Measurement

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Outline

1. Oscilloscopes
2. Time Domain Reflectometry (TDR)
3. Vector Network Analyzers
Oscilloscopes

‘Real time’ ‘Single Shot’ scopes

- Can capture one transient waveform
- Quality of measurement limited by bandwidth of oscilloscope
  - Frequency content above BW is attenuated
  - E.g. 30 ps edge into 3 GHz BW oscilloscope will become a \((0.35/BW) = 116\) ps edge on screen
... Oscilloscopes

Sampling Oscilloscope

- Samples signal over multiple cycles
- Requires repetitive signal OR can be used to build an eye diagram
- Very high effective sampling rates possible (up to 50 Gsample/s)
Measuring Jitter with a DSO

DSO trigger circuit delay complicates jitter measurement
• delay line causes input samples to be the same as trigger samples
• result is that only trigger circuit jitter is displayed on first edge.
• for CSA8000B trigger delay is about 21 ns, trigger circuit jitter about 750 fs

\[ \sigma_{\tau} = \sqrt{\sigma_{\tau,\text{measured}}^2 - \sigma_{\tau,\text{trigger}}^2} \]
**Probing**

Two ways of connecting Oscilloscope to Device Under Test:

- 50 Ohm probe
  - e.g. SMA connector or GSG probe
  - Requires 50 Ohm interface
  - Must be designed in

- High impedance probe
  - Can use to sample a signal
  - Limited bandwidth

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Time Domain Reflectometry (TDR)

- TDR Stimulus
- 35 ps Rise Time
- Records Reflections on High-Speed Sampling Scope, Automatically Calculates Impedances, Delays based on Known Input

PCB

Wiring Trace

TDR Plug-In
Reflection Noise from Parasitics

Lumped elements = ‘parasitics’ or ‘discontinuities’.

Buffer

Chip ‘lead’

Via

Crossover

Receiver

Circuit or Thévenin Equivalent (‘Behavioral Model’)

Rout

Z0

Rin
Reflections at lumped loads

1. Reflections from lumped loads

\[ \frac{\Delta V}{V} = \frac{\tau}{t_r} (1 - e^{-t_r/\tau}) \]

\[ \tau = \frac{Z_0 C}{2} \]
...Reflections from

\[ \frac{\Delta V}{V} = \frac{\tau}{t_r} \left(1 - e^{(-t_r/\tau)}\right) \]

\[ \tau = \frac{L}{2Z_0} \]
TDR Case Study

Example: RAMbus design

- Want RIMM connector to exhibit $Z = (L/C)^{1/2}$ to 10% of nominal

As built: $Z$ out of range

Add capacitor to bring $Z$ down
Case Study - Connector Design

J. Diepenbrock, et.al. EPEP’00
Vector Network Analyzer

Measures transmitted and reflected power and voltage ratios (S21, S11) as a function of frequency

- Best way to measure frequency-dependent effects
- More complex than TDR
- More accurate than TDR and gives higher frequency information

\[ S_{11} \approx \frac{P_{\text{reflected}}}{P_{\text{incident}}} \]

\[ DUT \]

\[ S_{21} \]
Matrix Parameters

\[
\begin{bmatrix}
V_1 \\
V_2
\end{bmatrix}
= 
\begin{bmatrix}
Z_{11} & Z_{12} \\
Z_{21} & Z_{22}
\end{bmatrix}
\begin{bmatrix}
I_1 \\
I_2
\end{bmatrix}
\]

\[
\begin{bmatrix}
I_1 \\
I_2
\end{bmatrix}
= 
\begin{bmatrix}
Y_{11} & Y_{12} \\
Y_{21} & Y_{22}
\end{bmatrix}
\begin{bmatrix}
V_1 \\
V_2
\end{bmatrix}
\]

\[
\begin{bmatrix}
b_1 \\
b_2
\end{bmatrix}
= 
\begin{bmatrix}
S_{11} & S_{12} \\
S_{21} & S_{22}
\end{bmatrix}
\begin{bmatrix}
a_1 \\
a_2
\end{bmatrix}
\]

\[
\begin{bmatrix}
V_1 \\
I_1
\end{bmatrix}
= 
\begin{bmatrix}
A & B \\
C & D
\end{bmatrix}
\begin{bmatrix}
V_2 \\
-I_2
\end{bmatrix}
\]

[S] usually expressed in dB
- S11 often referred to as “return” loss
- S21 often referred to as insertion loss
VNA Calibration

Excellent accuracy (O(0.05 dB)) possible because of calibration.

\[ \textbf{S}_{11}, \textbf{S}_{21}, \textbf{S}_{12}, \textbf{S}_{22} \] – Measured S-parameters

\[ \textbf{S}_{11}, \textbf{S}_{21}, \textbf{S}_{12}, \textbf{S}_{22} \] – DUT S-parameters

\( E_{xx} \) – Error Terms – Forward/Reverse

\( E_L \) – load match

\( E_S \) – source match

\( E_R \) – reflection tracking

\( E_T \) – transmission tracking

\( E_D \) – directivity

\( E_X \) – isolation
Measurement Procedure

1. Conduct measurements using high frequency 50 Ohm probes

2. Conduct measurements to create data for “de-embedding the test fixture”
   *Original measurement includes cables, probes, etc. in S11, S12.*
   *Want S11 and S12 for Device Under Test (DUT): i.e. Move reference planes from VNA to DUT:*

3. Perform de-embedding calculations

4. Fit to circuit model
Structures for Deembedding the Test Fixture

Measurements must be deembedded to remove contributions of CPW line (test fixture)

- ‘Improved Deembedding Technique’ requires three measurements
  - Open-line
  - Thru-line
  - DUT

\[
Y_{Device} = \frac{1}{1 - \frac{1}{Y_{DUT} - Y_{OPEN}}} - \frac{1}{Y_{THRU} - Y_{OPEN}}
\]

An improved de-embedding technique for on-wafer high-frequency characterization
Koolen, M.C.A.M.; Geelen, J.A.M.; Versleijen, M.P.J.G.;
9-10 Sept. 1991 Page(s):188 - 191
Extraction of Model Element Values

Closed form extraction

- Deembedded S-Parameters
- Convert to ABCD Parameters
- Extract model element values for capacitance and resistance

\[
A = \frac{(1 + S_{11}) \cdot (1 - S_{22}) + S_{12} \cdot S_{21}}{2 \cdot S_{21}}
\]

\[
B = \frac{(1 + S_{11}) \cdot (1 + S_{22}) - S_{12} \cdot S_{21}}{2 \cdot S_{12}}
\]

\[
C = \frac{(1 - S_{11}) \cdot (1 - S_{22}) - S_{12} \cdot S_{21}}{2 \cdot S_{21}}
\]

\[
D = \frac{(1 - S_{11}) \cdot (1 + S_{22}) + S_{12} \cdot S_{21}}{2 \cdot S_{21}}
\]

\[
Z_D = B \quad Z_S = \frac{Z_D}{A - 1}
\]

\[
A = 1 + \frac{Y_S}{Y_D} \quad D = 1 + \frac{Y_S}{Y_D}
\]

\[
B = \frac{1}{Y_D} \quad C = 2 \cdot Y_s + \frac{Y_s^2}{Y_D}
\]
Results

Device

Extracted Model

Measured vs. S parameters from model:

Equivalent Circuit Model
Summary

Oscilloscope Measurements:
- Be aware of bandwidth limitations of scope and measurement probes
- High-Z vs. 50 Ohm probes:
  - 50 Ohm provide wider BW but measurement goes ‘off board’
  - High-Z to probe internal signals

TDR:
- Easy and useful technique
- Directly provides Z, L, C, tdelay of each element in connection path
- Useful debugging tool

VNA:
- Best way to obtain frequency-dependencies
- Best way to fit more complex models
- More complex procedure