Second order aspects of characteristic impedance determination

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MOS-AK Workshop **July 2, 2023** **Puebla, Puebla, México**

Acknowledgment:

This work was partially funded by Conacyt, México, through grants 285199 and 288875, and doctoral studies scholarship 719285 (Y.R.)

The presenting author (RM) thanks the INAOE for the continuous support of the RF Project.

He also thanks MOS-AK (WG) for the invitation to be here today.

Motivation:

- Transmission lines are used as interconnects in discrete (PCB) and integrated circuits.
- They have been employed as such for several decades.
- And even though they are very simple structures, determining their characteristic impedance (Z_c) is not straightforward.
- This is because, in order to be measured, probing platforms and probes are needed.
- These introduce two more structures to the setup on either port.
- Characterizing these additional components is a must to obtain reliable values for Z_c.

Problem Statement:

- Fluctuations in transmission line measurements versus frequency curves have been observed, and generally, they have been modeled by a lumped admittance in each port.
- These fluctuations are associated with resonances originated by standing waves bouncing back and forth between the transitions at the transmission line terminations —probing platforms, pads.
- It is difficulty, if not impossible, to completely remove the parasitic effect of these transitions by de-embedding the measurements.

Problem Statement:

- Besides these resonances the additional transition from probing pads to the transmission line used to connect to the VNA introduces more reflections.
- This makes obtaining smooth and physically expected frequency-dependent curves a tough task, to say the least.
- Hence, these effects must be quantified and taken into account to correctly model the measured transmission line.

Contribution:

- We point out —for the first time to the best of our knowledge— that these fluctuations also occur in the transition itself.
- These are associated with resonances originated by standing waves bouncing back and forth in the transitions at the transmission line terminations.
- We herein propose a distributed model to consider the extra reflections satisfactorily.

Theoretical background:

- Accurate knowledge of the complex Z_c is necessary for TL characterization and some calibration routines.
- A measurement of a “pure” TL provides, once S parameter data is transformed to an ABCD matrix:

$$\mathbf{T}_h = \begin{bmatrix} \cosh(\gamma l) & Z_c \sinh(\gamma l) \\ \sinh(\gamma l)/Z_c & \cosh(\gamma l) \end{bmatrix}$$

- From which the characteristic impedance can be determined.

$$Z_c = \sqrt{\mathbf{T}_h\ [1,2]/\mathbf{T}_h\ [2,1]}$$

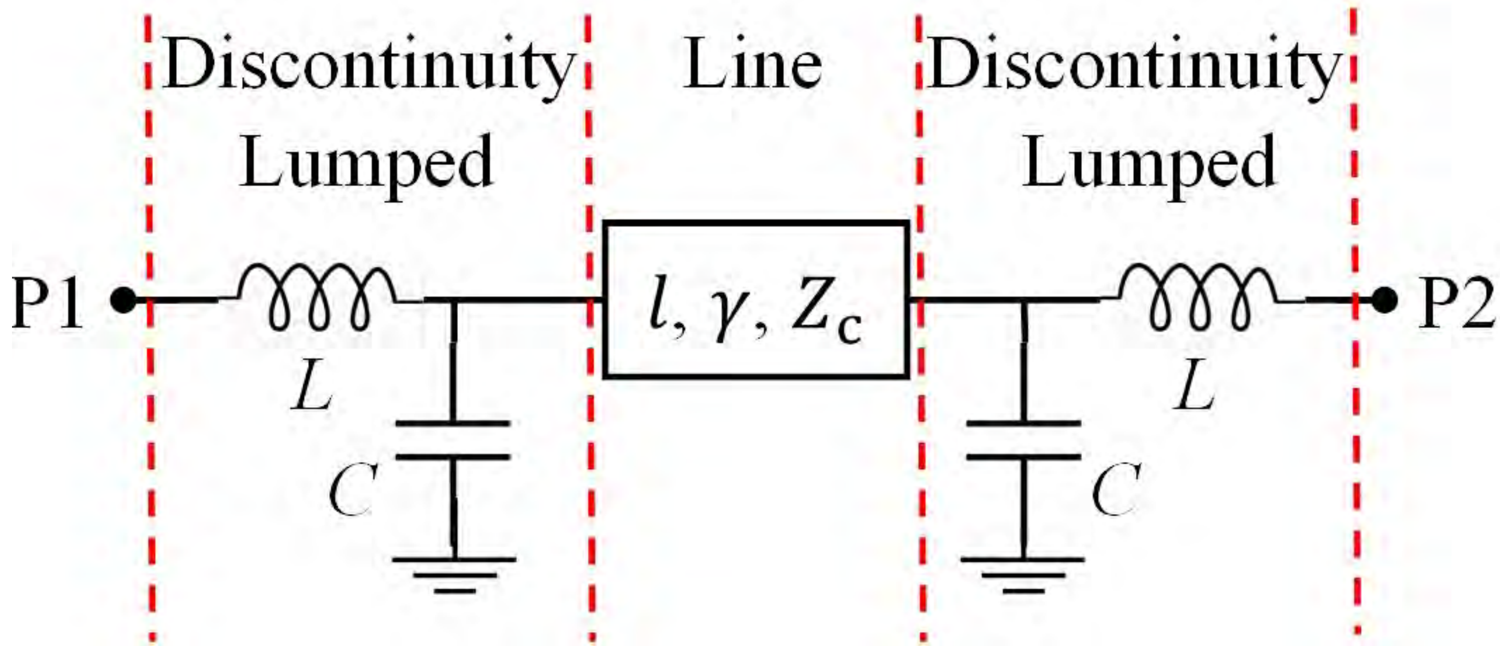
Theoretical background:

- But we cannot measure a “pure” transmission line, since the measurement necessarily involves probing pads or platforms. Thus the measurement becomes:

$$\mathbf{T}_{LhL} \approx \begin{bmatrix} 1 & j\omega L \\ j\omega C & 1 \end{bmatrix} \mathbf{T}_h \begin{bmatrix} 1 & j\omega L \\ j\omega C & 1 \end{bmatrix}$$

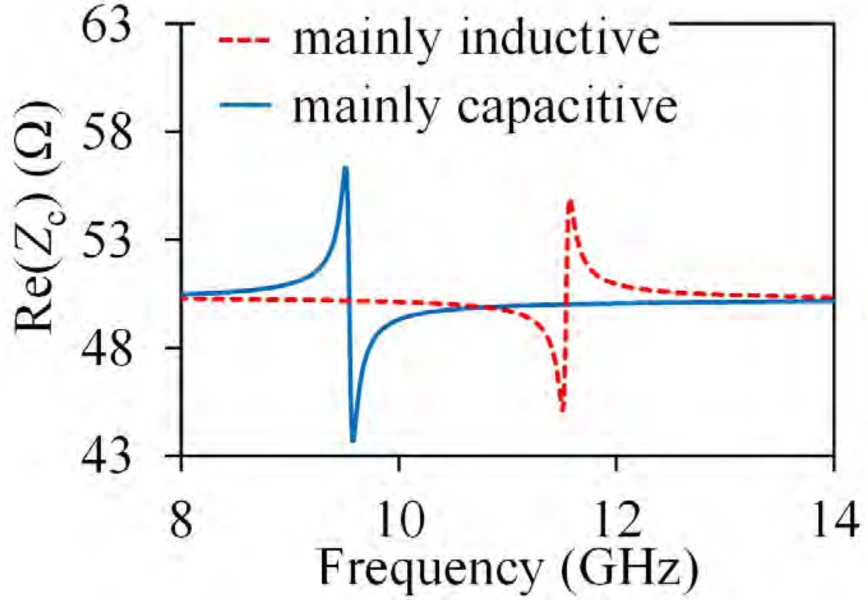
- Where the probing platforms are modeled by lumped admittances.

Traditional model:



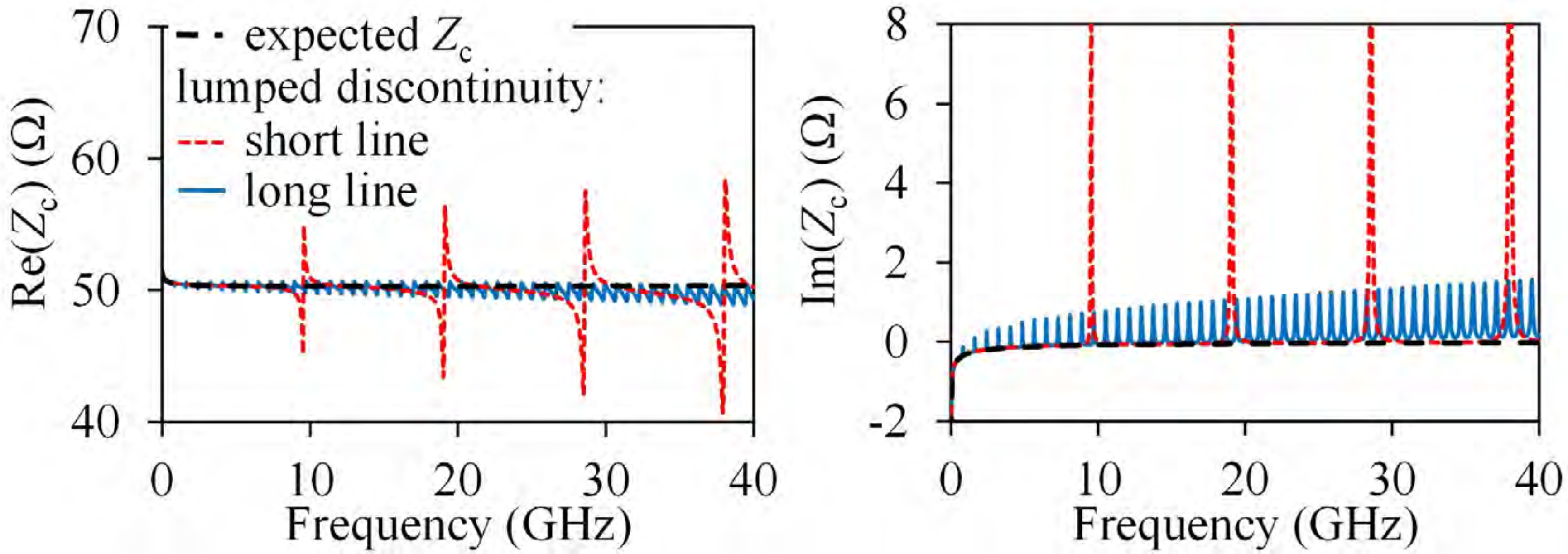
Theoretical background:

- Hence, $Z_c = \sqrt{\mathbf{T}_h\ [1,2]/\mathbf{T}_h\ [2,1]}$ does not yield the value of Z_c but curves that include glitches around a constant value for Z_c.



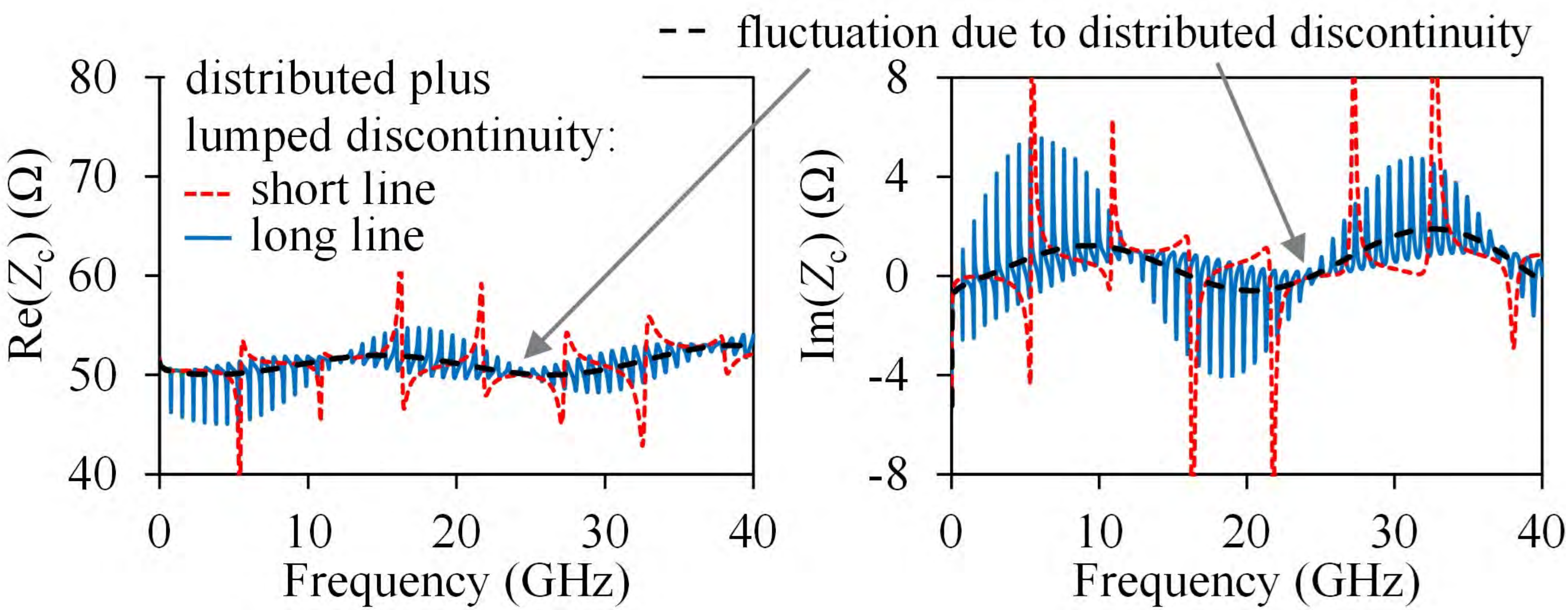
Theoretical background:

- The periodicity of the glitches depends on line length:



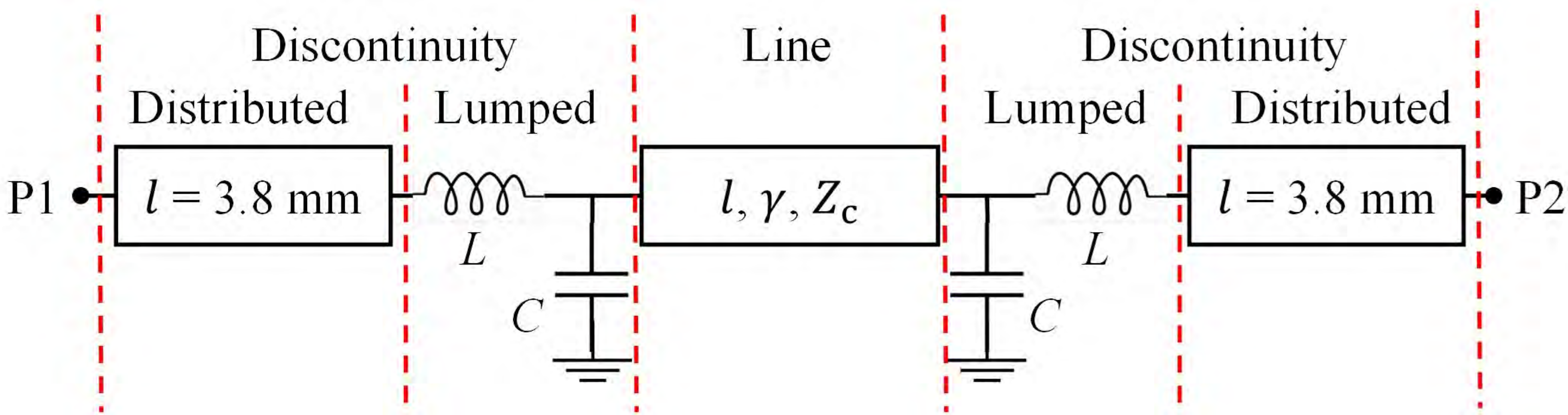
Experimental observations:

- We observed an additional fluctuation upon measuring TLs:



Experimental observations:

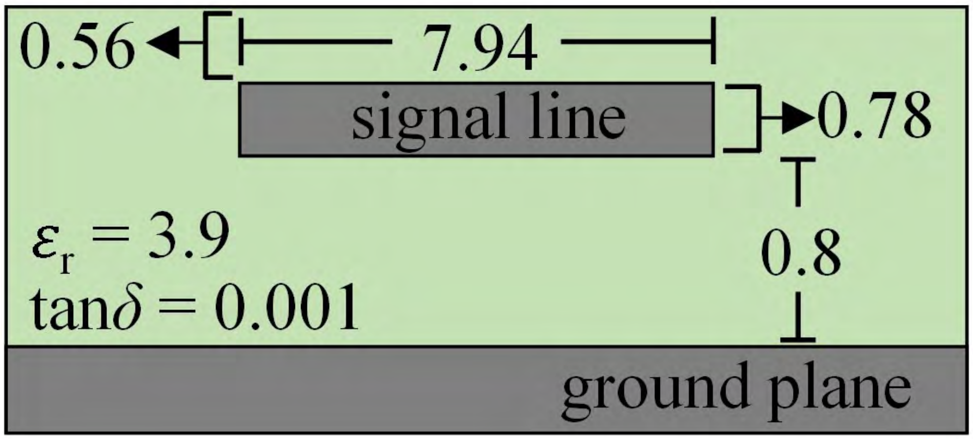
- These can be modeled with a distributed model to account for the connector:

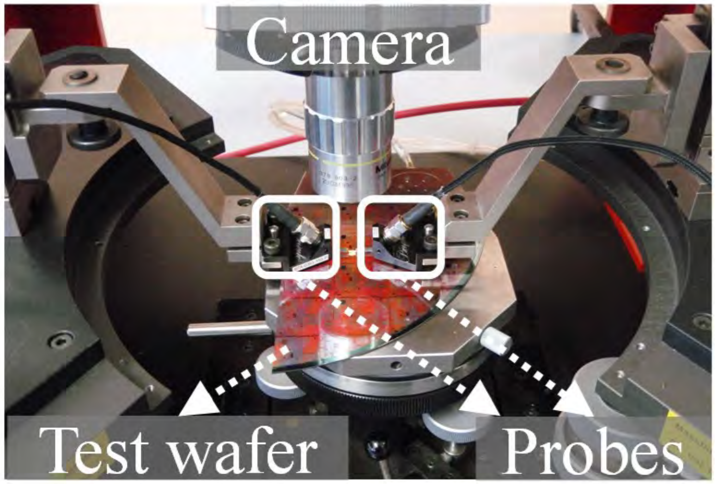


Experimental considerations:

- To prove the hypothesis, three different types of structures were built, measured and analyzed.
  - Lines on chip on a CMOS process, measured with probes.
  - Lines on PCB terminated with probe adapters.
  - Lines on PCB terminated with coaxial connectors.

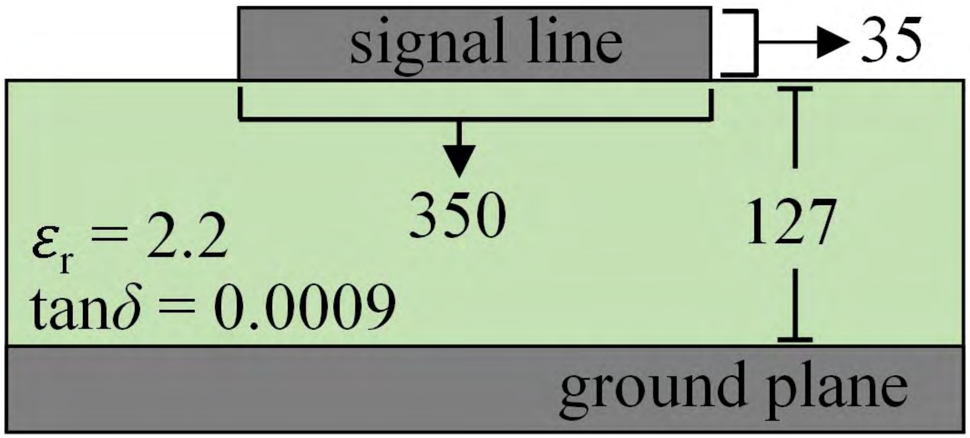
On-chip lines terminated with probe-pads

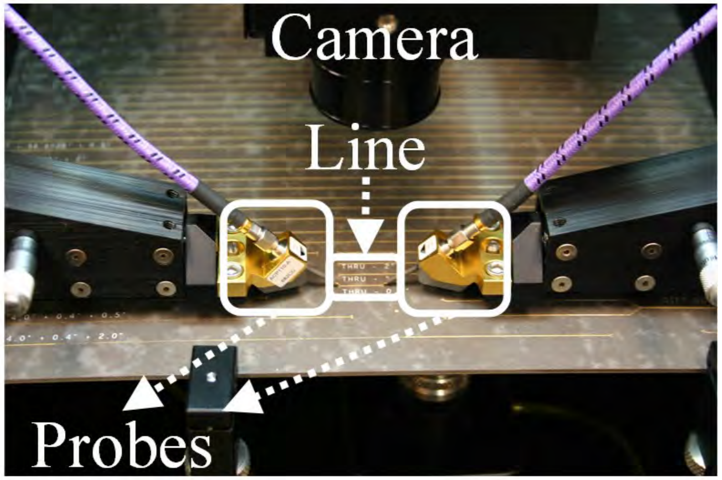




Lengths l=1,380µm; 2,450µm; 4,600µm.

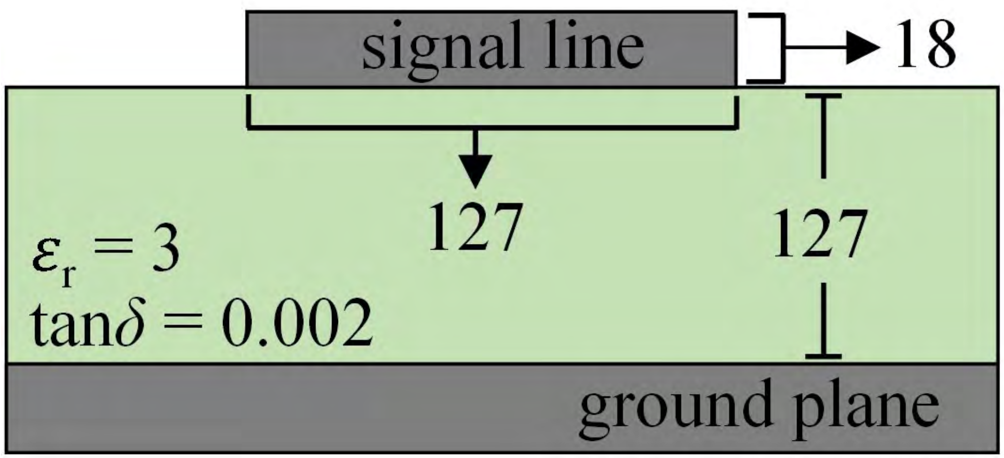
PCB lines terminated with probe-pads

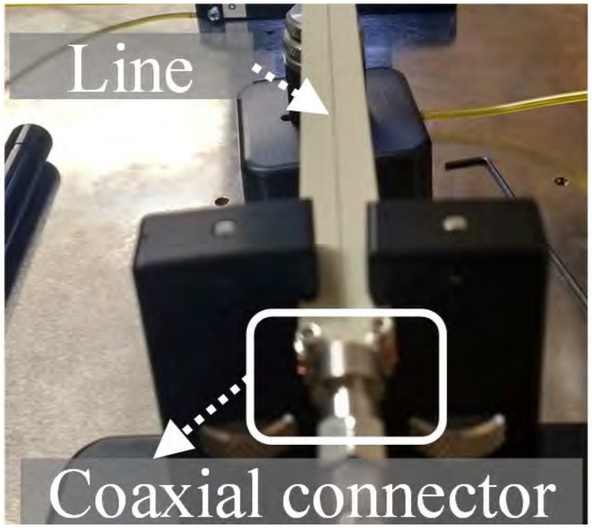




Lengths l=12.7mm; 101.6mm. $Z_c \approx 51\Omega$.

PCB lines terminated with coaxial connectors

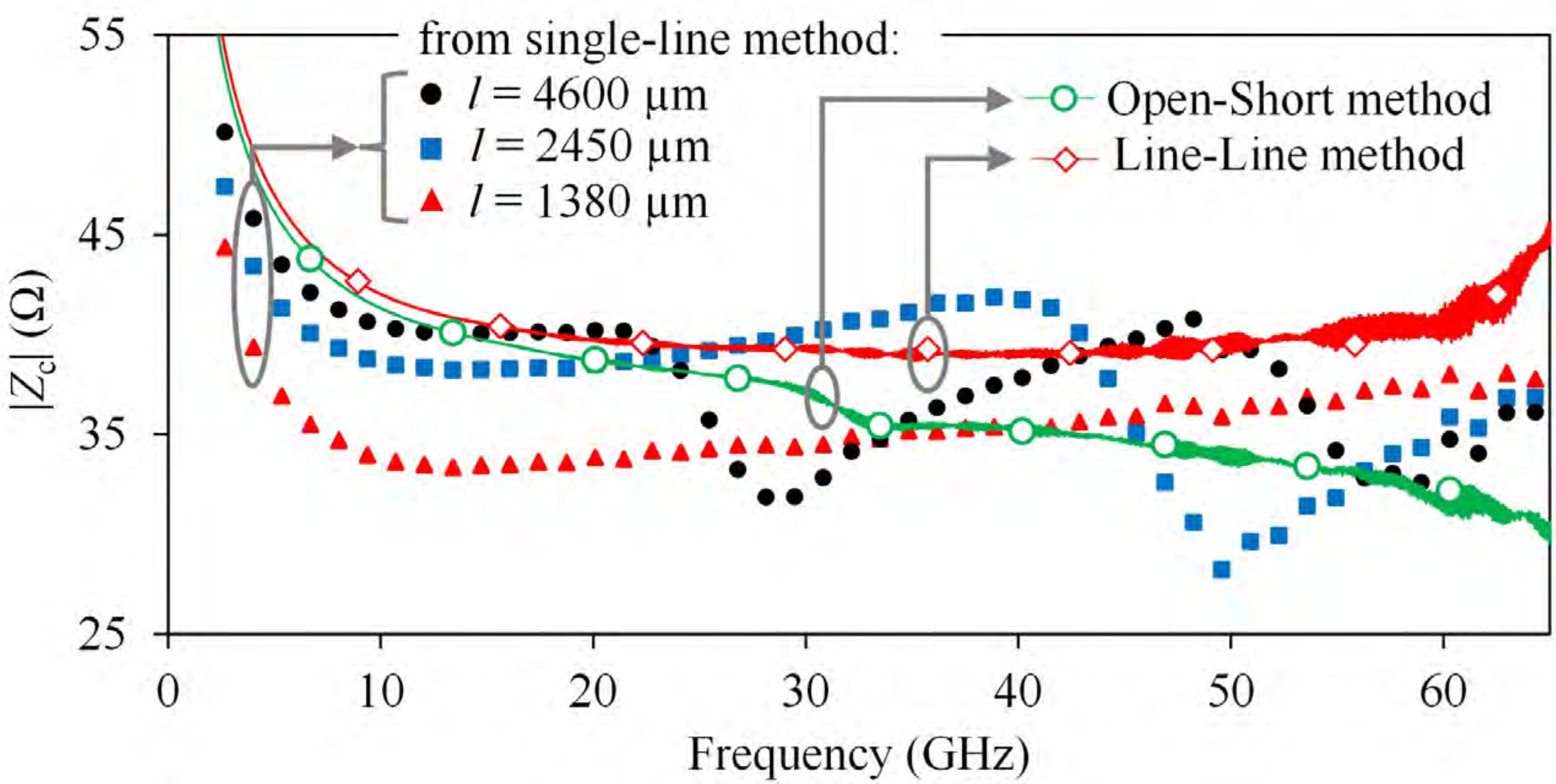




Lengths l=25.4mm; 317.5mm. $Z_c \approx 72\Omega$.

40 GHz General Precision Connector, 2.92mm interface.

Results —On chip lines



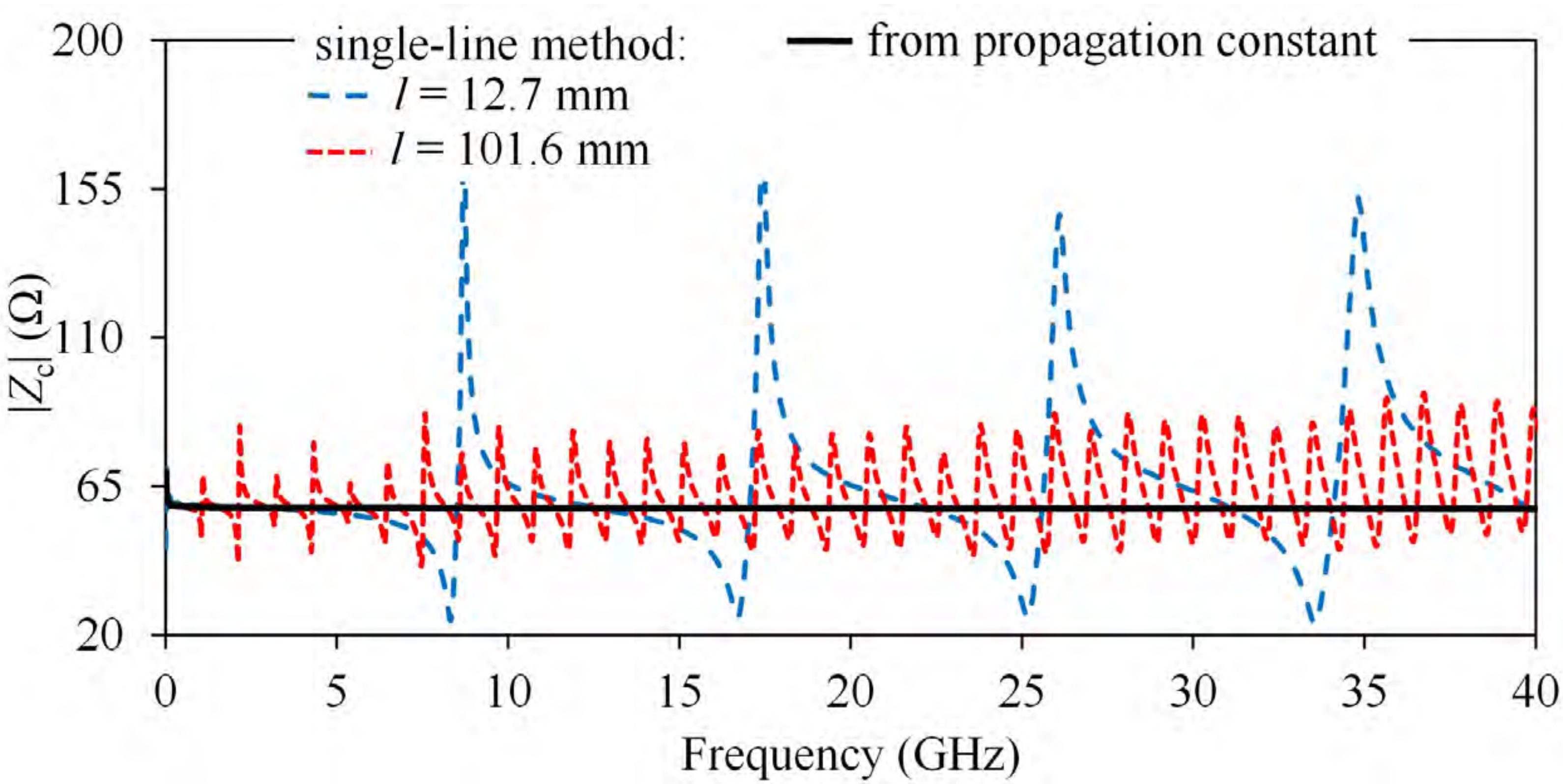
Analysis:

- The figure presents Z_c using $Z_c = \sqrt{\mathbf{T}_h[1,2]/\mathbf{T}_h[2,1]}$ for different line lengths.
- In addition to the fluctuations due to the transistions, Z_c exhibits large discrepancies depending on line length, which is unexpected.
- Using the open-short method, the fluctuations due to discontinuities are smoothed, but an unexpected Z_c roll-off is observed as frequency increases.

Analysis:

- The variation is attributed to the consideration that the open and short transitions between the pads and the line is abrupt.
- Using the line-line method, a quasi flat Z_c is achieved from 10 GHz to 50 GHz, whose value can be expected to be close to the expected one.
- The extraction method considers that the transition can be represented by means of a lumped shunt admittance.
- This assumption is valid provided the pad array is relatively small, true for on-chip interconects, not for PCB.

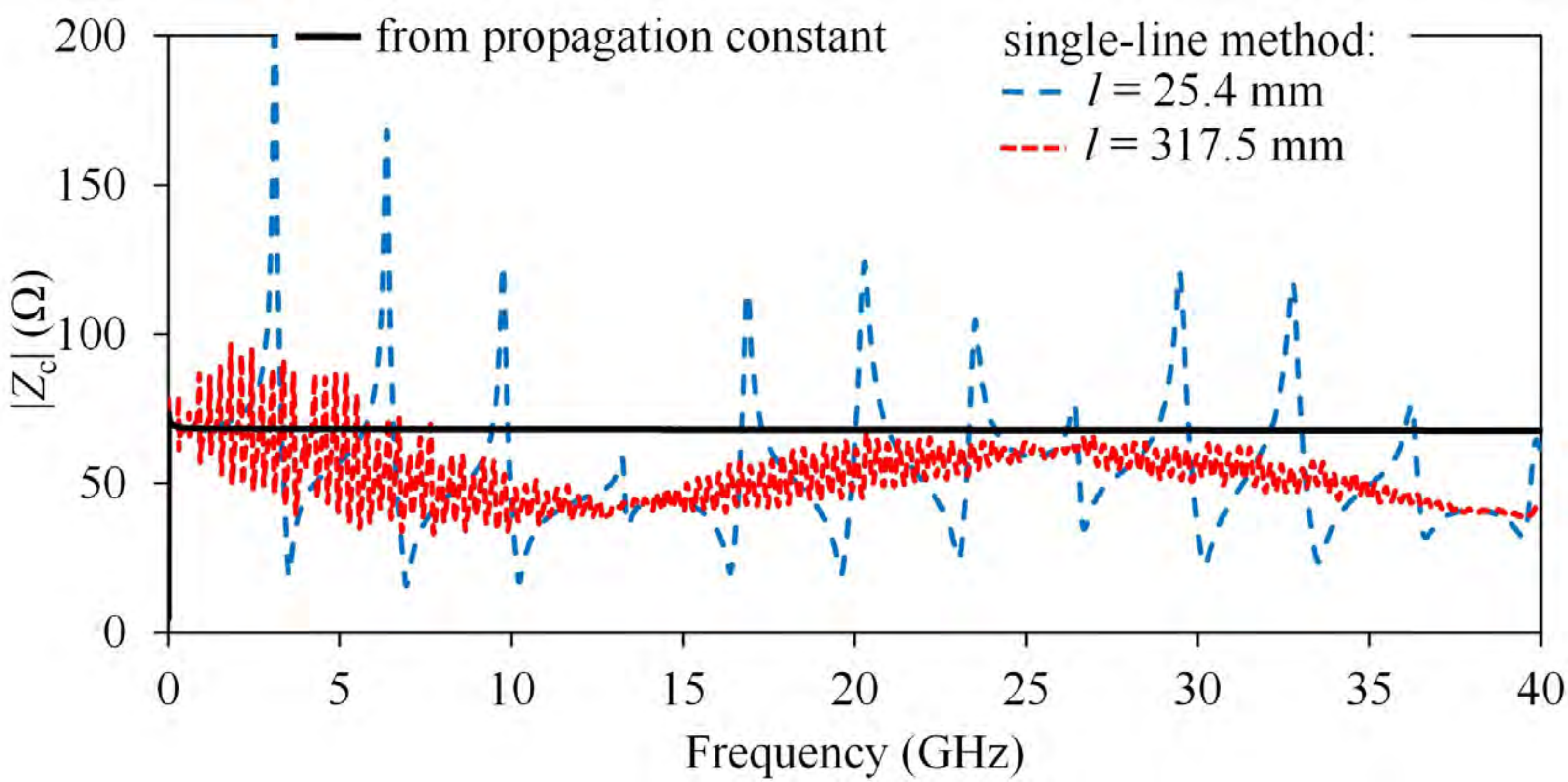
Results —PCB with probe pads



Analysis:

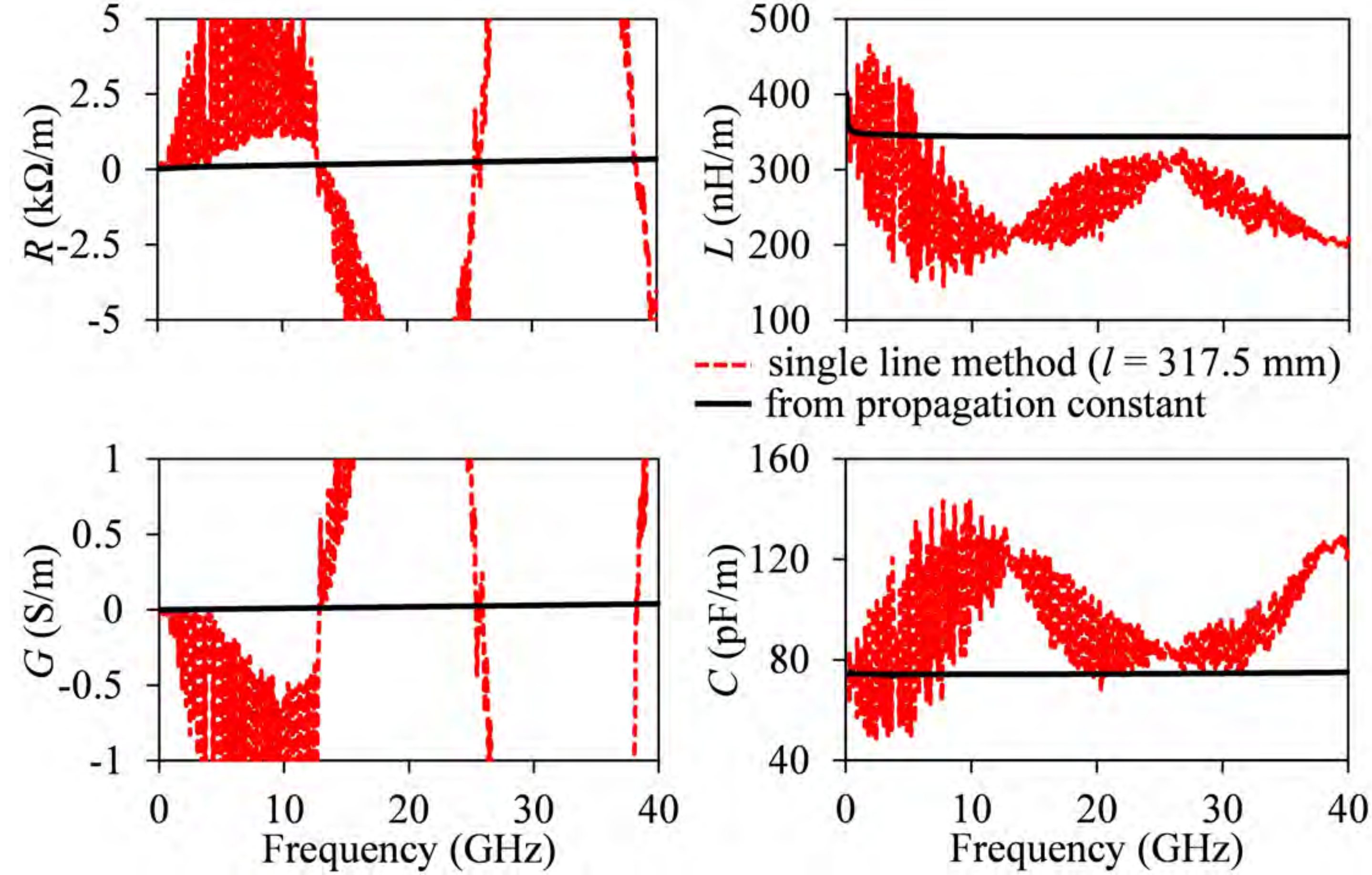
- On these lines, the resistance PUL is much smaller, but the associated length might be considerable, and a significant number of fluctuations may be observed within a few tenths of GHz.
- The reflections have a greater magnitude for the short line, but occur at a higher rate in the long one.
- Z_c obtained from γ is smooth, and can be a good approximation.
- Knowledge of frequency-dependent complex permittivity as well as loss tangent are necessary to apply the method.

Results —PCB with coaxial connectors



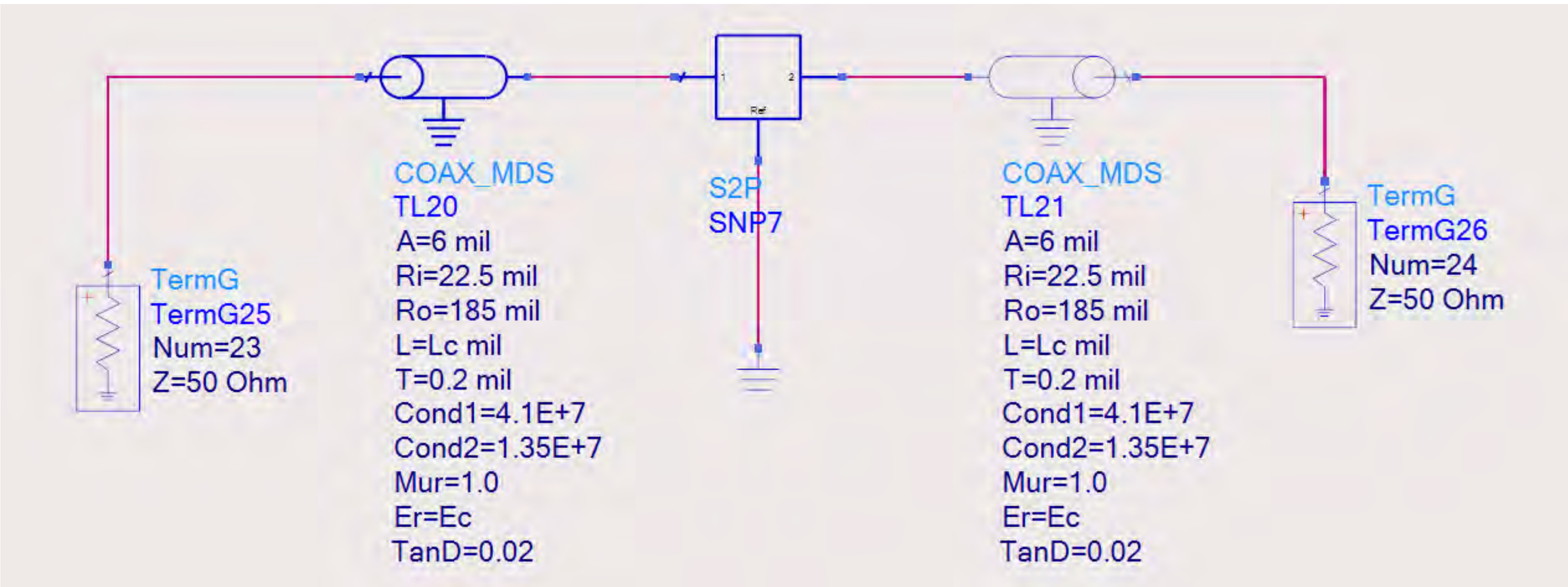
Analysis:

- These lines (connector terminated) exhibit an additional effect that considerably hinders the accurate determination of Z_c.
- Since the electrical length of the connector is large, fluctuations also appear at lower periodicities.
- To account for them, a distributed model for the connector is necessary.
- An important consequence is the difficulty in determining transmission line parameters accurately, as shown in the following graph.



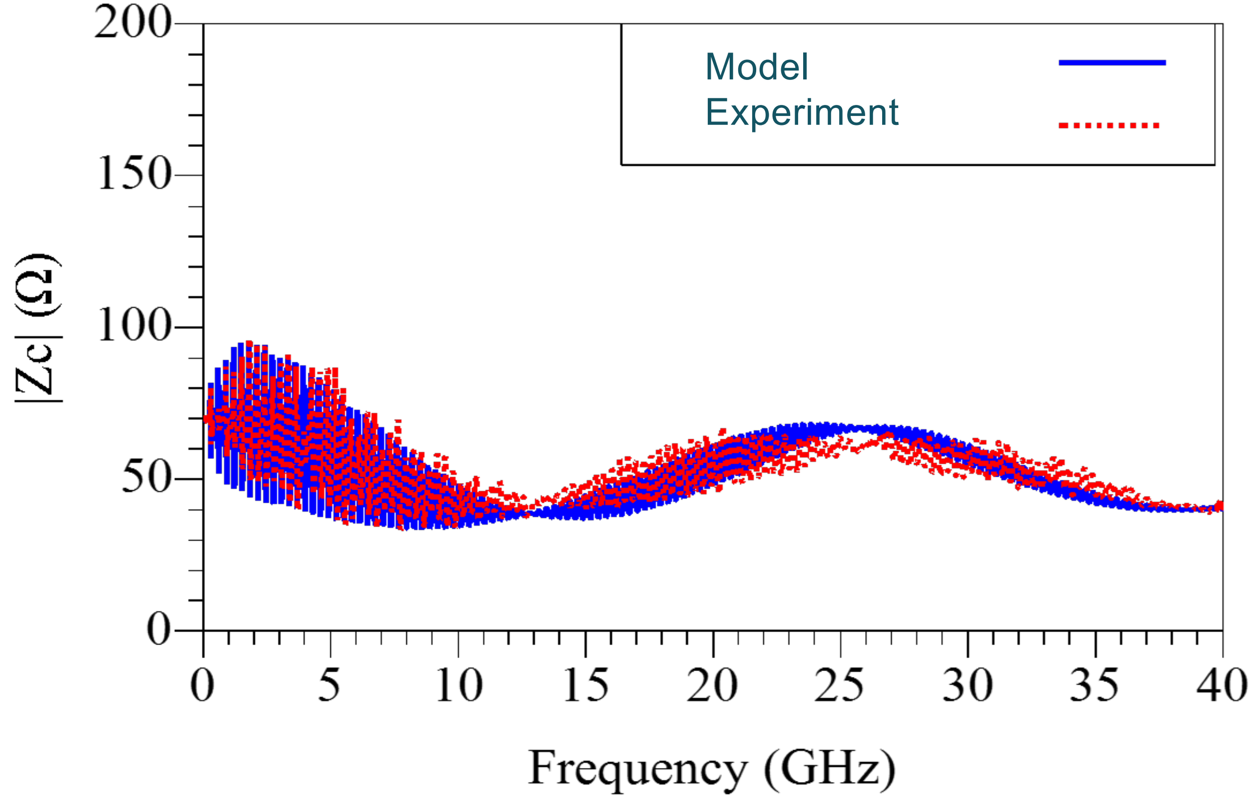
5
2.5
0
-2.5
-5
R (kΩ/m)
500
400
300
200
100
L (nH/m)
single line method (l = 317.5 mm)
from propagation constant
1
0.5
0
-0.5
-1
G (S/m)
0
10
20
30
40
Frequency (GHz)
160
120
80
40
C (pF/m)
0
10
20
30
40
Frequency (GHz)

Model:


COAX_MDS
TL20
A=6 mil
Ri=22.5 mil
Ro=185 mil
L=Lc mil
T=0.2 mil
Cond1=4.1E+7
Cond2=1.35E+7
Mur=1.0
Er=Ec
TanD=0.02
S2P
SNP7
COAX_MDS
TL21
A=6 mil
Ri=22.5 mil
Ro=185 mil
L=Lc mil
T=0.2 mil
Cond1=4.1E+7
Cond2=1.35E+7
Mur=1.0
Er=Ec
TanD=0.02
TermG
TermG25
Num=23
Z=50 Ohm
TermG
TermG26
Num=24
Z=50 Ohm

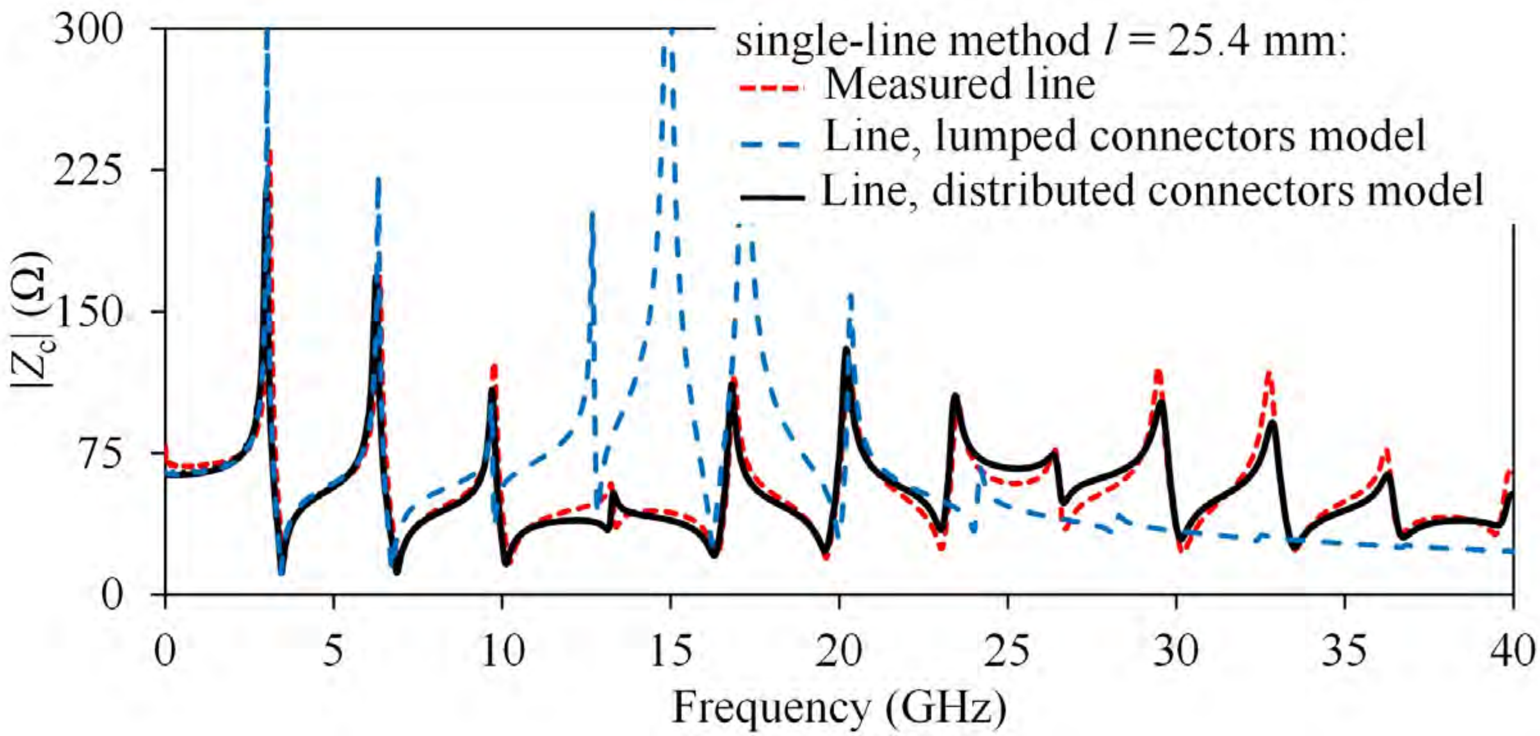
Measurement vs Model:

PCB line terminated with a coaxial connector, *l*=317.5 mm



Measurement vs Model:

PCB line terminated with a coaxial connector, *l*=24.5 mm



Discussion:

- For microstrip lines manufactured on PCB the Z_c curve does not considerably vary with frequency since the losses are relatively small.
- On chip lines present very thin films, which translate into resistances per unit length in the order of KΩ/m.
- This high resistance causes the characteristic impedance to have a strong variation over a wide range of frequencies.

Conclusion:

- Short lines —for instance on chip— are less impacted by the effect described herein than long lines —those on PCB, for example.
- In fact, algorithms such as the line-line one provide good results by modeling the transition as a a shunt admittance up to some tens of GHz.
- For long lines, however, the fluctuation effect is considerable.

Conclusion:

- The effect is accentuated when using transitions that exhibit a noticeable distributed nature within the measurement range.
- We have proposed a distributed transmission line model to represent this effect.
- To the best of our knowledge, this is the first time this effect has been reported.

Thank you very much for your kind attention!

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