Second order aspects of characteristic impedance determination

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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 $Z_c$. 

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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:

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

- From which the characteristic impedance can be determined.

$$Z_c = \sqrt{T_h [1,2]/T_h [2,1]}$$
Theoretical background:

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

$$ T_{lhL} \approx \begin{bmatrix} 1 & j\omega L \\ j\omega C & 1 \end{bmatrix} T_h \begin{bmatrix} 1 \\ j\omega C \\ 1 \end{bmatrix} $$

- Where the probing platforms are modeled by lumped admittances.
Traditional model:
Theoretical background:

- Hence, \( Z_c = \sqrt{T_h [1,2]/T_h [2,1]} \) 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:

![Graph showing fluctuation due to distributed discontinuity with different line types for short and long lines.](image)
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 $l=1,380\mu\text{m}; 2,450\mu\text{m}; 4,600\mu\text{m}$.
PCB lines terminated with probe-pads

\[ \varepsilon_r = 2.2 \]
\[ \tan \delta = 0.0009 \]

Lengths \( l = 12.7 \text{mm}; 101.6 \text{mm} \).
\( Z_c \approx 51\Omega \).
PCB lines terminated with coaxial connectors

Lengths $l=25.4\text{mm}; 317.5\text{mm}$. $Z_c \approx 72\Omega$.
40 GHz General Precision Connector, 2.92mm interface.
Results — On chip lines

![Graph showing results for on chip lines](image)

from single-line method:
- $l = 4600 \, \mu m$
- $l = 2450 \, \mu m$
- $l = 1380 \, \mu m$

Open-Short method
Line-Line method
Analysis:

- The figure presents \( Z_c \) using \( Z_c = \sqrt{\frac{T_{h[1,2]}}{T_{h[2,1]}}} \) for different line lengths.
- In addition to the fluctuations due to the transitions, \( Z_c \) 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 interconnects, 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 $\gamma$ 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

![Graph showing impedance vs frequency with different line methods and lengths.]
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.
\[ R \text{ (kΩ/m)} \]

\[ L \text{ (nH/m)} \]

\[ G \text{ (S/m)} \]

\[ C \text{ (pF/m)} \]

- Single line method \((l = 317.5 \text{ mm})\)
- From propagation constant
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 $K\Omega/m$.
- 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 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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