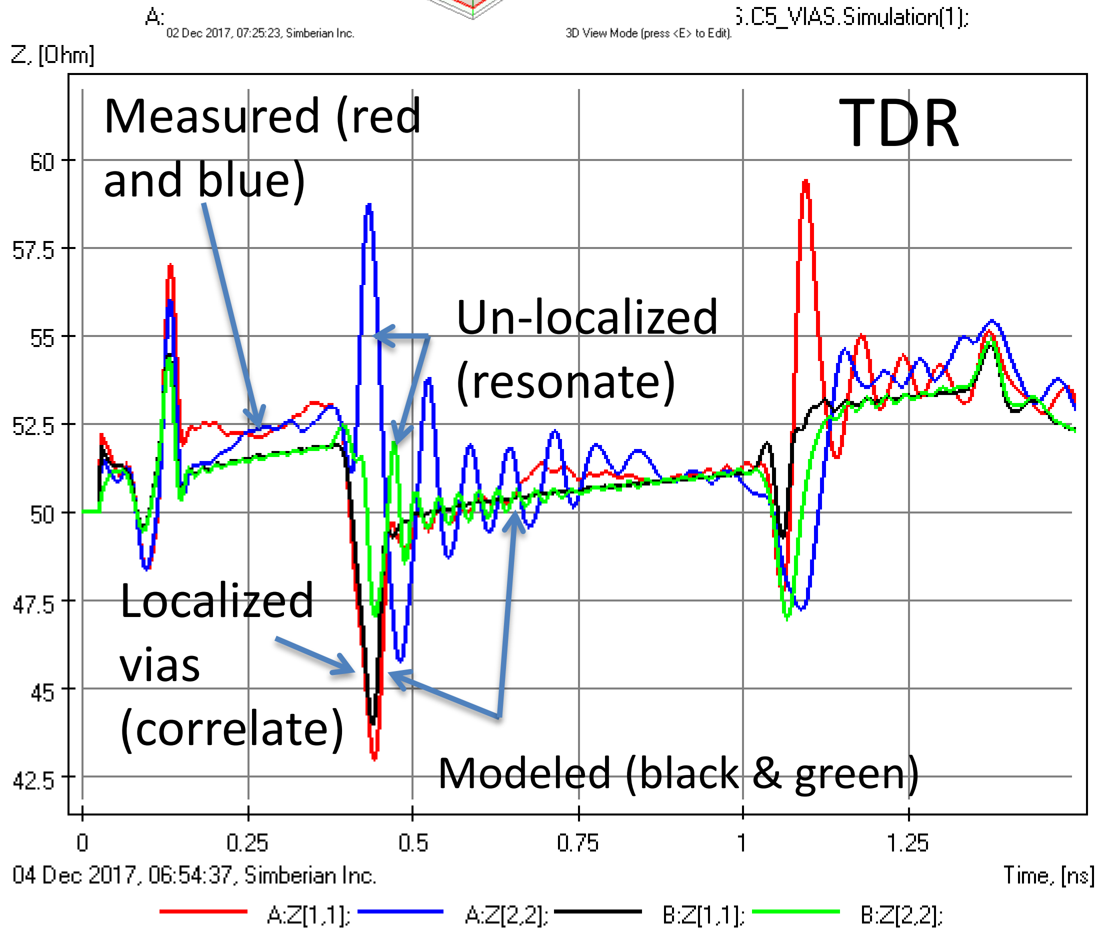
Shape and size of all traces are adjusted…

S-parameters & TDR

Reality: Localization breaks around 5 GHz (expected, no stitching vias…); Un-localized via resonates…

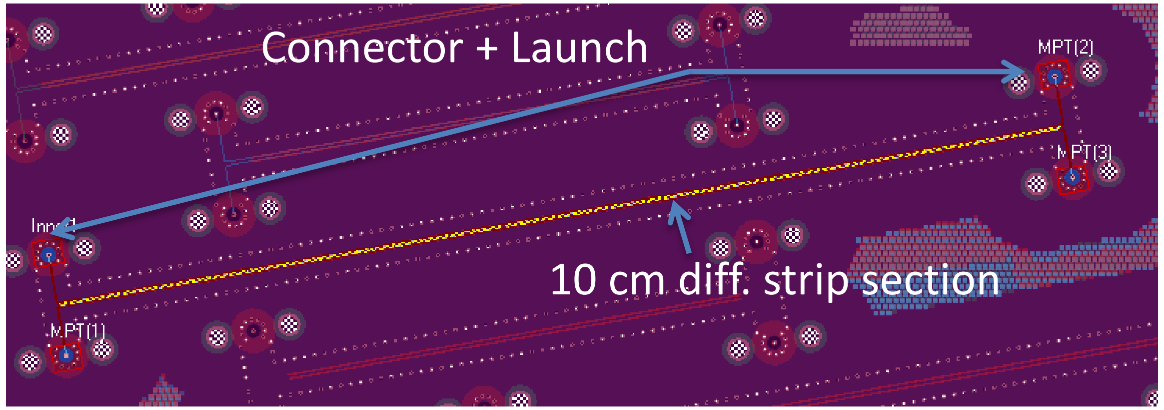
Acceptable correspondence only up to 5-7 GHz

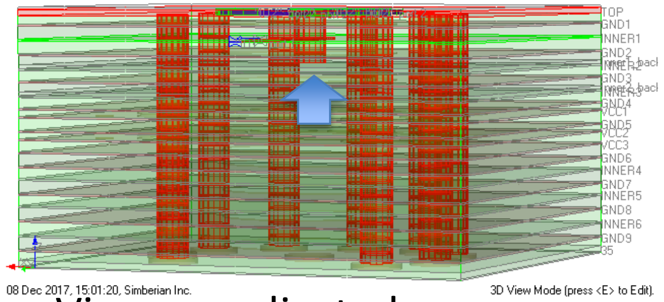




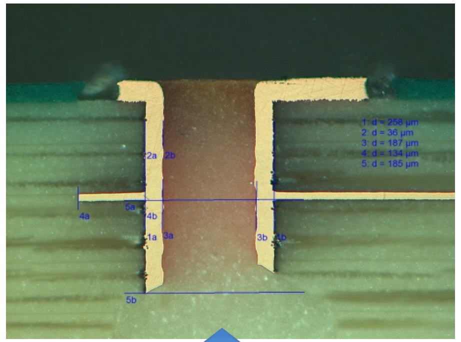
INNER1: 10 cm diff. strip link

De-compositional EM analysis
All trace widths and backdrill are adjusted





Via span adjusted as on x-section, no filling

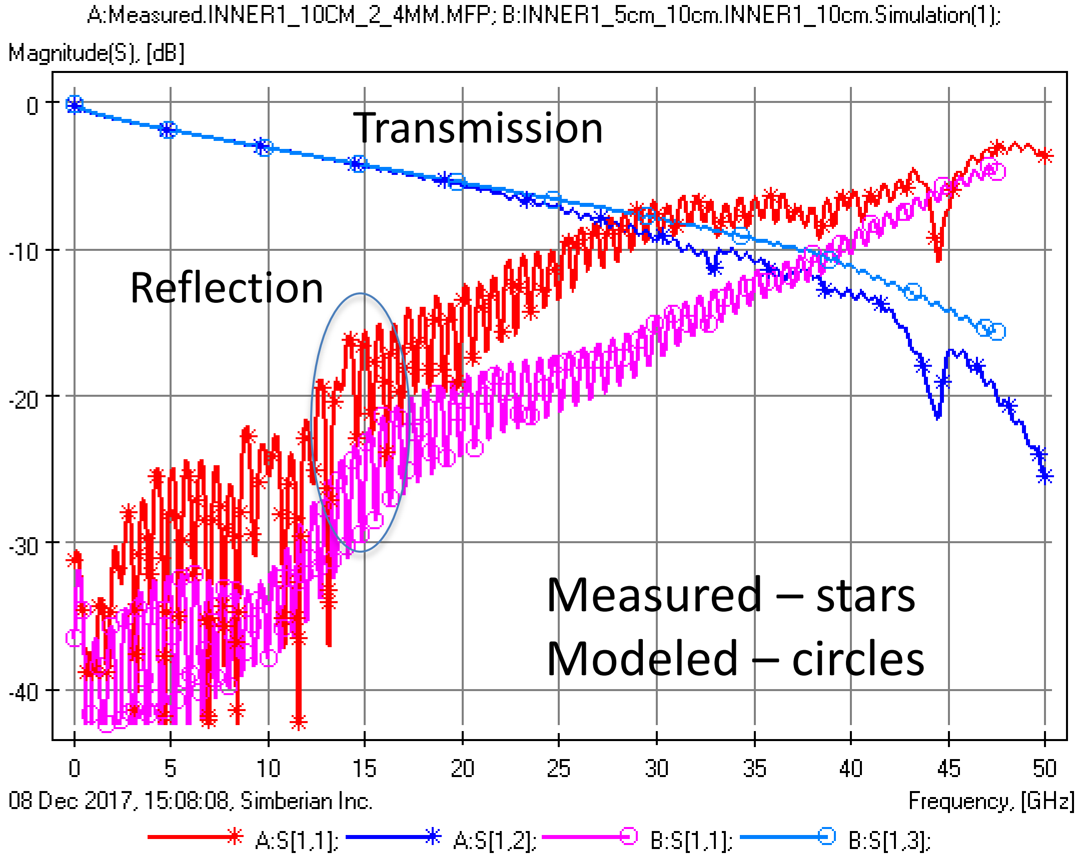


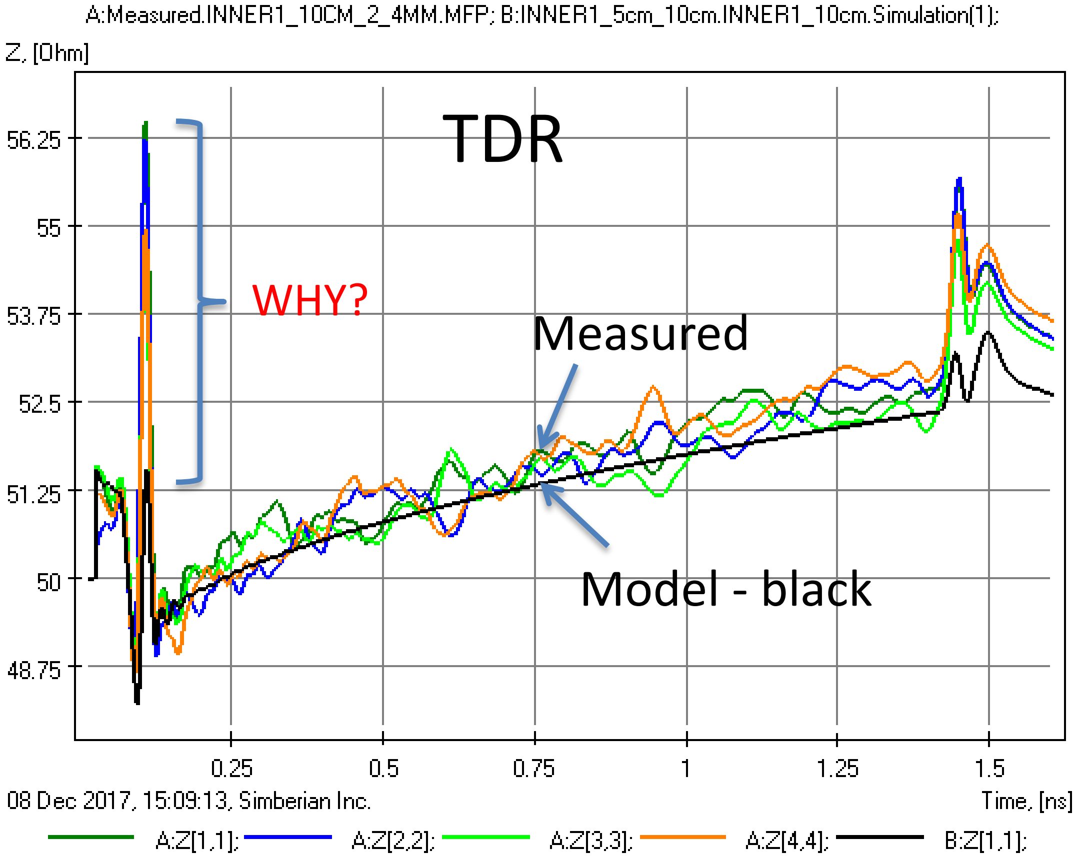
Epoxy?

Single-ended S-parameters & TDR

Via simulated as tube, no epoxy filling in the model - epoxy Dk is close to Dk of the layers (3.4)

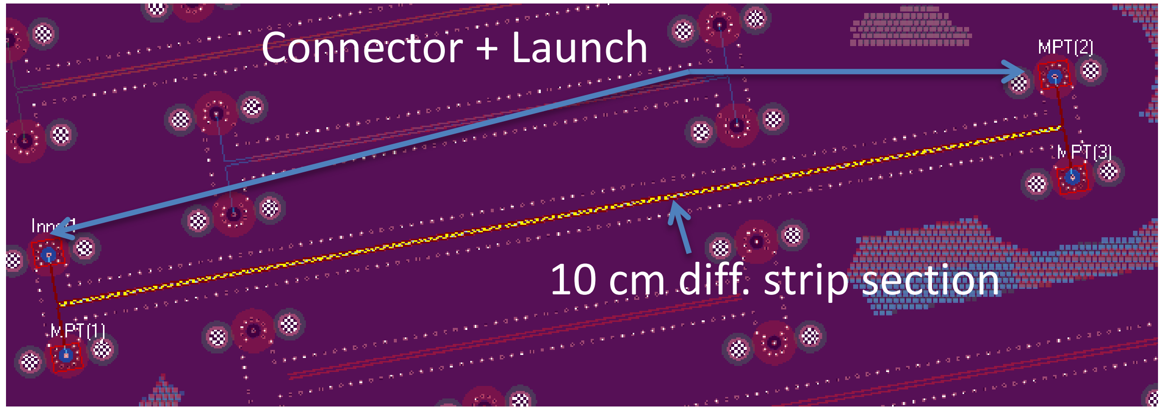
Reality: Very large difference in reflection, launch is much more inductive than expected…

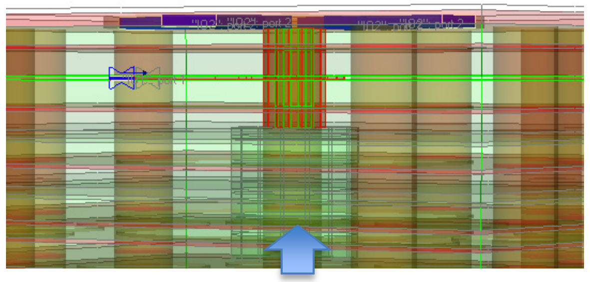




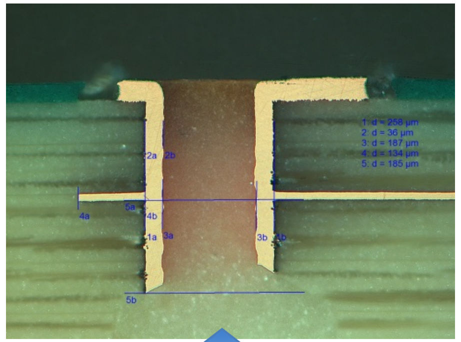
INNER1: 10 cm diff. strip link

De-compositional EM analysis
All trace widths and backdrill are adjusted





Via span adjusted as on x-section, air in backdrill

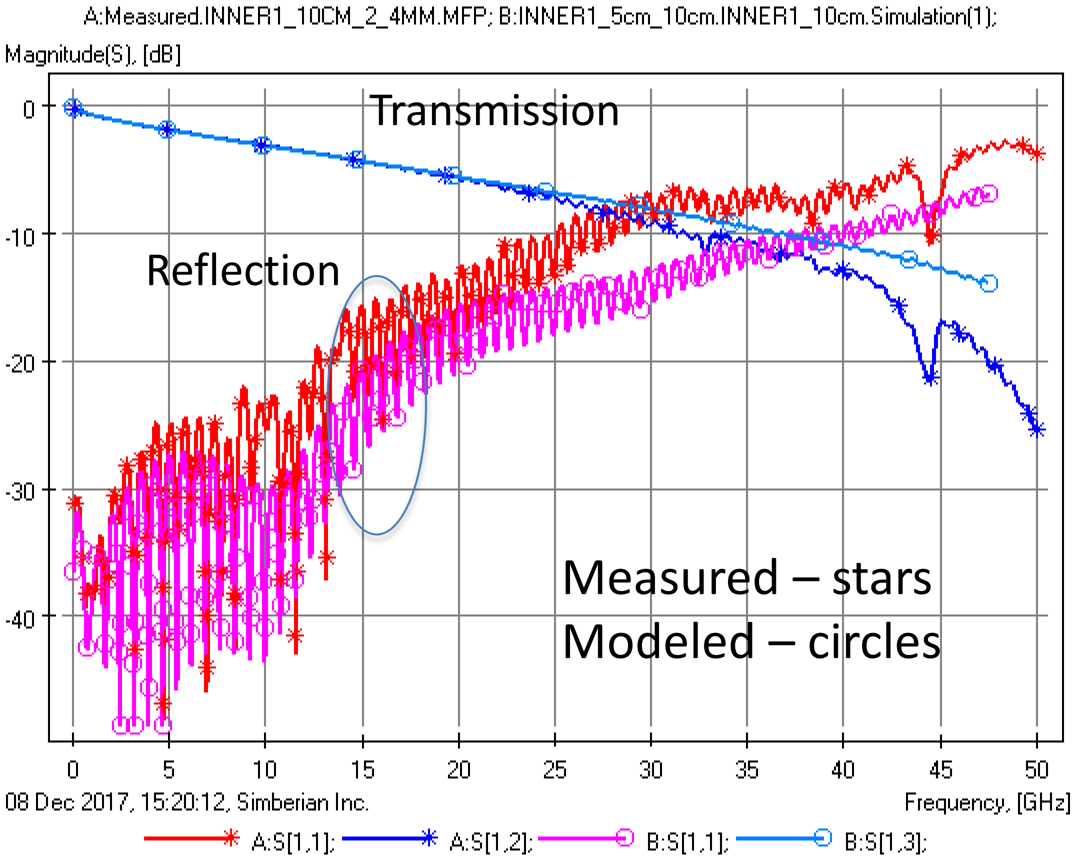


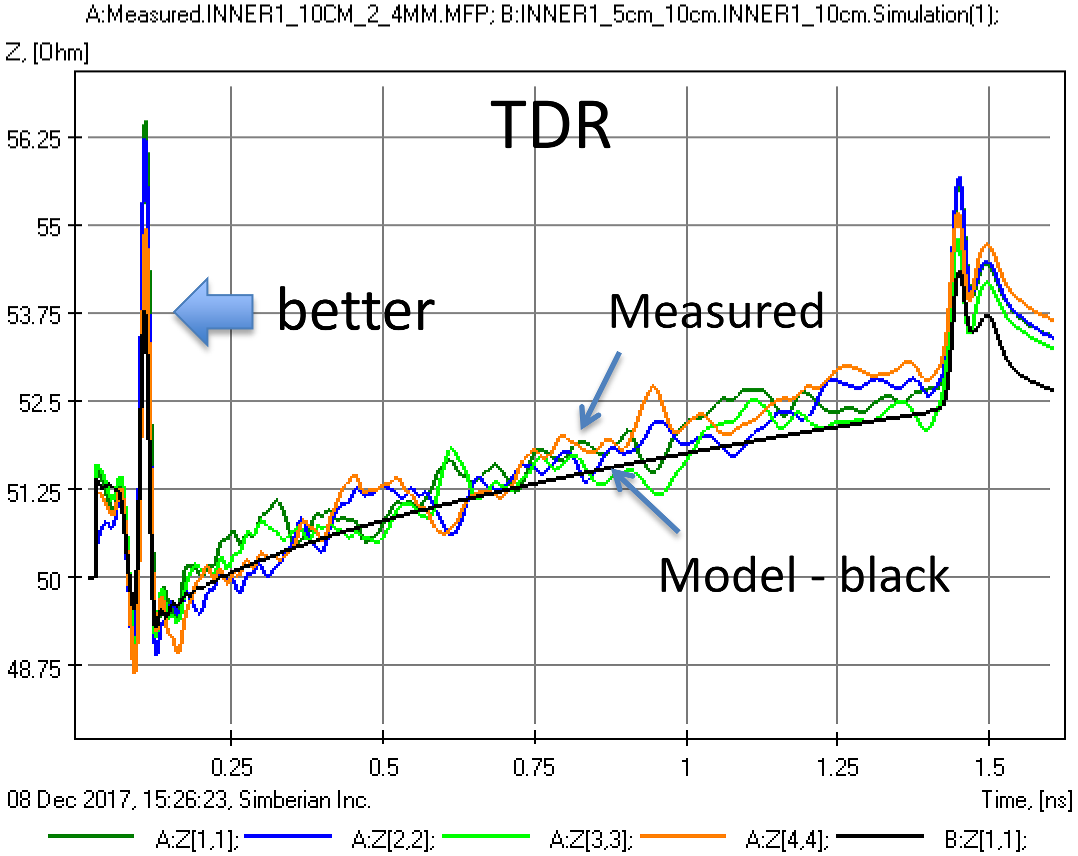
Air?

Single-ended S-parameters & TDR

Via simulated as tube, backdrilled area is filled with air

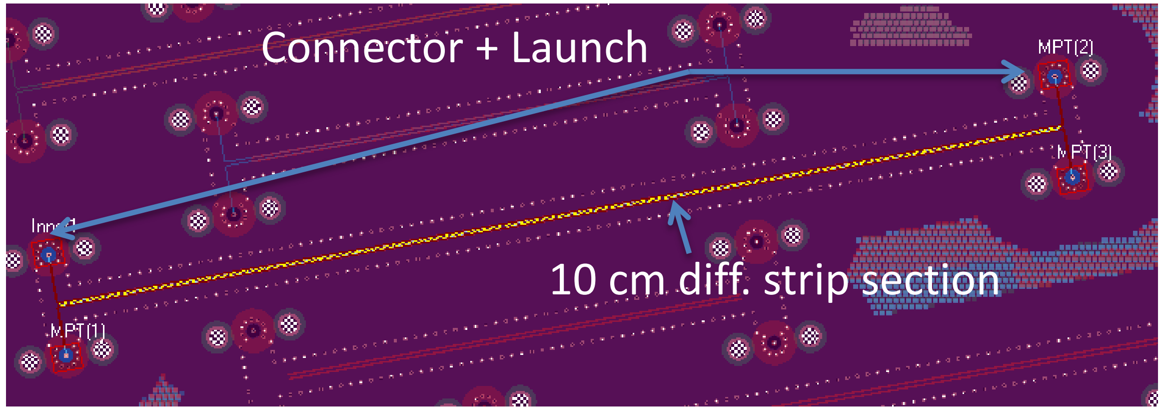
Reality: Still difference in reflection, launch is still more inductive than expected…

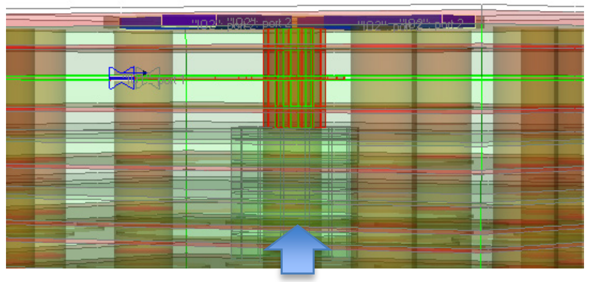




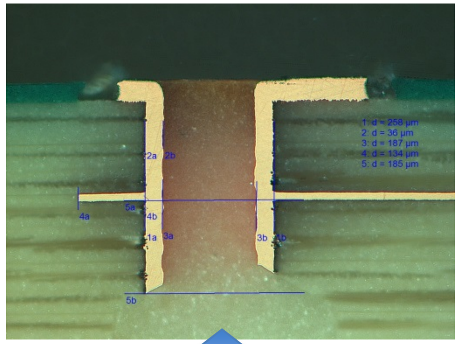
INNER1: 10 cm diff. strip link

De-compositional EM analysis
All trace widths and backdrill are adjusted





Via span adjusted as on x-section, air in backdrill



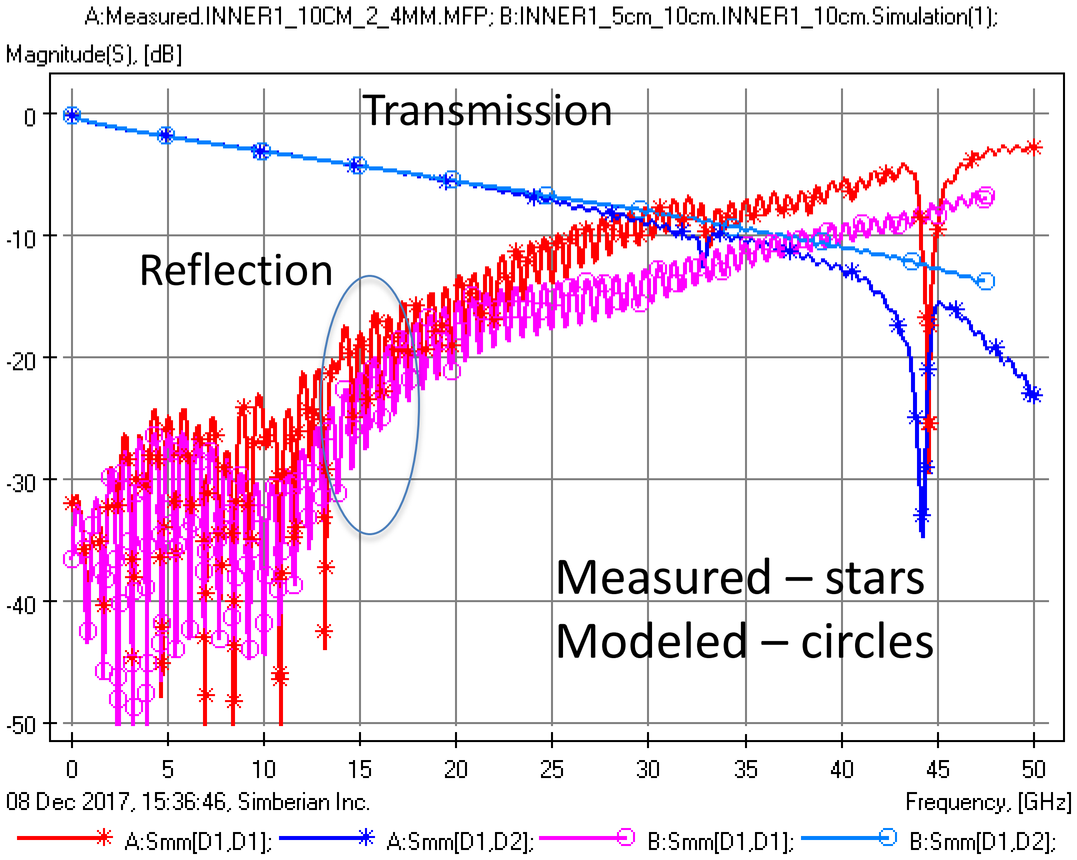
Air?

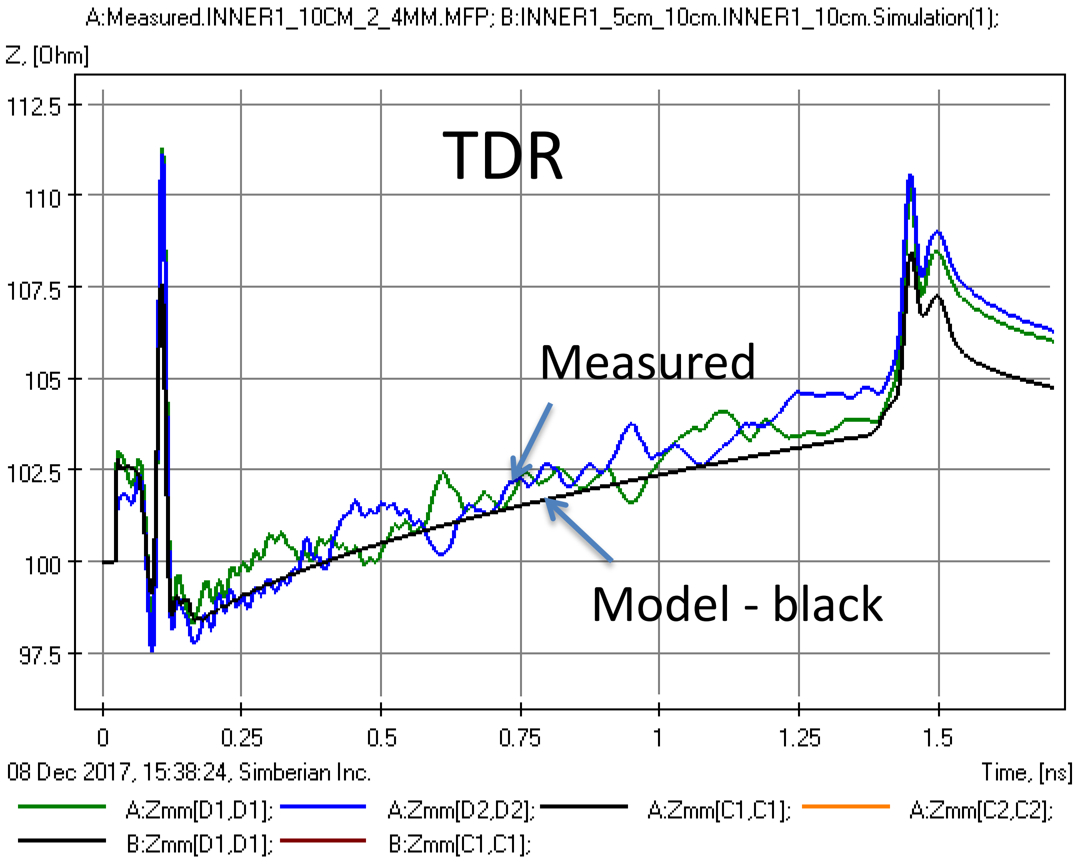
Differential S-parameters & TDR

Via simulated as tube, backdrilled area is filled with air

Reality: Difference in reflection, launch is more inductive than expected…

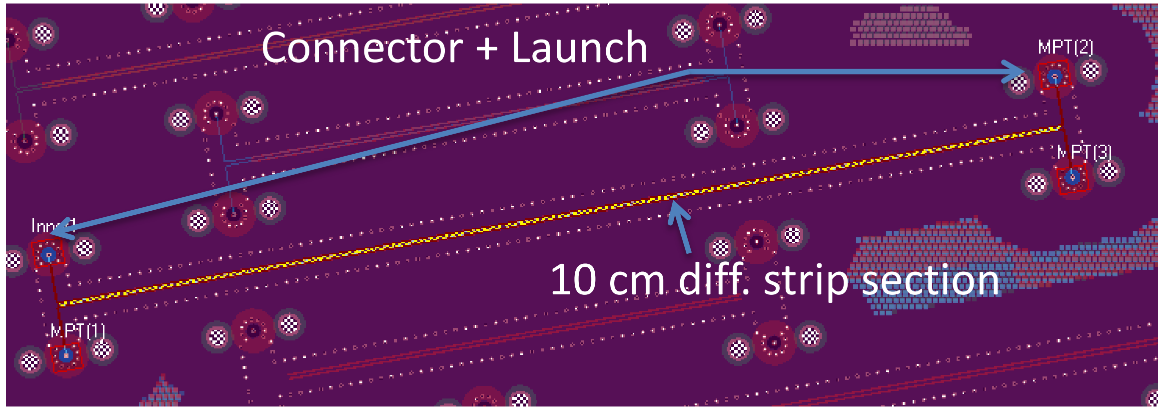
Acceptable correspondence up to 25 GHz

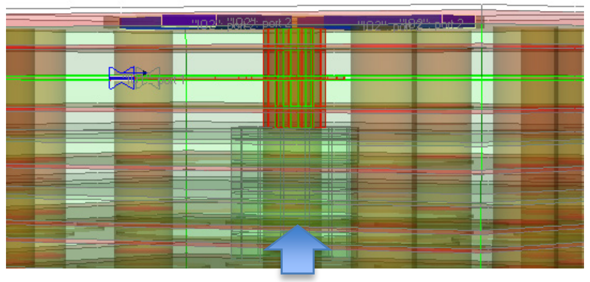




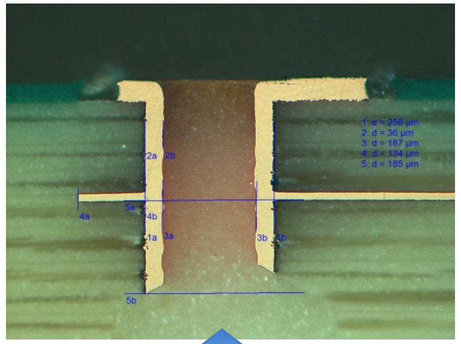
INNER1: 10 cm diff. strip link

De-compositional EM analysis
All trace widths and backdrill are adjusted





Via span adjusted as on x-section, air in backdrill

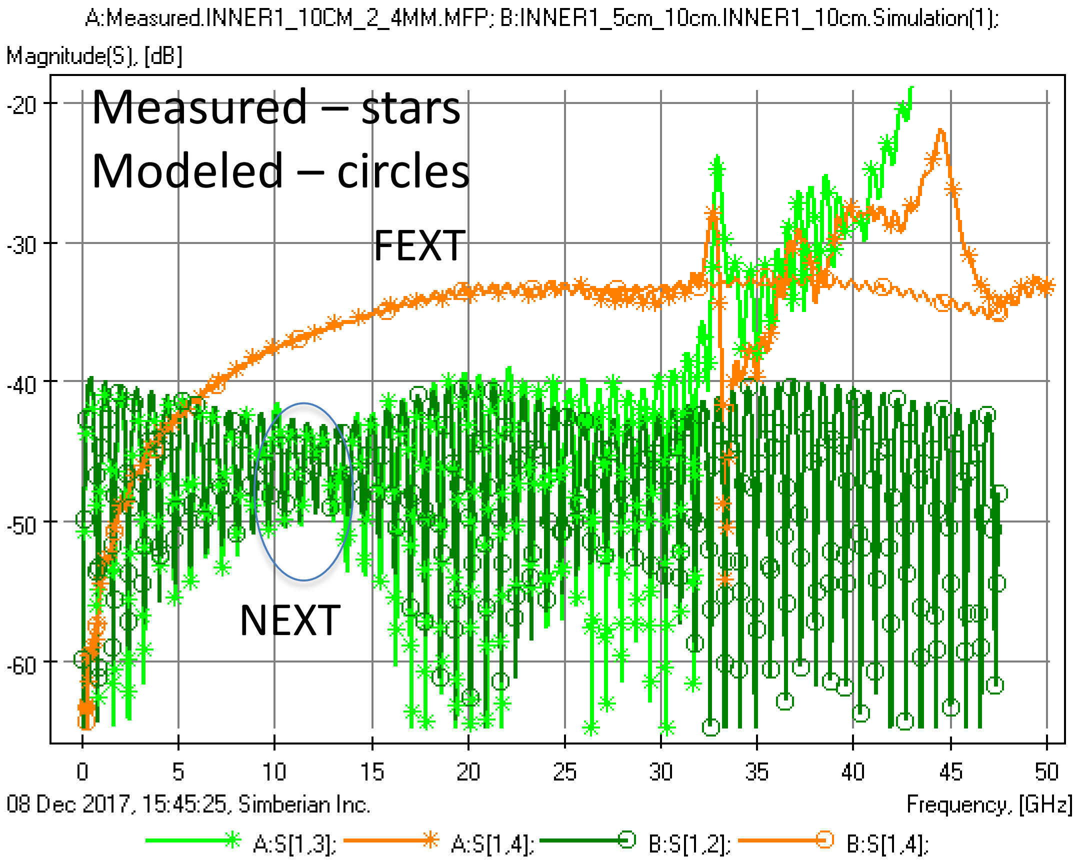


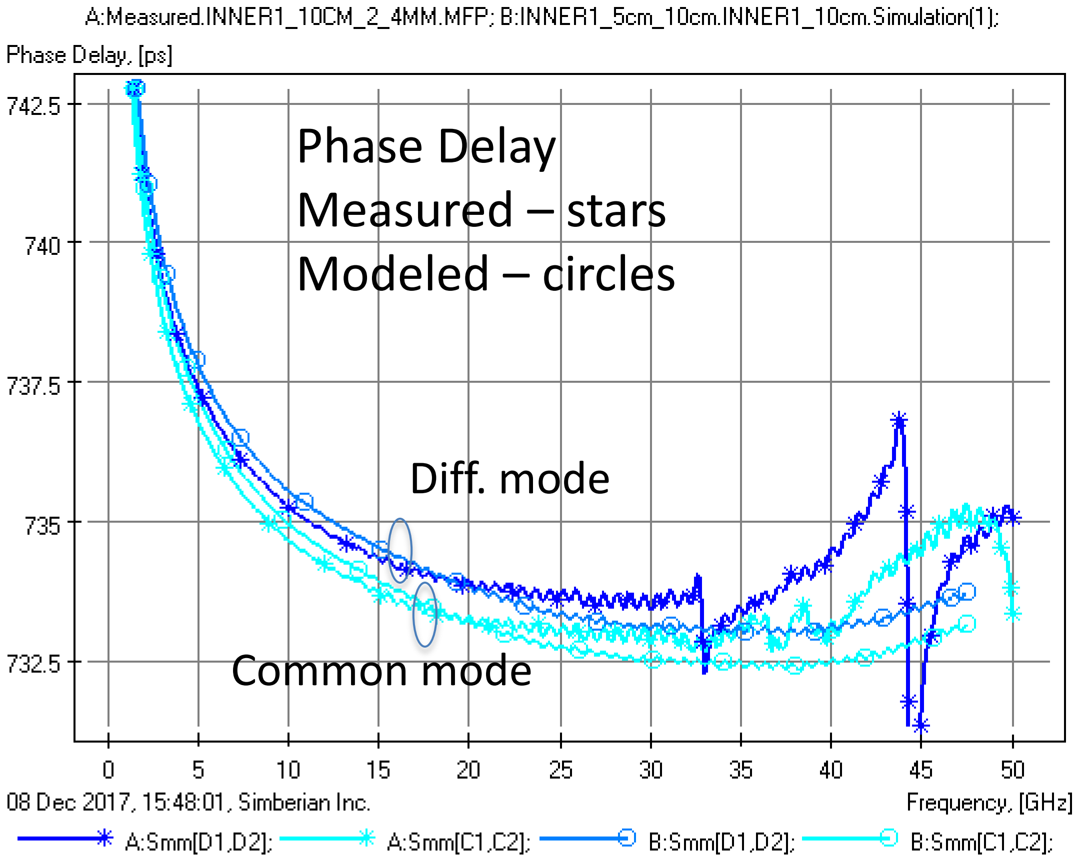
Air?

S-parameters

Via simulated as tube, backdrilled area is filled with air

Acceptable correspondence up to 25-30 GHz…





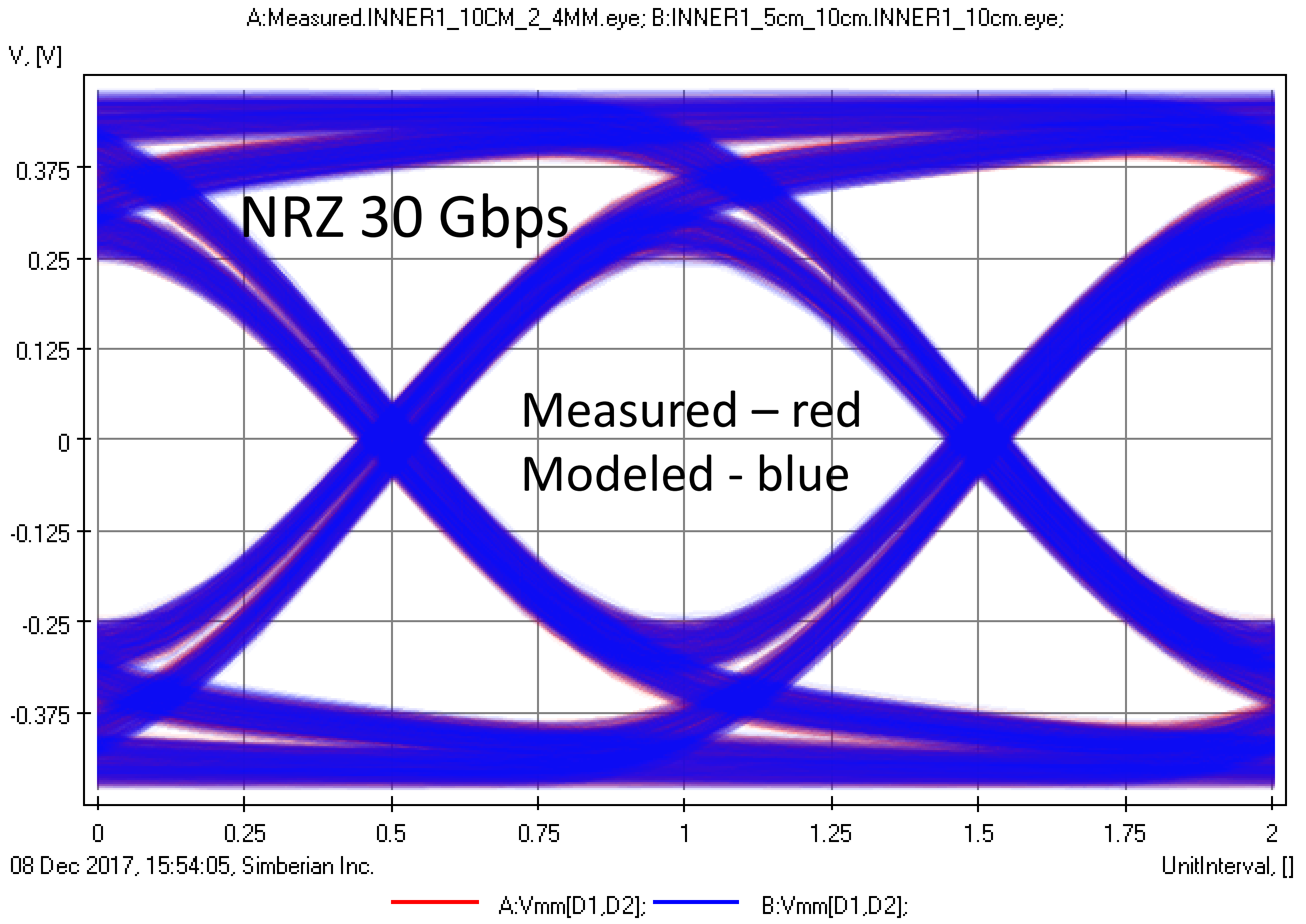
INNER1: 10 cm diff. strip link

- Eye diagrams comparison

Eye Analyzer

Show Eye Metrics: Selected ☑ Auto-open

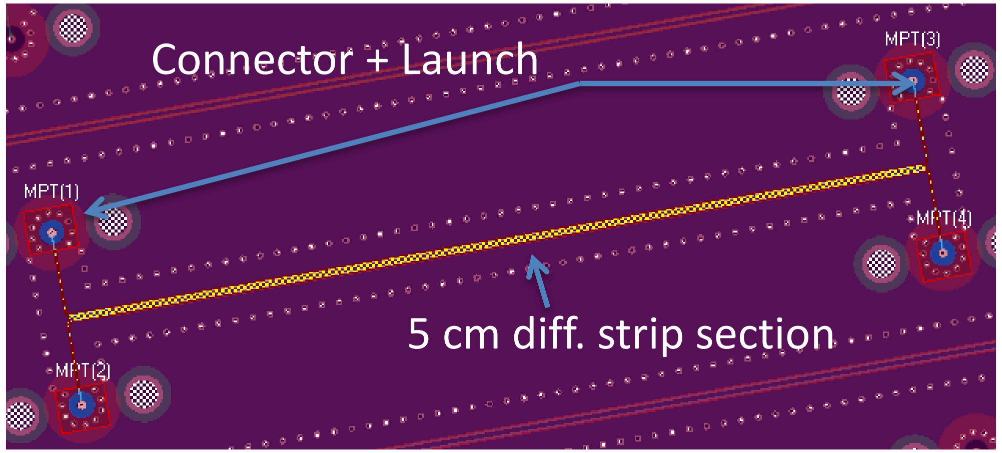
Parameter	Measured.INN...	INNER1_5cm_10...
Eye Level Zero (V)	-0.361166	-0.361673
Eye Level One (V)	0.357265	0.358314
Eye Level Mean (V)	-0.000858437	3.76714e-005
Eye Amplitude (V)	0.718431	0.719987
Eye Height (V)	0.479863	0.475425
Eye Width (UI)	0.883814	0.873171
Eye Opening Factor	0.667932	0.660324
Eye Signal to Noise	5.65211	5.40594
Eye Rise Time (20-80) (UI)	0.513887	0.517424
Eye Fall Time (80-20) (UI)	0.514326	0.518256
Eye Jitter (PP) (UI)	0.116186	0.126829
Eye Jitter (RMS) (UI)	0.0294568	0.0307682

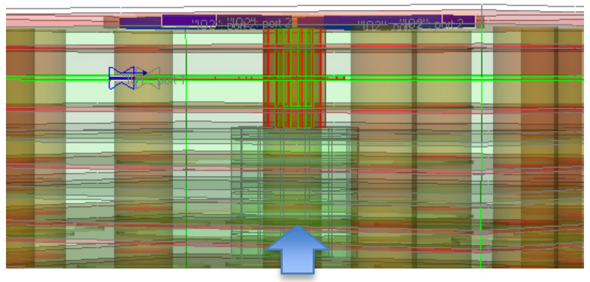


~1% difference in eye heights and widths; Possible reason – impedance variations, launch mismatch and localization loss…

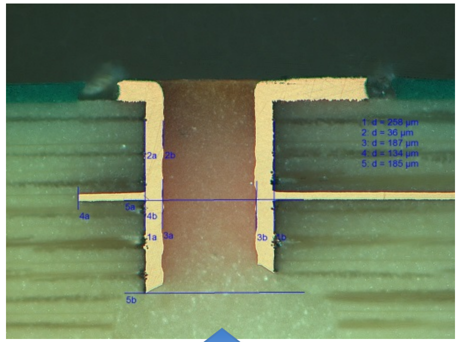
INNER1: 5 cm diff. strip link

De-compositional EM analysis
All trace widths and backdrill are adjusted





Via span adjusted as on x-section, air in backdrill



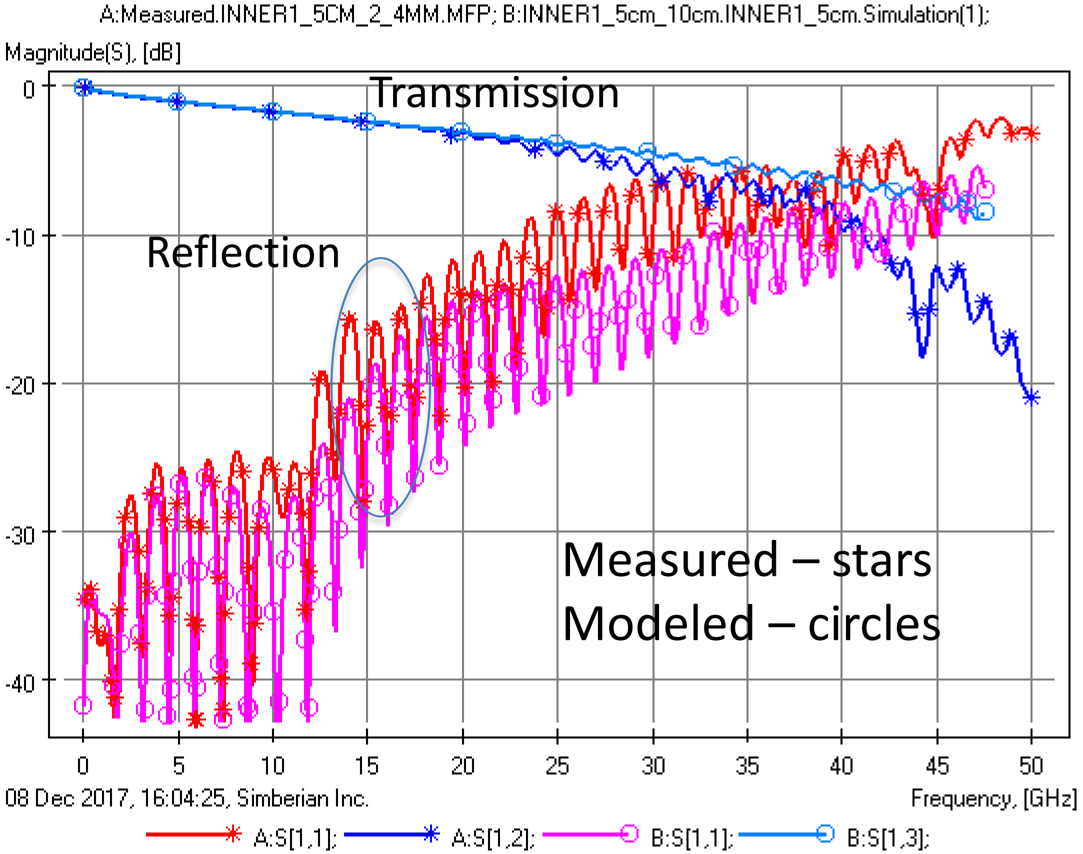
Air?

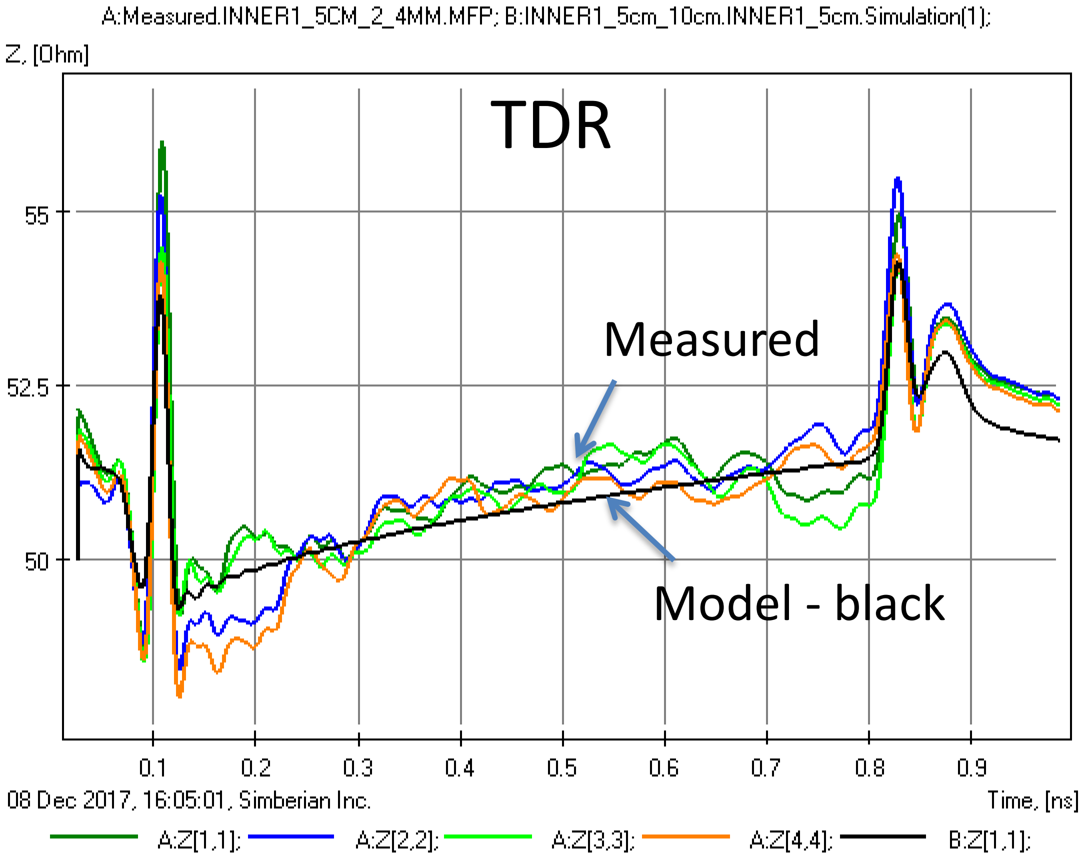
Single-ended S-parameters & TDR

Via simulated as tube, backdrilled area is filled with air

Reality: Difference in reflection, launch is more inductive than expected…

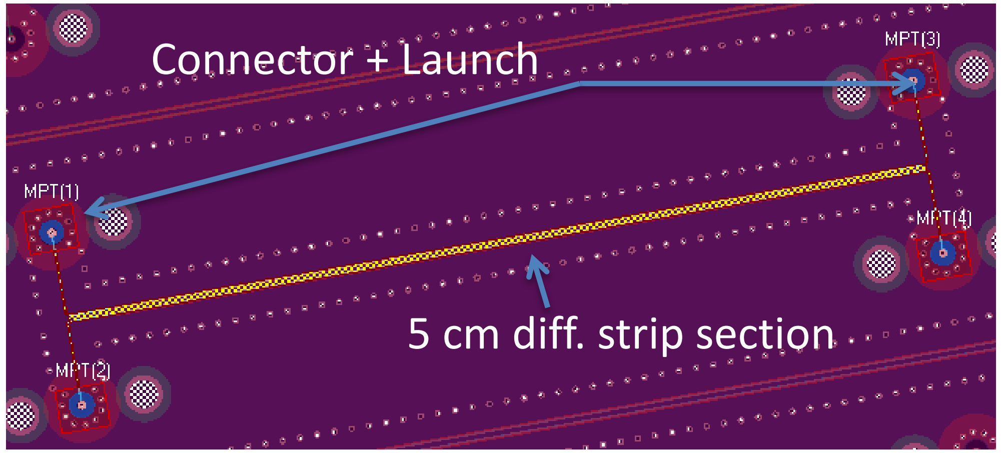
Acceptable correspondence up to 25 GHz

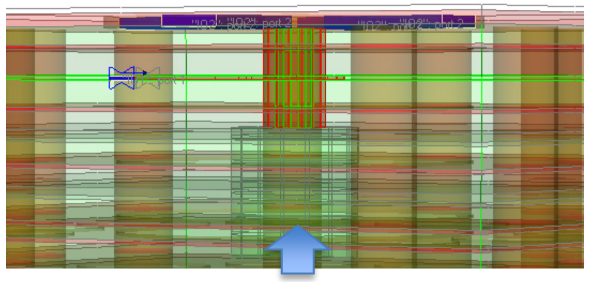




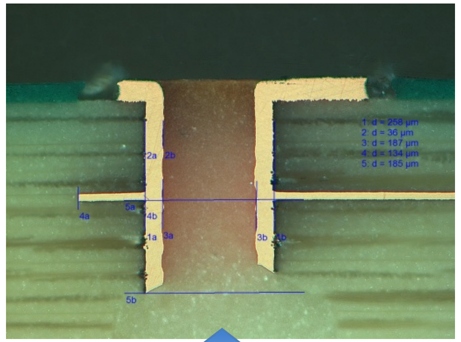
INNER1: 5 cm diff. strip link

De-compositional EM analysis
All trace widths and backdrill are adjusted





Via span adjusted as on x-section, air in backdrill



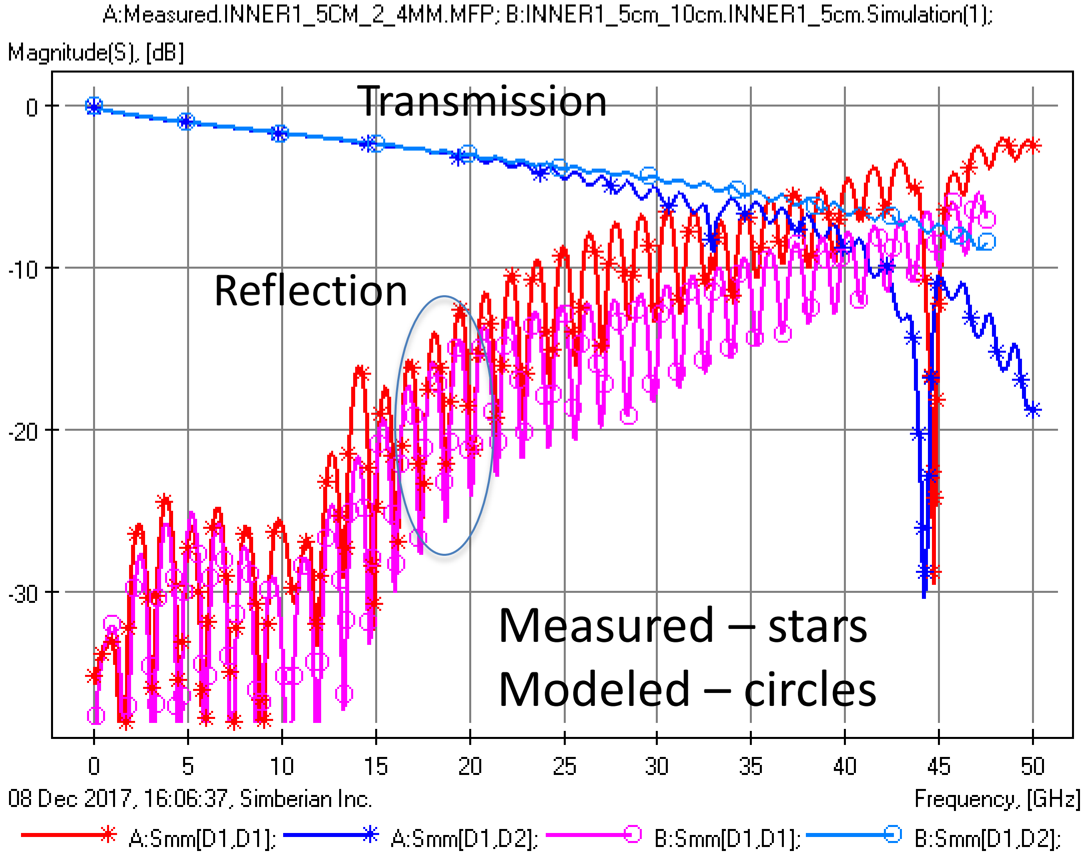
Air?

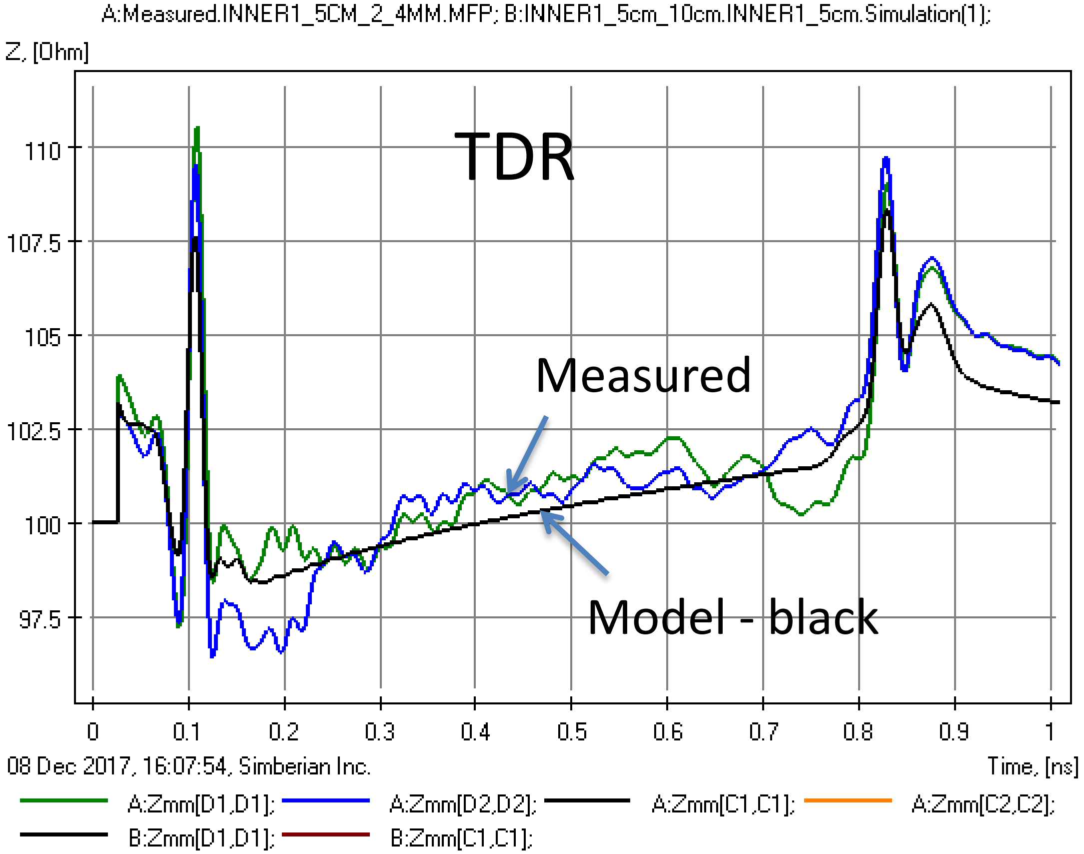
Differential S-parameters & TDR

Via simulated as tube, backdrilled area is filled with air

Reality: Difference in reflection, launch is more inductive than expected…

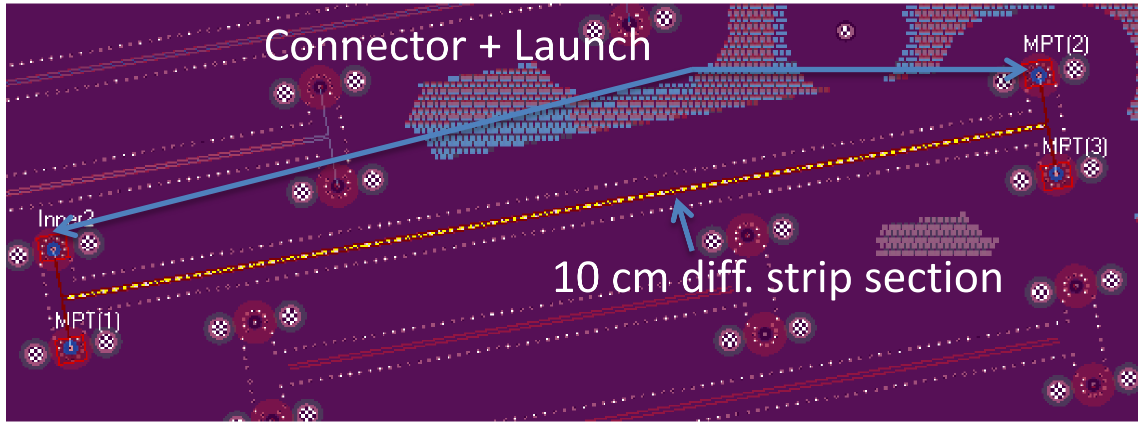
Acceptable correspondence up to 25 GHz

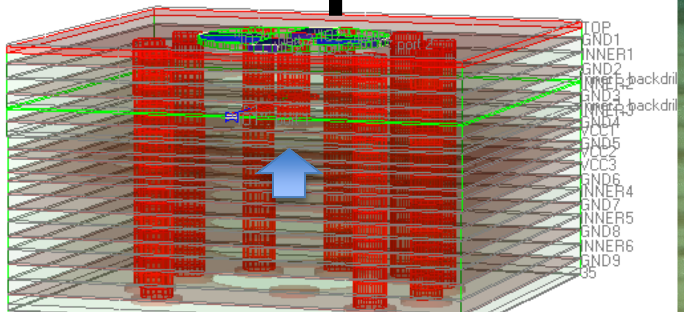




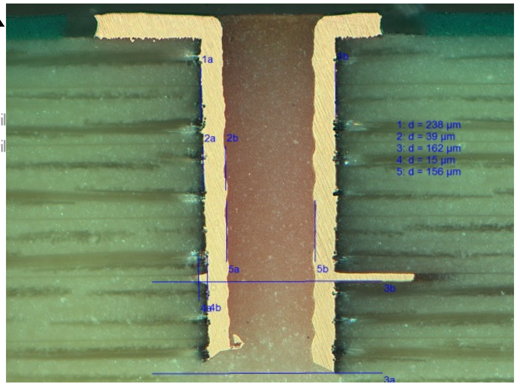
INNER2: 10 cm diff. strip link

De-compositional EM analysis
All trace widths and backdrill are adjusted





Via span adjusted as on x-section, no filling

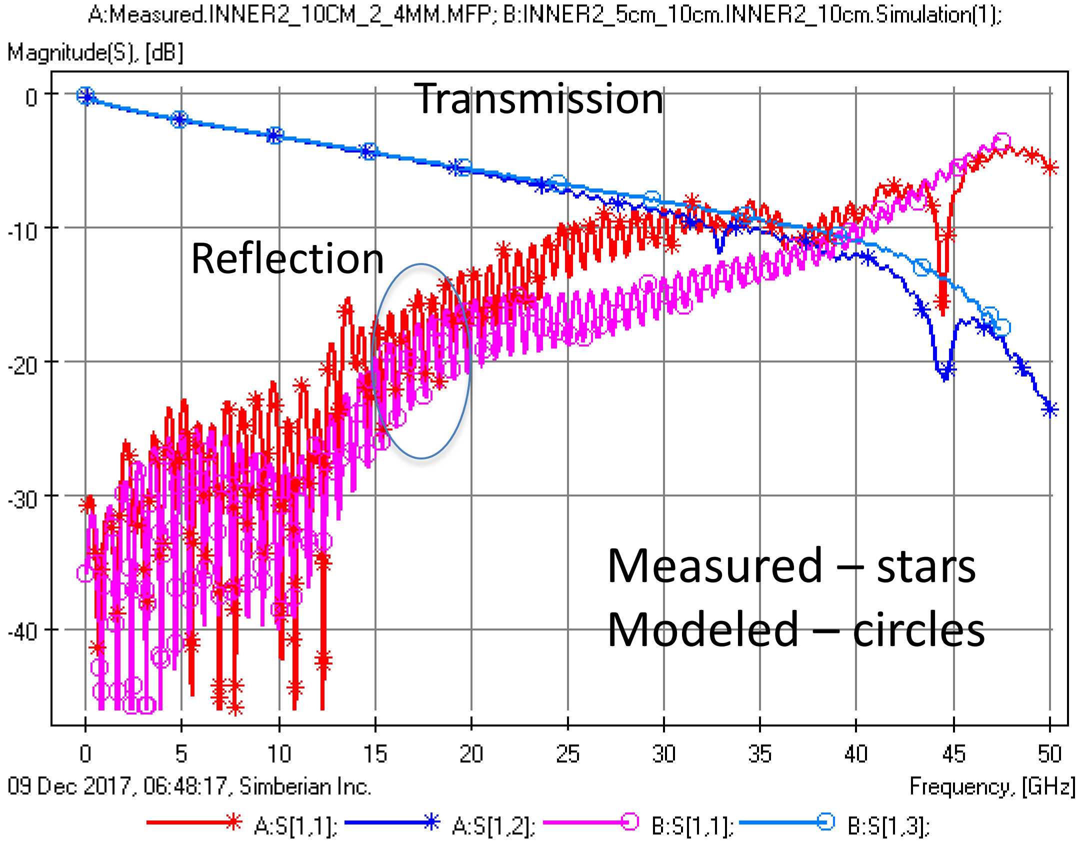


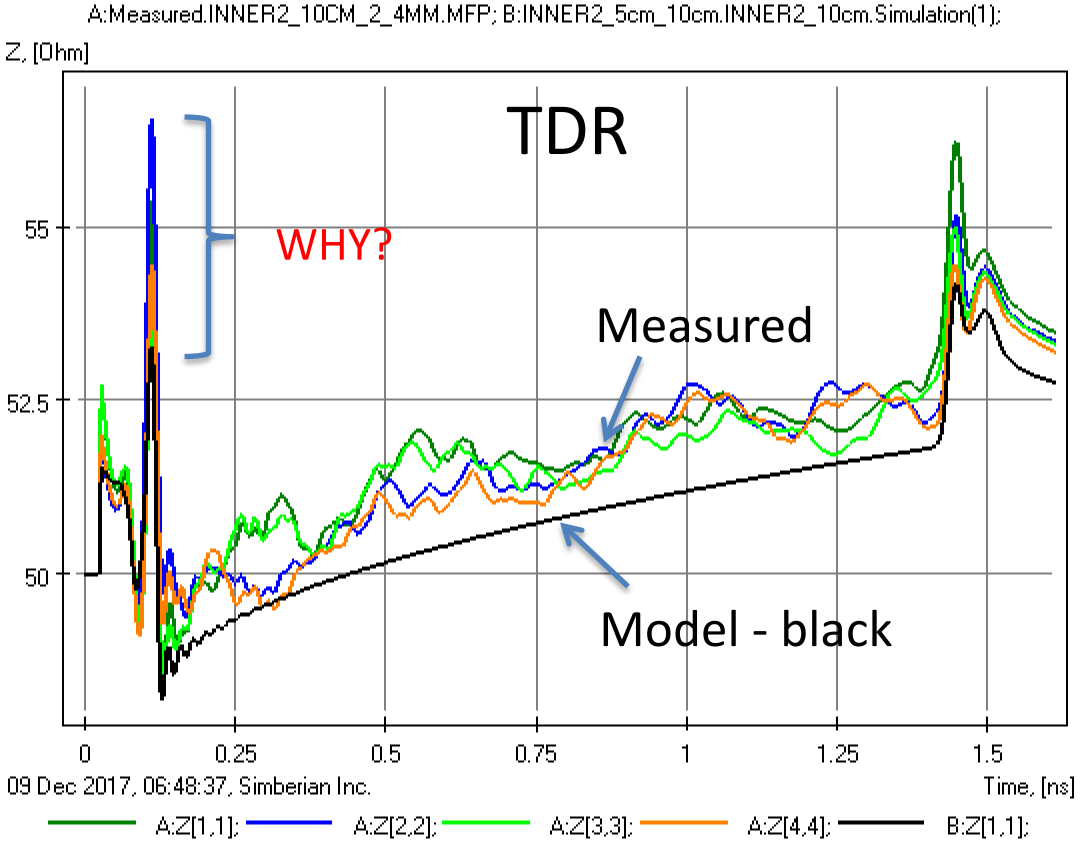
Epoxy?

Single-ended S-parameters & TDR

Via simulated as tube, no epoxy filling in the model - epoxy Dk is close to Dk of the layers (3.4)

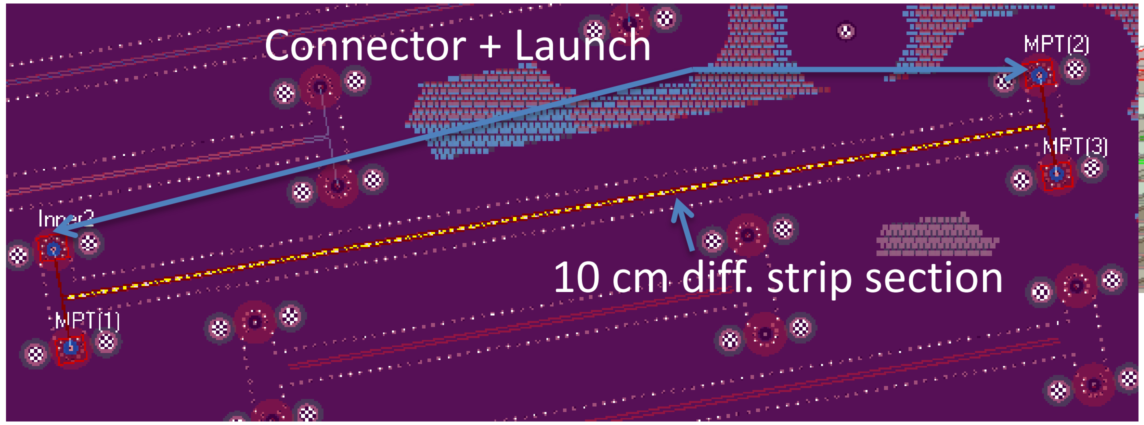
Reality: Large difference in reflection, launch is much more inductive than expected, TDR impedance is higher (trace width is 95 um instead of 99 um)…

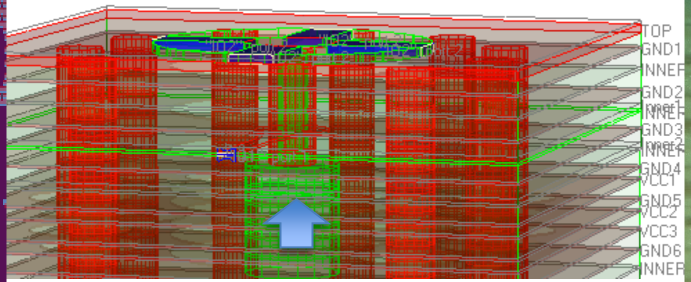




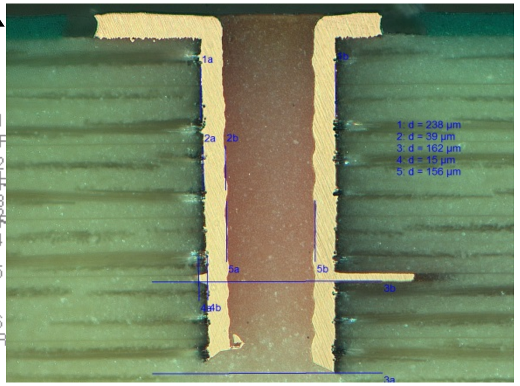
INNER2: 10 cm diff. strip link

De-compositional EM analysis
All trace widths and backdrill are adjusted





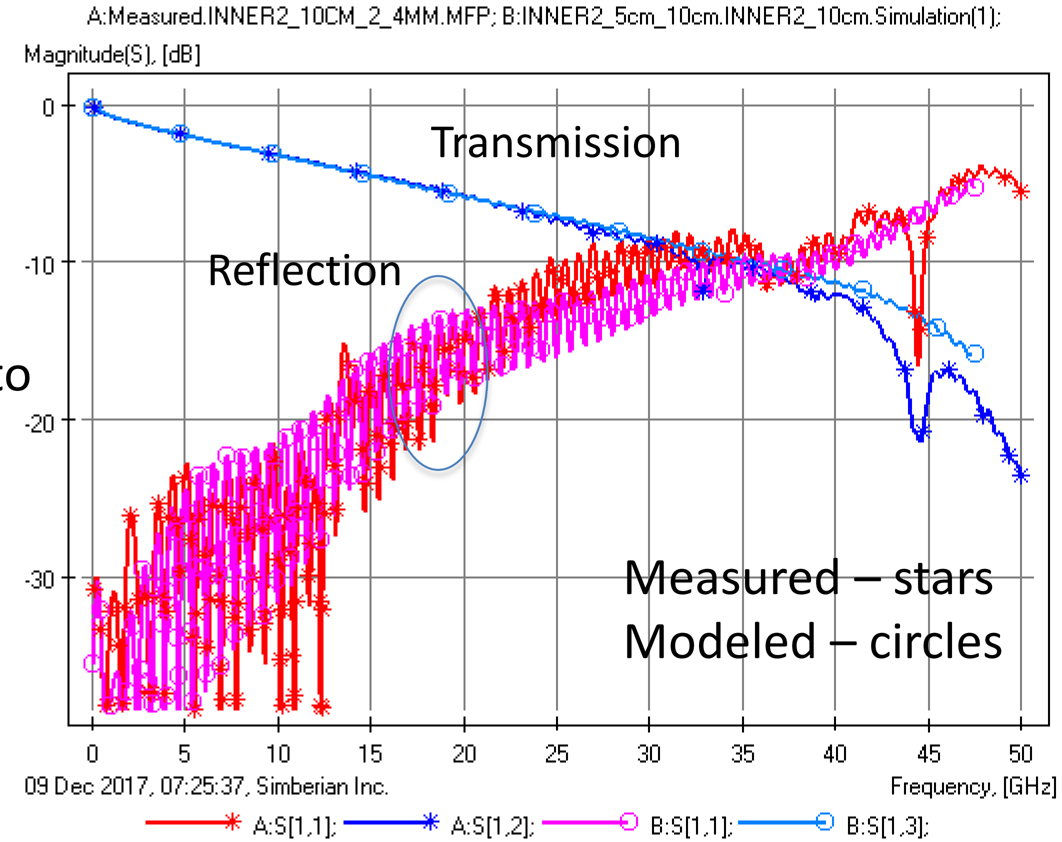
Via span adjusted as on x-section, air in backdrill

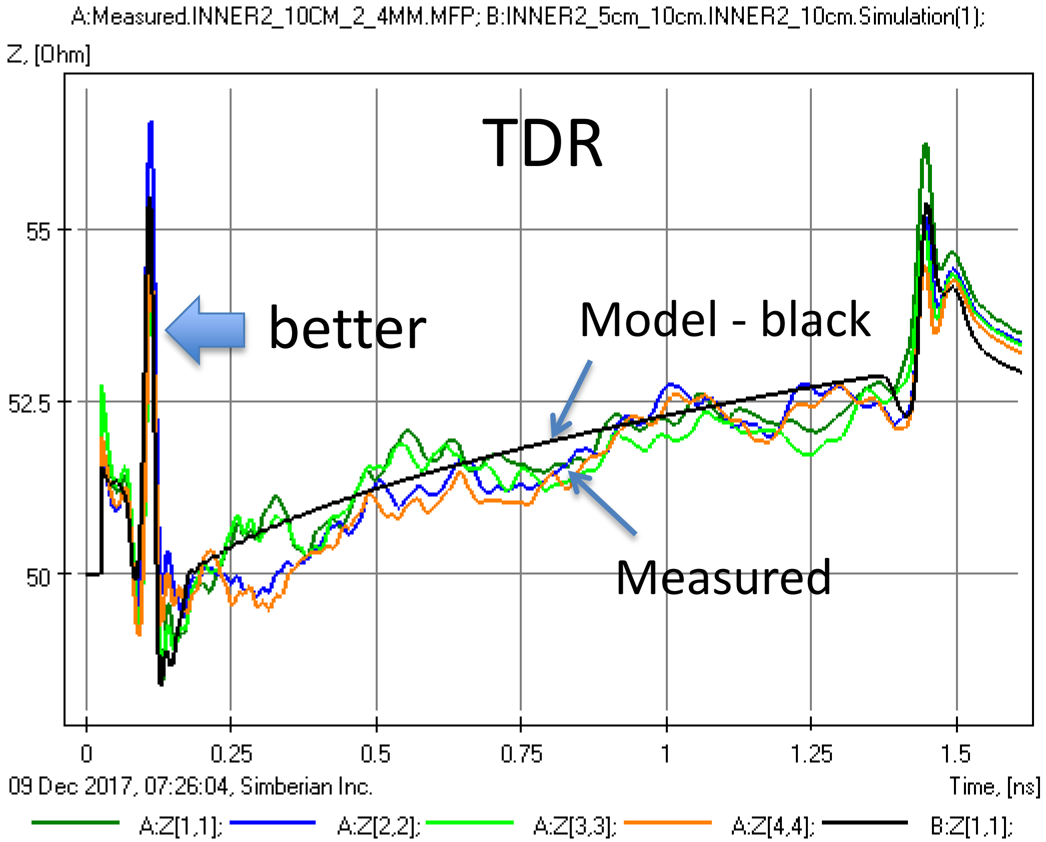


Single-ended S-parameters & TDR

Via simulated as tube, backdrilled area is filled with air

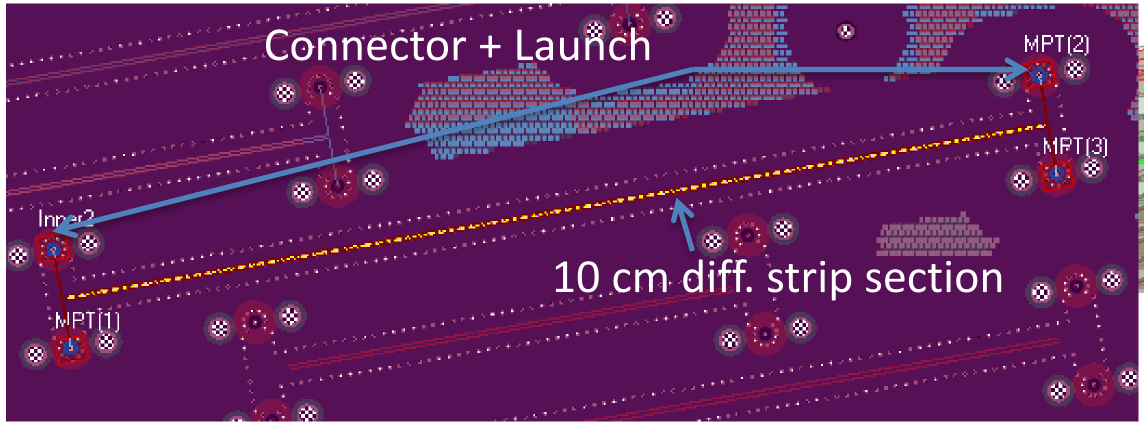
Acceptable correlation up to 25-30 GHz

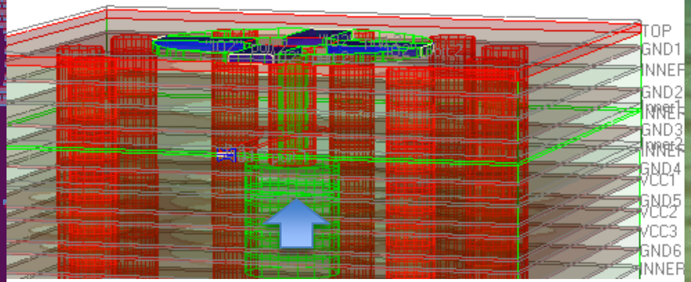


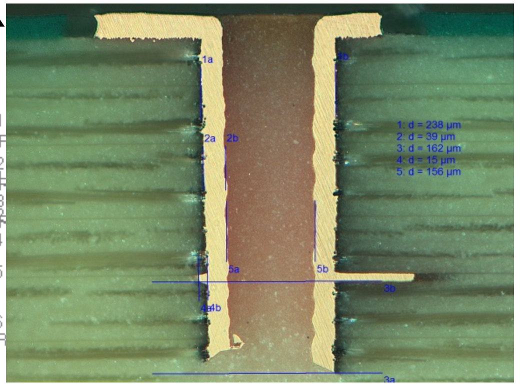


INNER2: 10 cm diff. strip link

De-compositional EM analysis
All trace widths and backdrill are adjusted







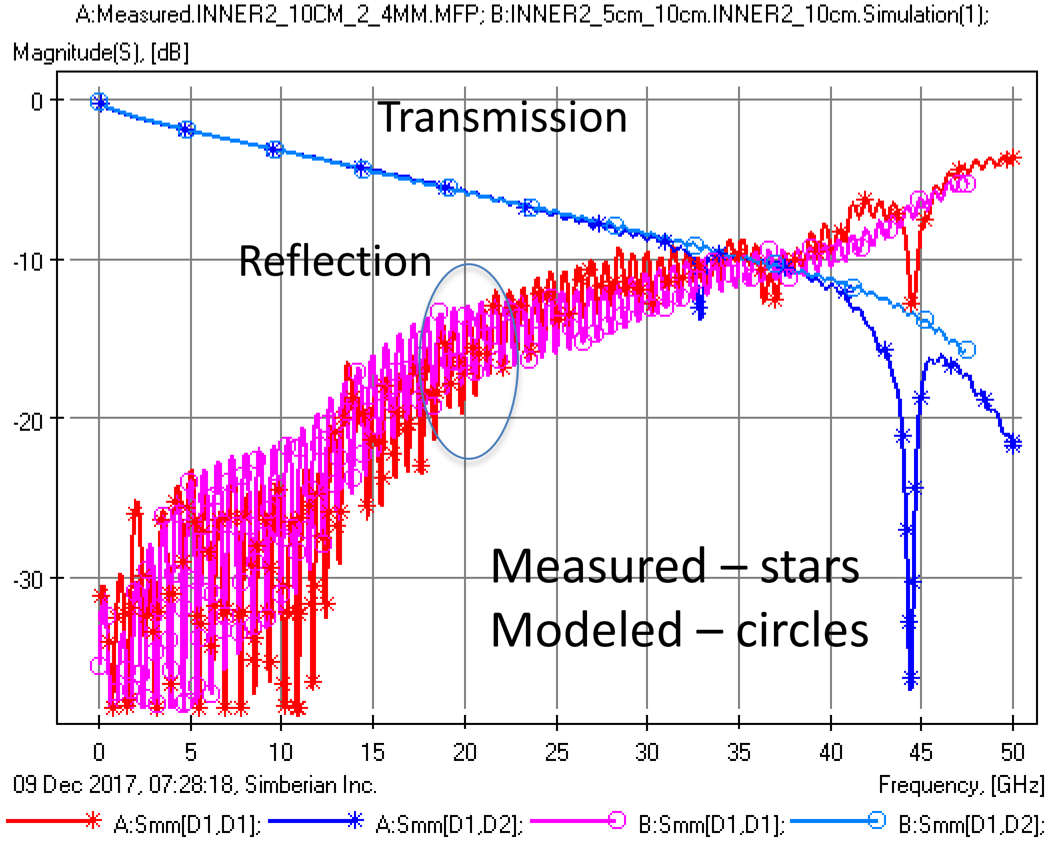
Via span adjusted as on x-section, air in backdrill

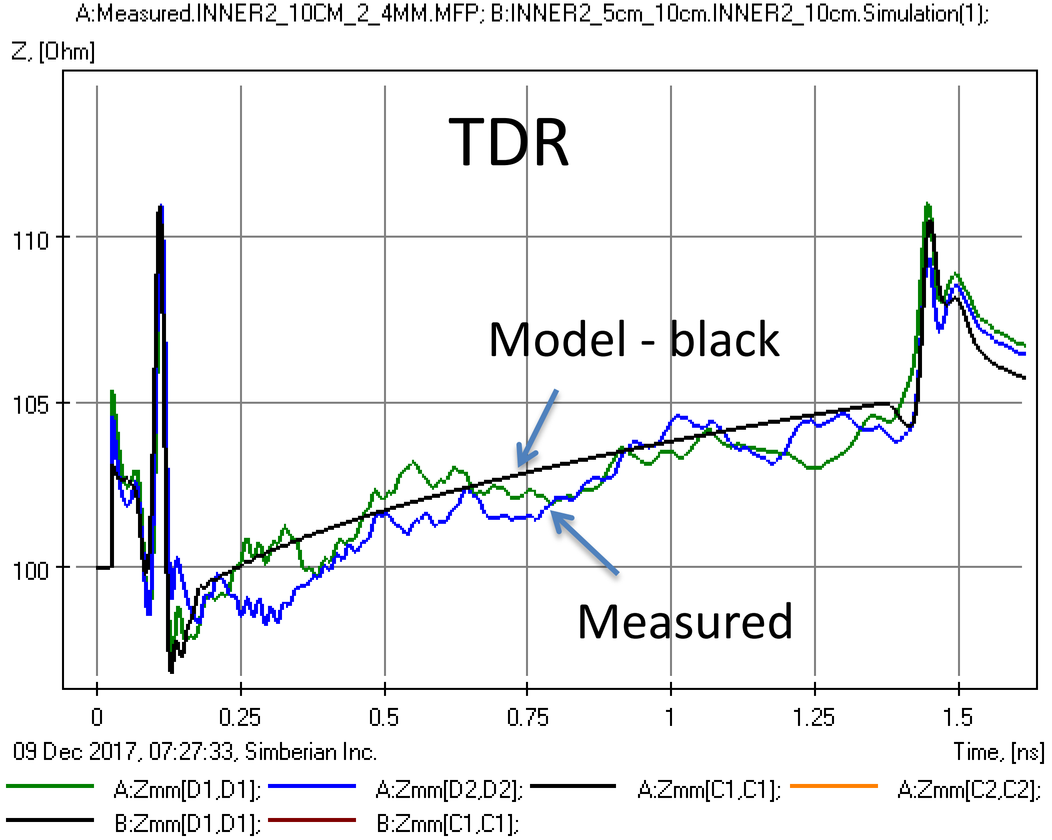
Air?

Differential S-parameters & TDR

Via simulated as tube, backdrilled area is filled with air

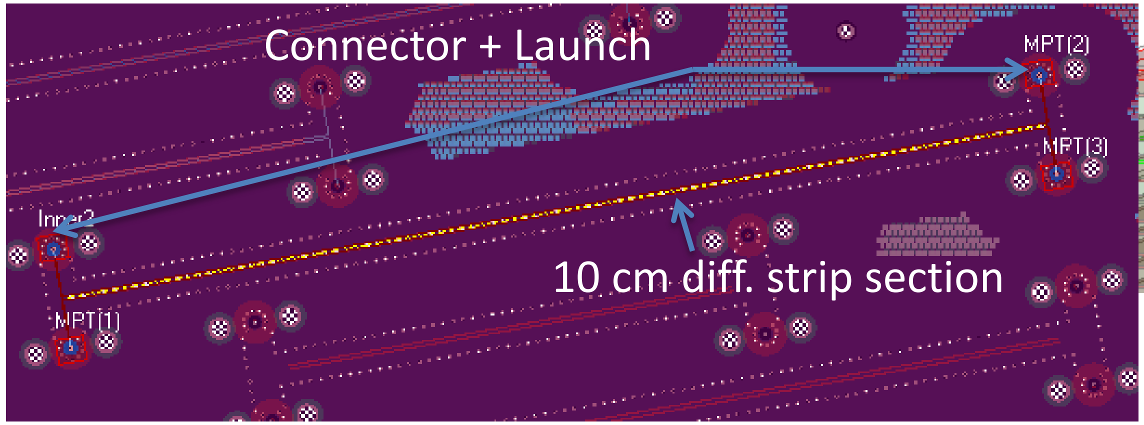
Acceptable correspondence up to 25-30 GHz

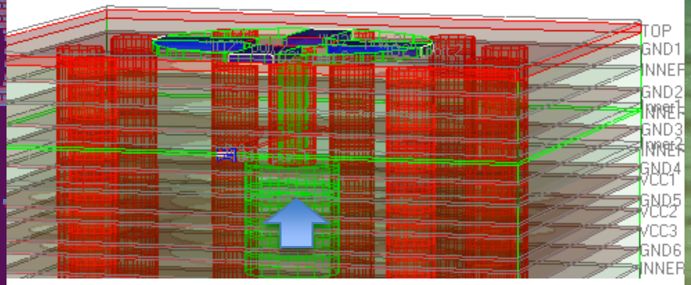




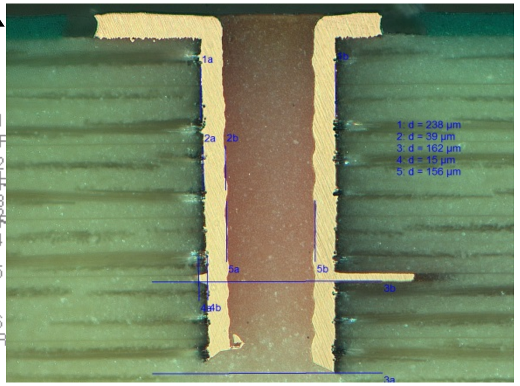
INNER2: 10 cm diff. strip link

De-compositional EM analysis
All trace widths and backdrill are adjusted





Via span adjusted as on x-section, air in backdrill

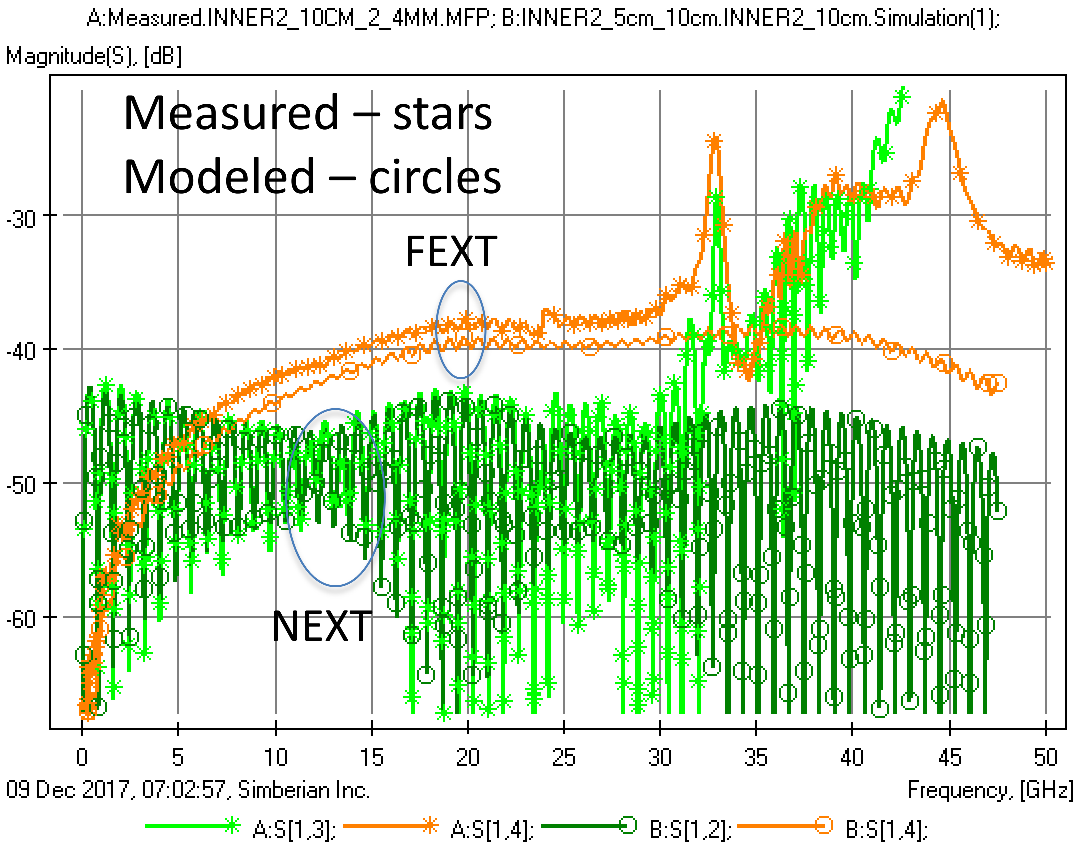


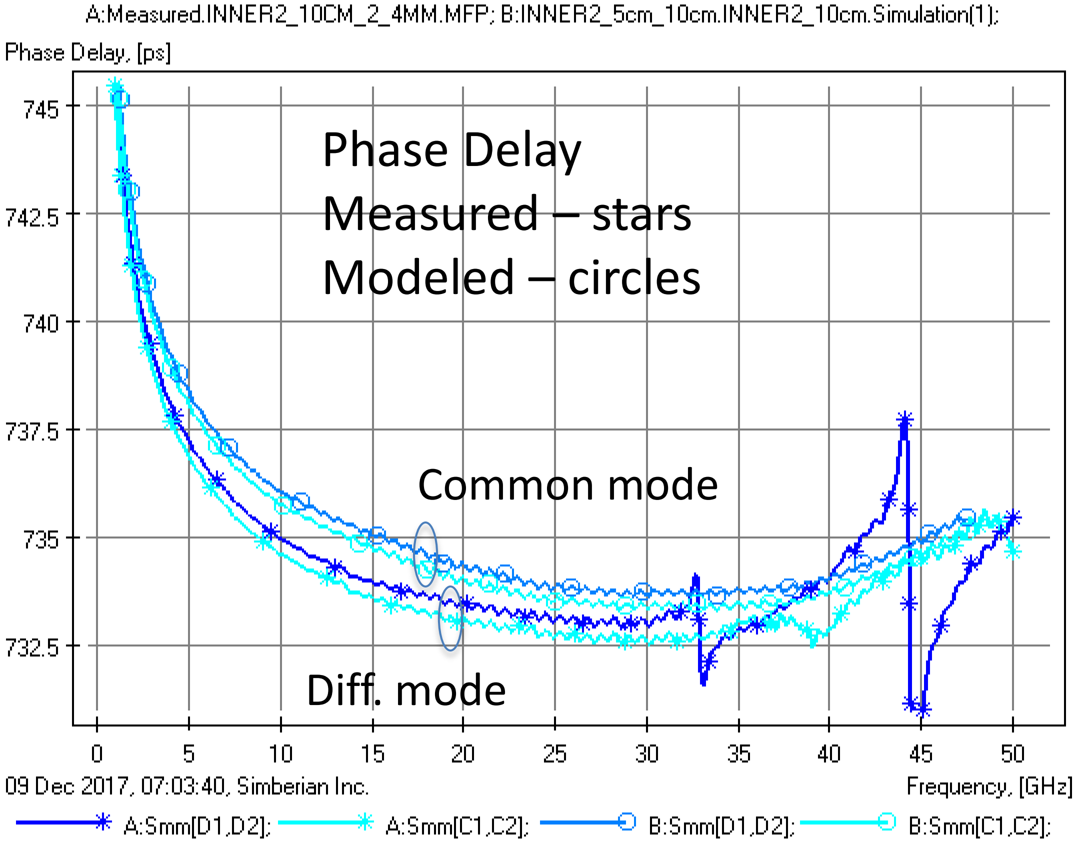
Air?

S-parameters

Via simulated as tube, backdrilled area is filled with air

Acceptable correspondence up to 25-30 GHz…





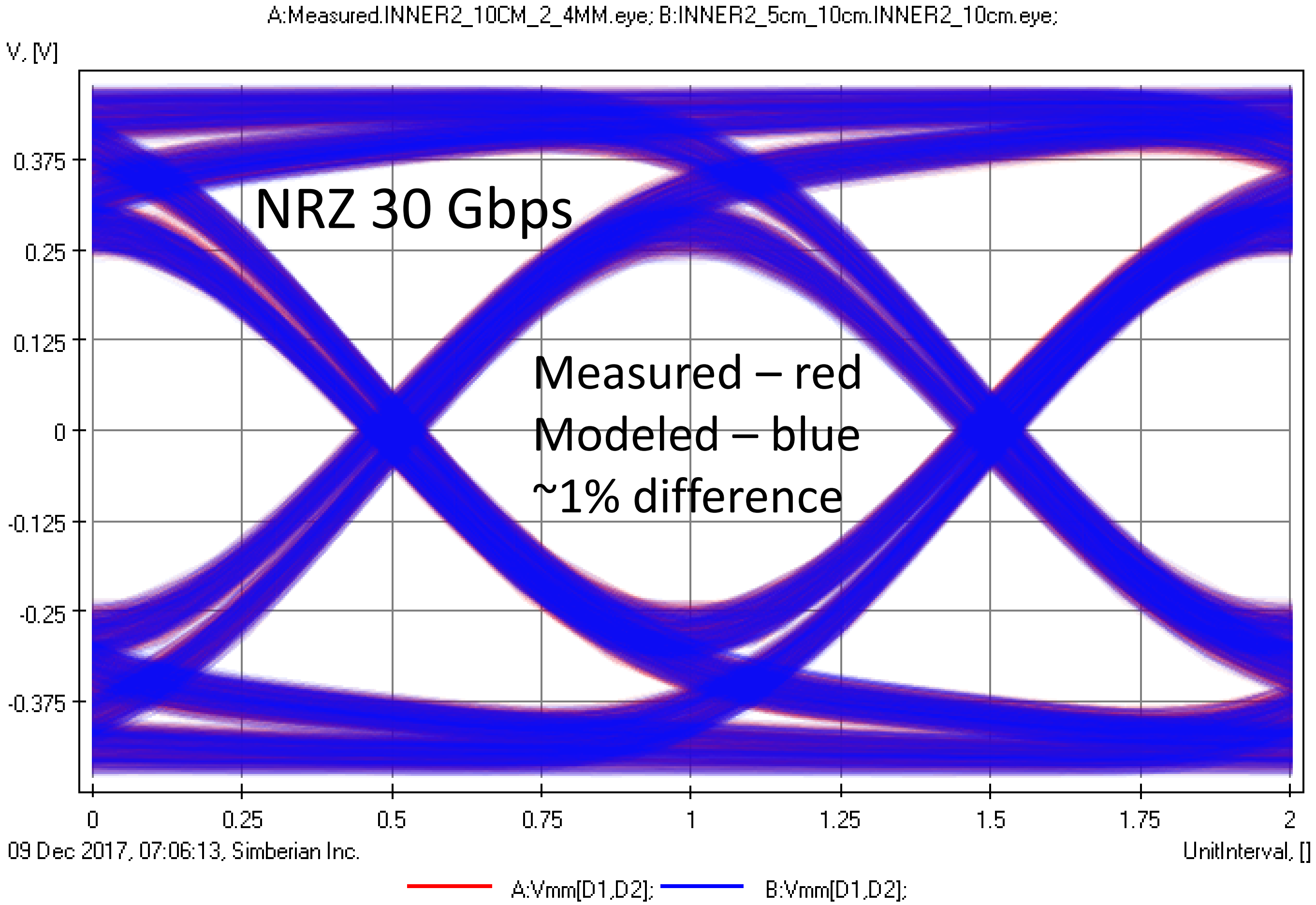
INNER2: 10 cm diff. strip link

- Eye diagrams comparison

Eye Analyzer

Show Eye Metrics: Selected ☑ Auto-open

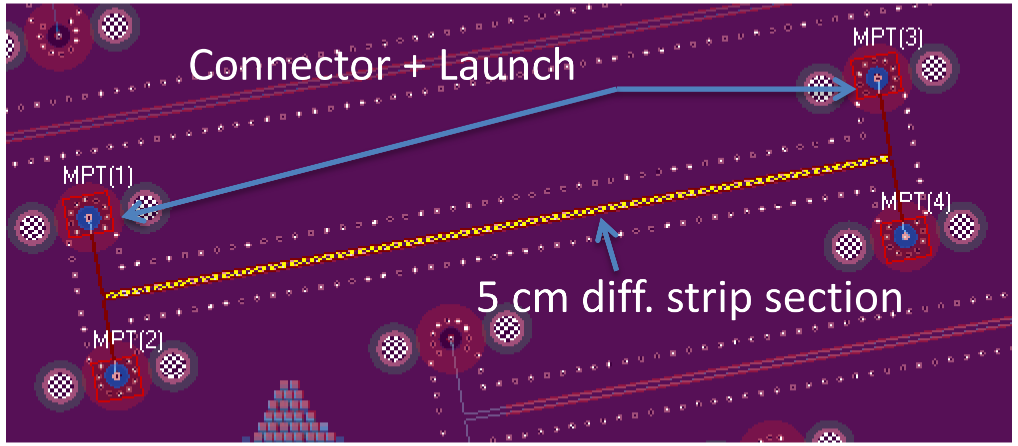
Parameter	Measured.INN...	INNER2_5cm_10...
Eye Level Zero (V)	-0.355785	-0.355356
Eye Level One (V)	0.353314	0.351455
Eye Level Mean (V)	-0.000921103	-0.00111774
Eye Amplitude (V)	0.709099	0.706812
Eye Height (V)	0.467076	0.465506
Eye Width (UI)	0.875831	0.870953
Eye Opening Factor	0.658689	0.6586
Eye Signal to Noise	5.46346	5.33217
Eye Rise Time (20-80) (UI)	0.516625	0.515859
Eye Fall Time (80-20) (UI)	0.51764	0.517155
Eye Jitter (PP) (UI)	0.124169	0.129047
Eye Jitter (RMS) (UI)	0.0314568	0.0307587

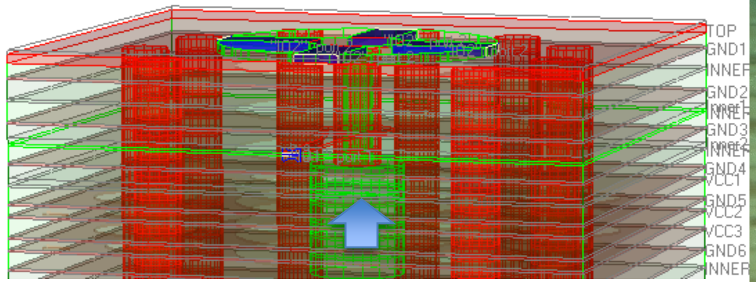


~1% difference in eye heights and widths; Possible reason – impedance variations, launch mismatch and localization loss…

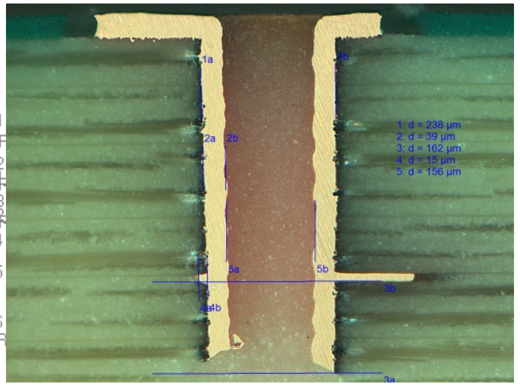
INNER2: 5 cm diff. strip link

De-compositional EM analysis
All trace widths and backdrill are adjusted





Via span adjusted as on x-section, air in backdrill

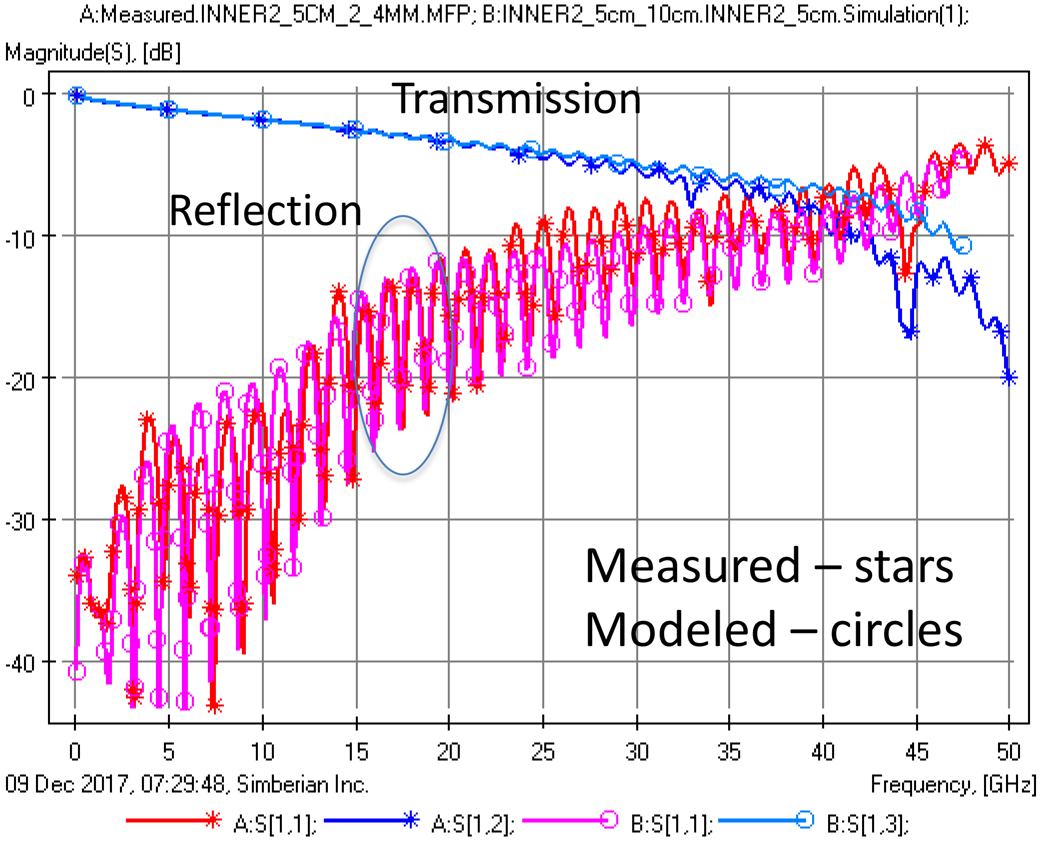


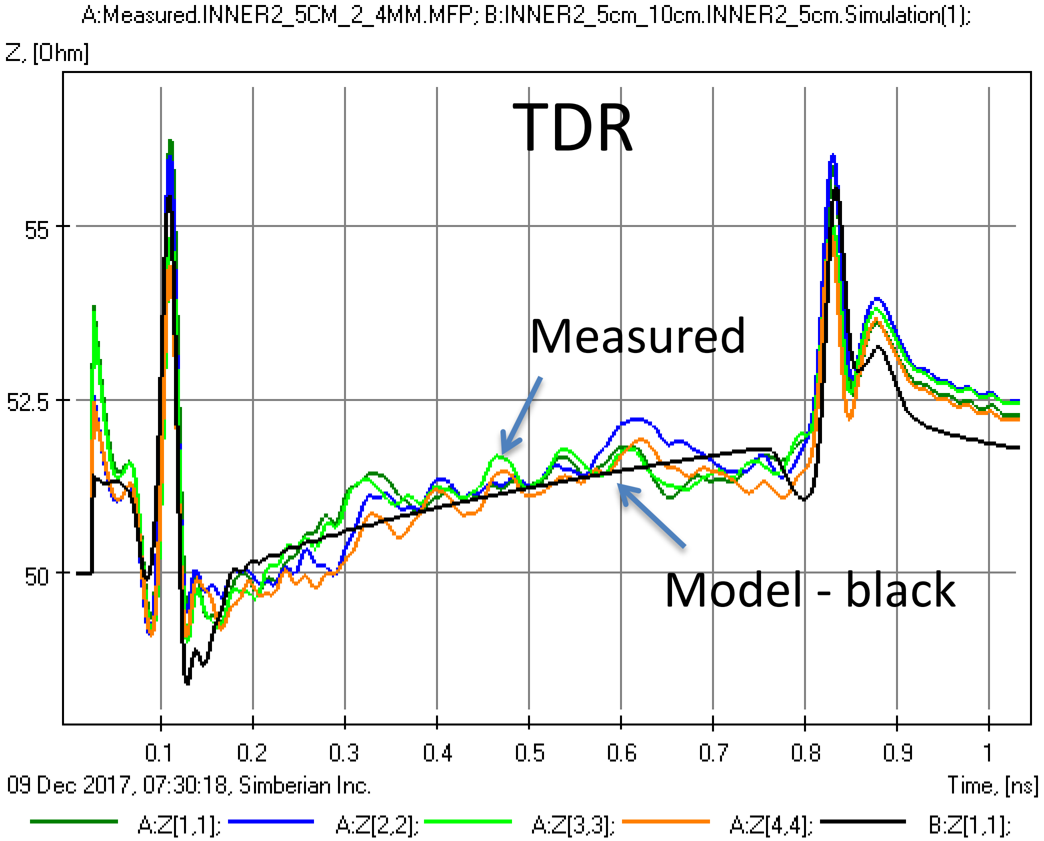
Air?

Single-ended S-parameters & TDR

Via simulated as tube, backdrilled area is filled with air

Acceptable correspondence up to 25-30 GHz

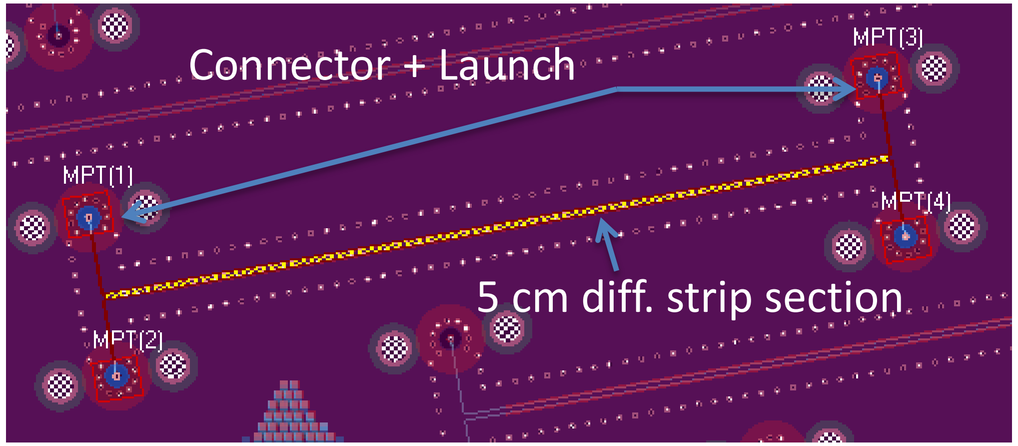


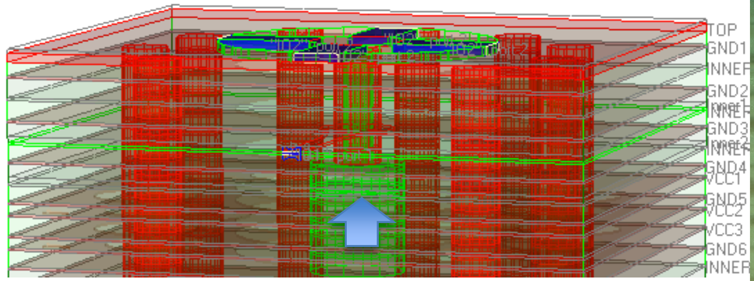


INNER2: 5 cm diff. strip link

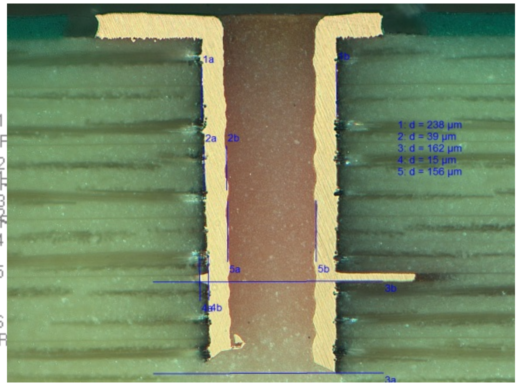
De-compositional EM analysis
All trace widths and backdrill are adjusted

Differential S-parameters & TDR





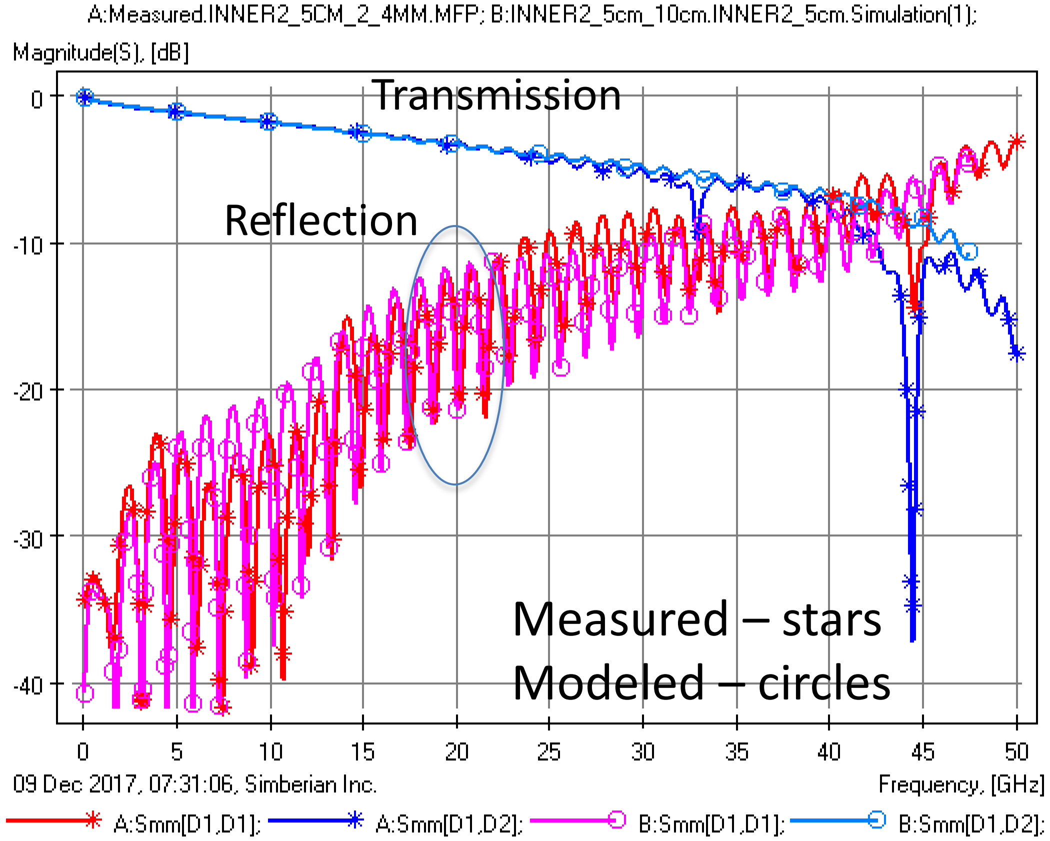
Via span adjusted as on x-section, air in backdrill

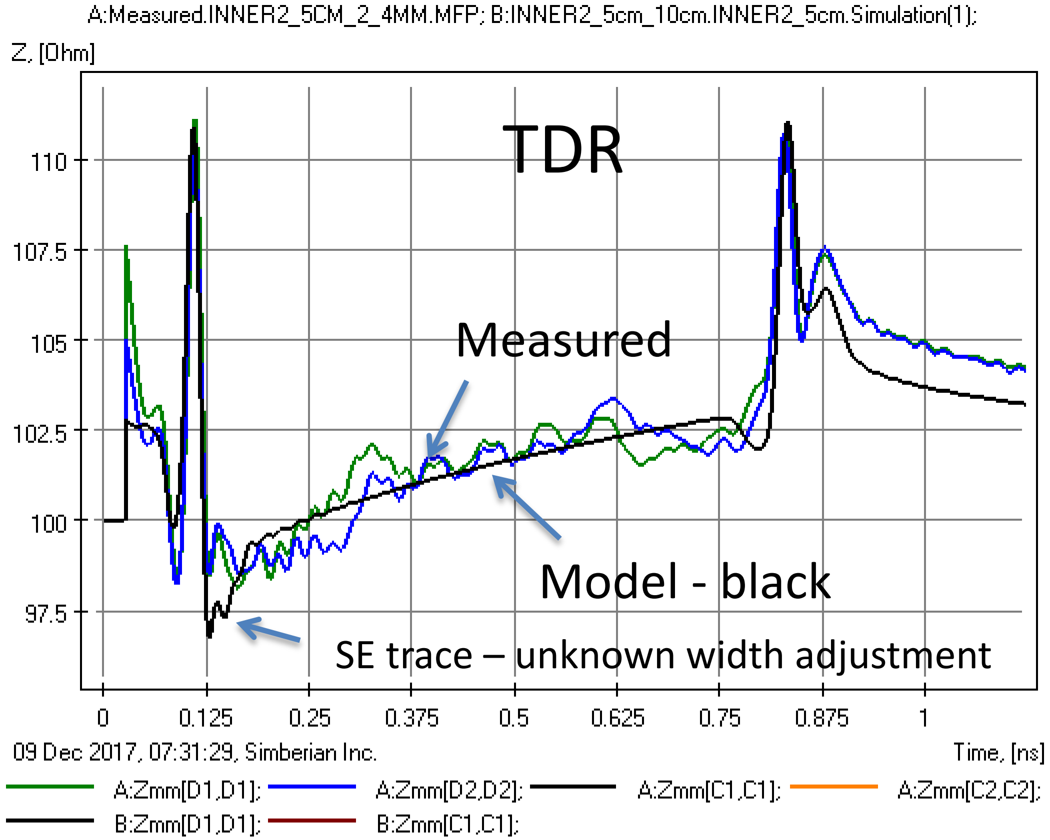


Air?

Via simulated as tube, backdrilled area is filled with air

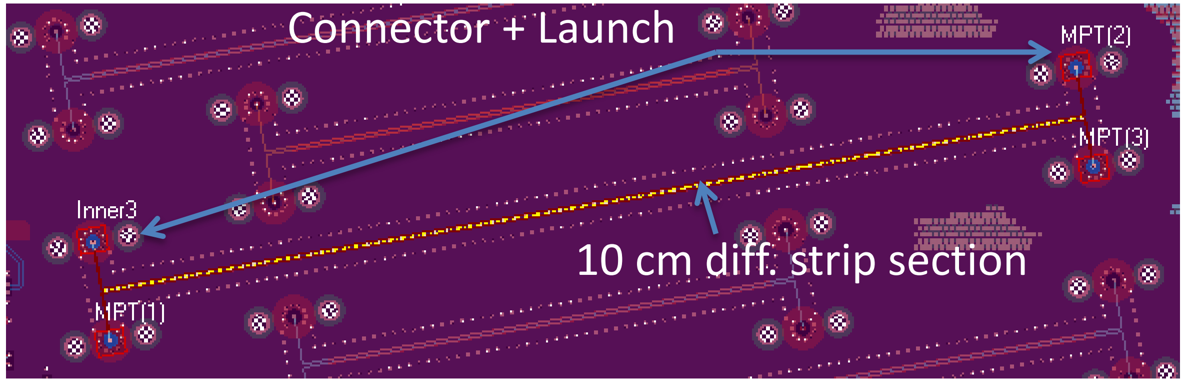
Acceptable correspondence up to 25-30 GHz



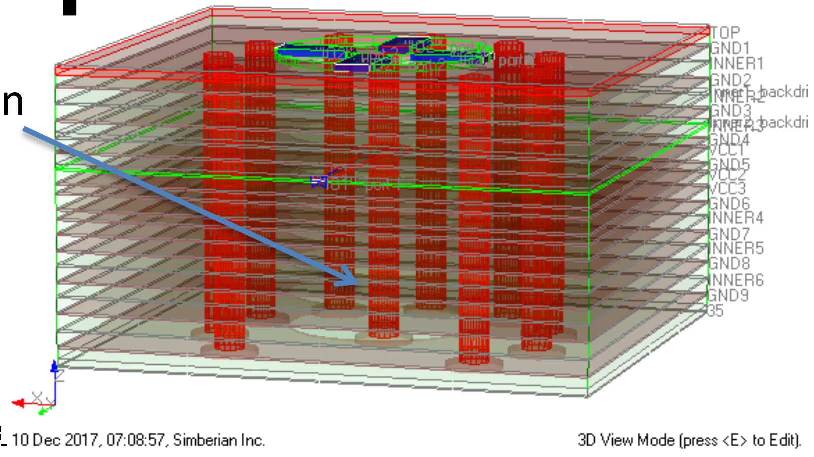


INNER3: 10 cm diff. strip link

De-compositional EM analysis
All trace widths are adjusted



Long stubs in all launches

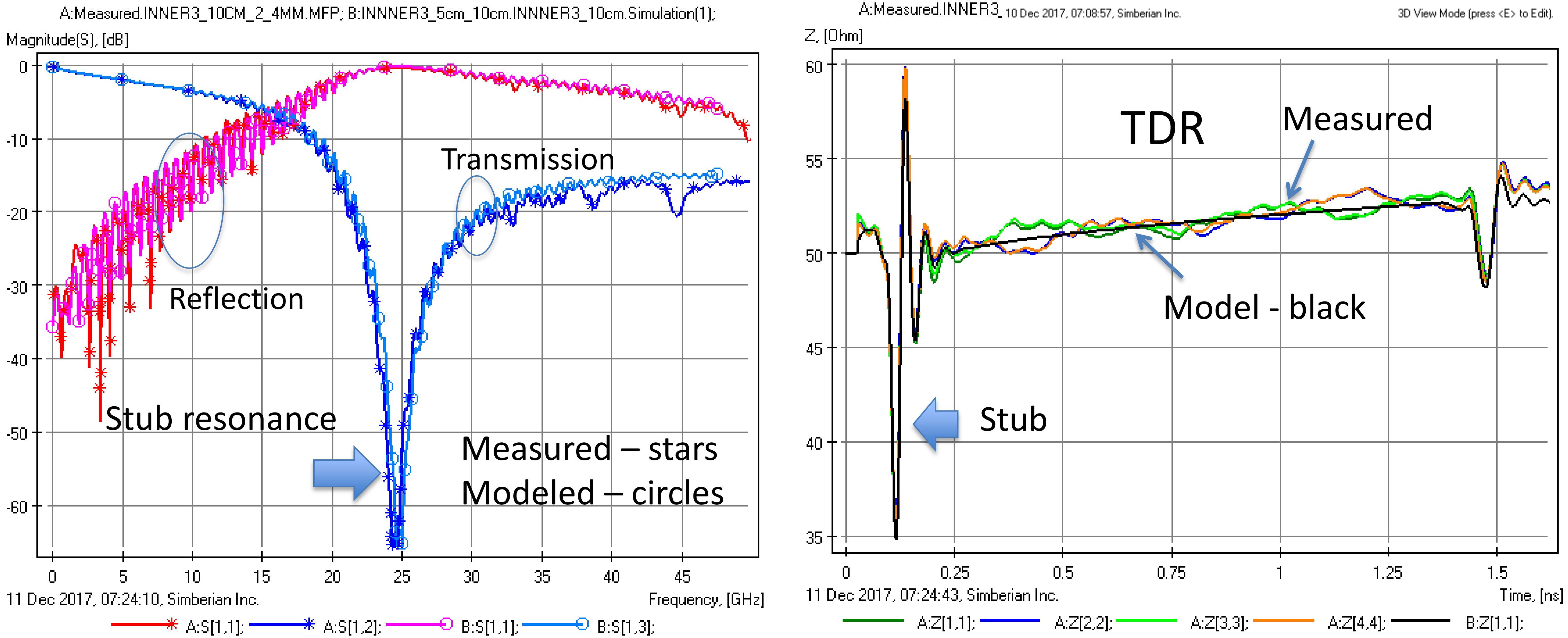


Single-ended S-parameters & TDR

Core/prepreg dielectric models – layered anisotropy

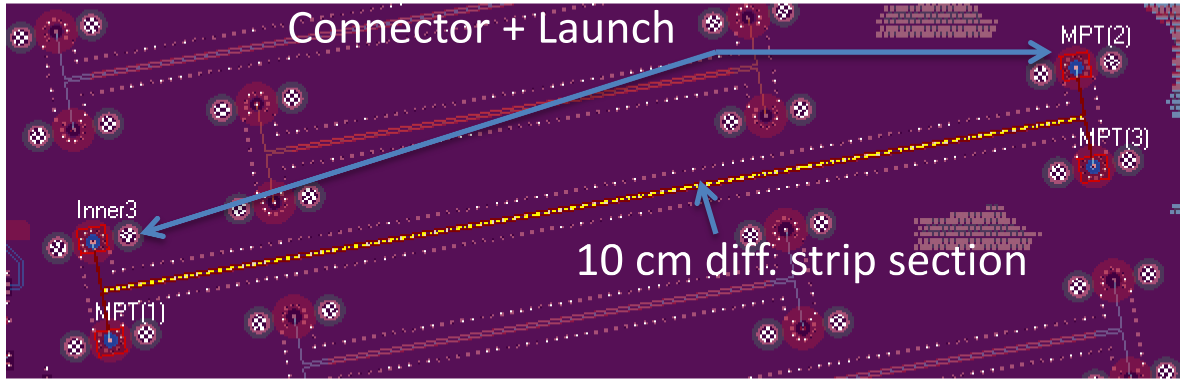
Reality: Resonance frequency is a little lower…

Acceptable correspondence up to 30 GHz!

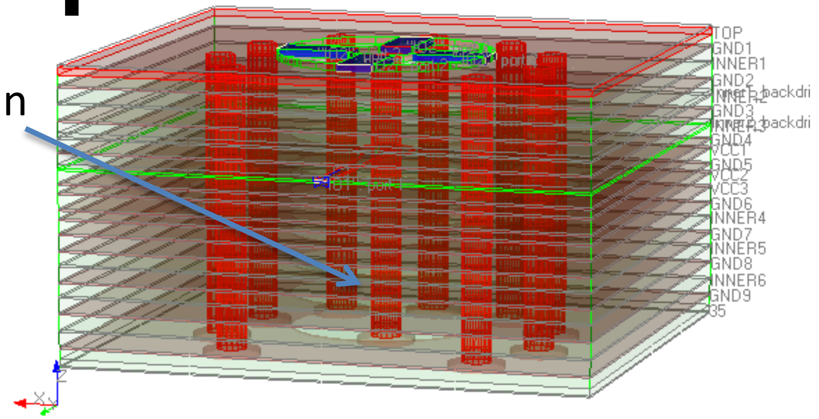


INNER3: 10 cm diff. strip link

De-compositional EM analysis
All trace widths are adjusted



Long stubs in all launches

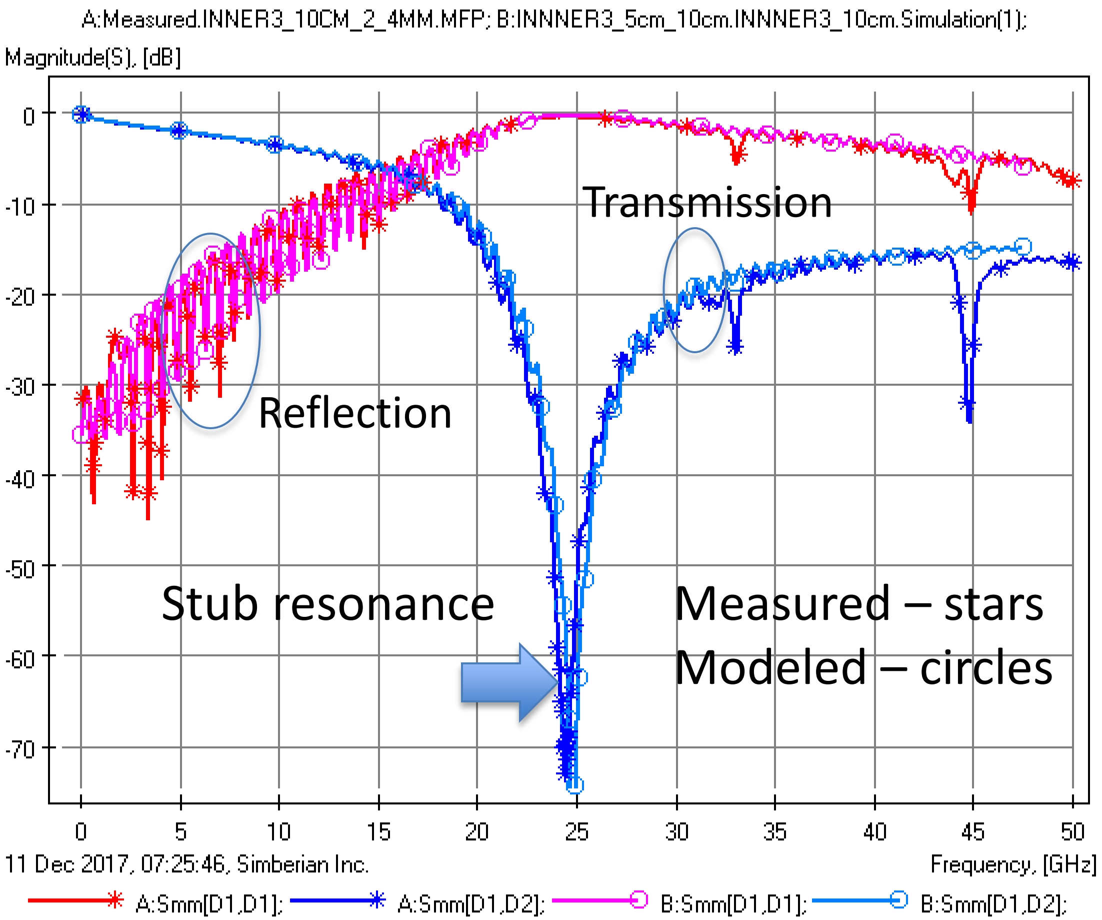


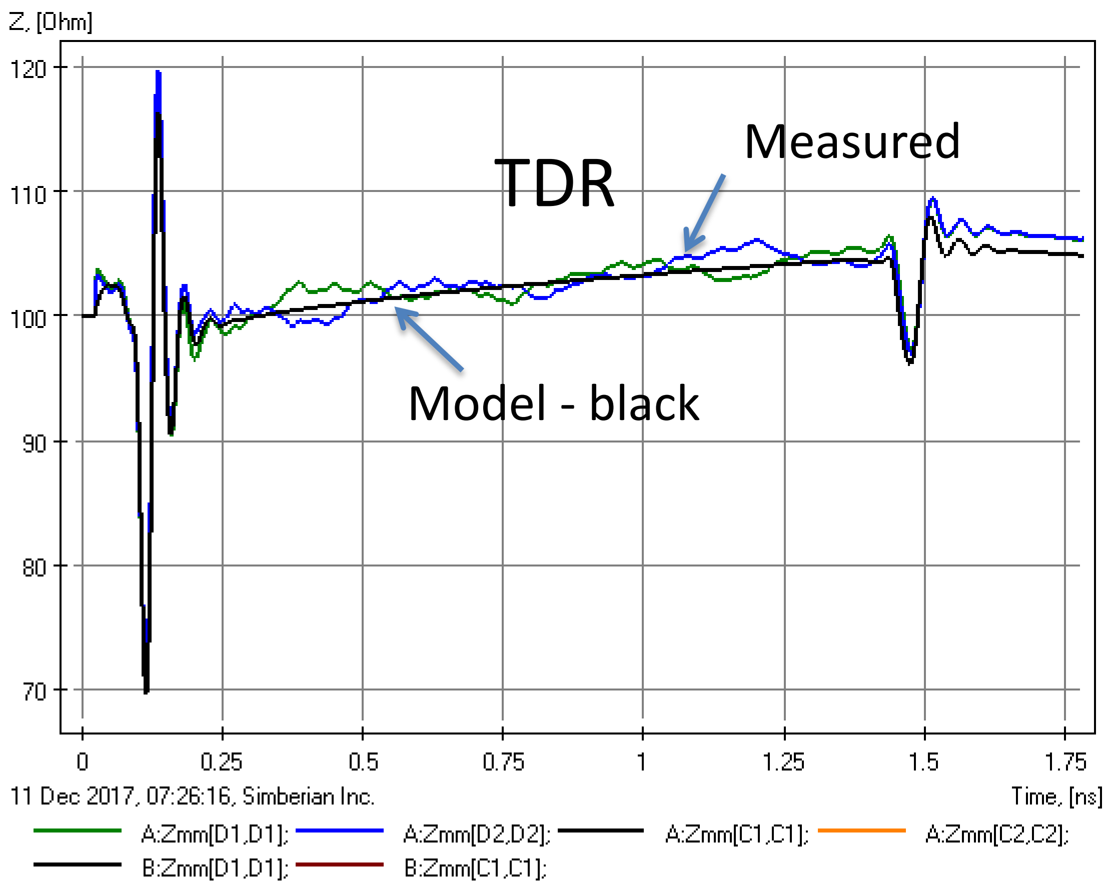
Differential S-parameters & TDR

Core/prepreg dielectric models – layered anisotropy

Reality: Resonance frequency is a little lower…

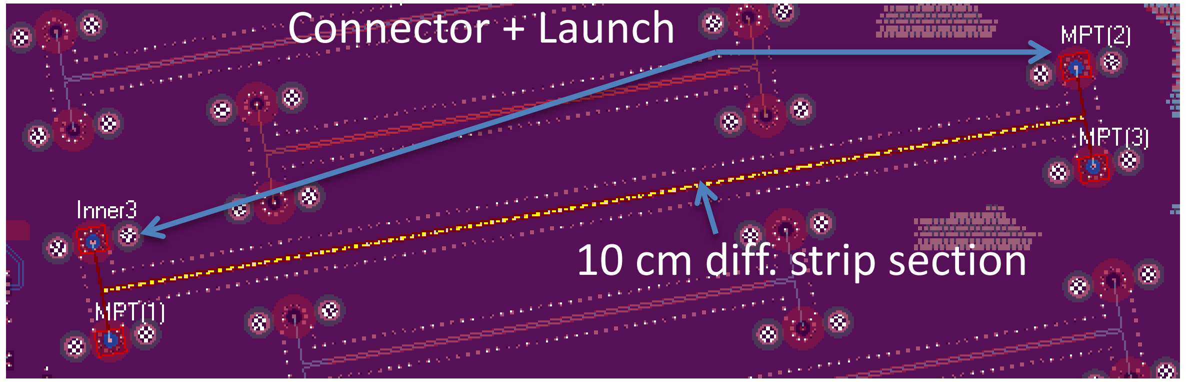
Acceptable correspondence up to 30 GHz!



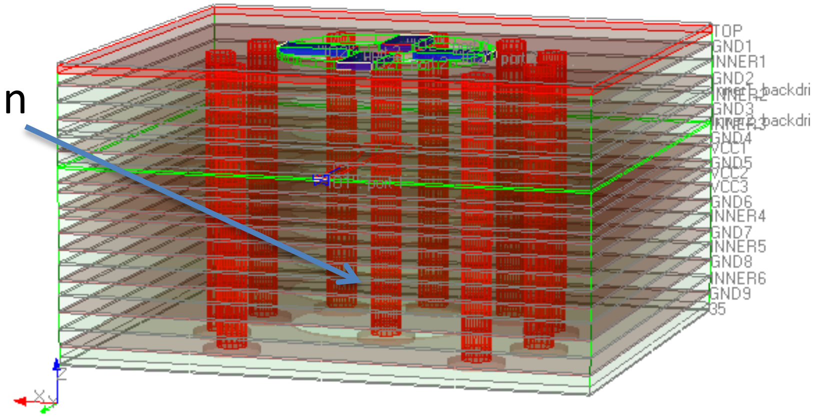


INNER3: 10 cm diff. strip link

De-compositional EM analysis
All trace widths are adjusted



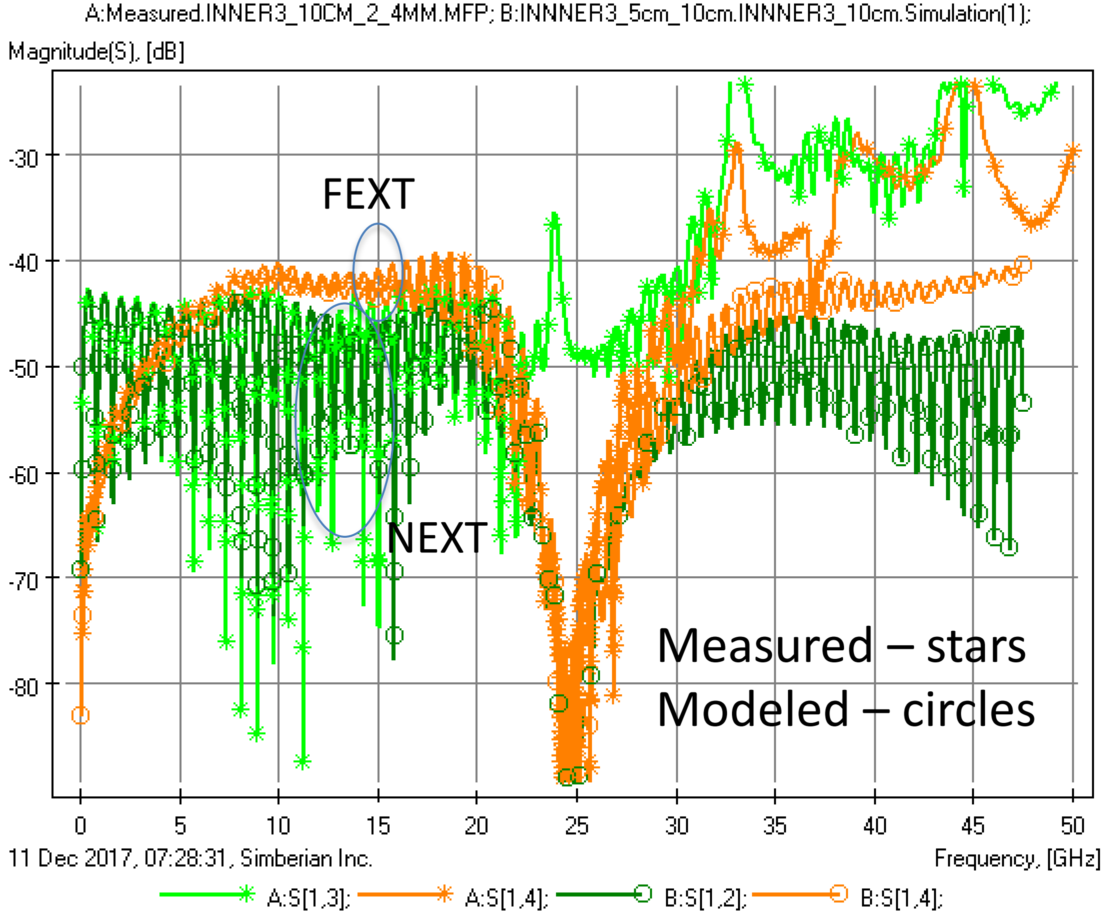
Long stubs in
all launches

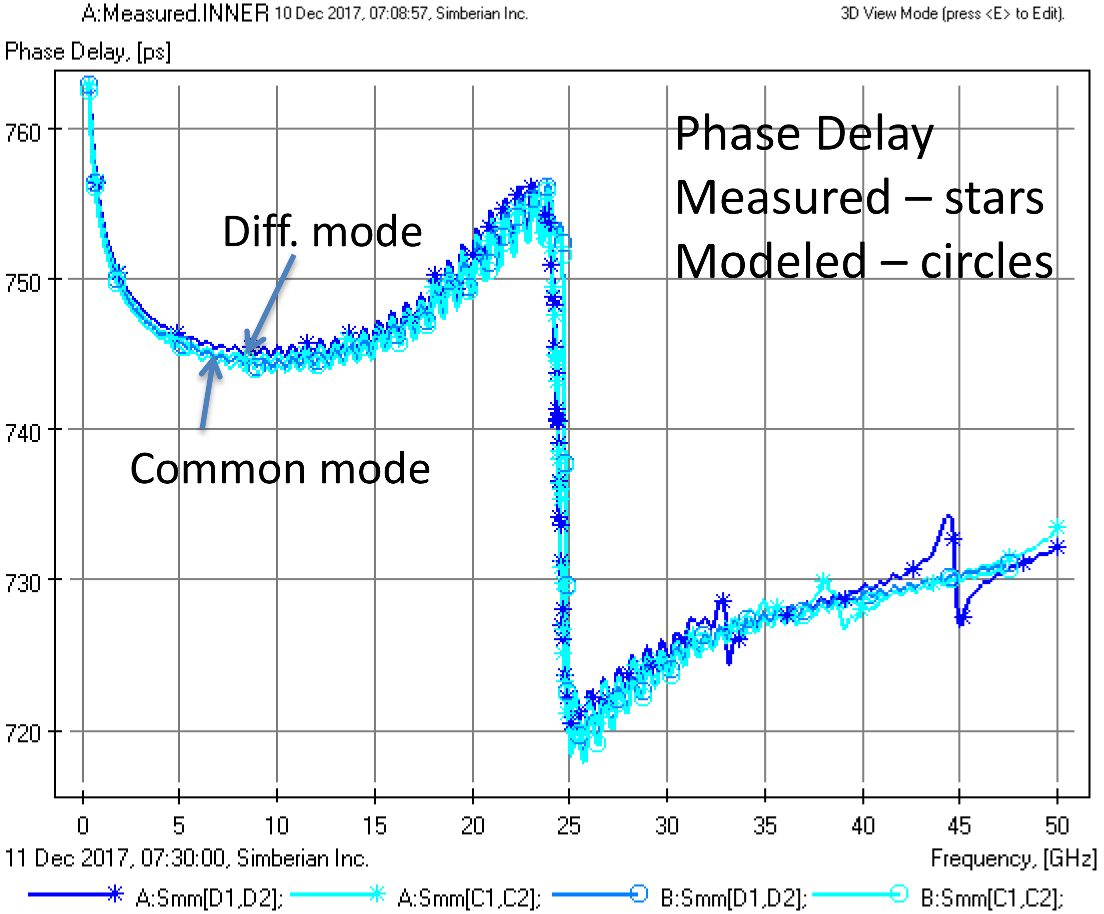


S-parameters

Via simulated as tube, backdrilled area is filled with air

Acceptable correspondence up to 20-30 GHz…





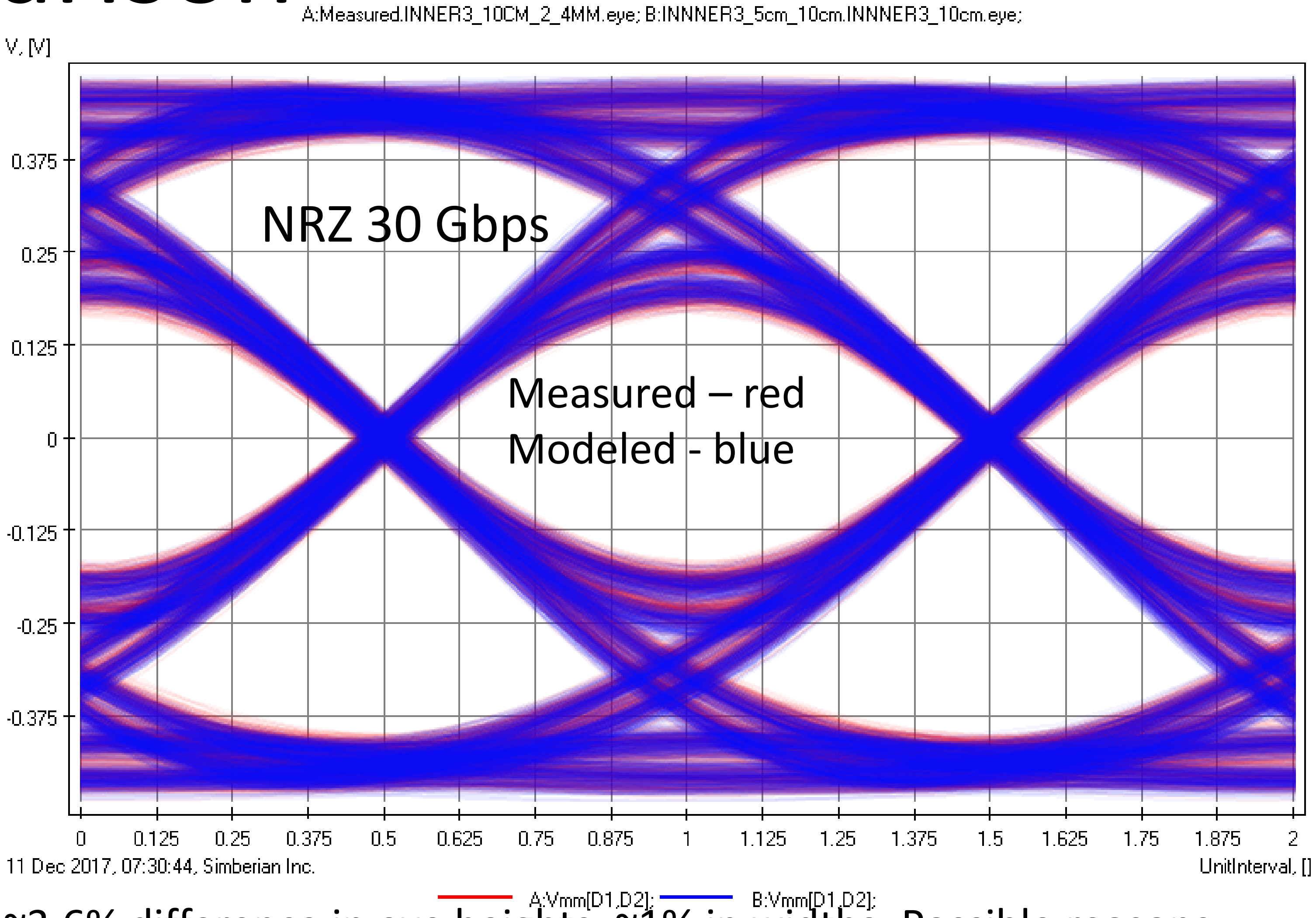
INNER3: 10 cm diff. strip link

- Eye diagrams comparison

Eye Analyzer

Show Eye Metrics: Selected ☑ Auto-open

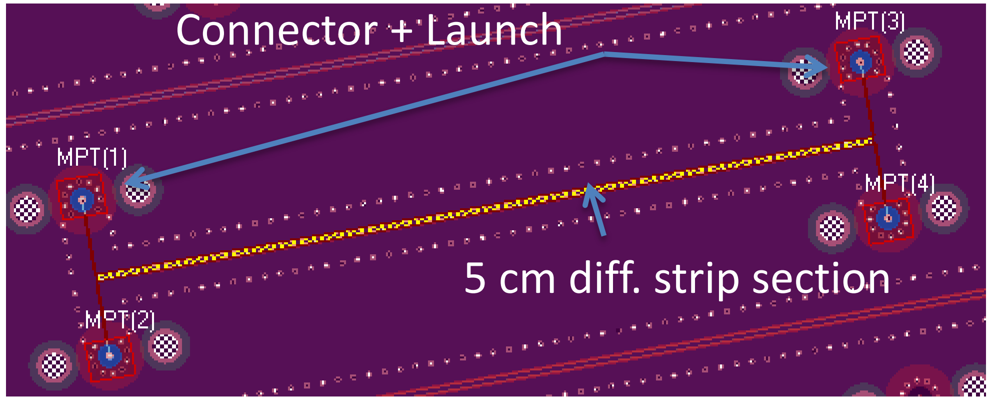
Parameter	Measured.INNER3...	INNNER3_5cm_10c...
Eye Level Zero (V)	-0.321587	-0.328955
Eye Level One (V)	0.324143	0.326591
Eye Level Mean (V)	-0.000666544	-0.00168175
Eye Amplitude (V)	0.645731	0.655546
Eye Height (V)	0.330606	0.342901
Eye Width (UI)	0.873614	0.882483
Eye Opening Factor	0.511987	0.523077
Eye Signal to Noise	3.80529	3.92785
Eye Rise Time (20-80) (UI)	0.61564	0.615358
Eye Fall Time (80-20) (UI)	0.616638	0.611377
Eye Jitter (PP) (UI)	0.126386	0.117517
Eye Jitter (RMS) (UI)	0.0222674	0.0215509



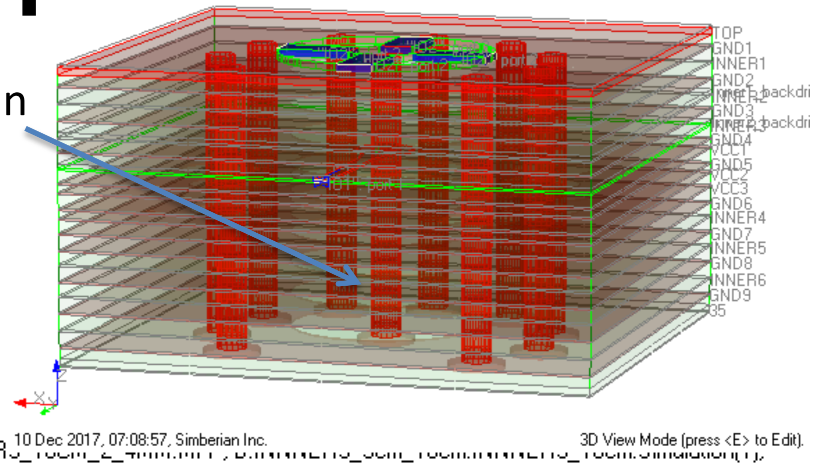
~3.6% difference in eye heights, ~1% in widths; Possible reasons – impedance variations, differences in reflections, loss of launch localization…

INNER3: 5 cm diff. strip link

De-compositional EM analysis
All trace widths are adjusted



Long stubs in all launches

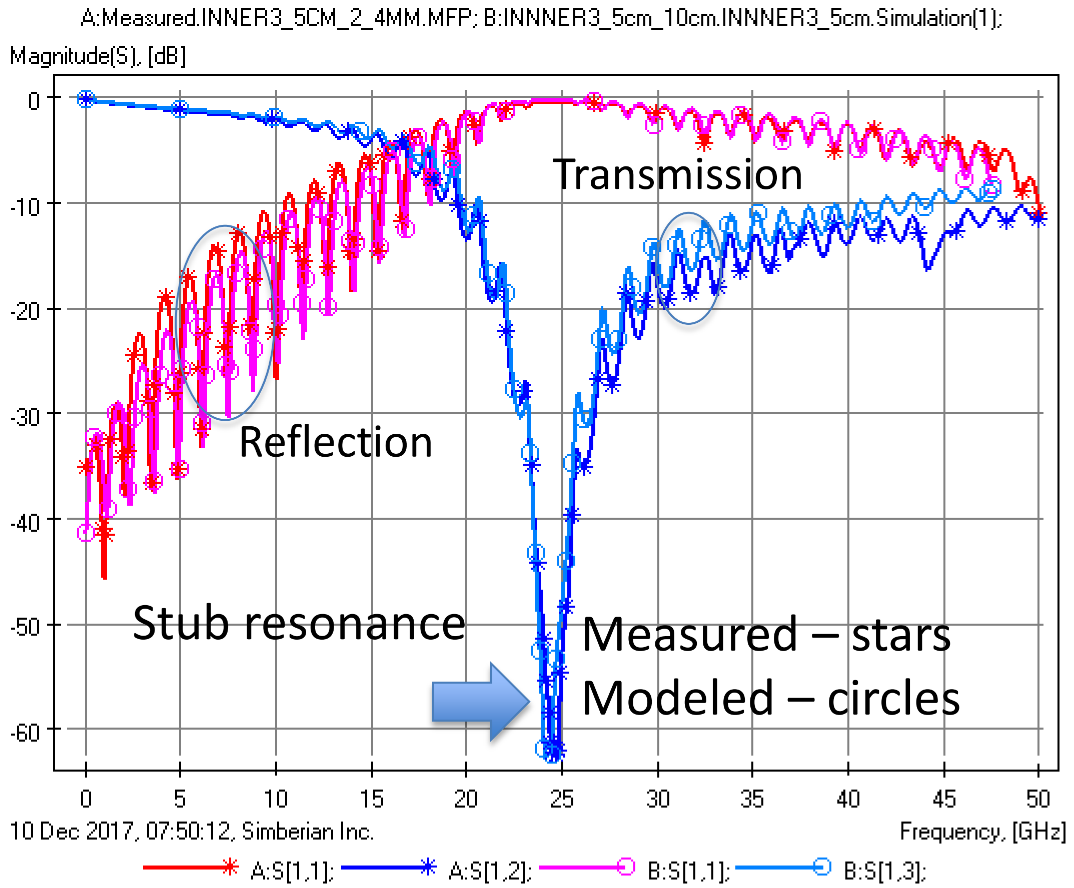


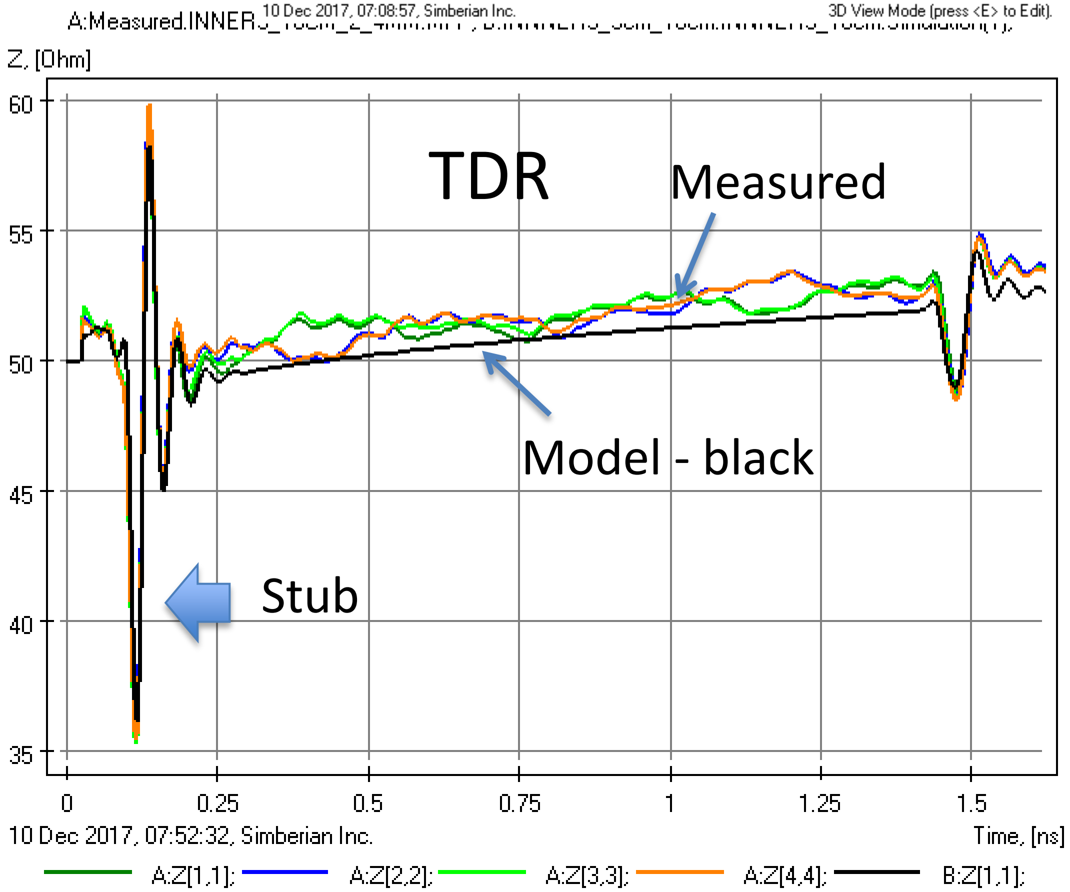
Single-ended S-parameters & TDR

Core/prepreg dielectric models – layered anisotropy

Reality: More reflections below the resonance…

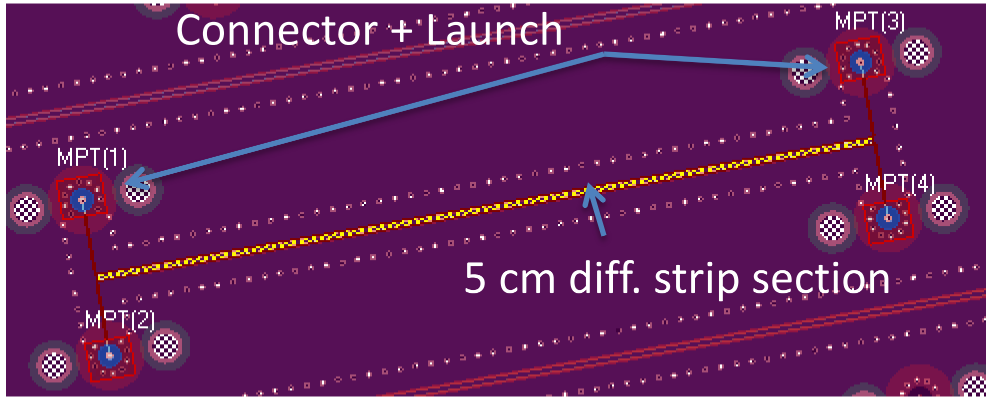
Acceptable correspondence up to 30 GHz!

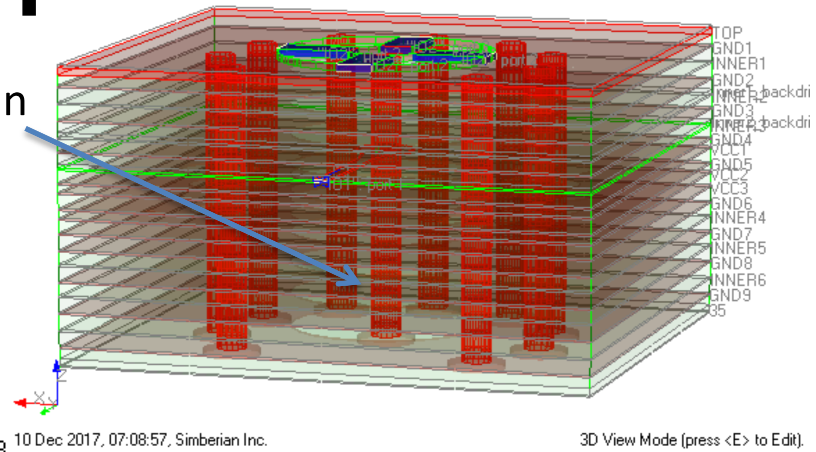




INNER3: 5 cm diff. strip link

De-compositional EM analysis
All trace widths are adjusted





Single-ended S-parameters & TDR

Core/prepreg dielectric models – layered anisotropy

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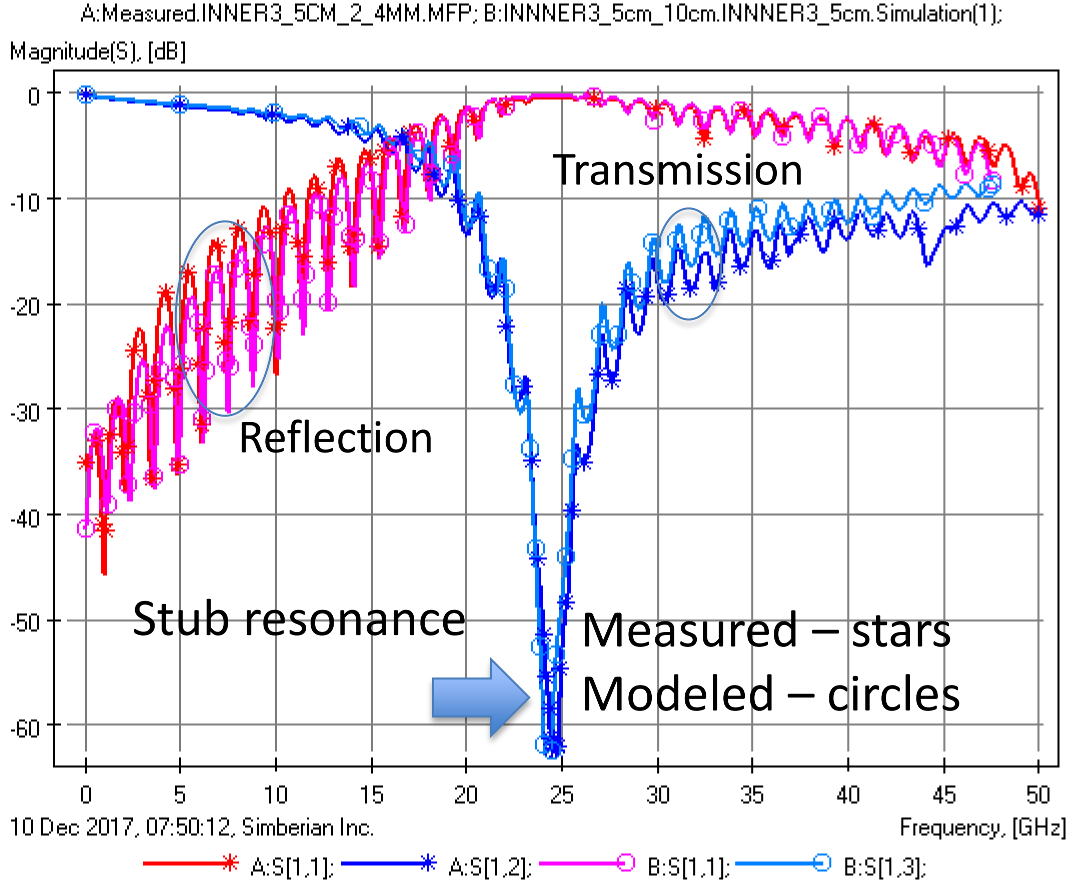
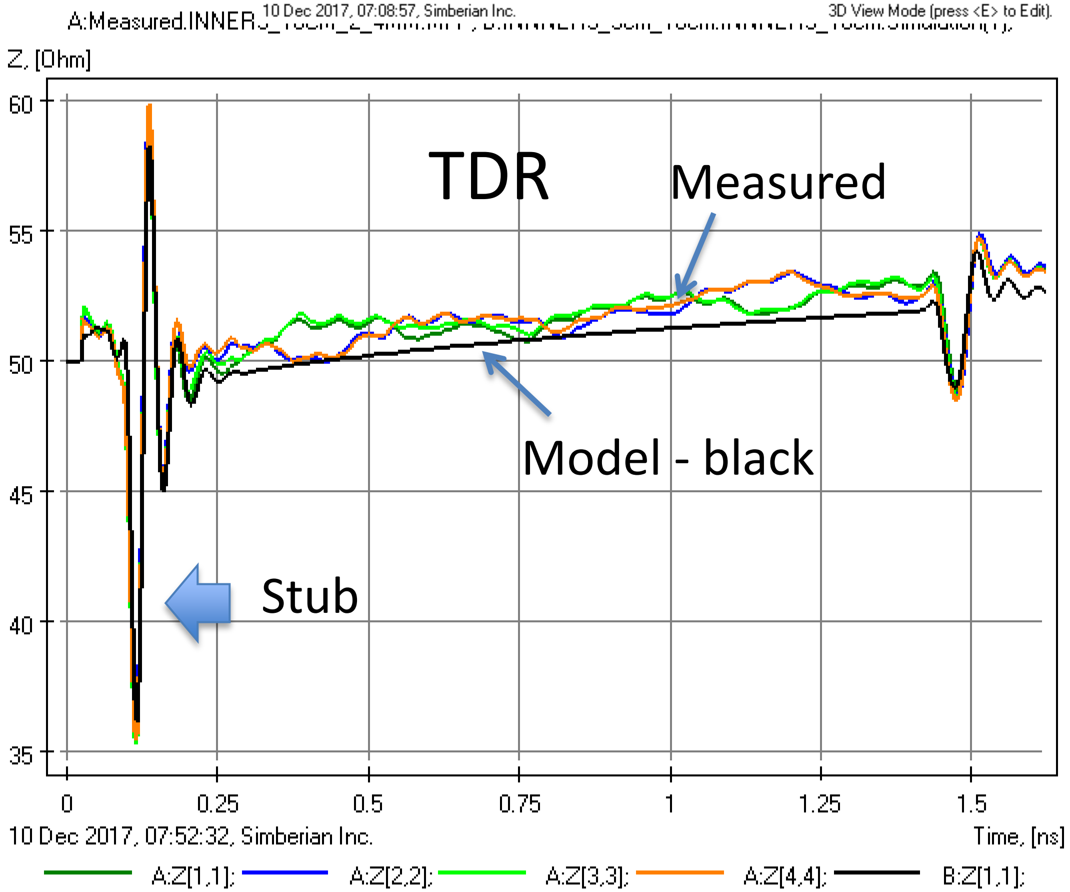
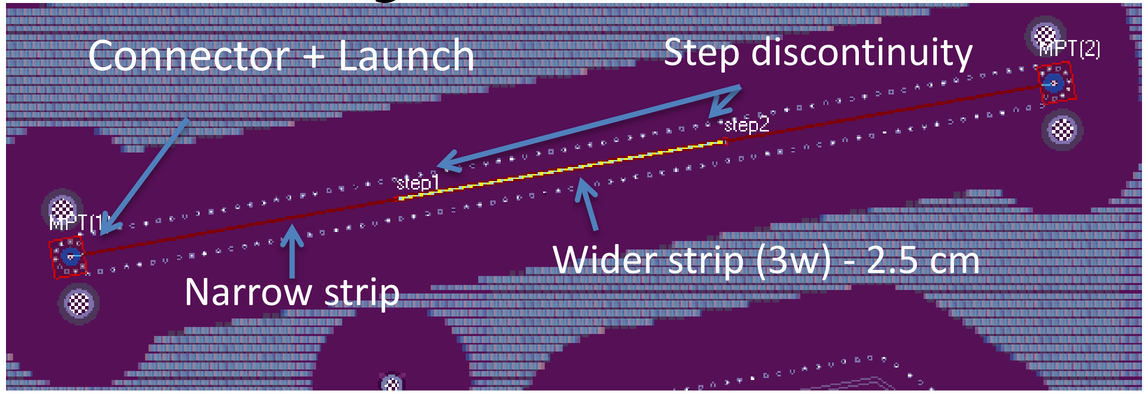
Acceptable correspondence up to 30 GHz!



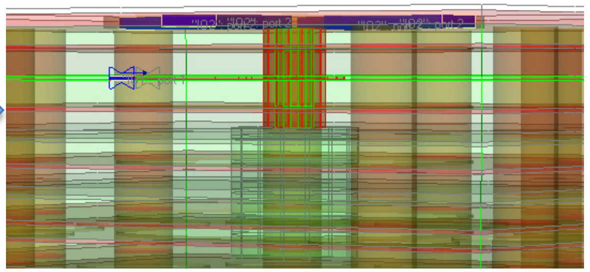


D1: Beatty standard in INNER1

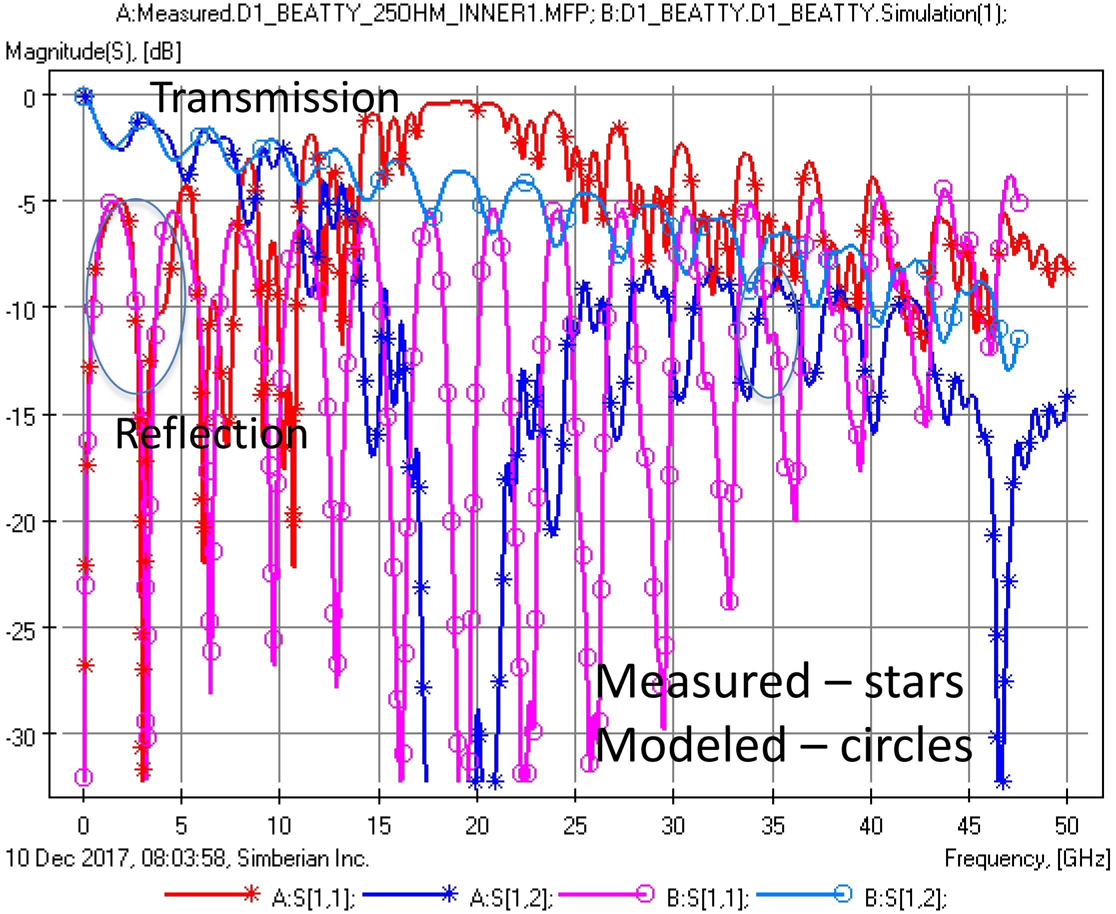
De-compositional EM analysis
All trace widths and backdrill are adjusted

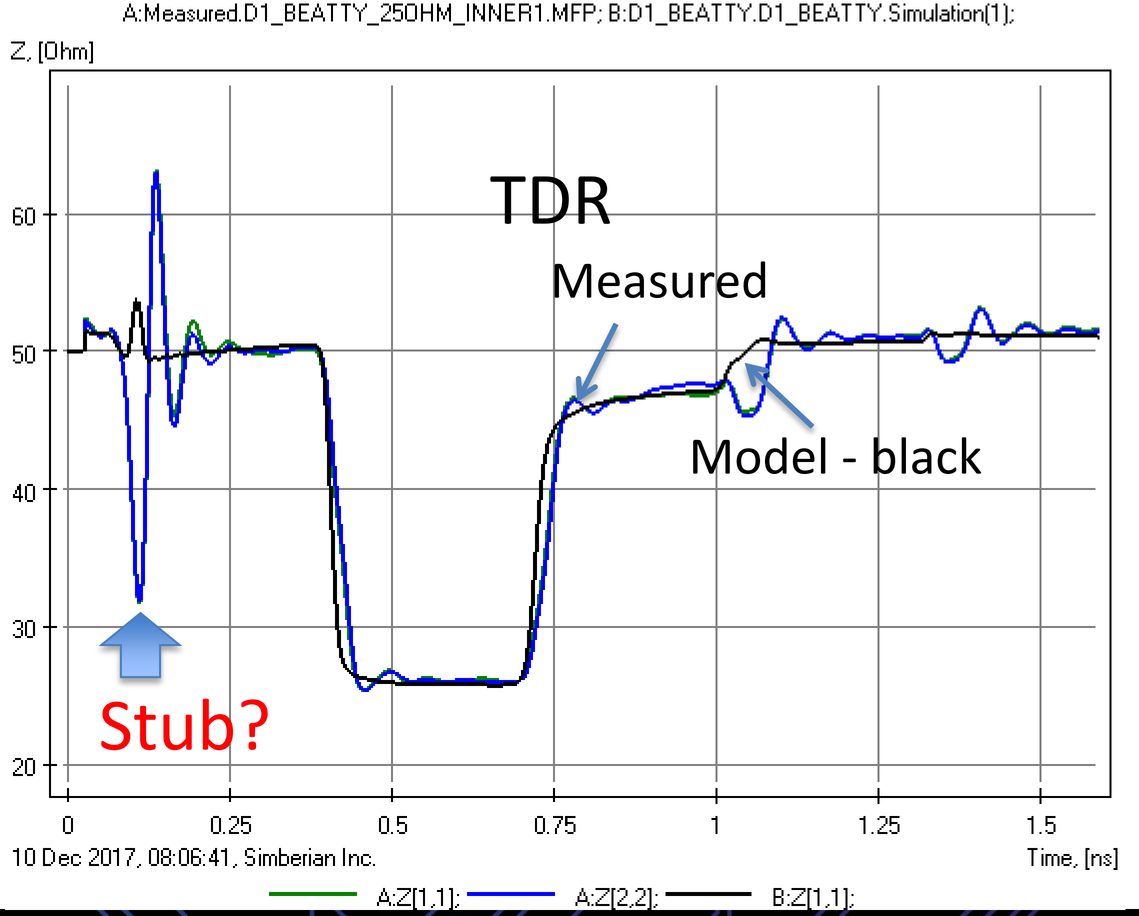


Via span adjusted as on x-section for 10 cm INNER1, air in backdrill
No x-section of launches on Beatty structure…



S-parameters & TDR



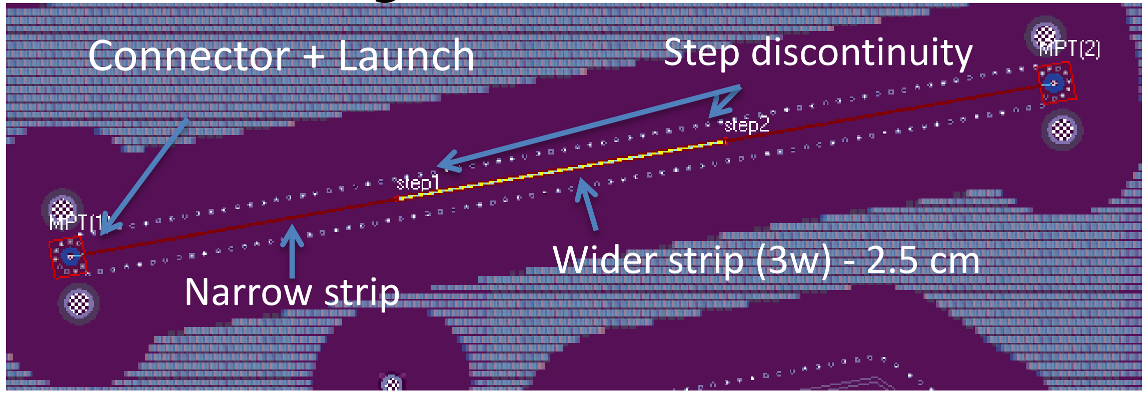


Reality: Large difference in transmission and reflection above 3 GHz – why?

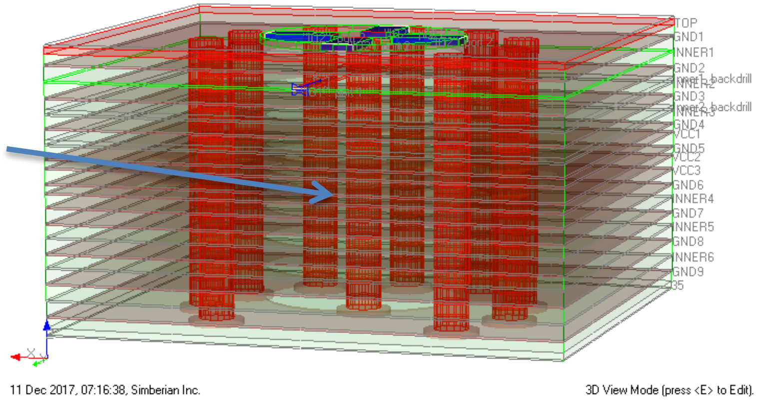
Possible reasons – stubs in launches are not backdrilled let't try it…

D1: Beatty standard in INNER1

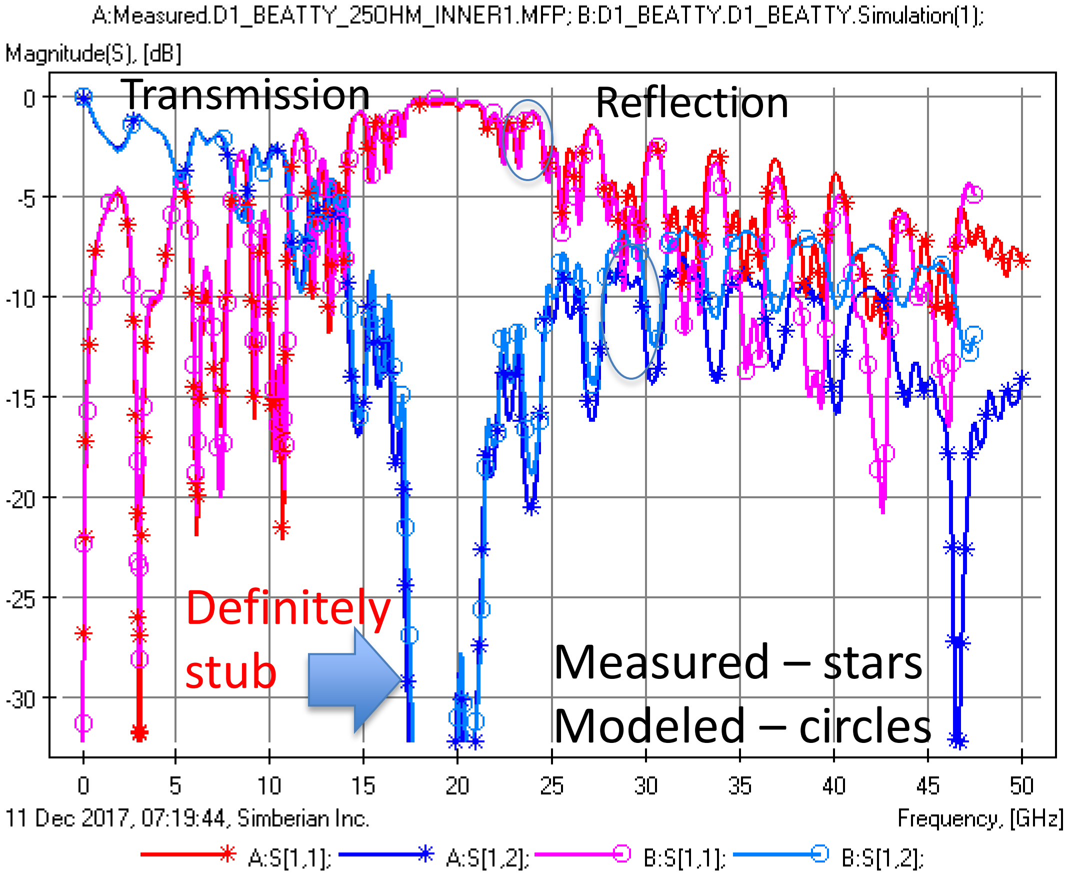
De-compositional EM analysis
All trace widths adjusted, no backdrill

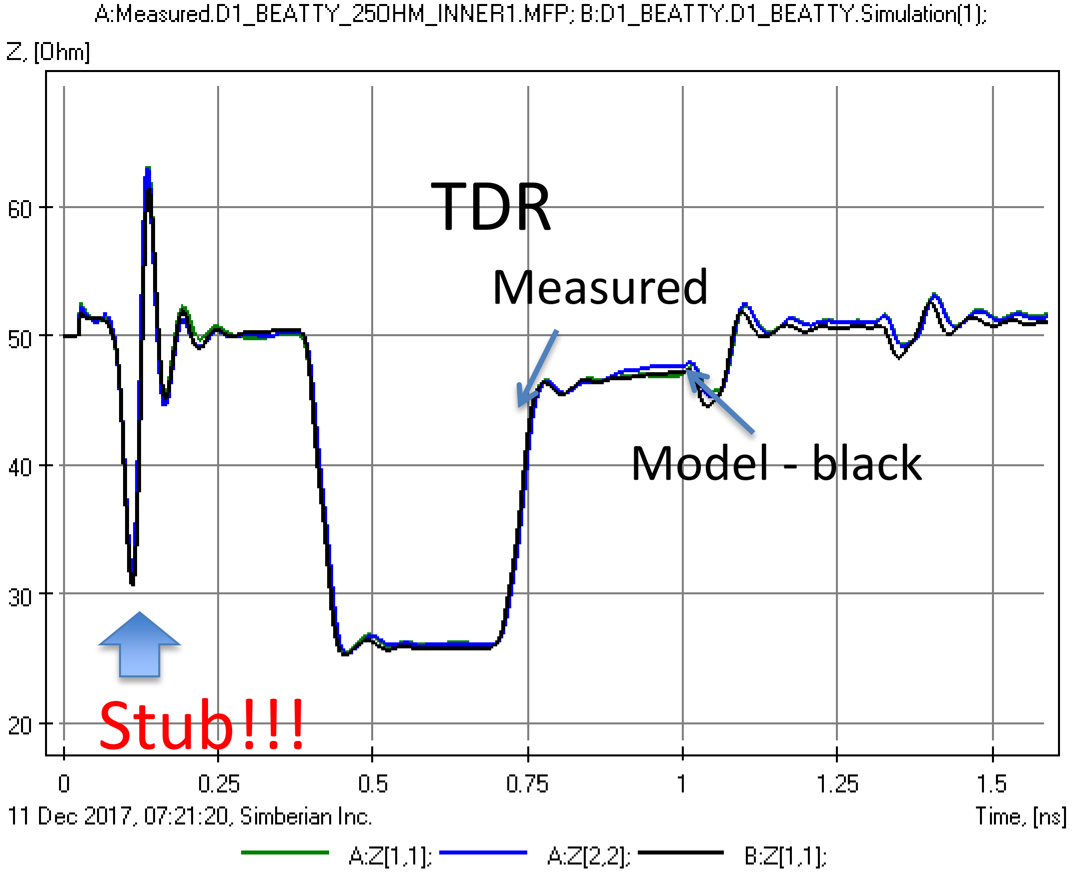


Vias on launches have long stubs



S-parameters & TDR

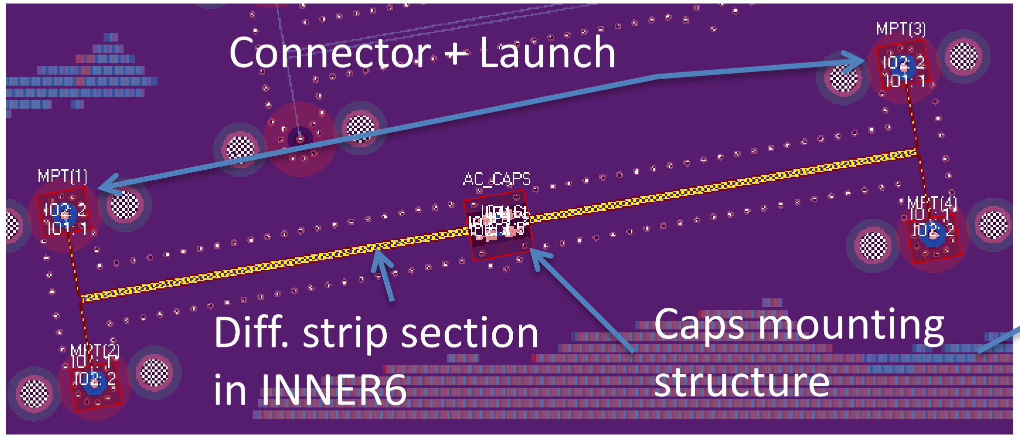


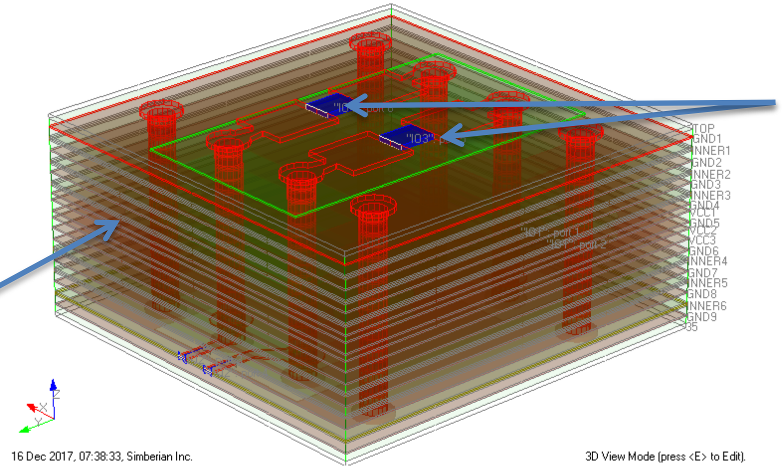


Acceptable correspondence
Though, it is not possible to use the structure for the loss validation without de-embedding – no structures to de-embed the launches…

F1: Link with 0402 AC coupling capacitors

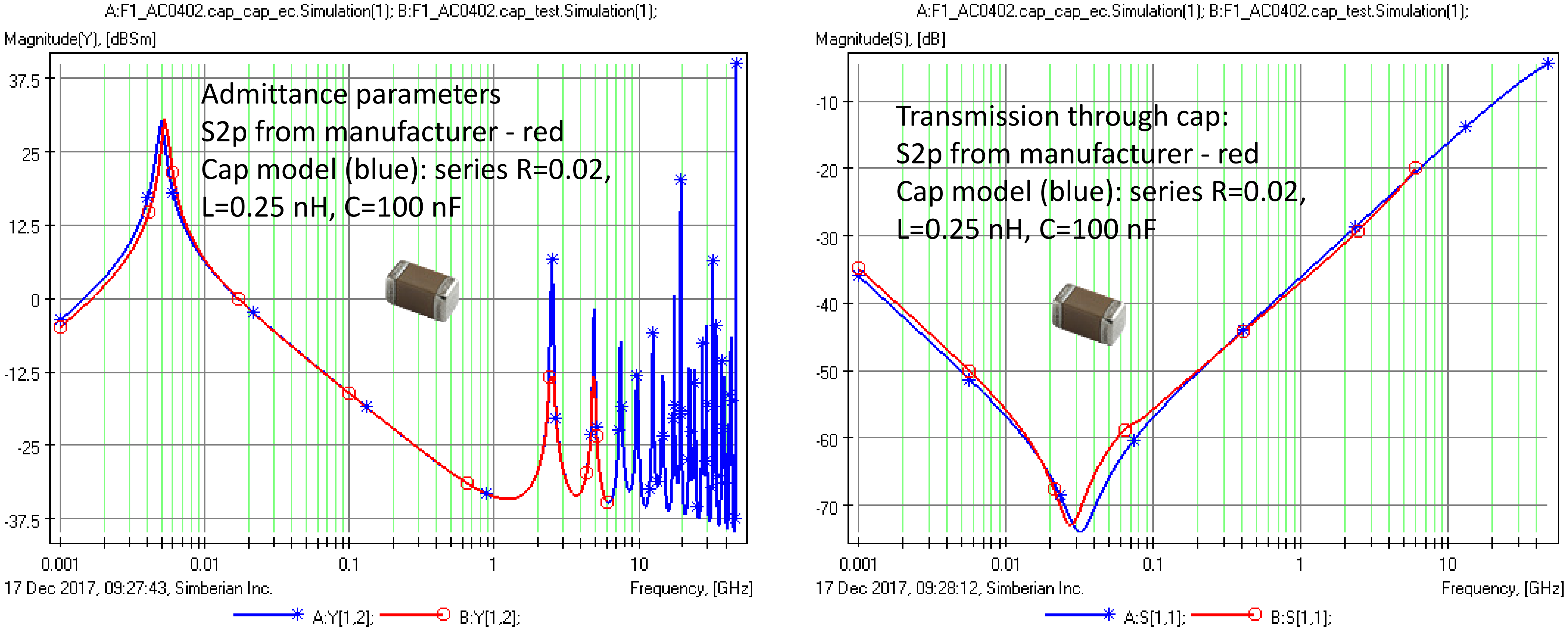
De-compositional EM analysis
All trace widths are adjusted





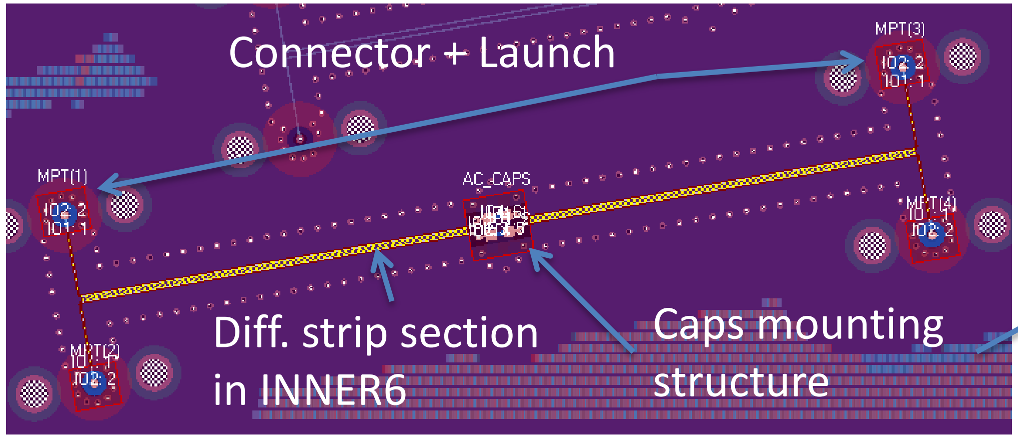
Reality: No data for the capacitor above 6 GHz!
Cap s2p are measured in series connection – include pads or not?

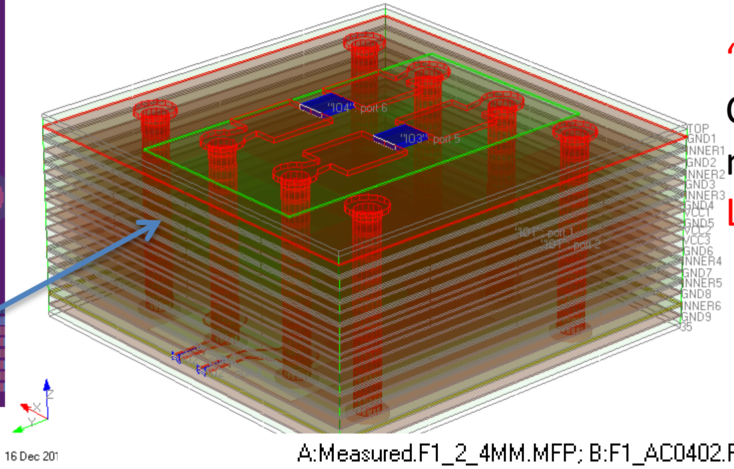
An RLC equivalent circuit can be synthetized to increase the model bandwidth – this is un-reliable model!



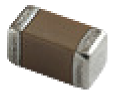
F1: Link with 0402 AC coupling capacitors

De-compositional EM analysis
All trace widths are adjusted

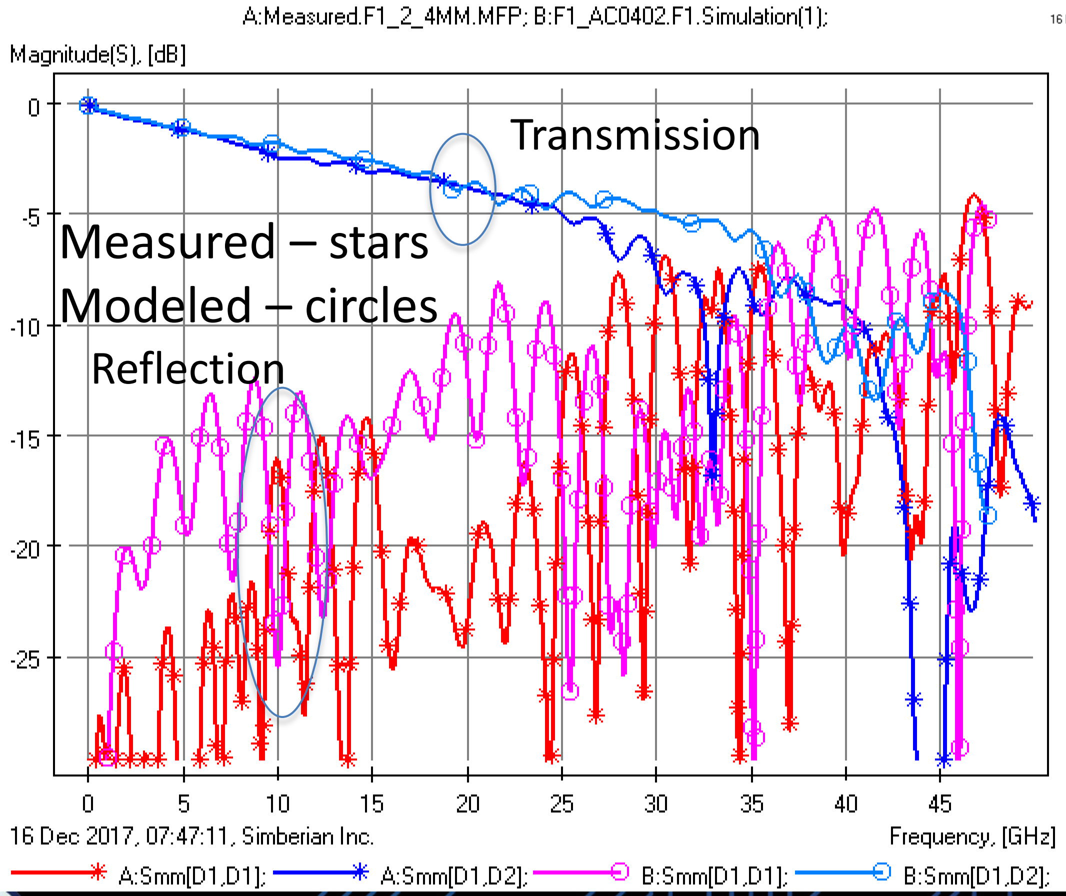


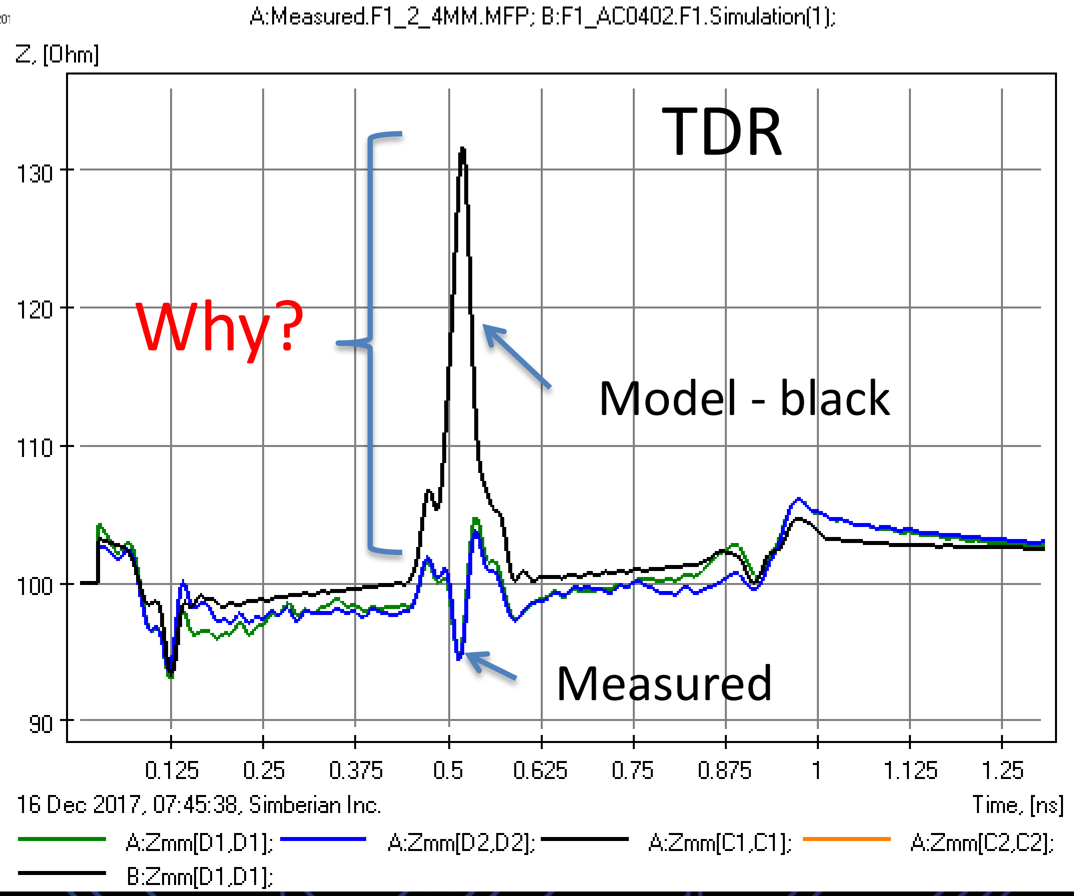


"Collapsed metal" option,
Cap model (fitted to s2p from manufacturer): R=0.02, L=0.25 nH, C=100 nF



First analysis
Differential S-parameters & TDR

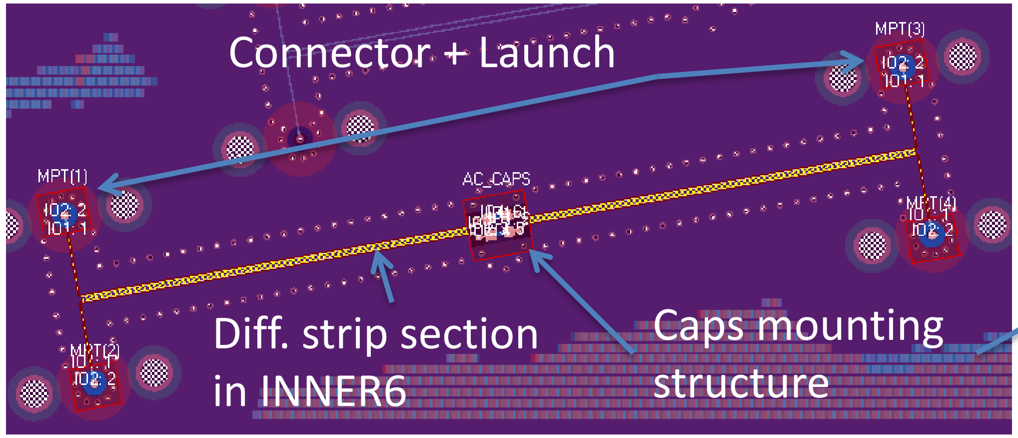


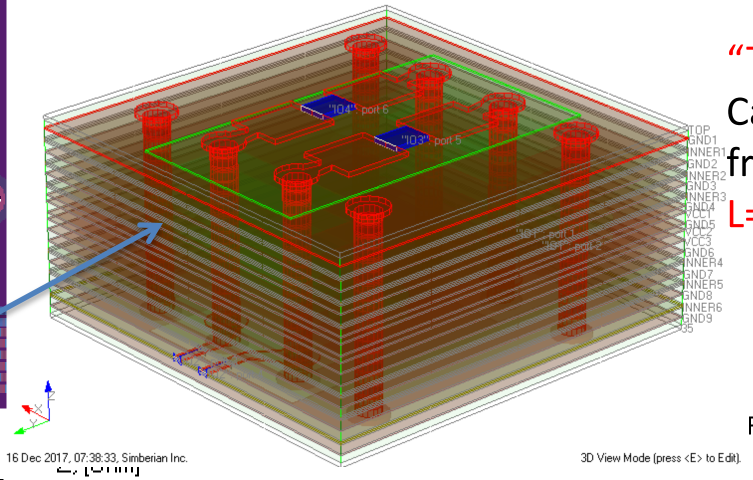


Reality: No correlation in reflection, the caps are much better in reality – investigate…

F1: Link with 0402 AC coupling capacitors

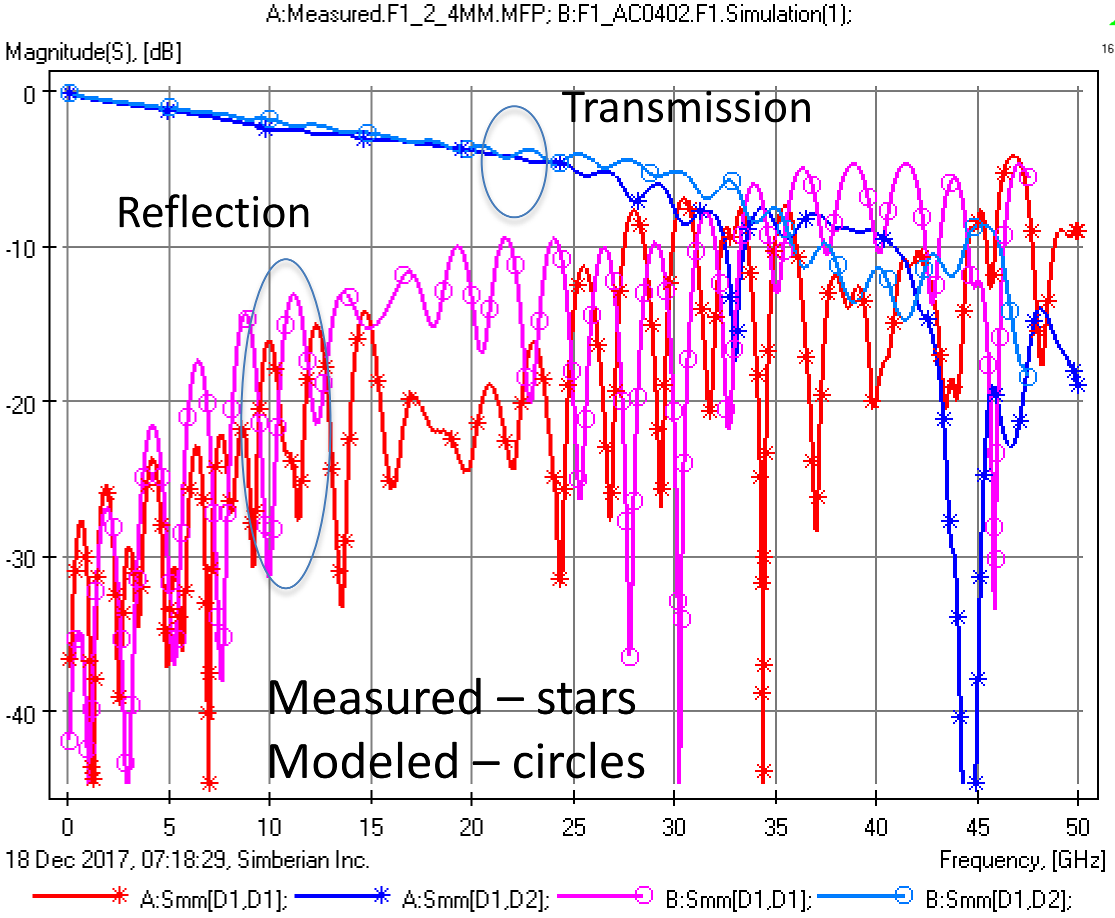
De-compositional EM analysis
All trace widths are adjusted

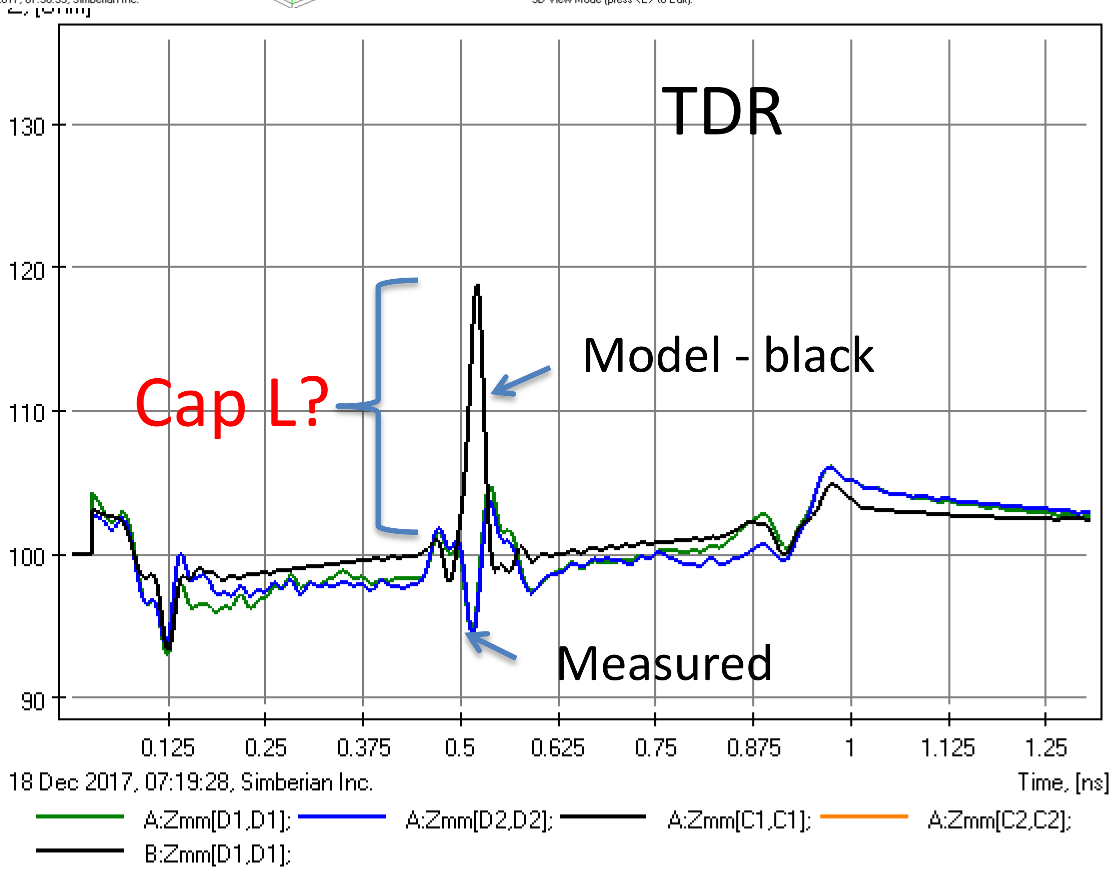




"Thick metal" option,
Cap model (fitted to s2p from manufacturer): R=0.02, L=0.25 nH, C=100 nF

Second analysis
Differential S-parameters & TDR





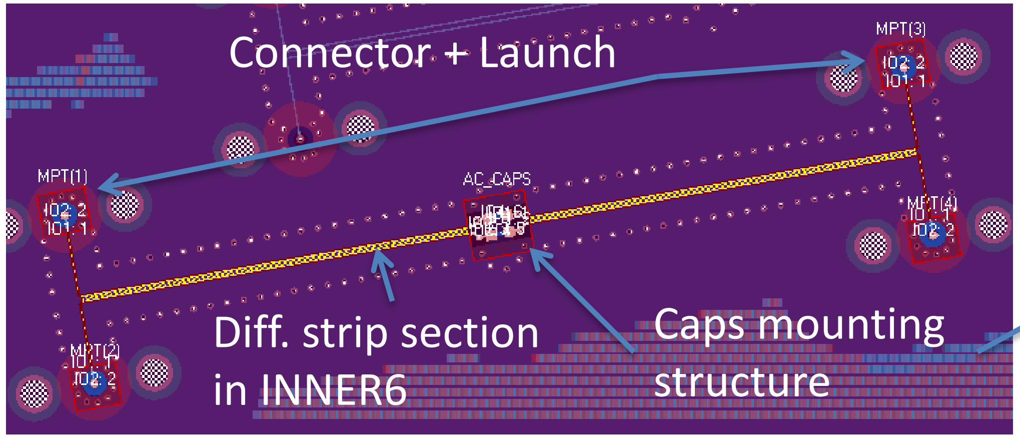
Reality: Better correlation in reflection, but the model has excessive inductance – the cap model includes part of the mounting structure…

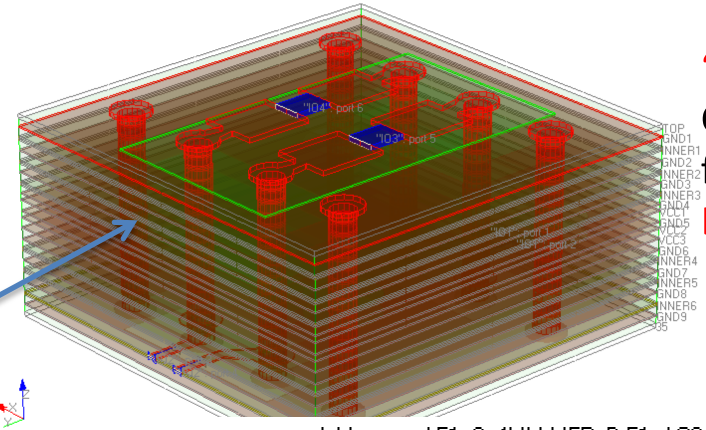
F1: Link with 0402 AC coupling capacitors

De-compositional EM analysis
All trace widths are adjusted

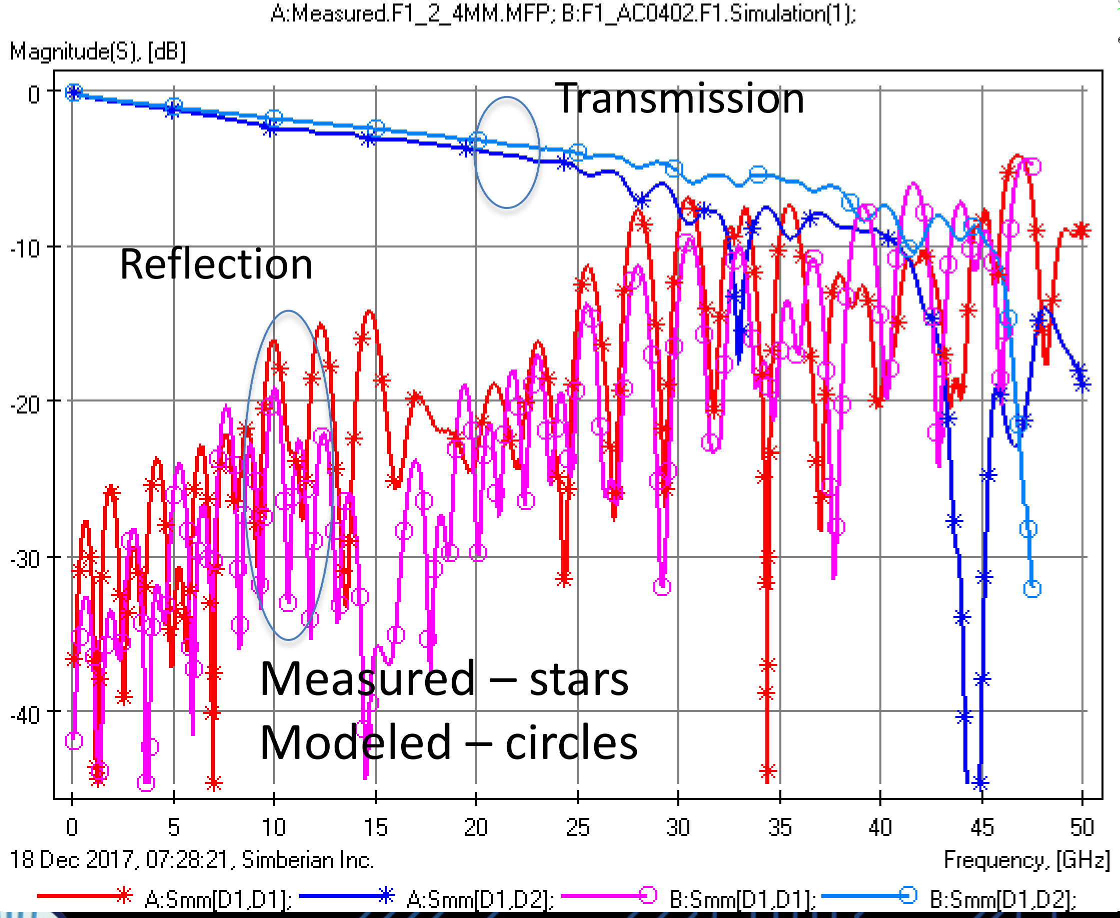
Final analysis
Differential S-parameters & TDR

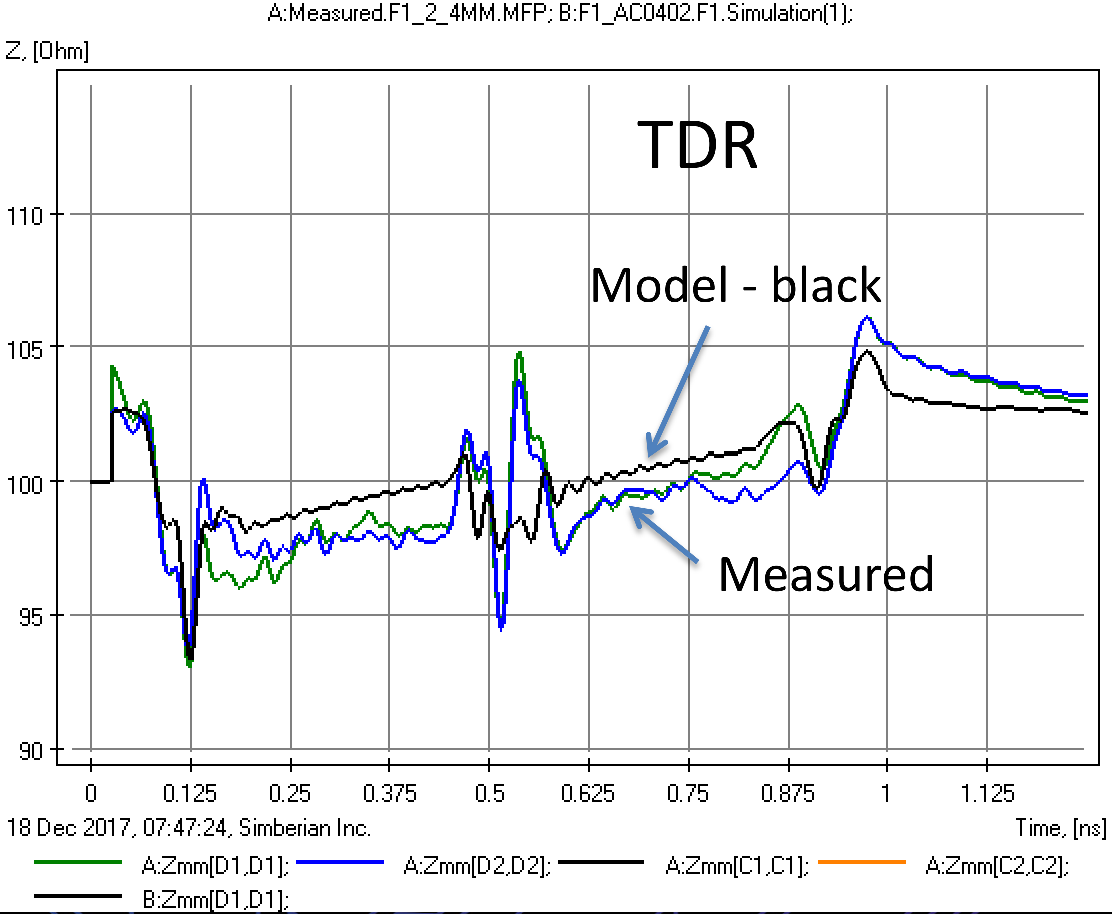
Reality: Larger reflections and larger transmission losses, capacitor model from manufacturer is not suitable for accurate analysis…





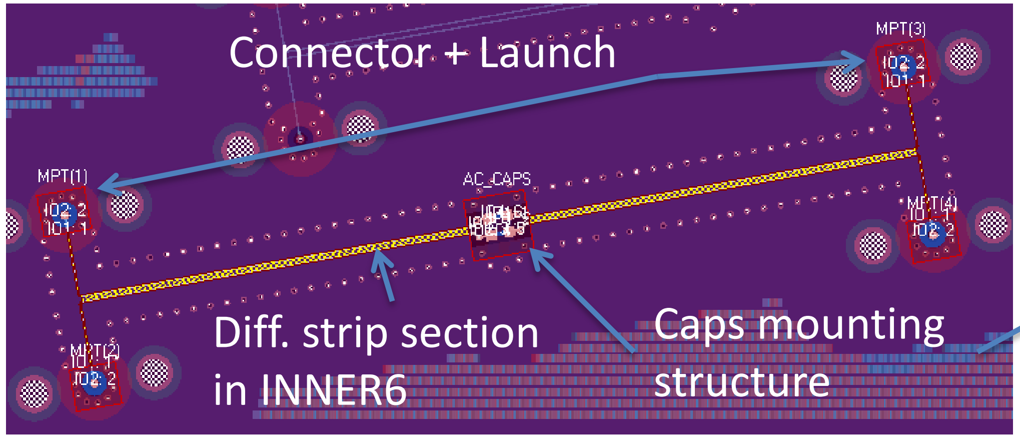
"Thick metal" option,
Cap model (fitted to s2p from manufacturer): R=0.02, L=0.0 nH, C=100 nF

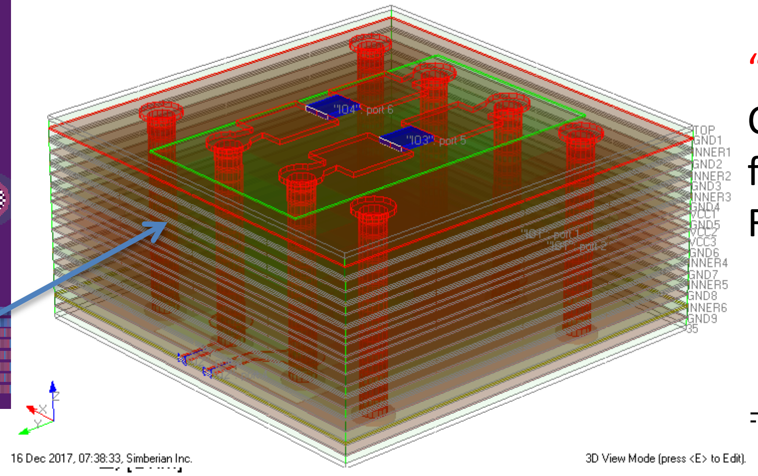




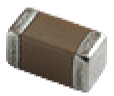
F1: Link with 0402 AC coupling capacitors

De-compositional EM analysis
All trace widths are adjusted

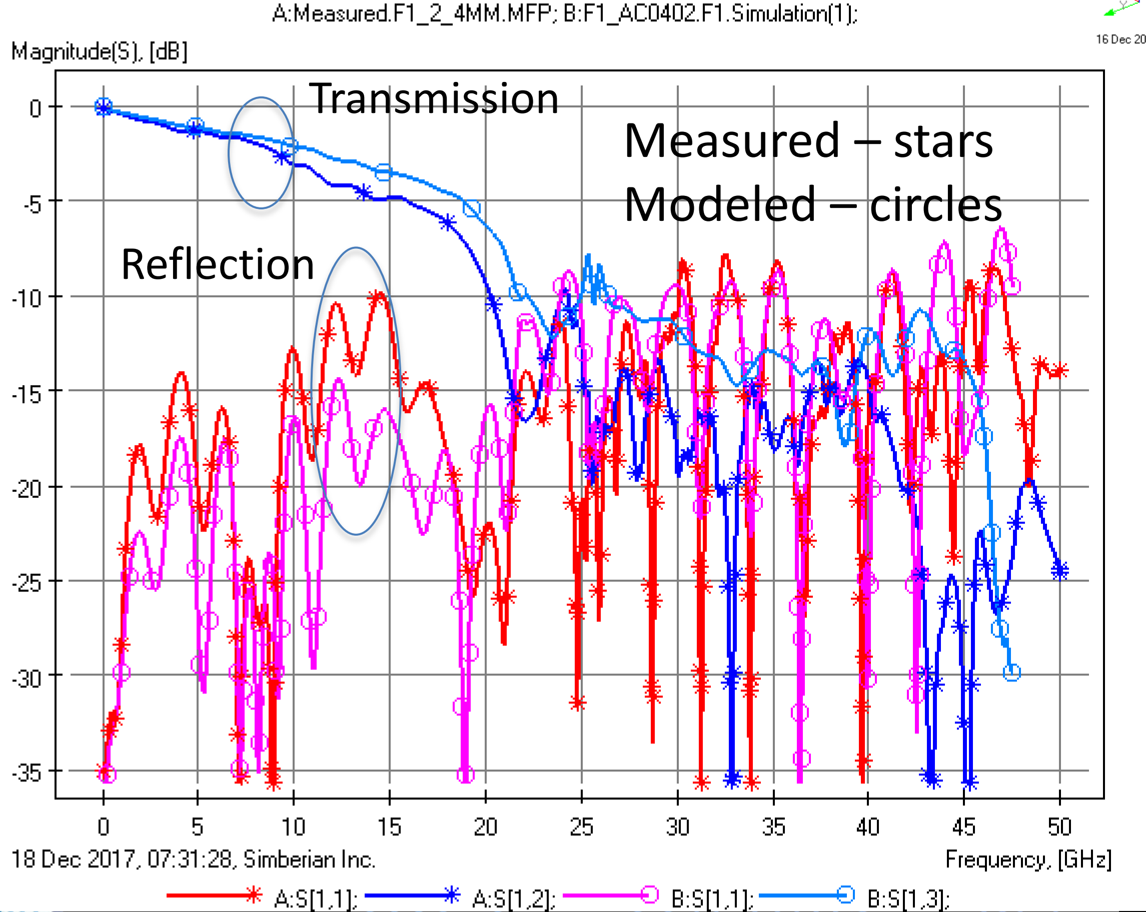


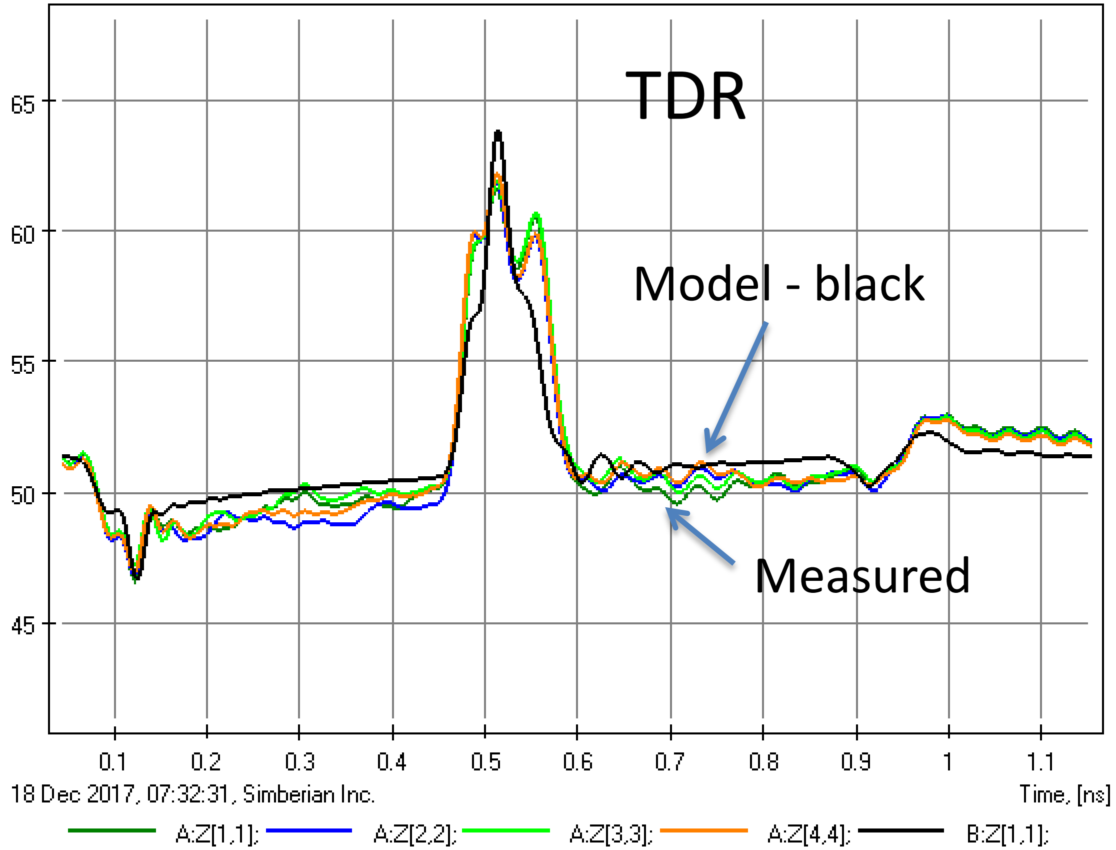


"Thick metal" option,
Cap model (fitted to s2p from manufacturer):
R=0.02, L=0 nH, C=100 nF



Final analysis
Single-ended S-parameters & TDR





Reality: Larger reflections and larger transmission losses, capacitor model from manufacturer is not suitable for accurate analysis…

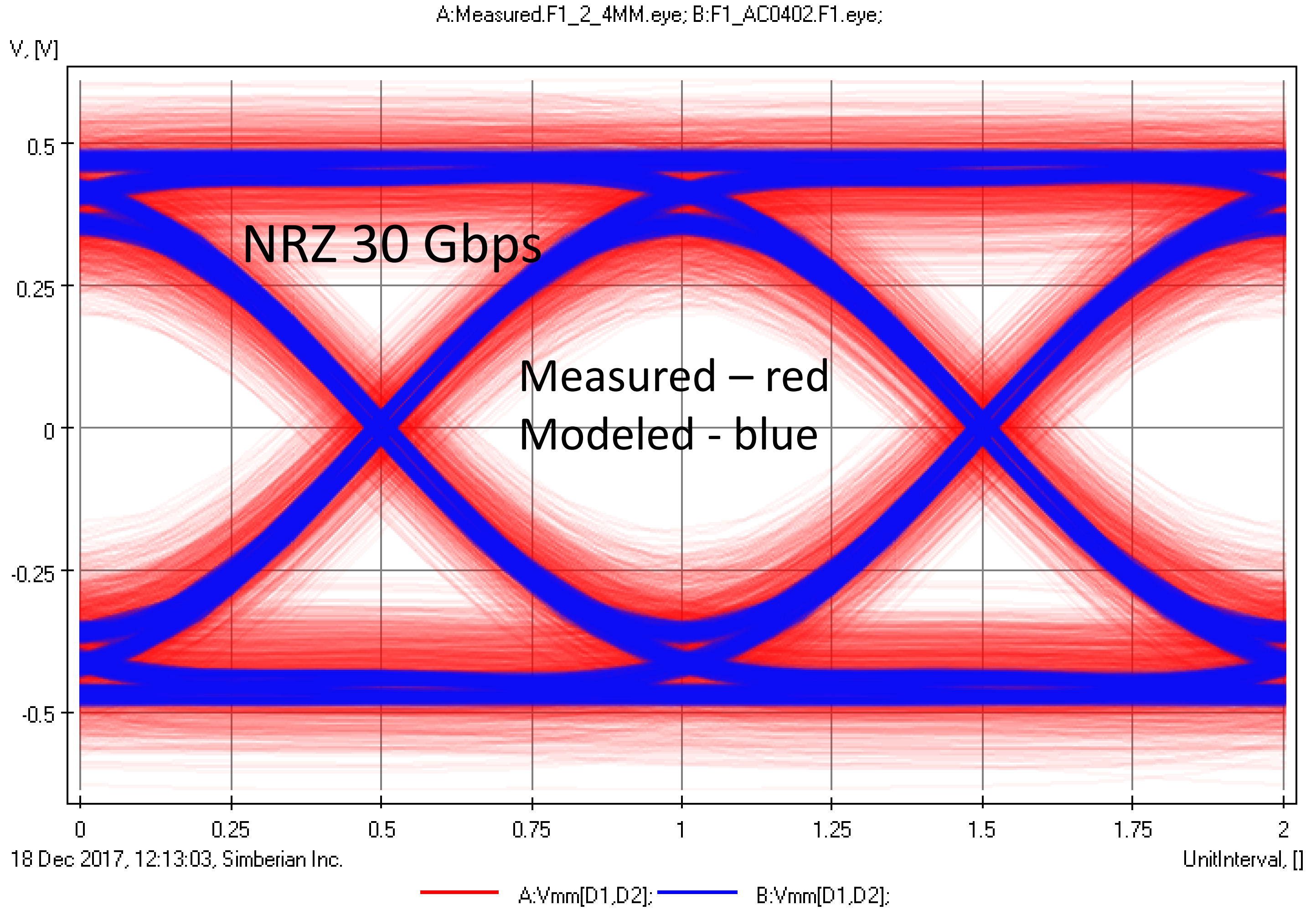
F2: Link with 0201 AC coupling capacitors

- Eye diagrams comparison

Eye Analyzer

Show Eye Metrics: Selected   Auto-open

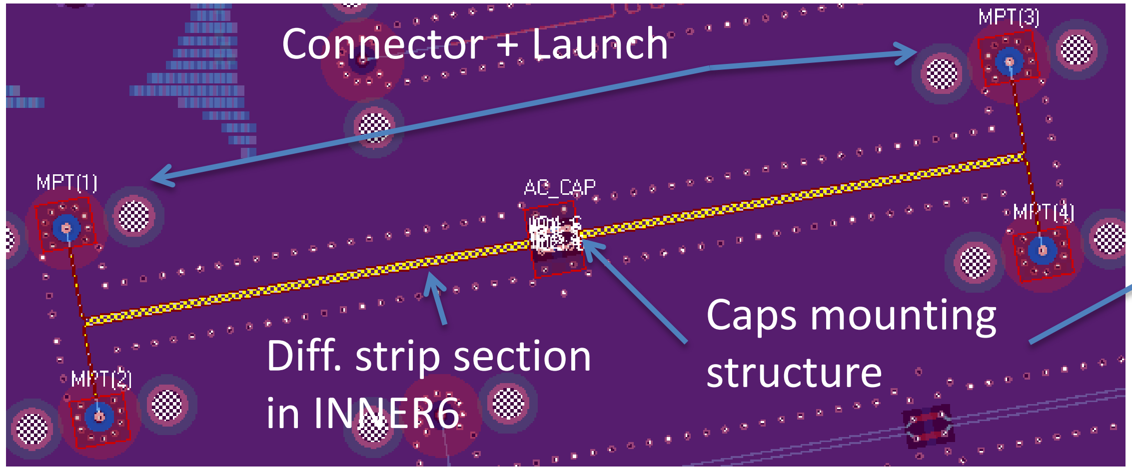
Parameter	Measured.F1_2_4M...	F1_AC0402.F1....
Eye Level Zero (V)	-0.390088	-0.410074
Eye Level One (V)	0.392817	0.411079
Eye Level Mean (V)	-0.0122794	0.000408482
Eye Amplitude (V)	0.782905	0.821153
Eye Height (V)	0.36302	0.646629
Eye Width (UI)	0.621729	0.941907
Eye Opening Factor	0.463683	0.787464
Eye Signal to Noise	5.4217	9.24654
Eye Rise Time (20-80) (UI)	0.488181	0.466329
Eye Fall Time (80-20) (UI)	0.488284	0.466431
Eye Jitter (PP) (UI)	0.378271	0.0580931
Eye Jitter (RMS) (UI)	0.0560791	0.0154872

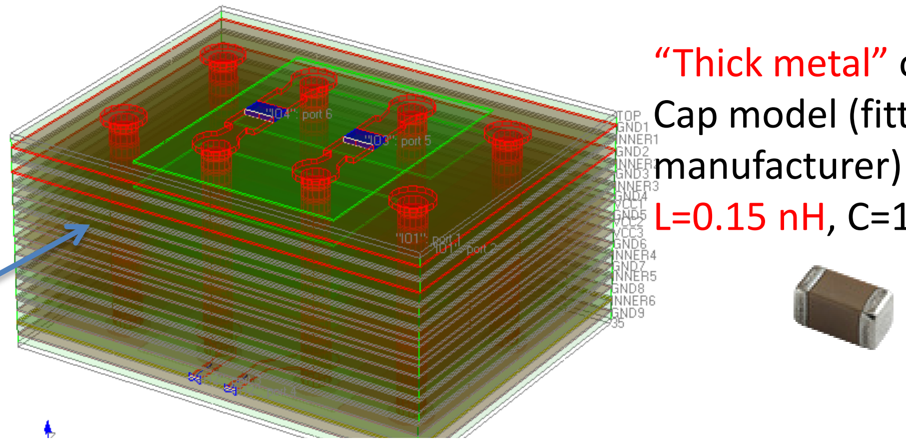


Un-acceptable difference; Possible reasons – cap model inductance, geometry differences…

F2: Link with 0201 AC coupling capacitors

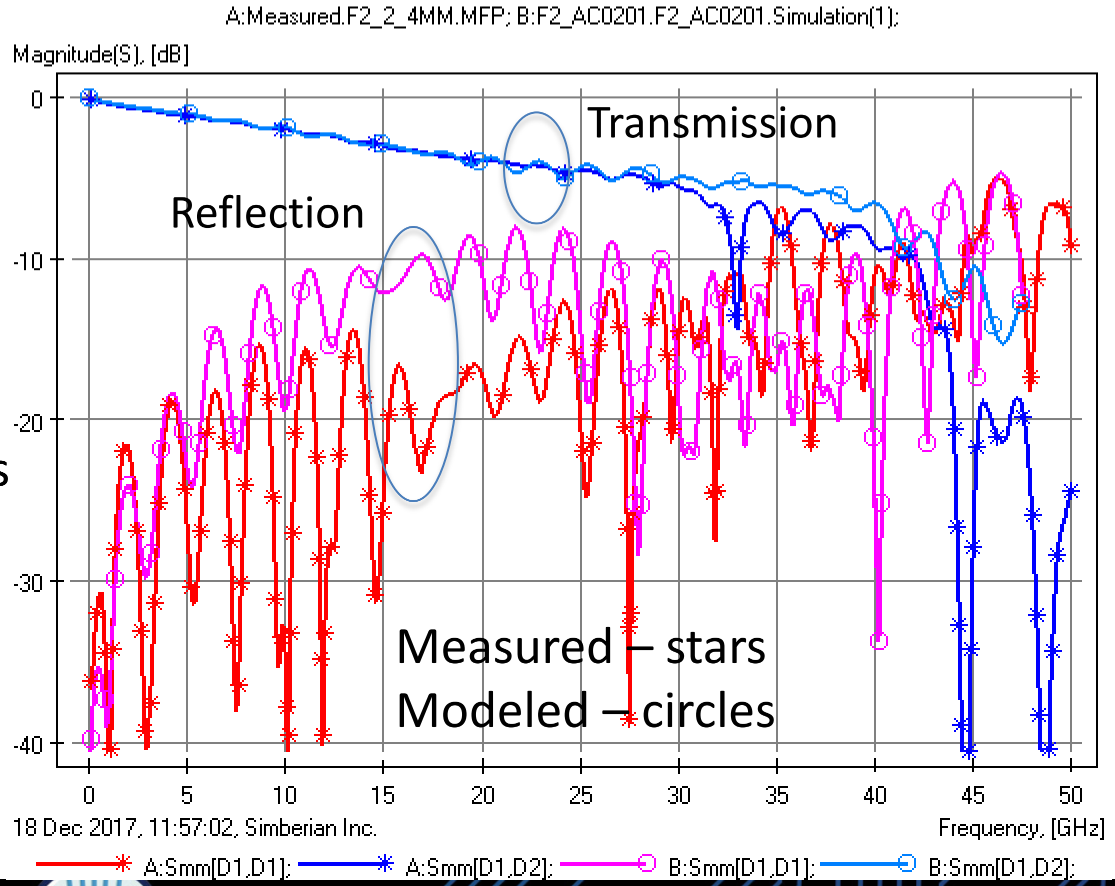
De-compositional EM analysis
All trace widths are adjusted

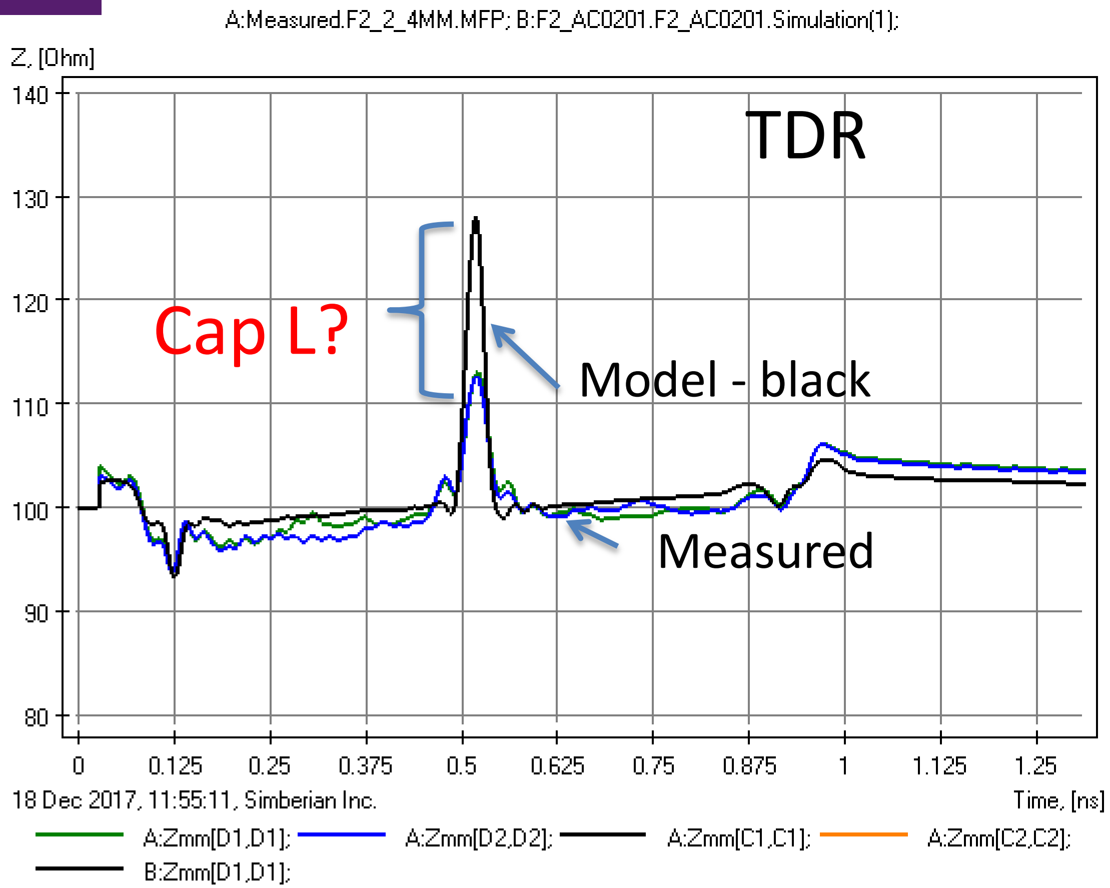




"Thick metal" option,
Cap model (fitted to s2p from manufacturer): R=0.025, L=0.15 nH, C=100 nF

First analysis
Differential S-parameters & TDR

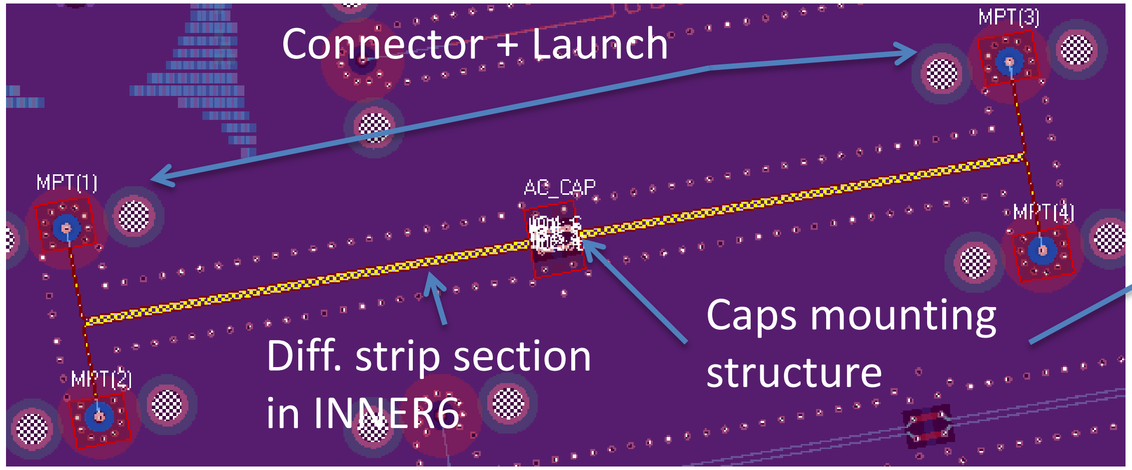


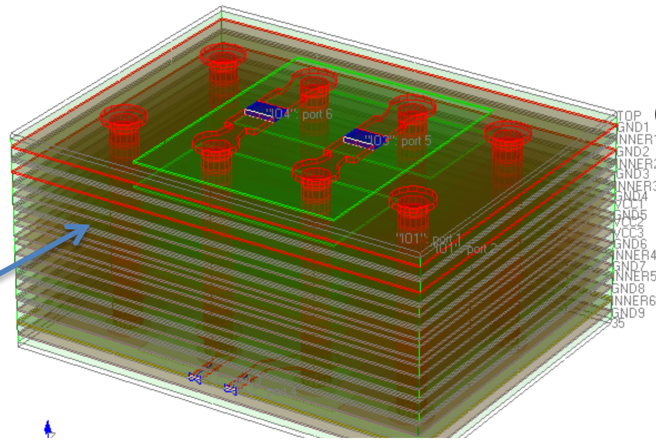


Reality: Bad correlation in reflection, the caps are less inductive in reality…

F2: Link with 0201 AC coupling capacitors

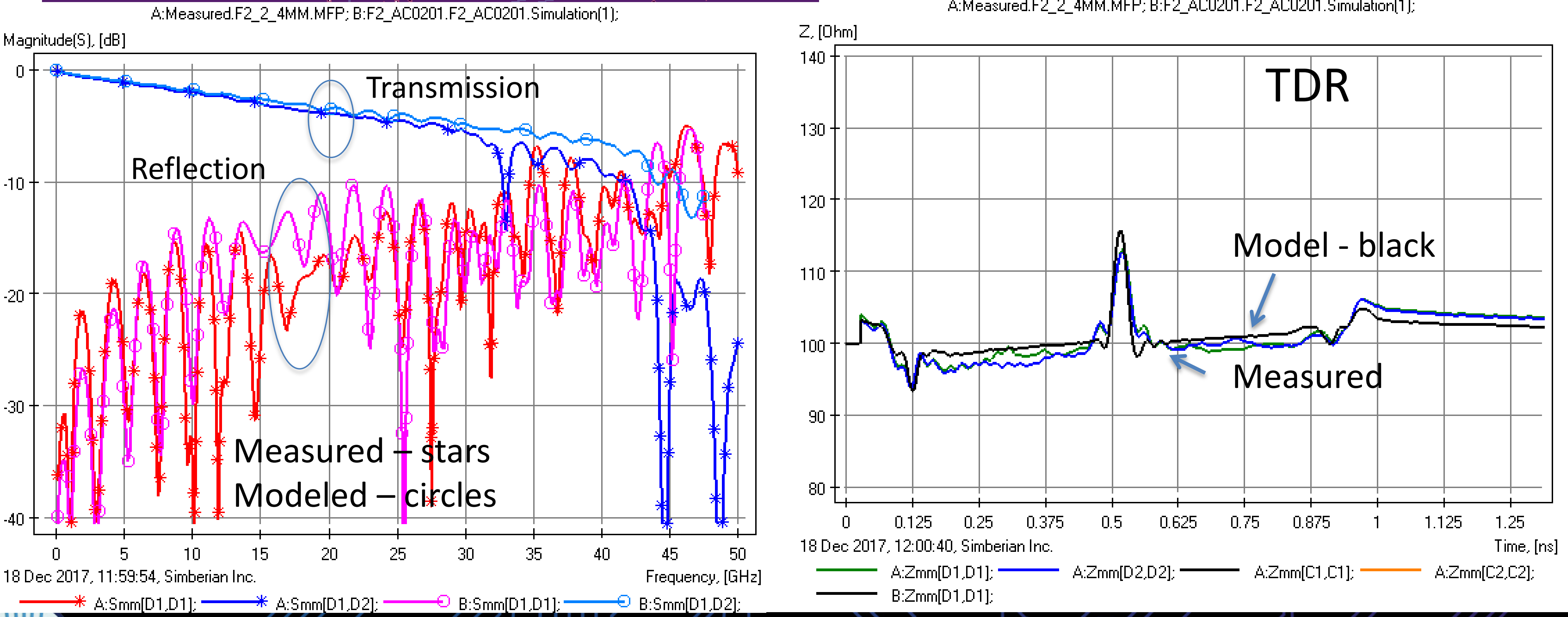
De-compositional EM analysis
All trace widths are adjusted





"Thick metal" option,
Cap model (fitted to s2p from manufacturer): R=0.025, L=0.0 nH, C=100 nF

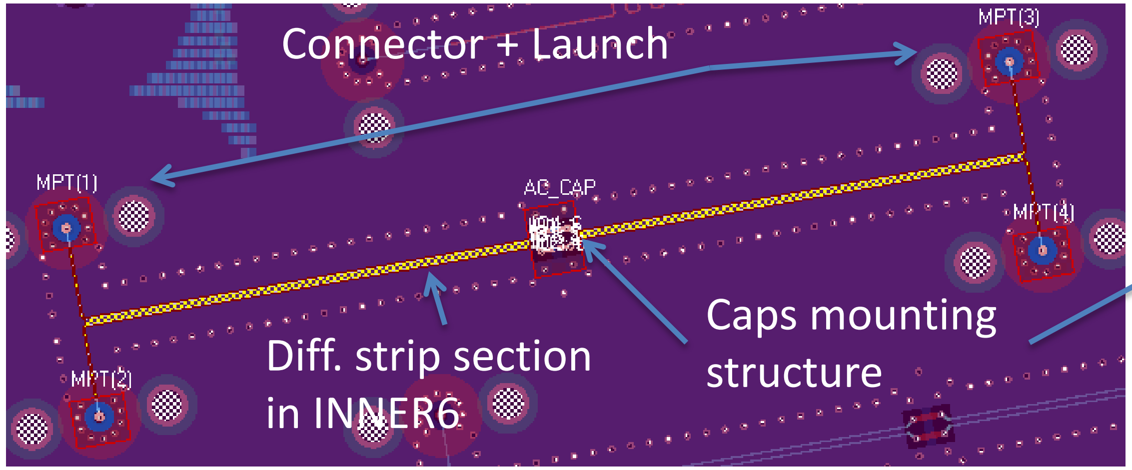
Final analysis
Differential S-parameters & TDR

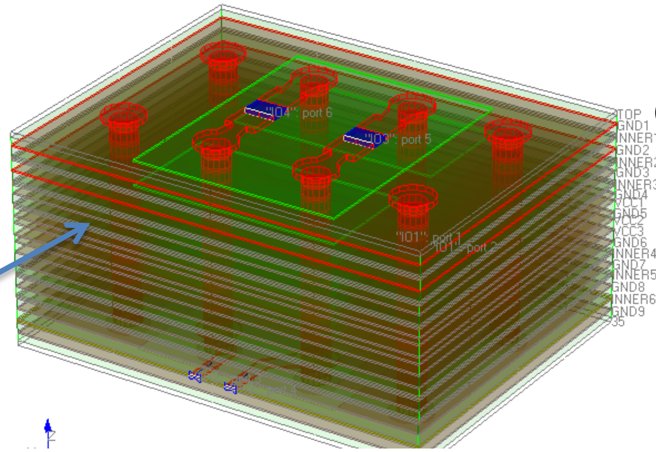


Reality: Better correlation without the capacitor internal inductance…

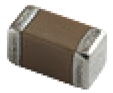
F2: Link with 0201 AC coupling capacitors

De-compositional EM analysis
All trace widths are adjusted

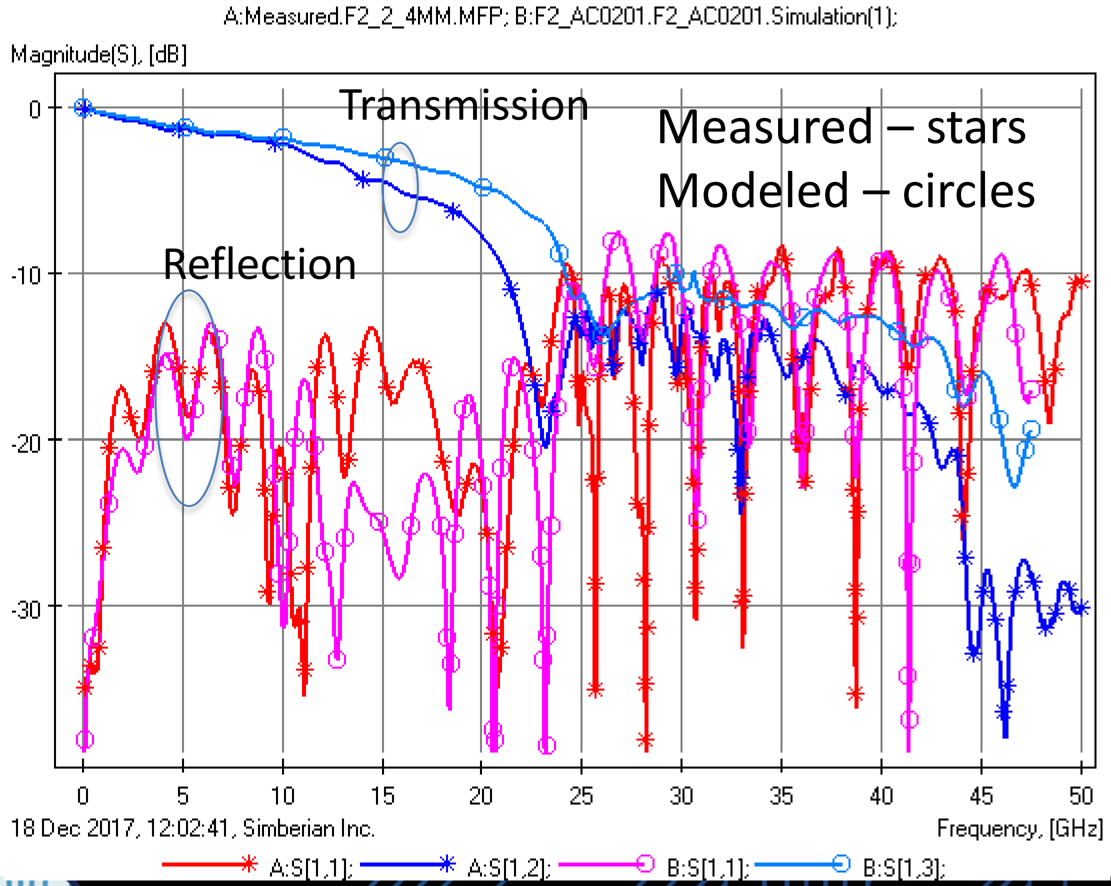


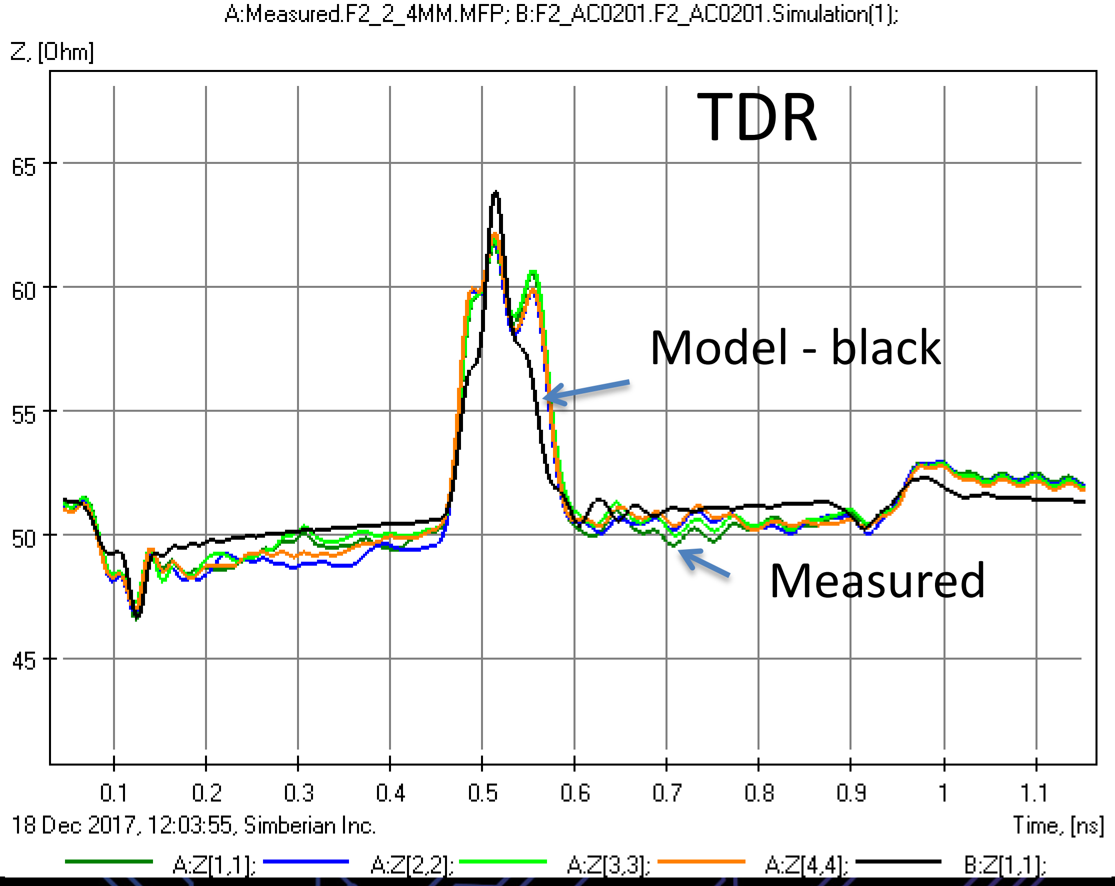


"Thick metal" option,
Cap model (fitted to s2p from manufacturer): R=0.025, L=0.0 nH, C=100 nF



Final analysis
Single-ended S-parameters & TDR





Reality: Large difference in single-ended S-parameters, acceptable TDR…

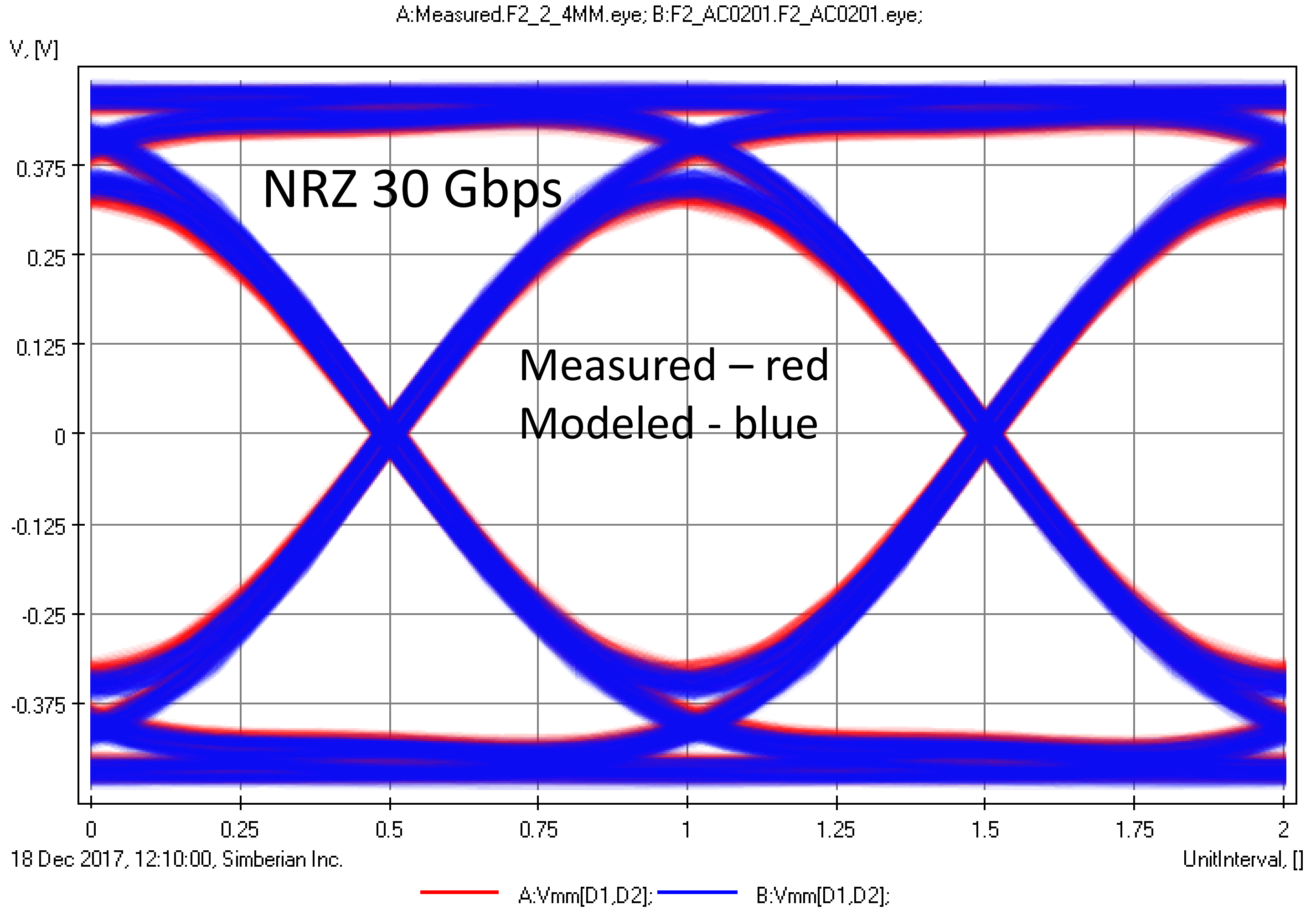
F2: Link with 0201 AC coupling capacitors

- Eye diagrams comparison

Eye Analyzer

Show Eye Metrics: Selected ☑ Auto-open

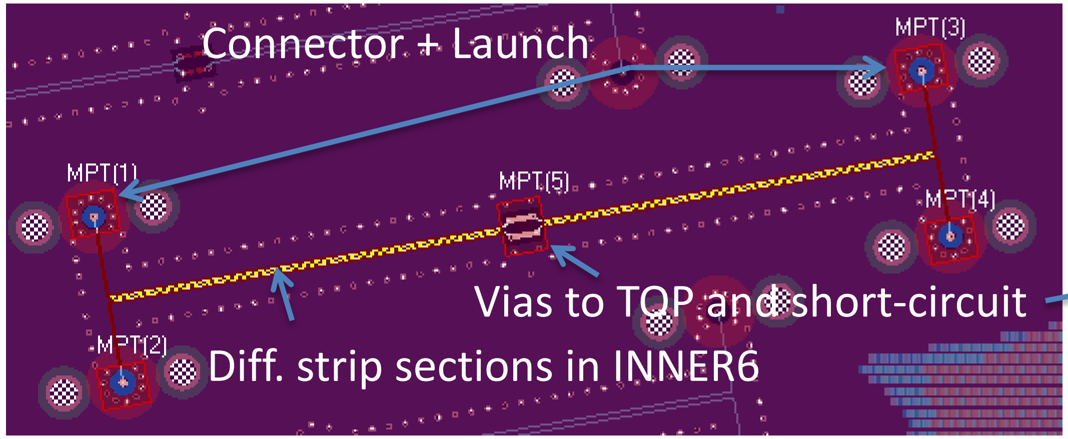
Parameter	Measured.F2_2_...	F2_AC0201.F2_AC...
Eye Level Zero (V)	-0.397961	-0.407479
Eye Level One (V)	0.397506	0.404991
Eye Level Mean (V)	8.17329e-005	-0.000942555
Eye Amplitude (V)	0.795466	0.81247
Eye Height (V)	0.603035	0.628716
Eye Width (UI)	0.931707	0.936585
Eye Opening Factor	0.75809	0.773832
Eye Signal to Noise	7.78942	8.44747
Eye Rise Time (20-80) (UI)	0.481123	0.472551
Eye Fall Time (80-20) (UI)	0.481216	0.472773
Eye Jitter (PP) (UI)	0.0682927	0.0634146
Eye Jitter (RMS) (UI)	0.0169048	0.0160042

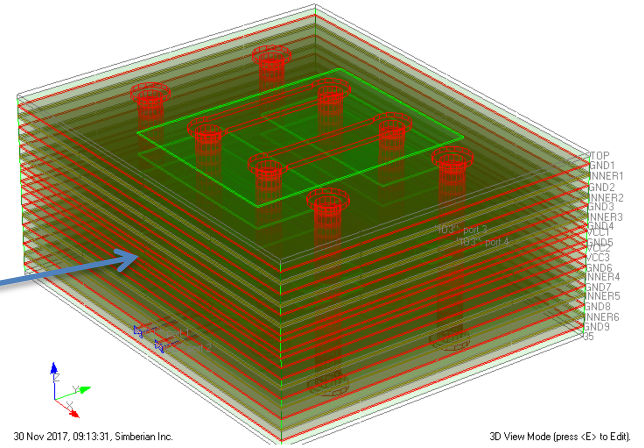


~3.3% difference in eye heights, ~1% in widths; Possible reasons – cap model inductance, impedance variations, loss of launch localization…

F3: Short-circuited pads for 0201 AC coupling cap

De-compositional EM analysis
All trace widths and shapes are adjusted

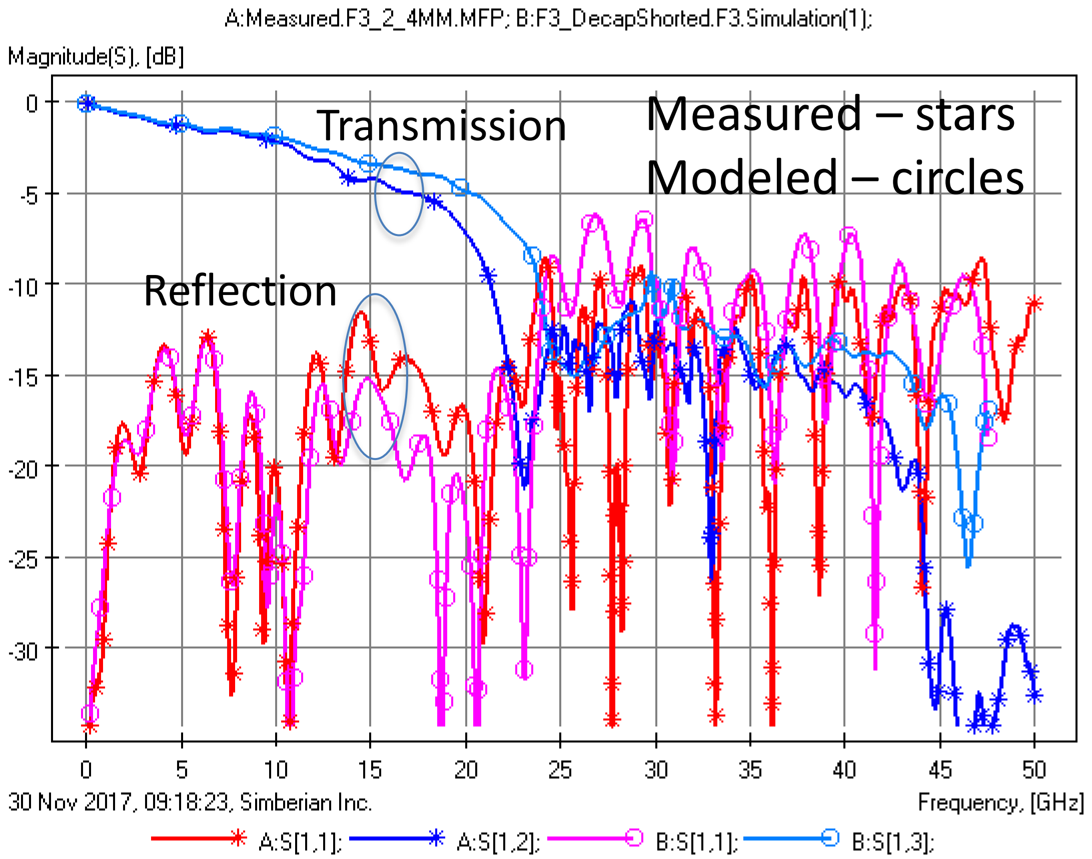


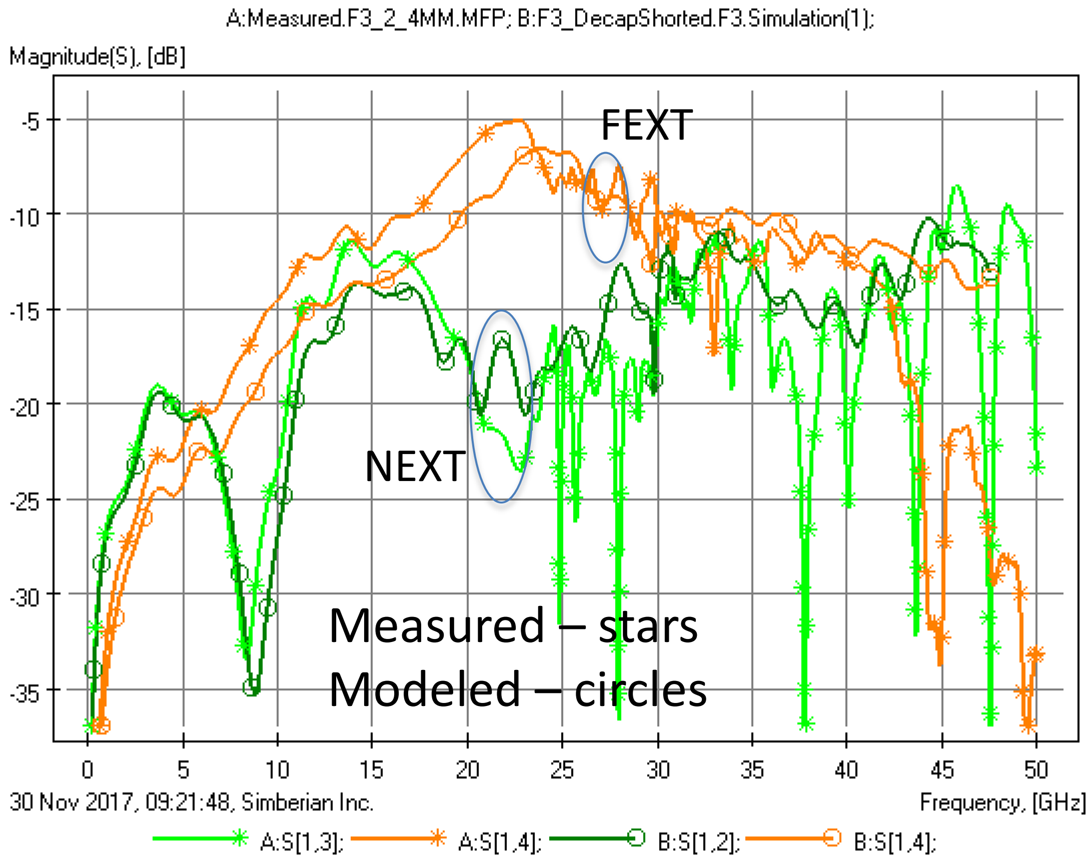


Single-ended S-parameters

Reality: Growing difference above 10 GHz – loss of localization? - investigate…

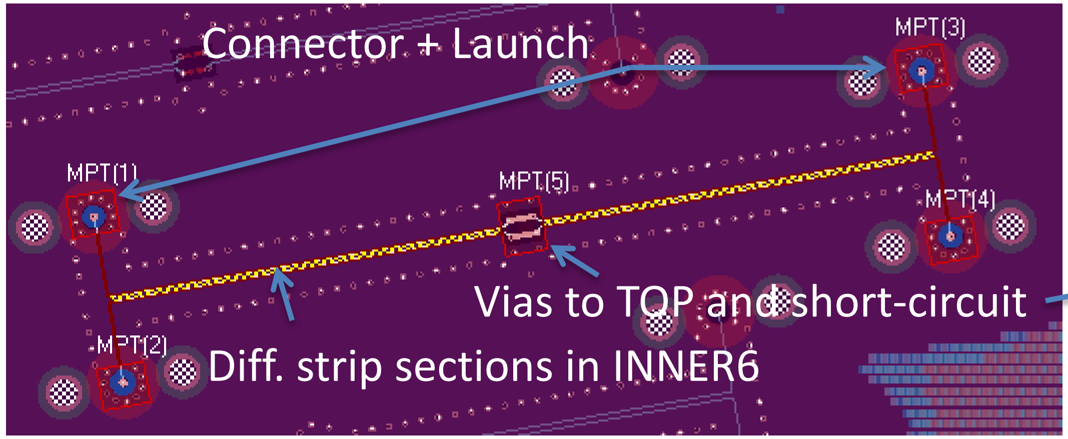
Acceptable correspondence only up to 10 GHz

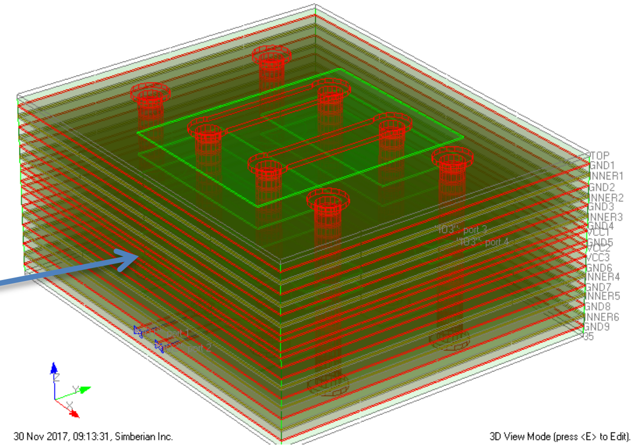




F3: Short-circuited pads for 0201 AC coupling cap

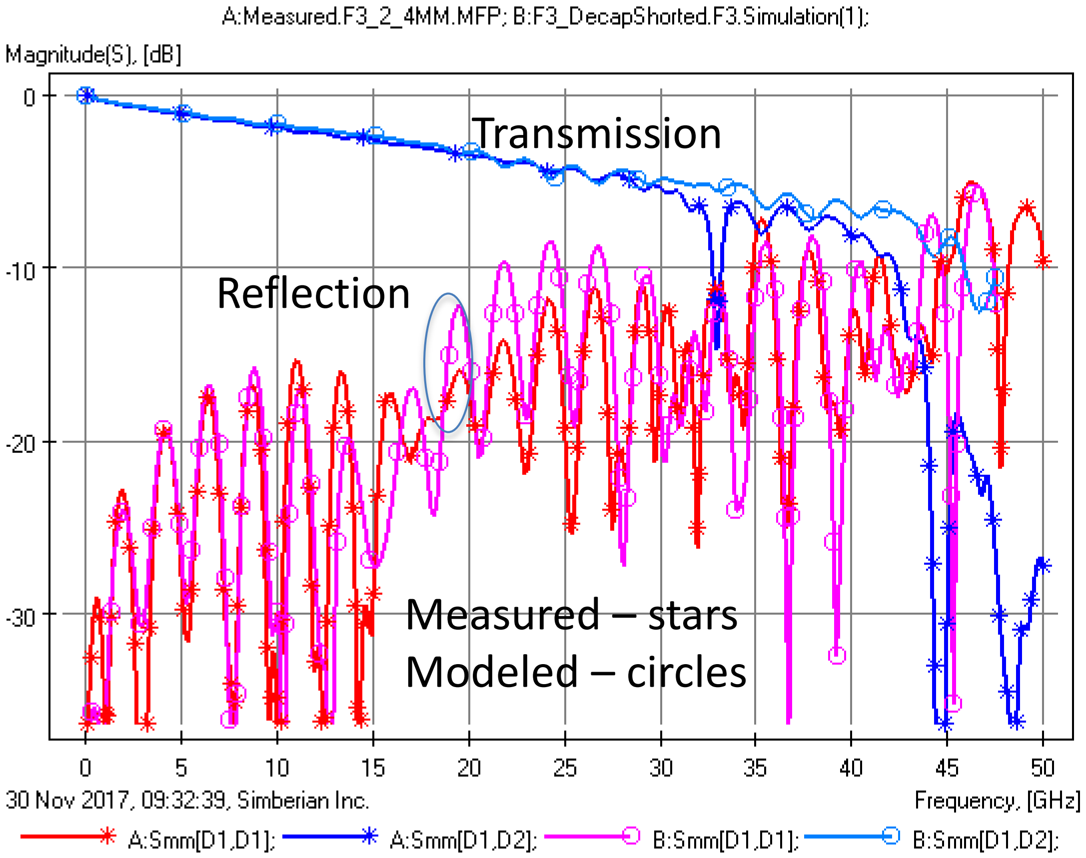
De-compositional EM analysis
All trace widths and shapes are adjusted

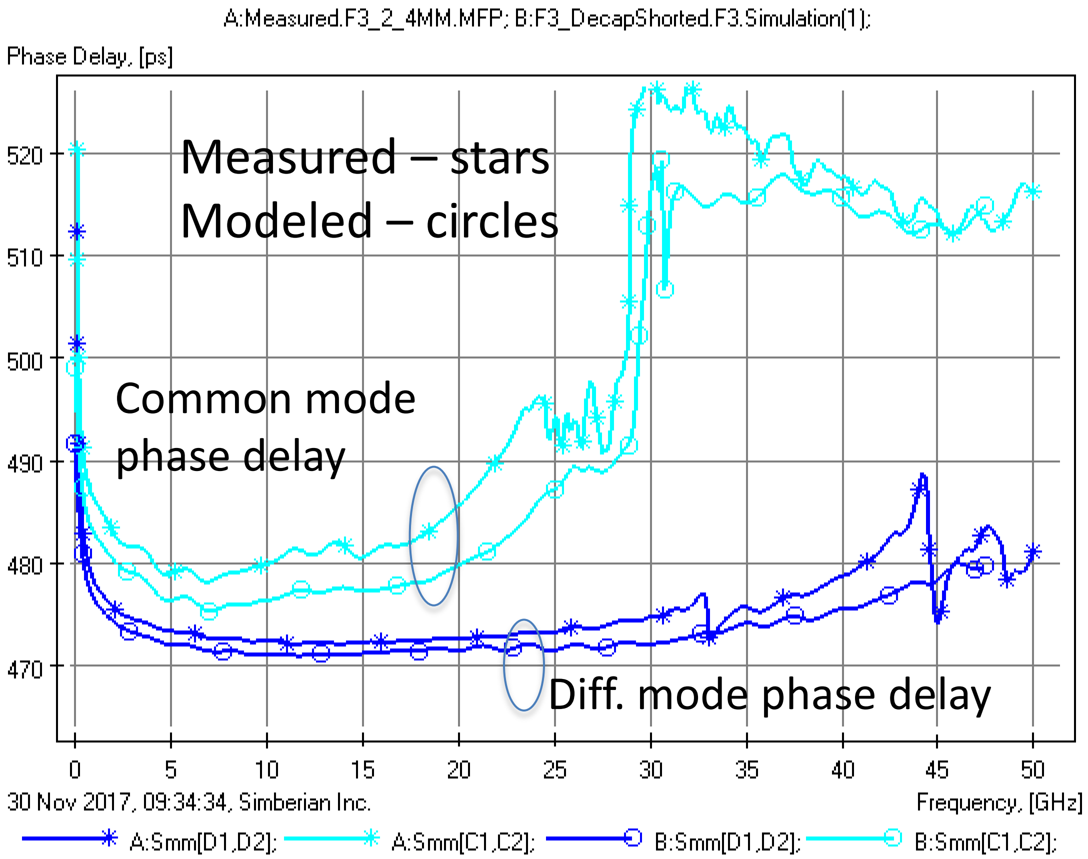




Mixed-mode S-parameters

Reality: Difference above 30 GHz – see reality above 30 GHz…

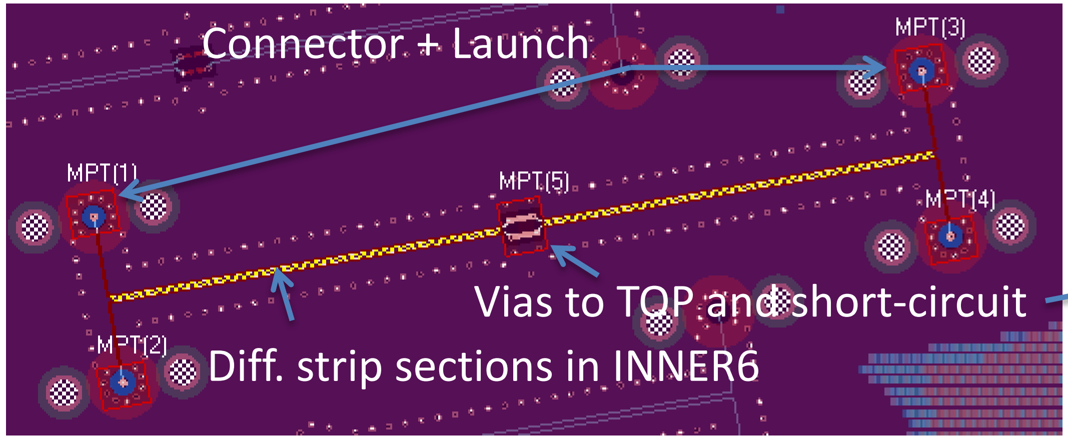


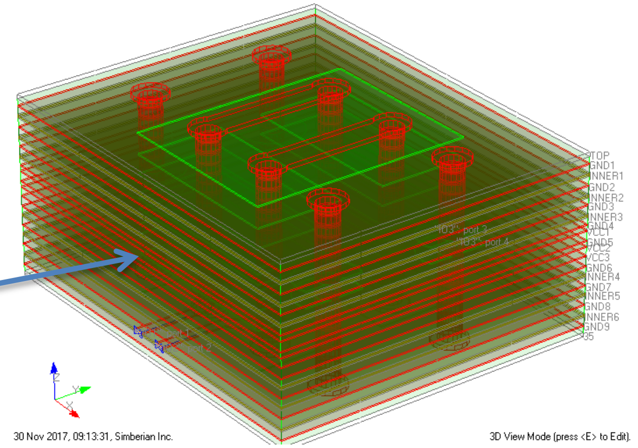


Questionable correspondence in common mode above 10 GHz
Acceptable correspondence for differential mode up to 30 GHz

F3: Short-circuited pads for 0201 AC coupling cap

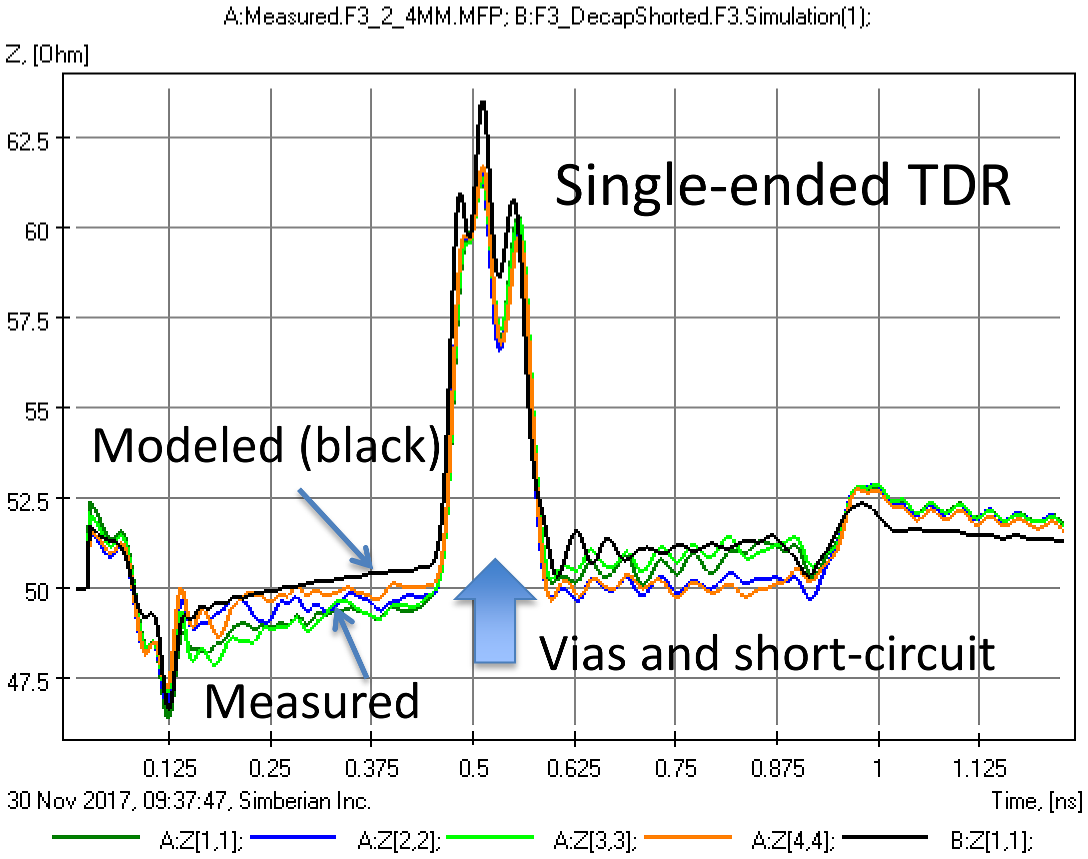
De-compositional EM analysis
All trace widths and shapes are adjusted

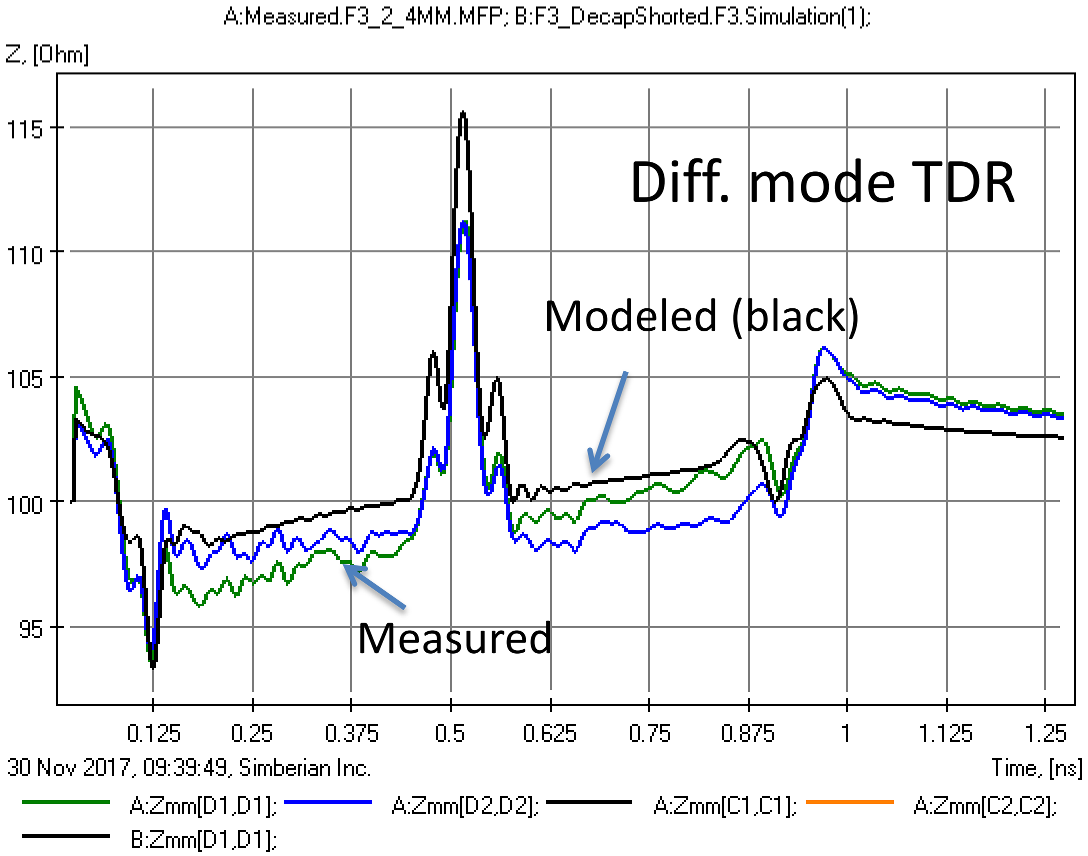




Reality: Vias and short-circuit are less capacitive – investigate (model or geometry?)…

Acceptable correspondence





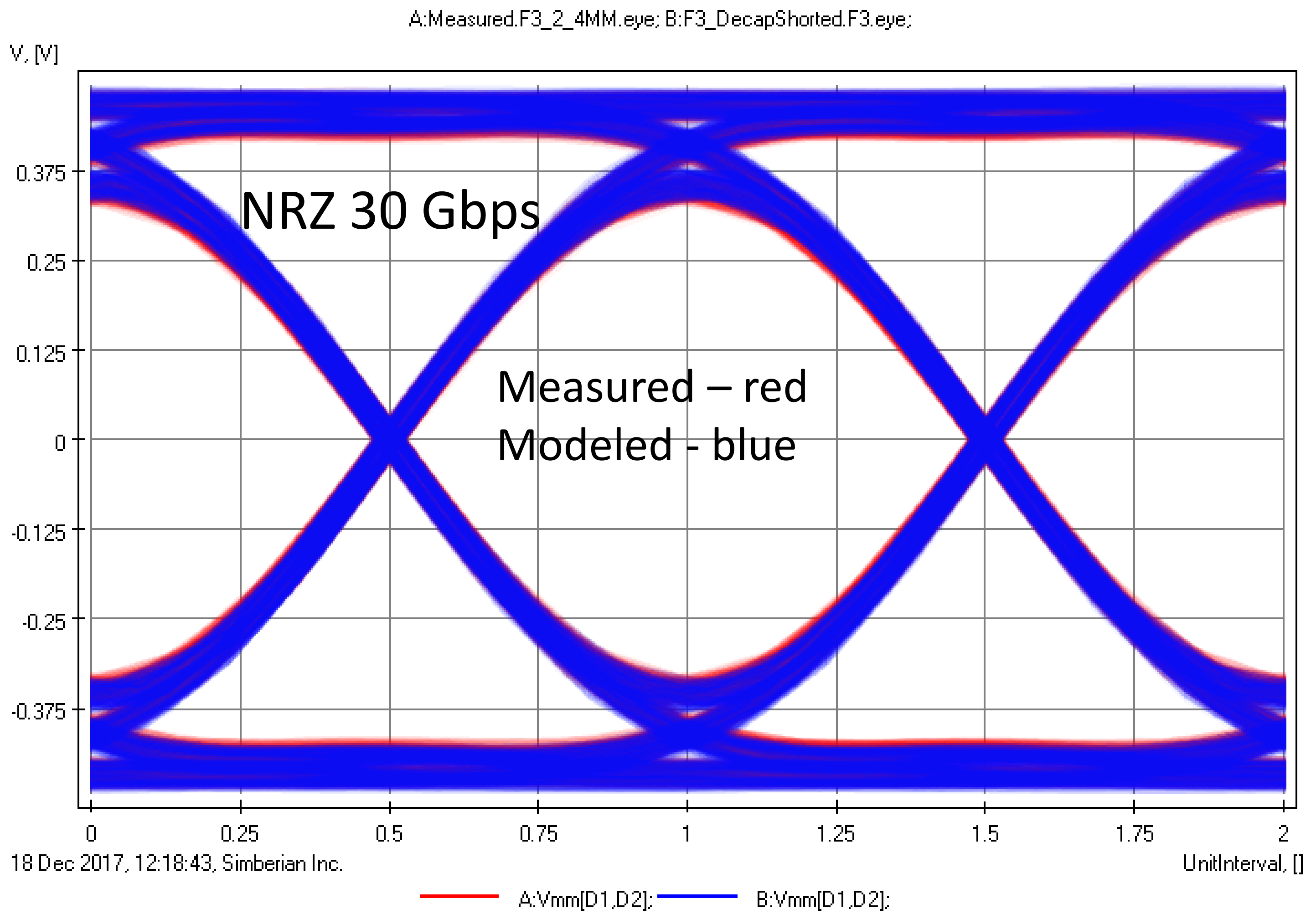
F3: Short-circuited pads for 0201 AC coupling cap

- Eye diagrams comparison

Eye Analyzer

Show Eye Metrics: Selected ☑ Auto-open

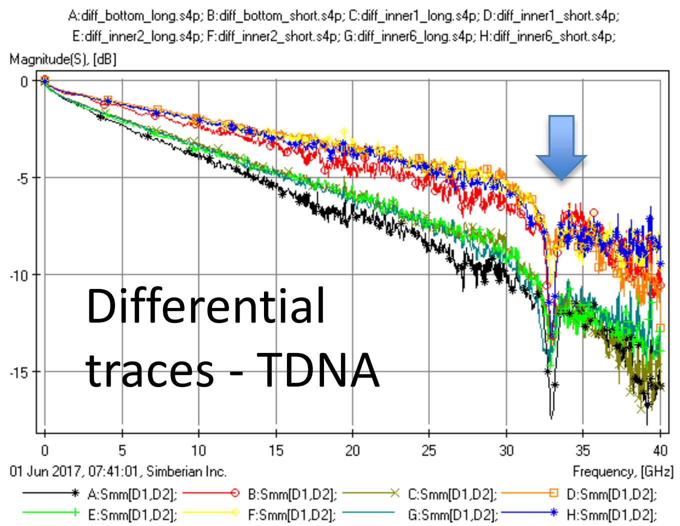
Parameter	Measured.F3_2_4...	F3_DecapShort...
Eye Level Zero (V)	-0.402872	-0.410173
Eye Level One (V)	0.40074	0.408334
Eye Level Mean (V)	0.0009437	0.000784197
Eye Amplitude (V)	0.803612	0.818507
Eye Height (V)	0.624931	0.637838
Eye Width (UI)	0.935698	0.937916
Eye Opening Factor	0.777652	0.779269
Eye Signal to Noise	8.70062	8.99069
Eye Rise Time (20-80) (UI)	0.470208	0.468474
Eye Fall Time (80-20) (UI)	0.470194	0.468455
Eye Jitter (PP) (UI)	0.0643016	0.0620843
Eye Jitter (RMS) (UI)	0.0164146	0.0149904

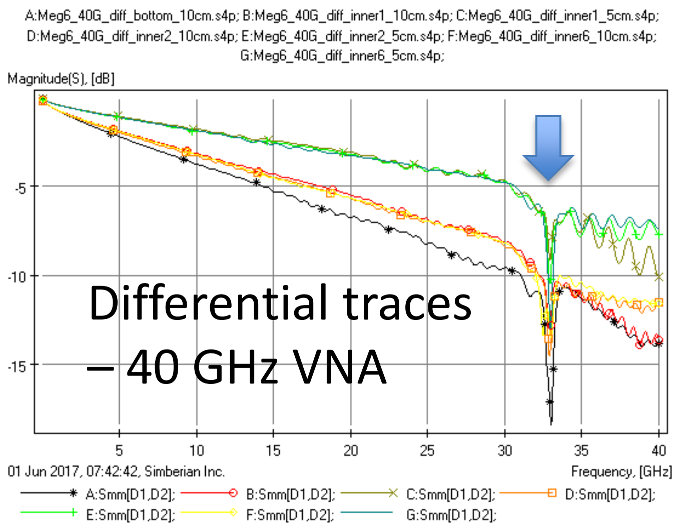


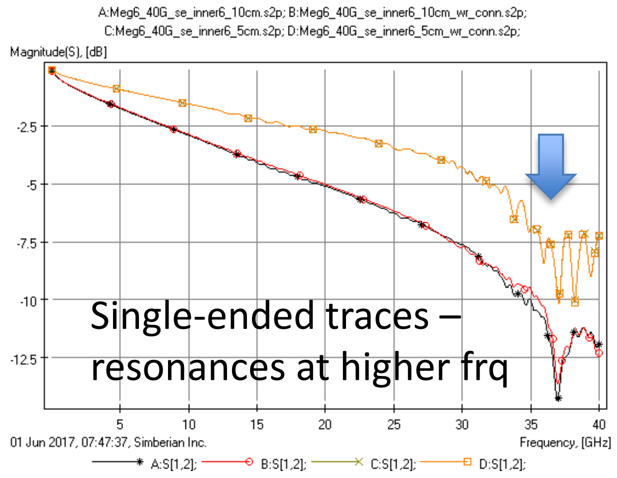
~2% difference in eye heights, ~1% in widths; Possible reasons – geometry differences, impedance variations, loss of launch localization…

Reality above 30 GHz

Reality: What caused the resonances?



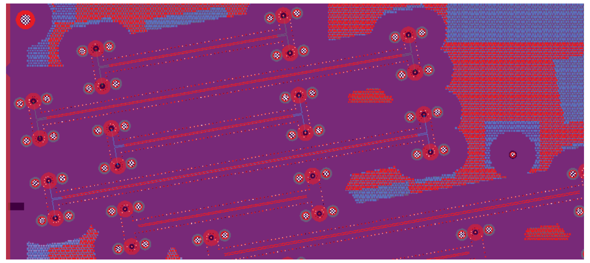


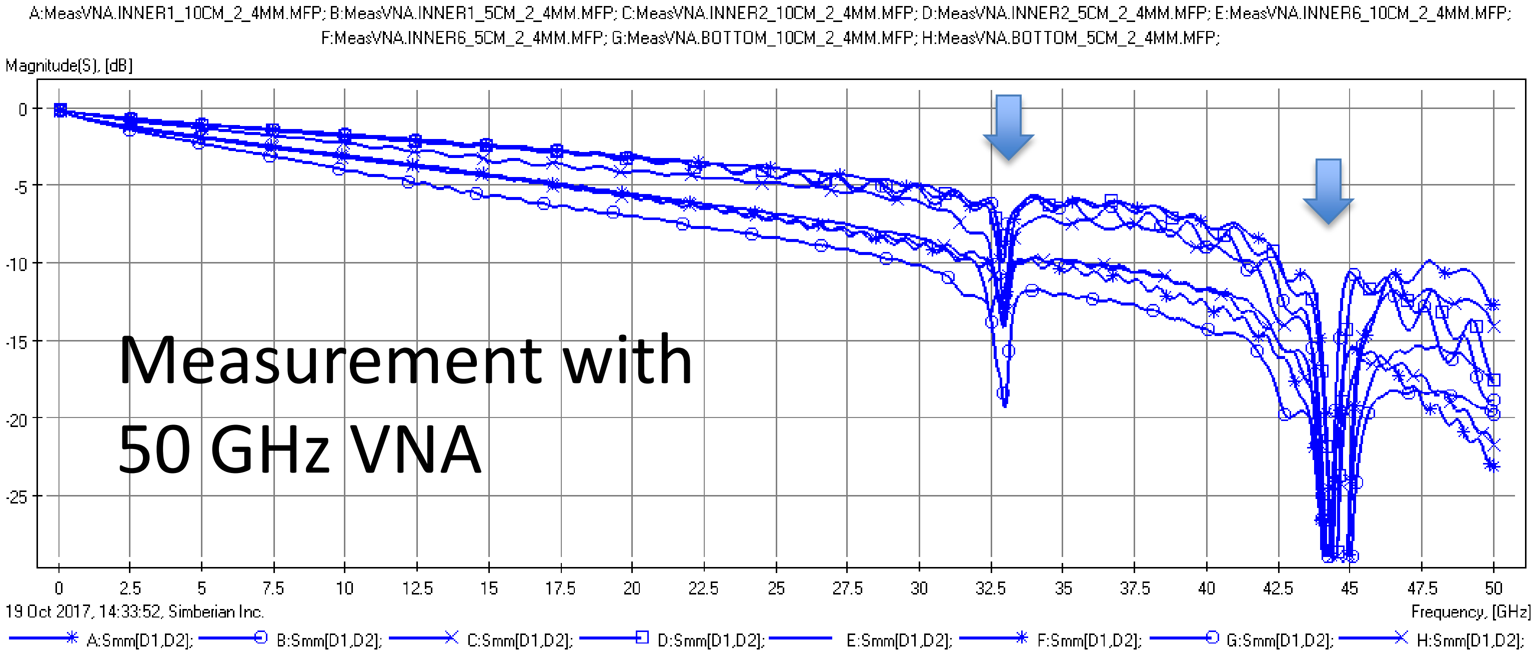


What caused it?

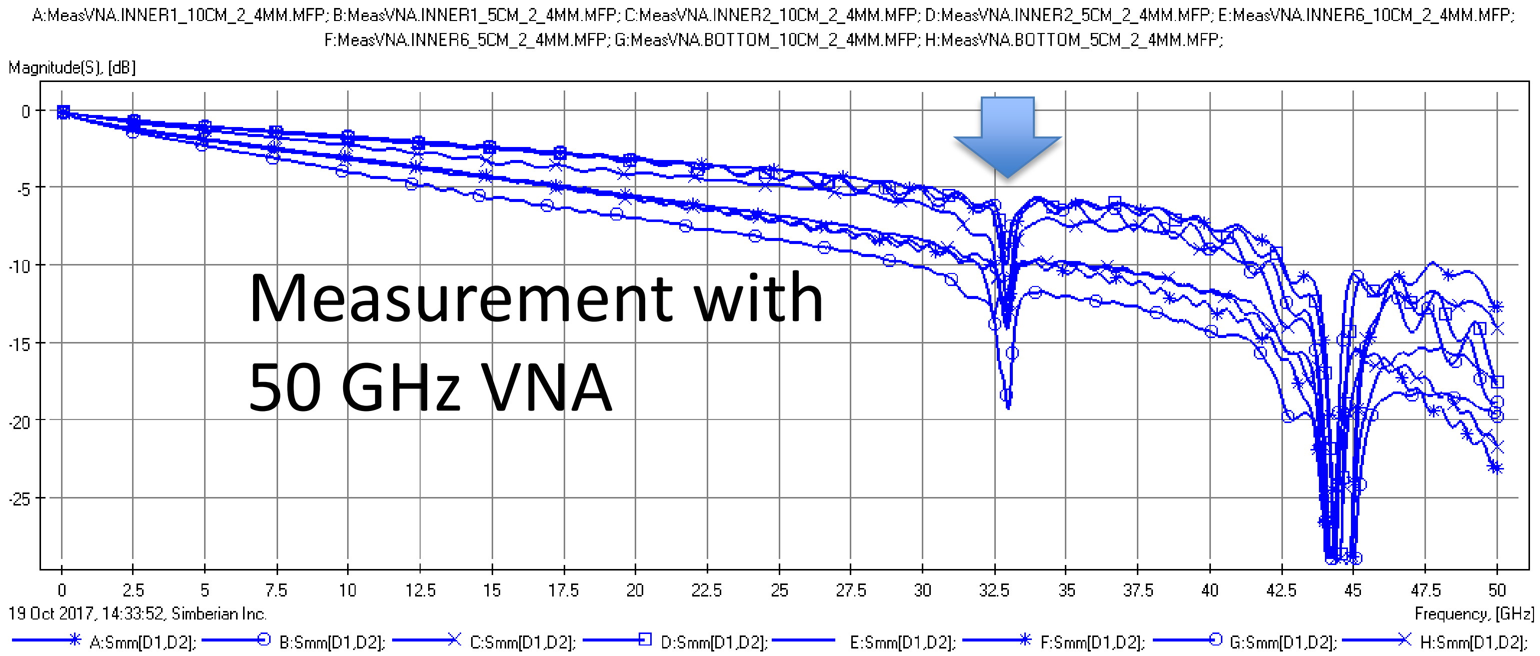
1. Fiber Weave Effect?
2. Connectors or adapters?
3. Launch localization?
4. Non of the above?

5 and 10 cm diff. traces in INNER1, INNER2, INNER6 and BOTTOM



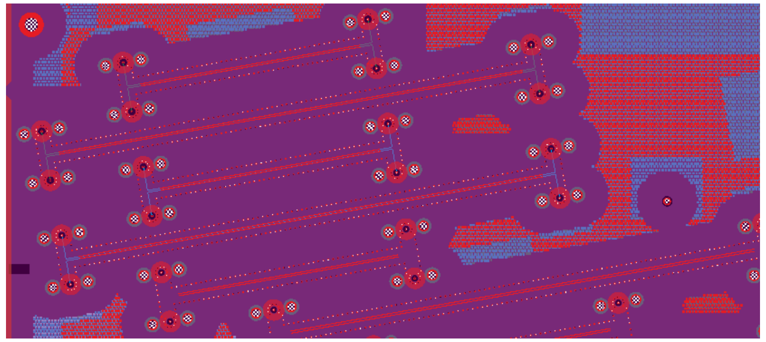


Reality: Resonance investigation

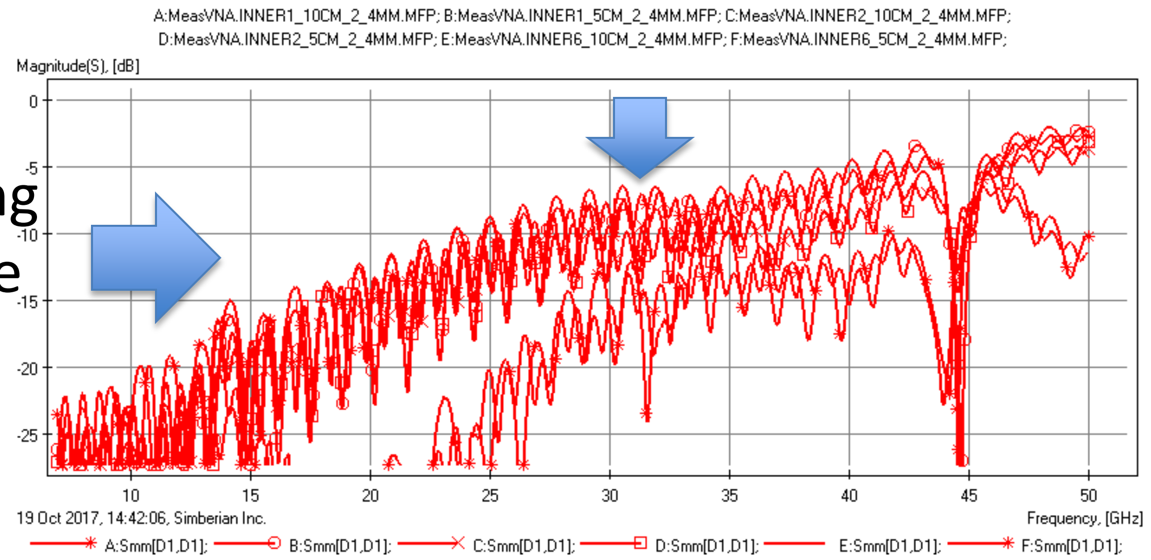


Measurement with 50 GHz VNA

5 and 10 cm diff. traces in INNER1, INNER2, INNER6 and BOTTOM

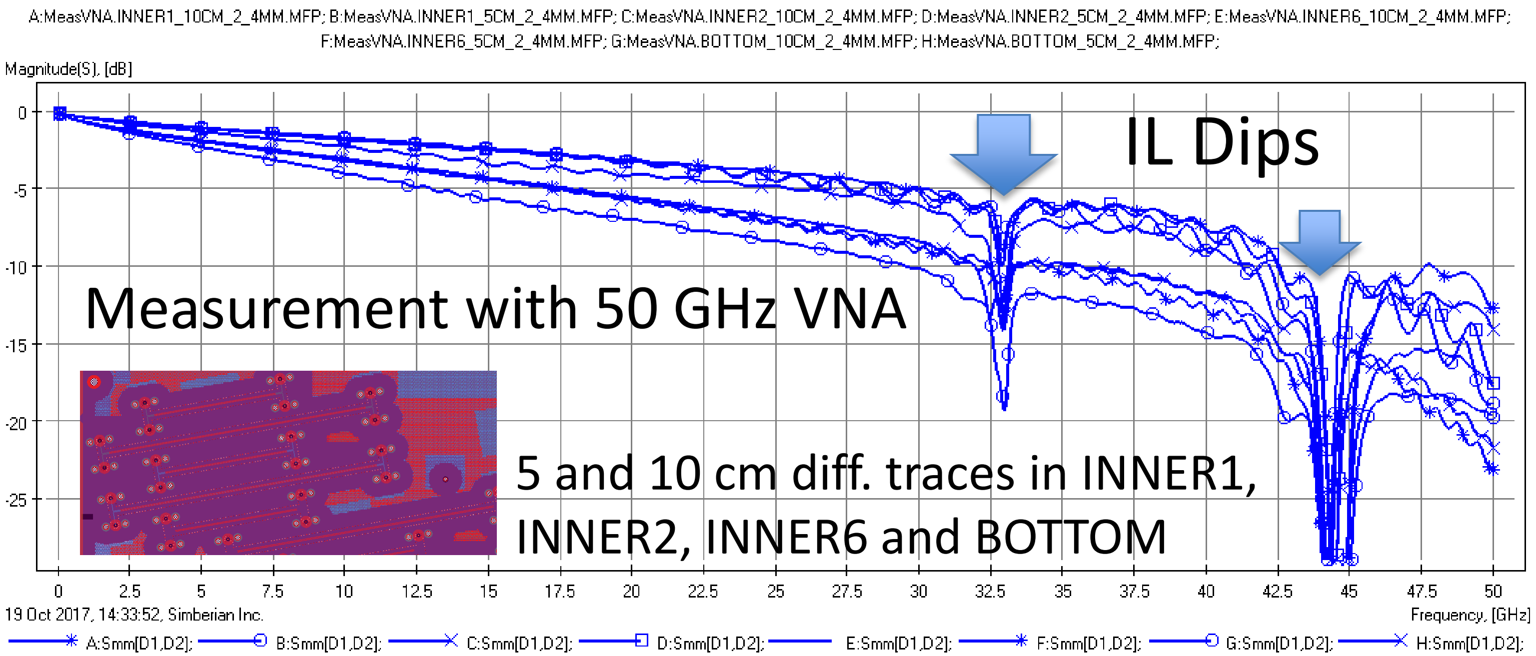


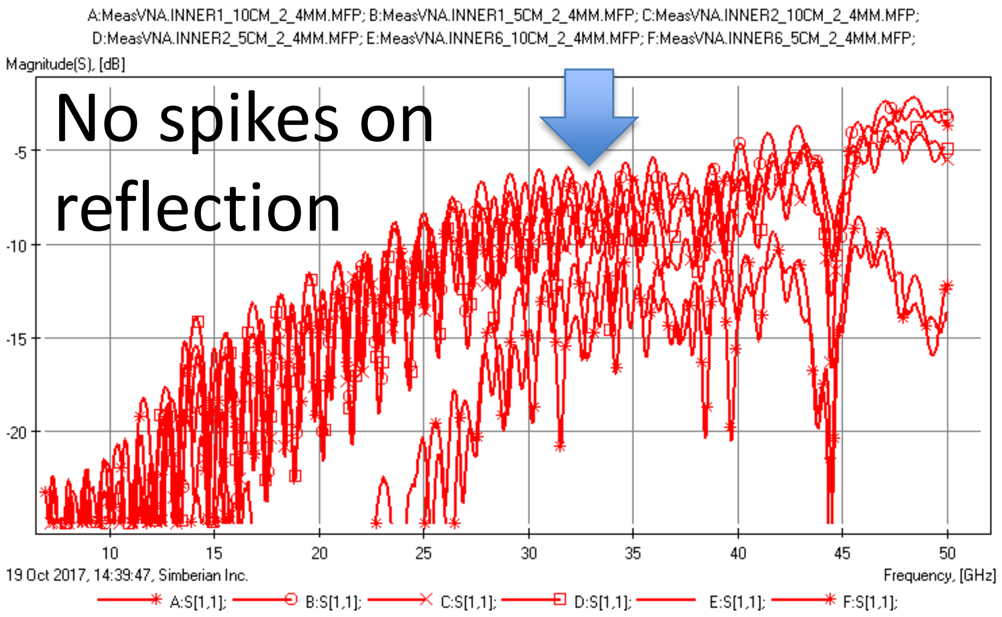
No matching peaks in the reflections



Looks like NOT a fiber weave effect…

Reality: Resonances investigation

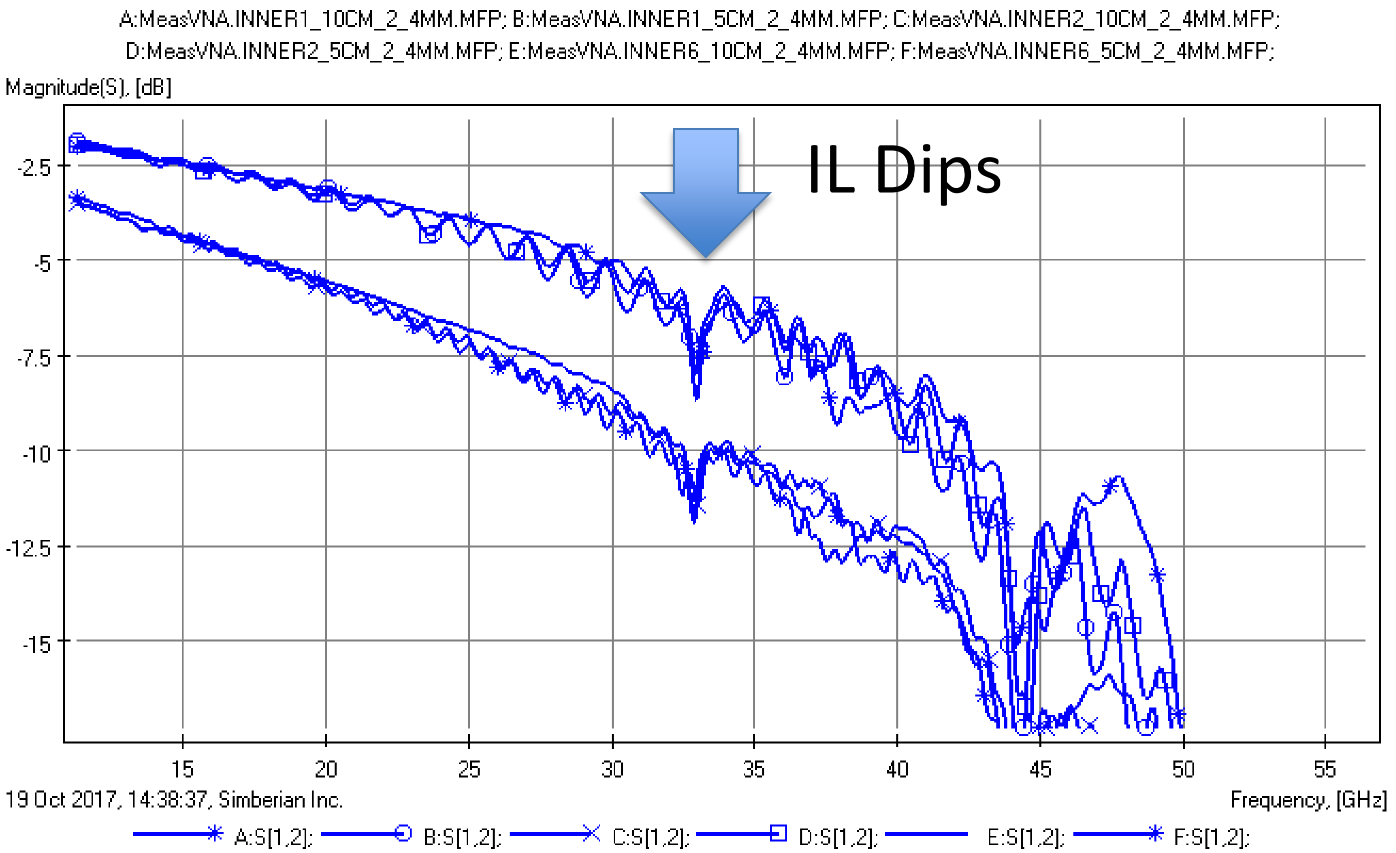


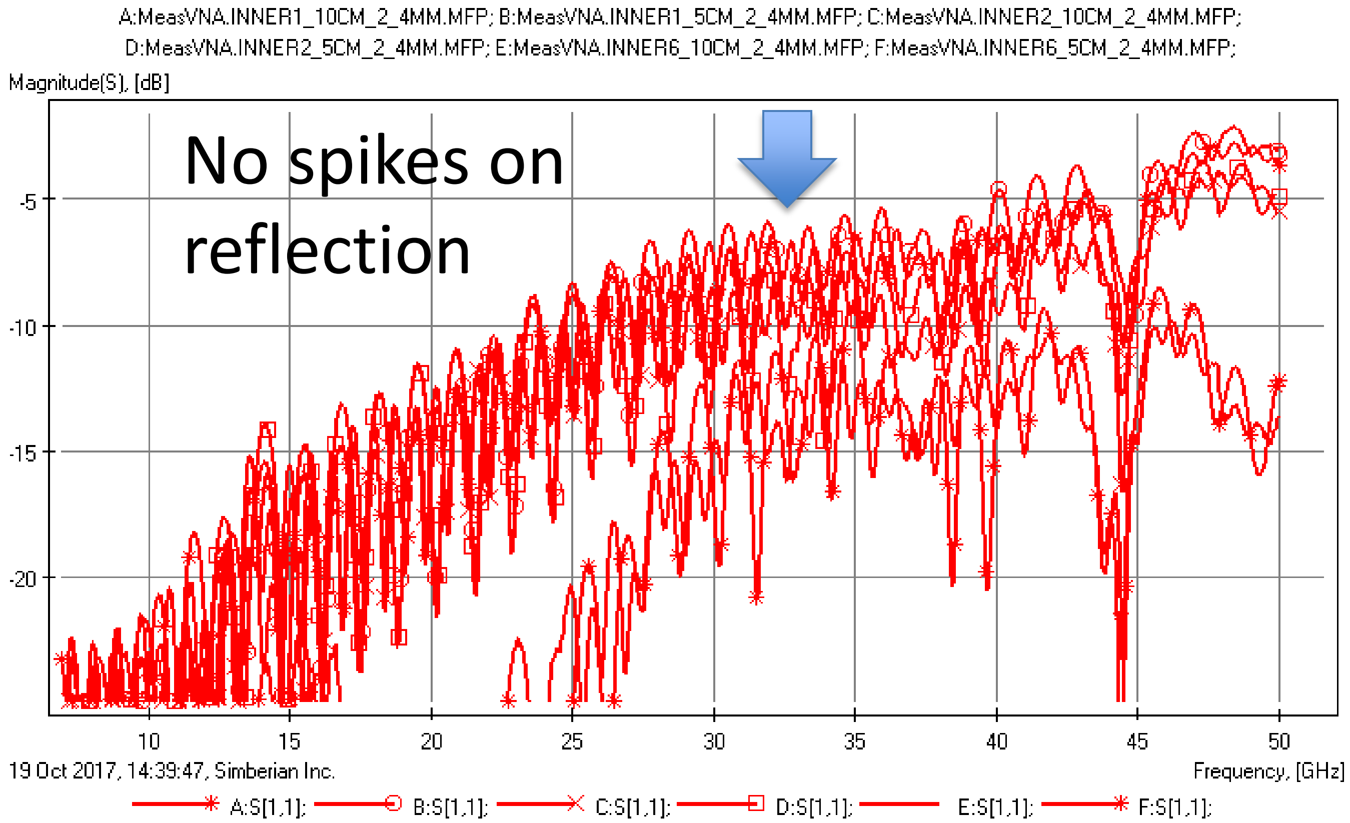


Looks like NOT a fiber weave effect – what would it be?

Reality: Resonance investigation

Single-ended S-parameters of diff. traces – dips in the insertion loss, but no matching peaks in the reflection



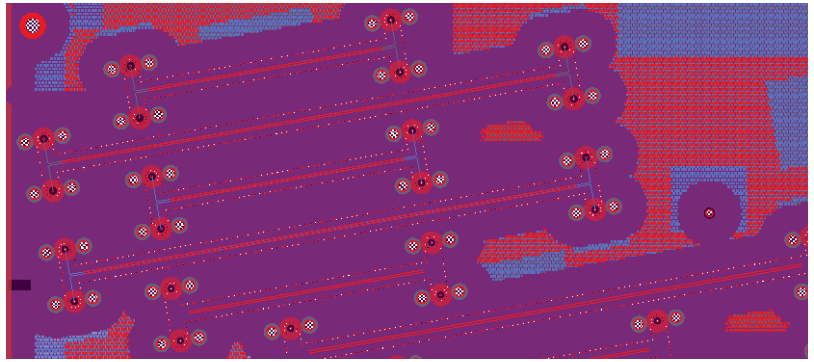


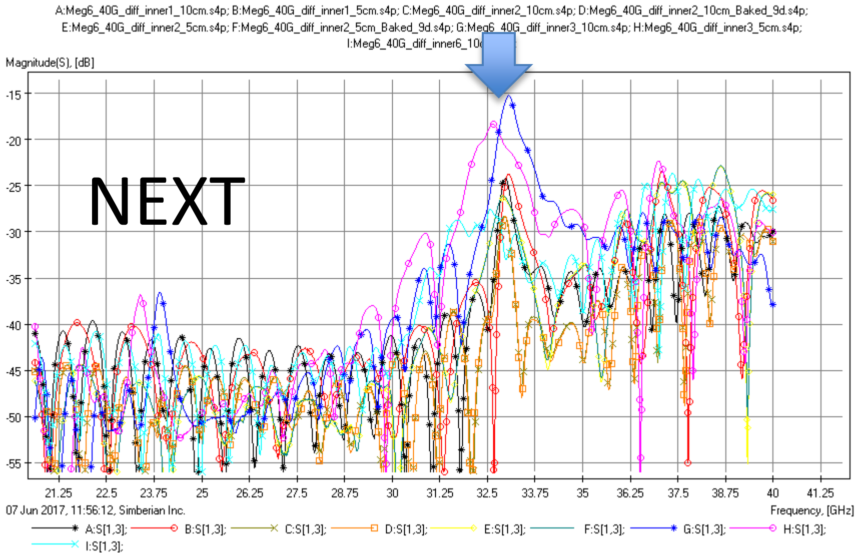
Definitely NOT the fiber weave effect…

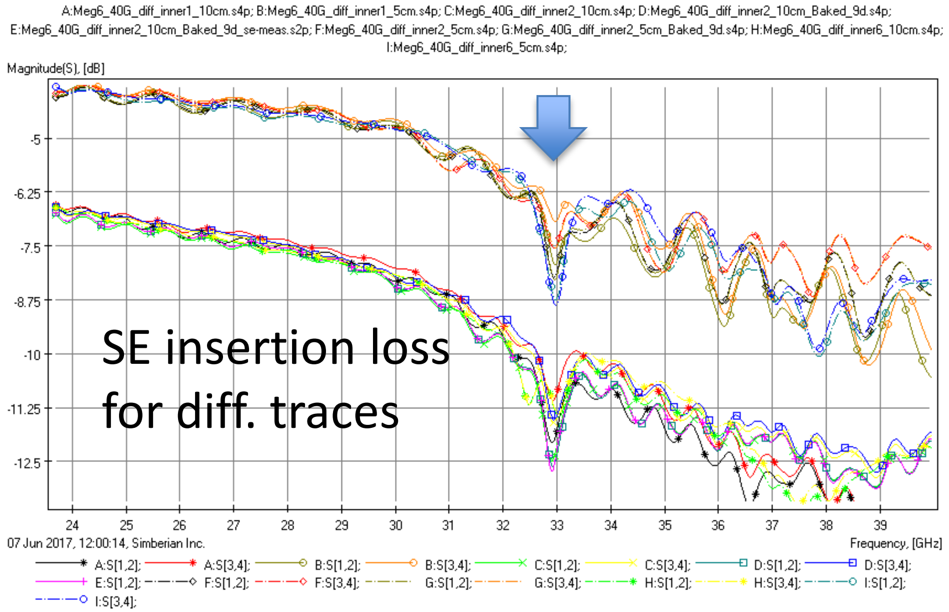
Reality: Resonance investigation

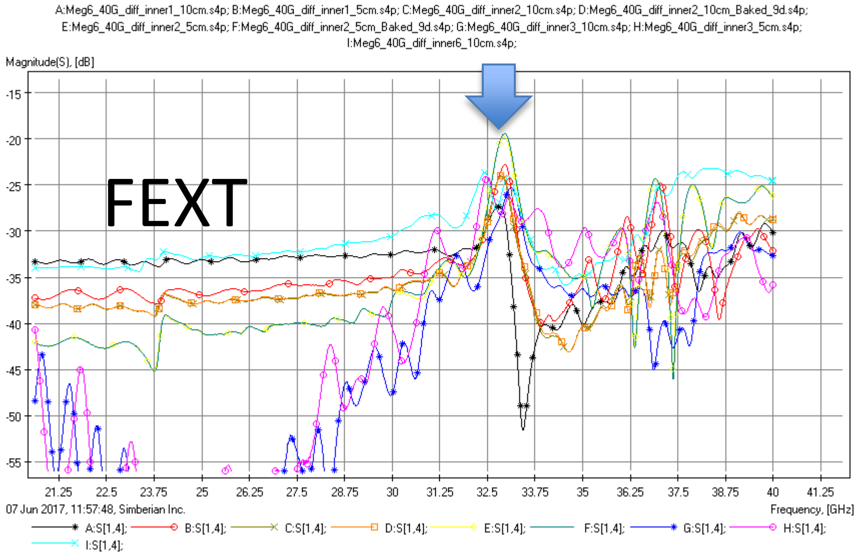
That is where the energy goes!

5 and 10 cm diff. traces in INNER1, INNER2, INNER6 and BOTTOM



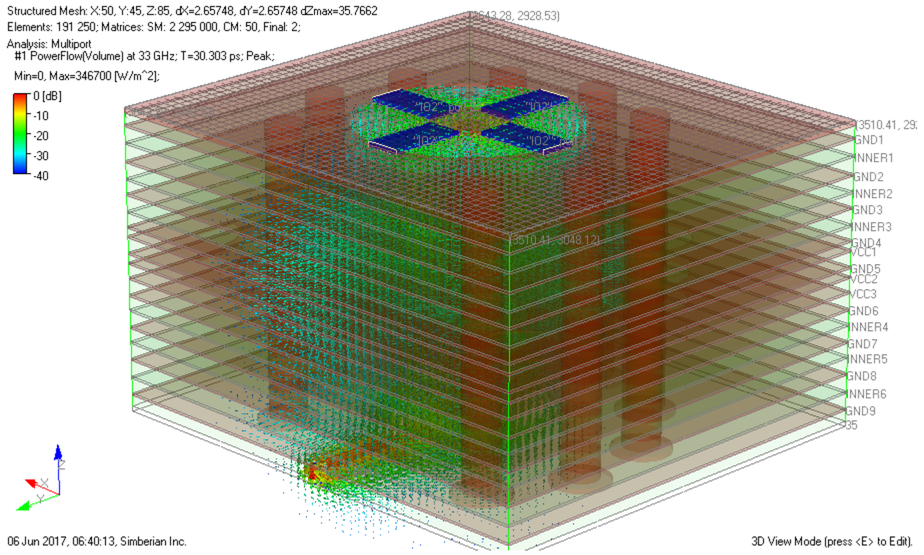


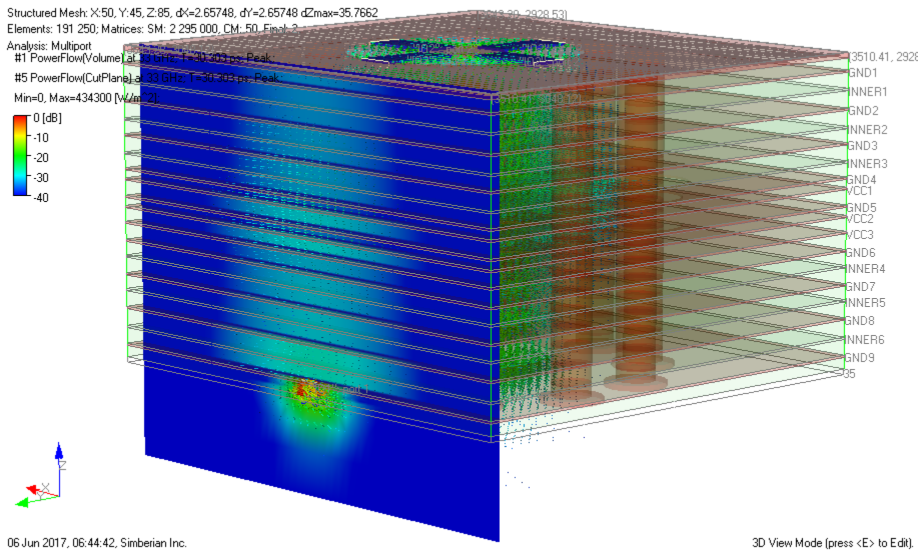




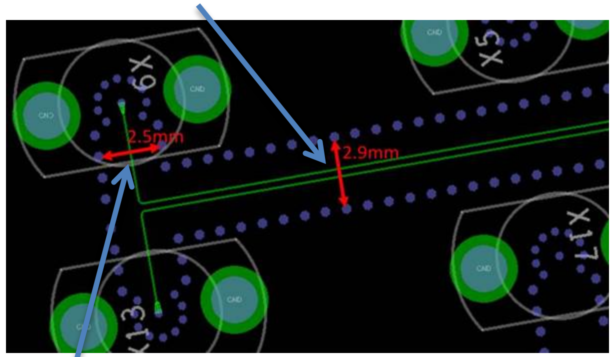
Launches are leaky above 30 GHz as designed!

Microstrip launch peak power flow density at 33 GHz



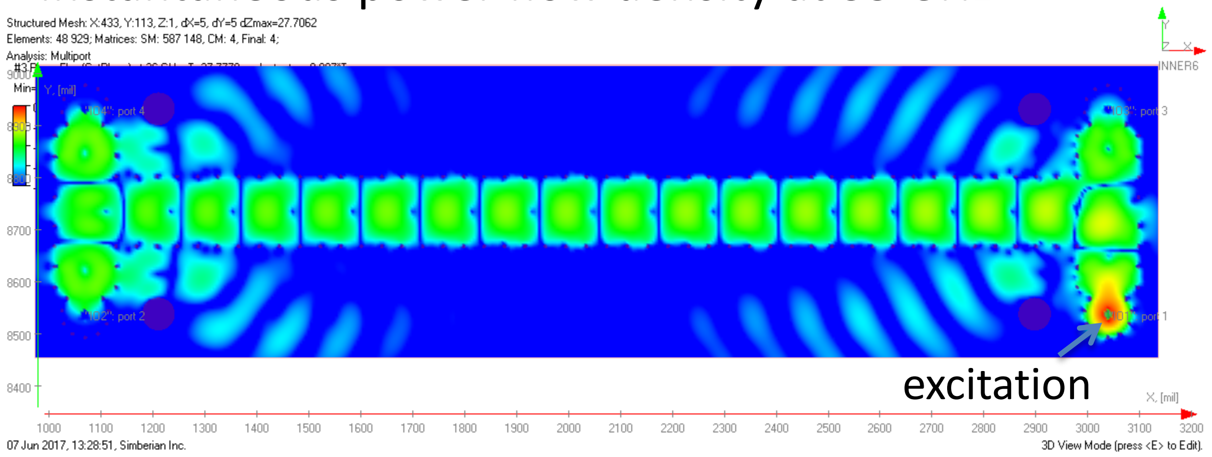


29 GHz cutoff frequency



32 GHz cutoff frequency

Instantaneous power flow density at 35 GHz

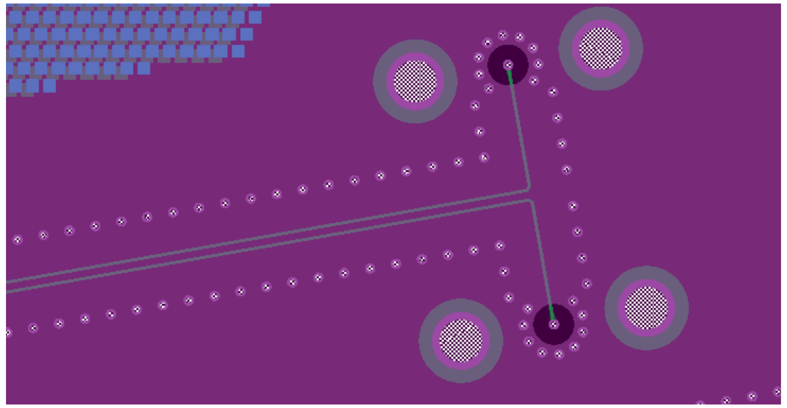


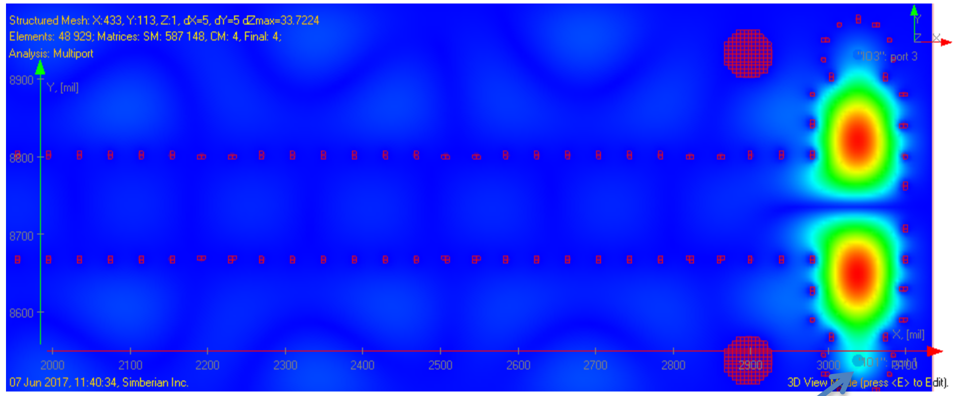
Energy leaked from the launches goes into Substrate Integrated Waveguide (SIW)

Simulated with Simbeor

Leaks and multipath propagation

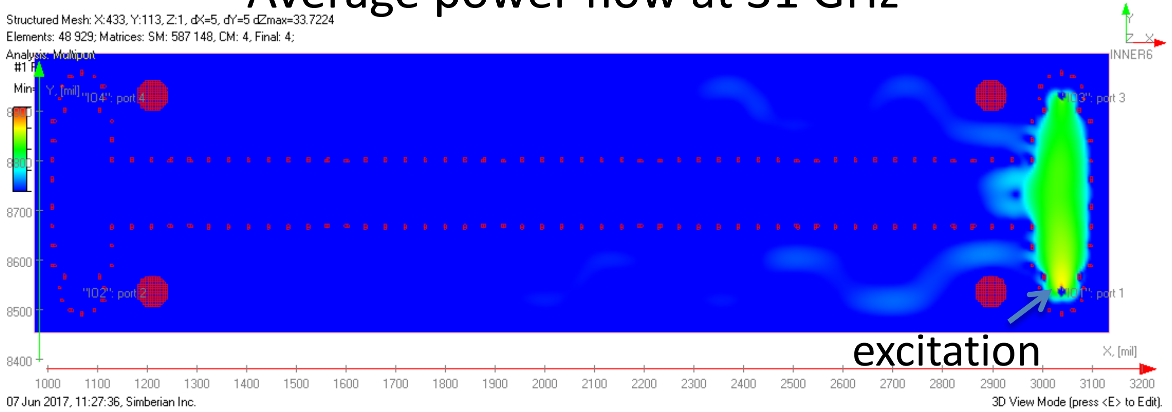
Max electric field intensity at 31 GHz the INNER6 layer for the structure feeding the bottom microstrip (mostly Z-directed component)



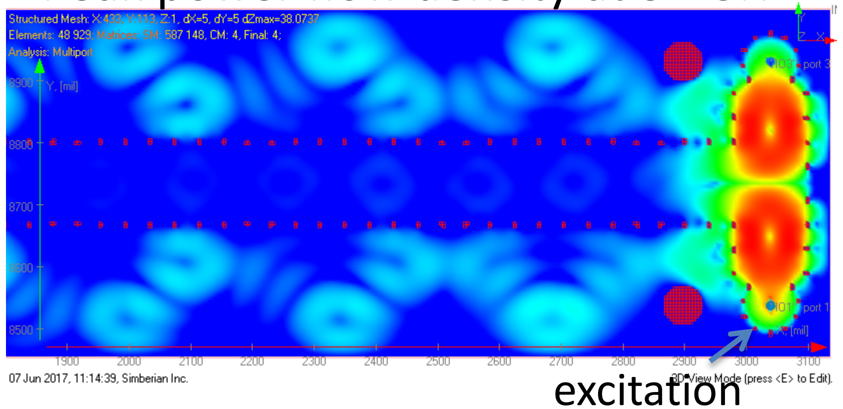


excitation

Average power flow at 31 GHz



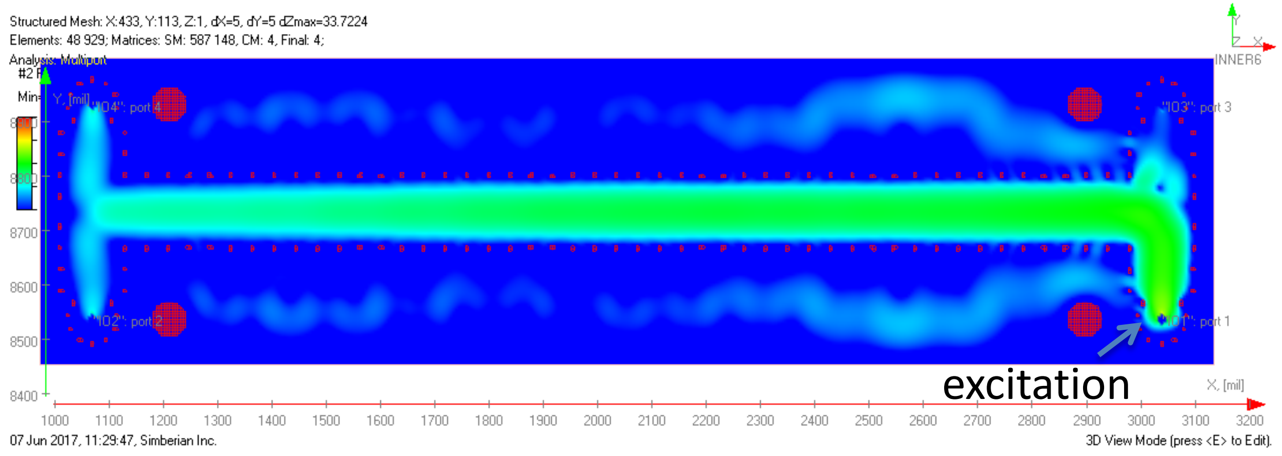
Peak power flow density at 31 GHz



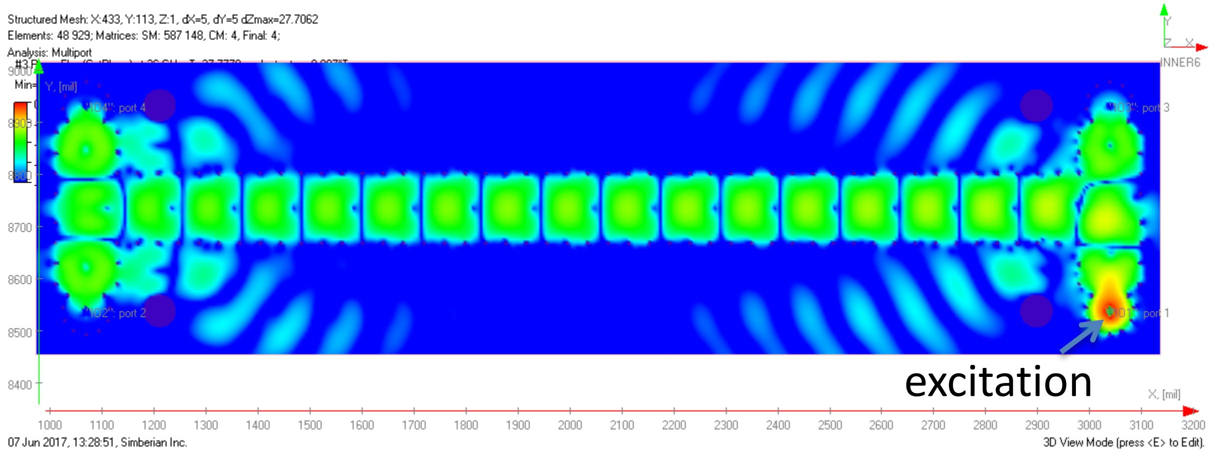
Simulated with Simbeor

Leaks and multipath propagation

Average power flow density at 35 GHz

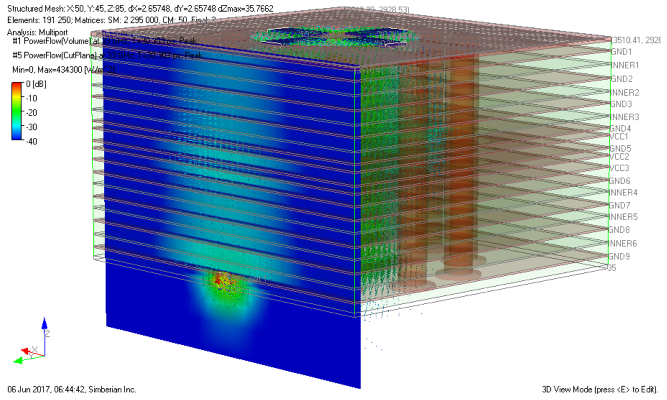


Instantaneous power flow density at 35 GHz



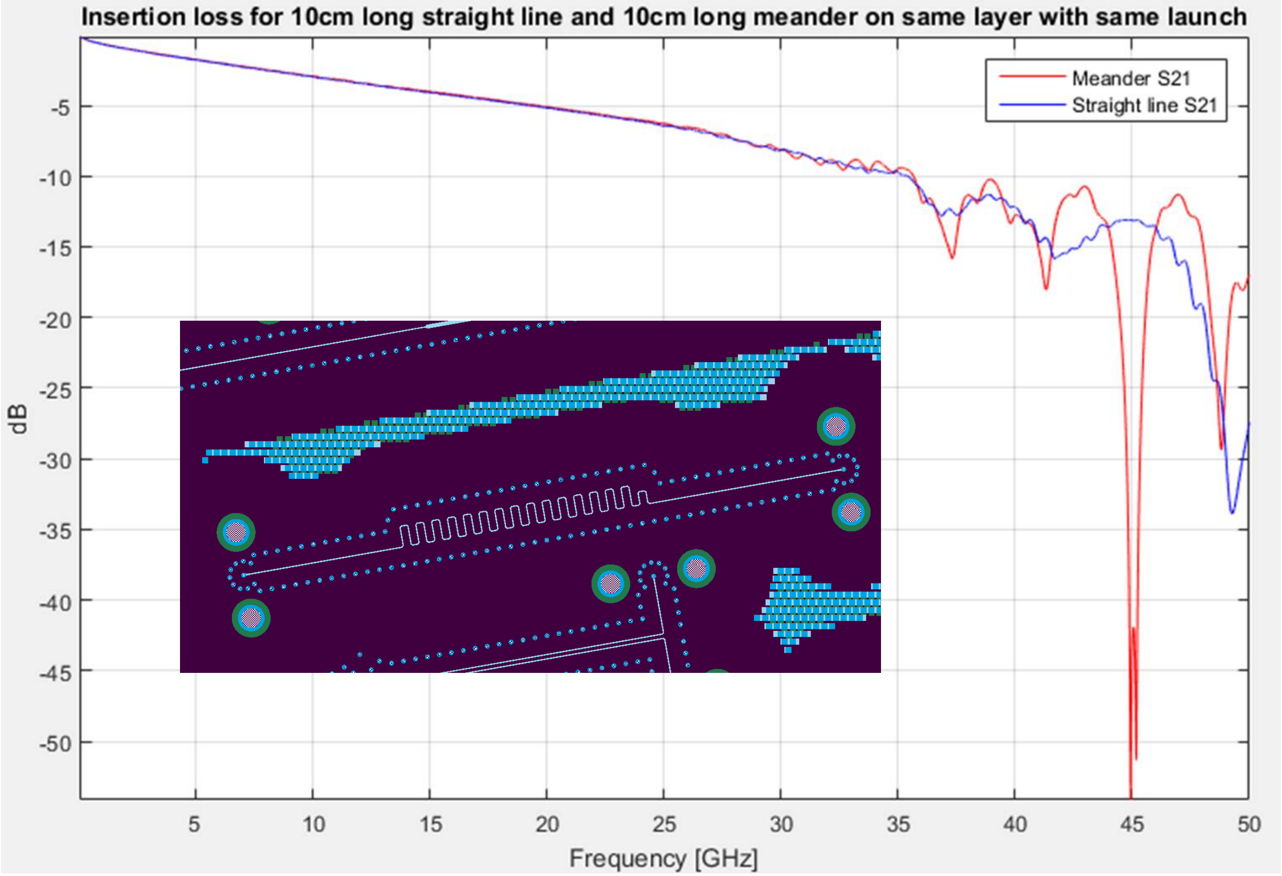
Lessons learned:

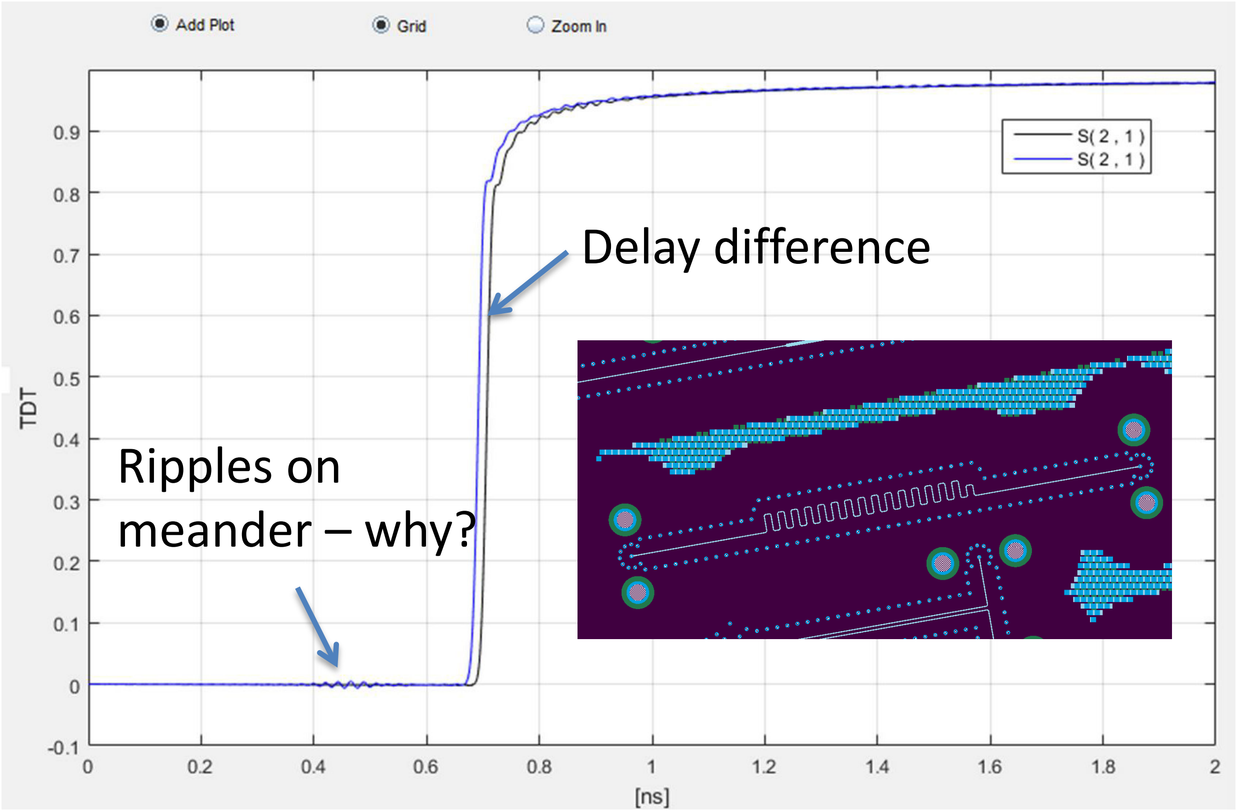
To extend the frequency range of the test structures to 40-50 GHz:
Launch vias should be closer to the signal via;
No gaps between the stitching vias on the strip side;
Stitching vias along the strips should be closer to the strip
Strip line is a waveguide with two reference planes and the **equipotentiality must be enforced** with stitching vias, to have predictable behavior;



Simulated with Simbeor

Meander vs. straight trace (both 10 cm)

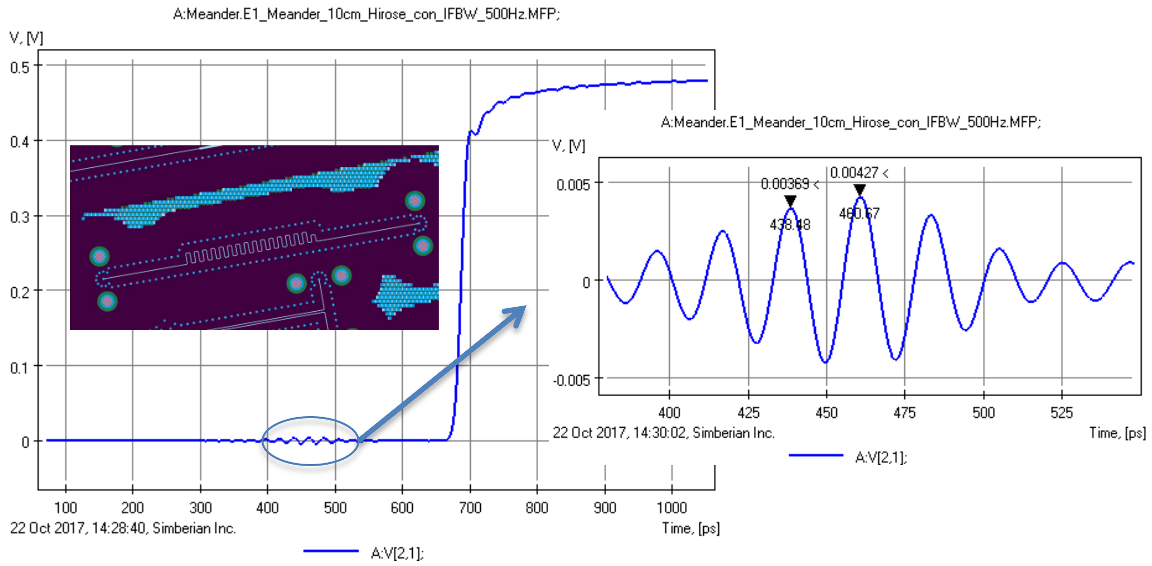


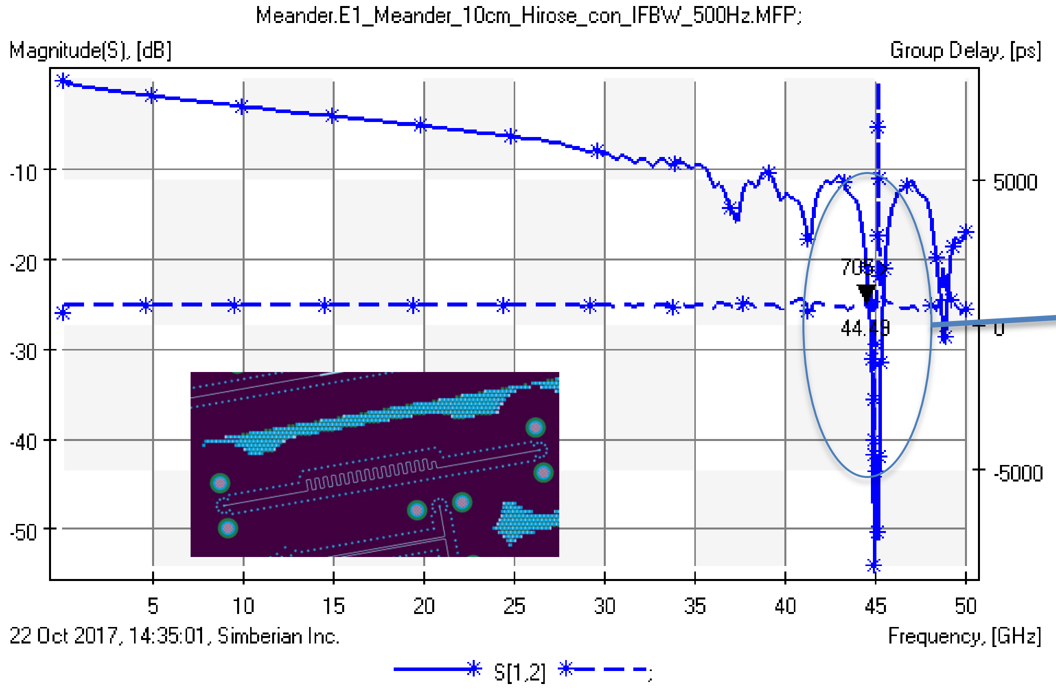


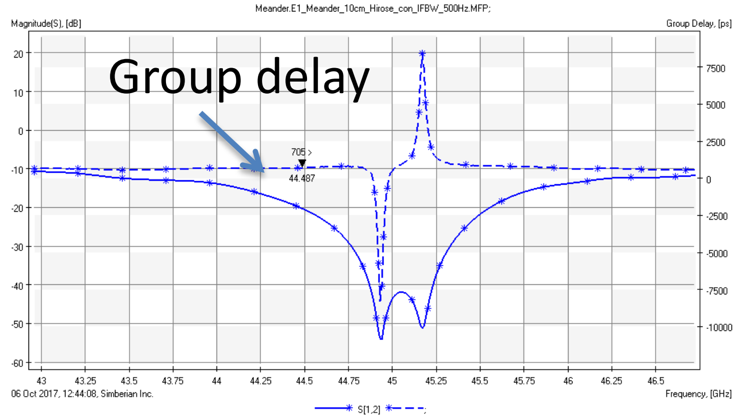
Measured with 50 GHz VNA

Multi-path propagation?

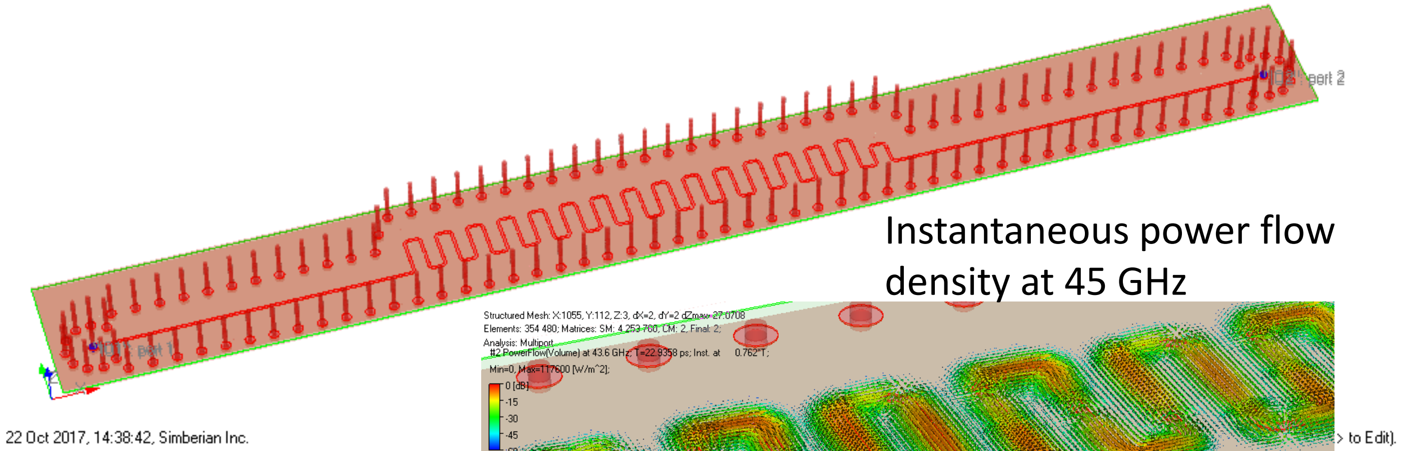
Measured with 50 GHz VNA



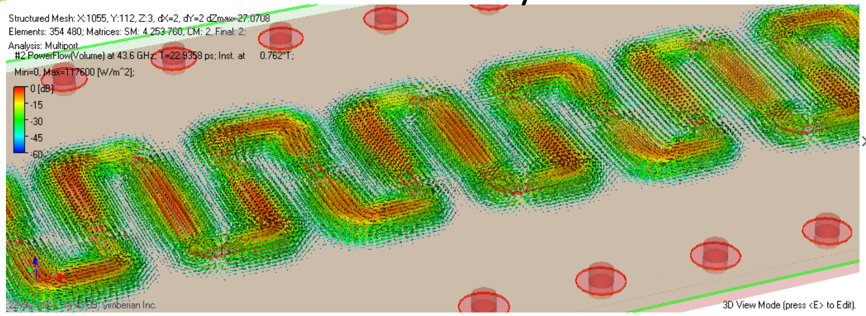




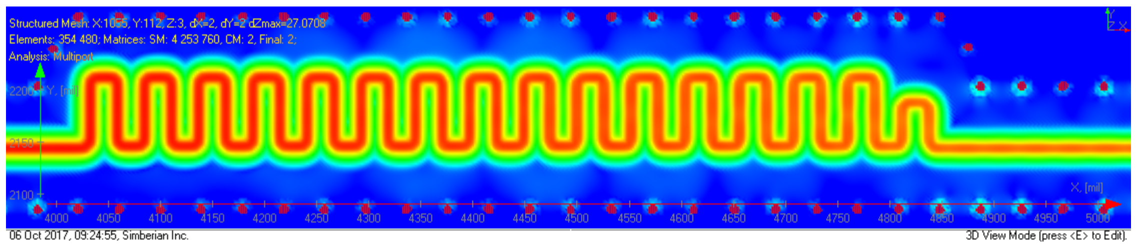
Multi-path propagation



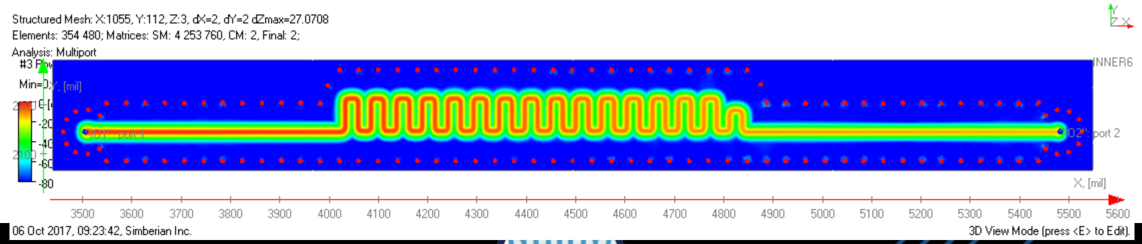
Instantaneous power flow density at 45 GHz

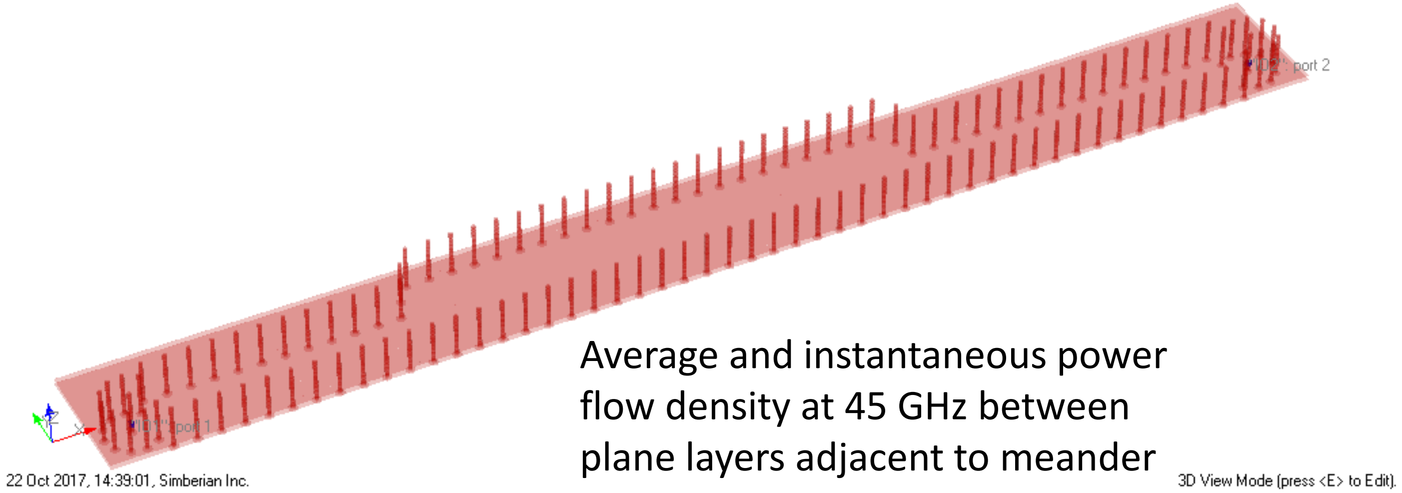


Max power flow density at 45 GHz

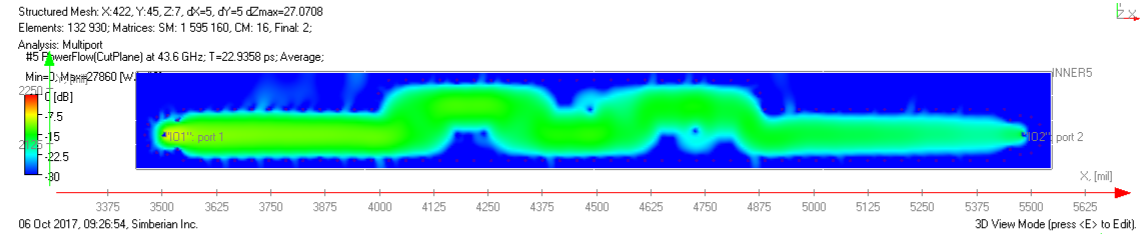


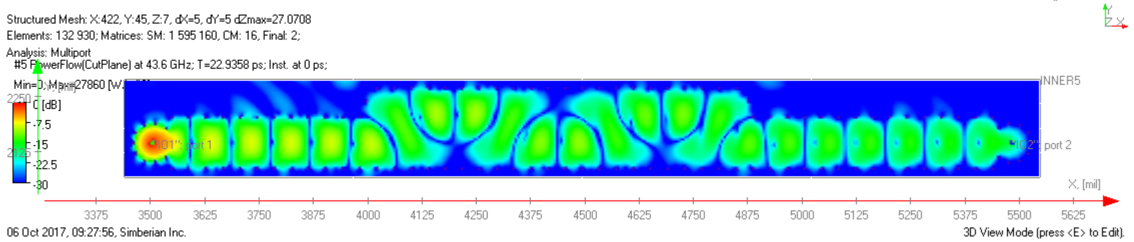
Average power flow density at 45 GHz





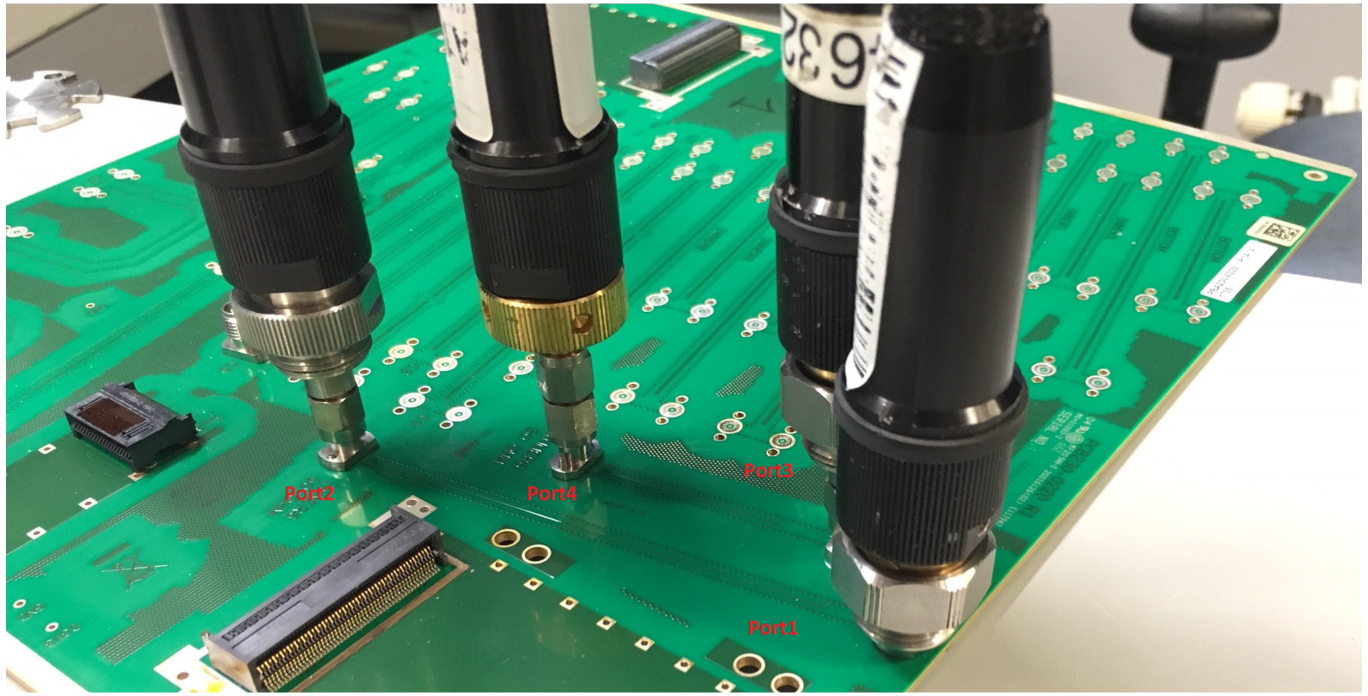
Average and instantaneous power flow density at 45 GHz between plane layers adjacent to meander

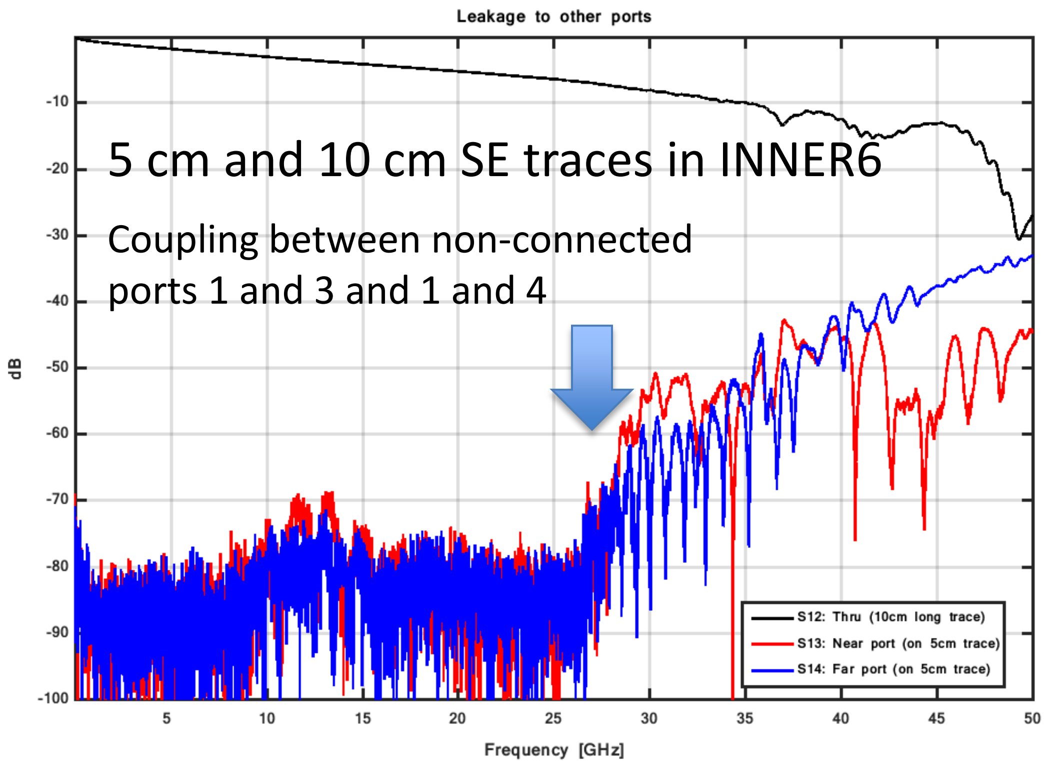




Simulated with Simbeor

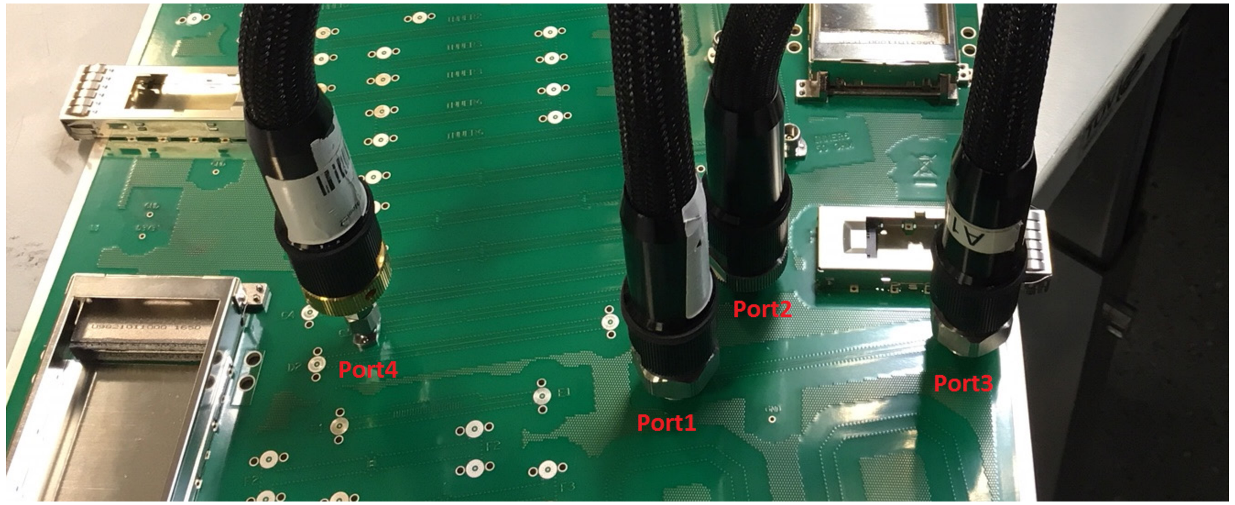
Reality: Unwanted coupling due to the leaks

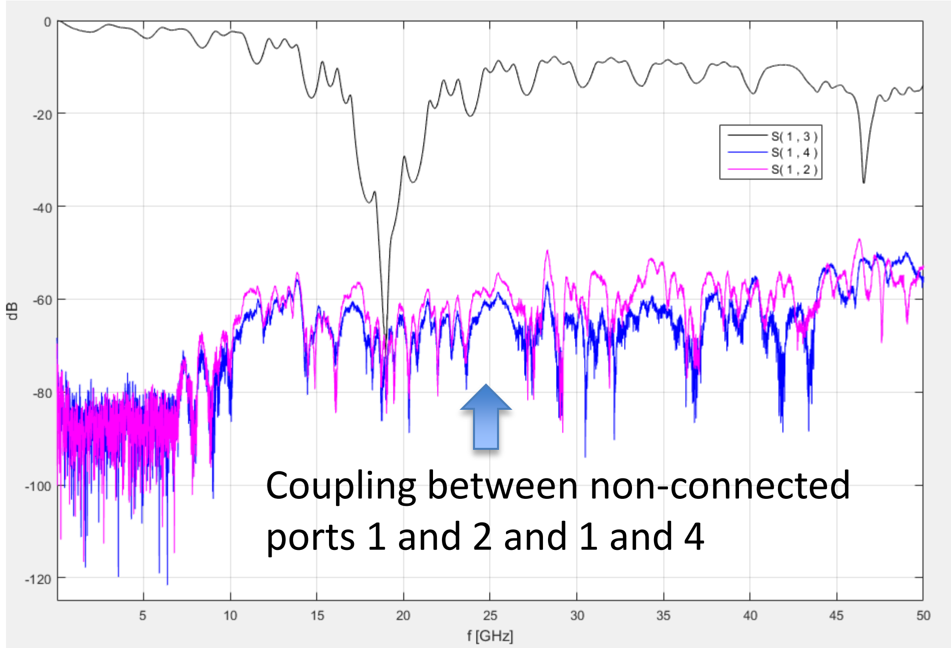


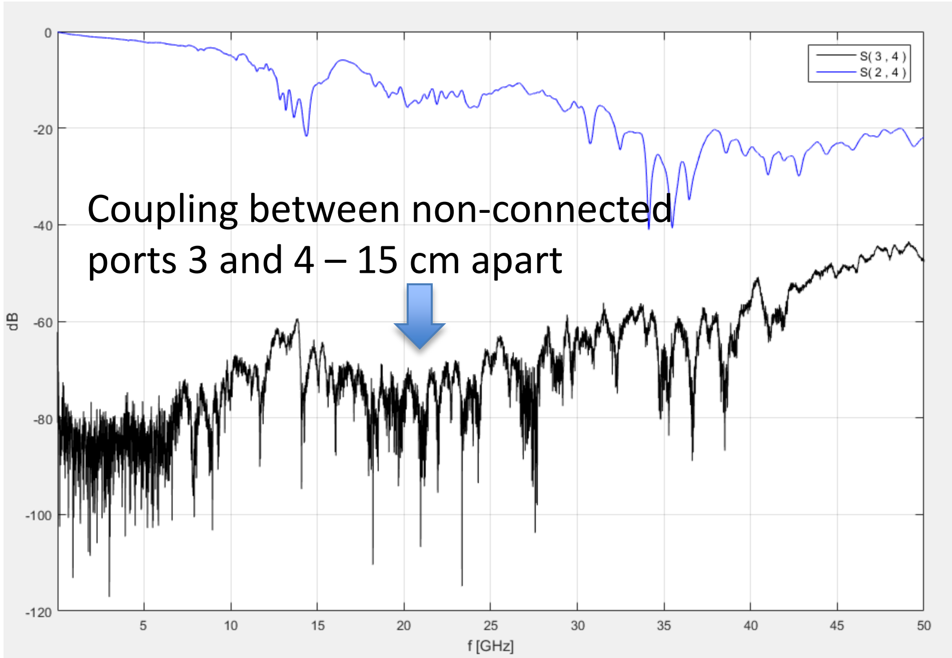


Lesson learned: The launch starts loosing the localization at about 27 GHz (30 GHz by design)

Reality: Unwanted coupling due to the leaks







Lesson learned: Use more stitching vias connecting reference planes EVERYWHERE!

Conclusion: Lessons Learned

- “Sink or swim” validation process has been successfully used in the “practical” project
- Accurate prediction of PCB behavior up to 40 GHz with typical trace width and low-cost manufacturing process is very ambitious goal due to the SI problem bandwidth and equal importance of low and high frequencies
  - Try before you invest into any measurement equipment – no matter how reputable is the vendor (applicable to EDA tools)
  - Launch and reference plane stitching localization degraded results above 30 GHz in this project
  - To extend the predictability up to 40-50 GHz, manufacturing tolerances should be substantially reduced, or trace widths increased and more homogeneous dielectrics used
  - Conductor roughness is the major contributor to the signal degradation - analysis without proper conductor roughness model would be useless, use of causal Huray-Bracken roughness model is critical to have good correlation
  - Identified dielectric parameters are very close to the vendor specs
  - Cross-sectioning revealed that manufacturer adjustments for strip lines are very close, but for microstrips are not acceptable
  - Ambiguities in use of AC cap capacitor models with the EM analysis
- Practical recommendations
  - Measurements should be planned in advance to have all matching parts (cables/connectors)
  - Layout needs careful inspection before manufacturing
  - Naming for stackup & nets should be consistent through the whole design/manufacturing cycle
  - To simplify comparisons, port numeration should be consistent in models and measurements
  - Keep connectors clean or apply for a license to get 100% pure alcohol if you are in Sweden ☺

EVERYTHING MATTERS FOR 40 GHz PCB INTERCONNECT DESIGN AND VALIDATION!