High Frequency Basics

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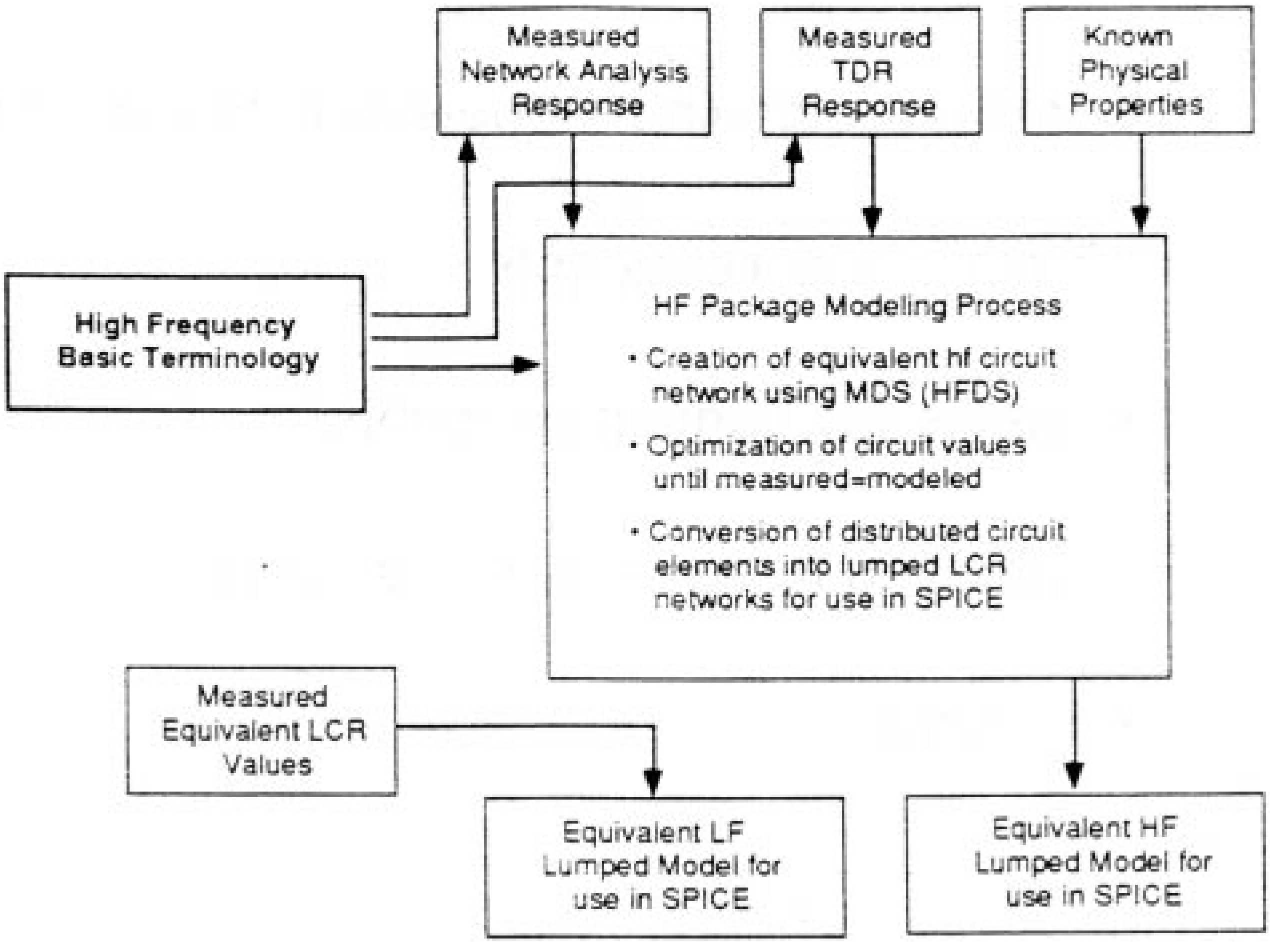
Current Activities:
Owner and operator of GigaTest Labs, Inc.. Tom provides as a service, electronic network measurements at microwave frequencies, on semiconductors, hybrids, packages, interconnect structures, components and systems. Certified network measurement equipment with a frequency range from 45 MHz to 40 GHz and results are verified.

Brief Synopsis of Background:
Applied Physics, University of Missouri at Rolla ('63–'65), University of Missouri at St. Louis ('69–'71). Instrumental in establishing Microwave Integrated Circuit and GaAs FET technologies at Teledyne MEC ('71–'80). Served as Manufacturing Manager at Harris Microwave Semiconductor ('80–'87) and made significant contributions to the growing GaAs device business. He established Strouth Technical Sales in 1987, representing leading edge manufactures of semiconductor technology, and GigaTest Labs in 1989, providing measurement services for the electronics industry.

Package Characterization and Modeling Process



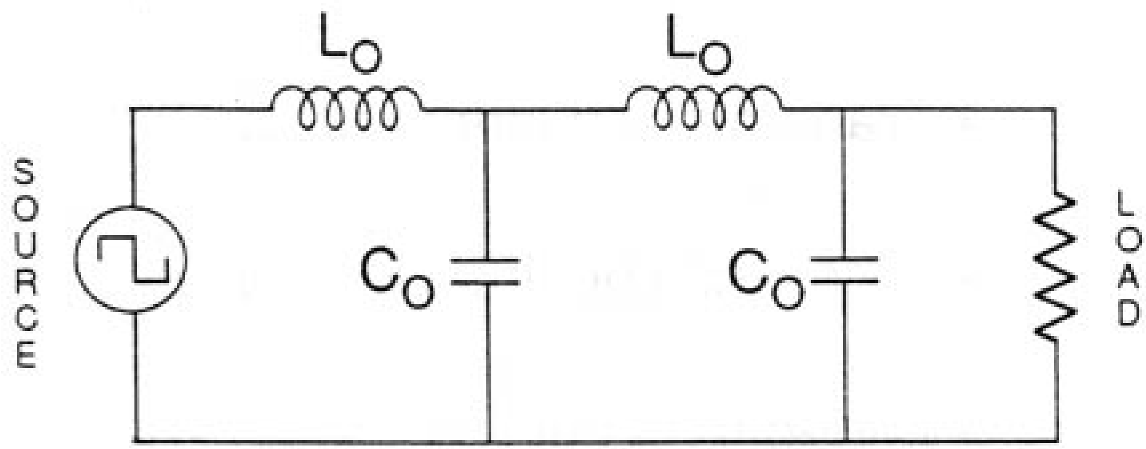
Outline

- Transmission line models and construction
- Time domain concepts
- Frequency domain concepts
- Time and frequency relationships
- Summary

Transmission Line Models and Construction

- Transmission line models
- Transmission line construction
- Impedance curves
- Transmission line crosstalk model

Simple Transmission Line Models



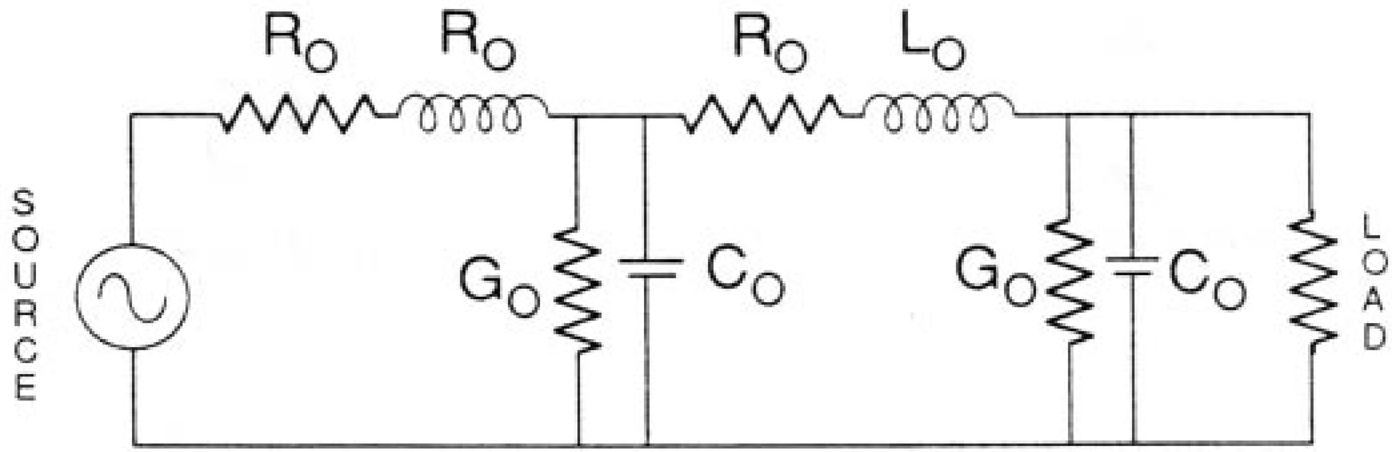
$$L_O = \frac{\text{Inductance}}{\text{Unit Length}}$$

$$C_O = \frac{\text{Capacitance}}{\text{Unit Length}}$$

Transmission Line Impedance

$$Z_O = \sqrt{\frac{L_O}{C_O}}$$

Transmission Line Model



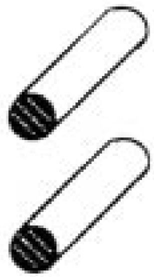
$L_O = \dfrac{\text{Inductance}}{\text{Unit Length}}$ $G_O = \dfrac{\text{Conductance}}{\text{Unit Length}}$

$C_O = \dfrac{\text{Capacitance}}{\text{Unit Length}}$ $R_O = \dfrac{\text{Resistance}}{\text{Unit Length}}$

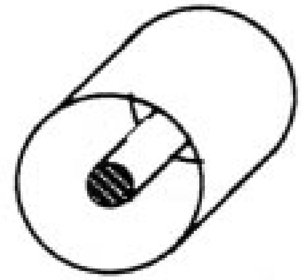
Transmission Line Impedance

$$Z_O = \sqrt{\frac{R_O + j\omega L_O}{G_O + j\omega C_O}}$$

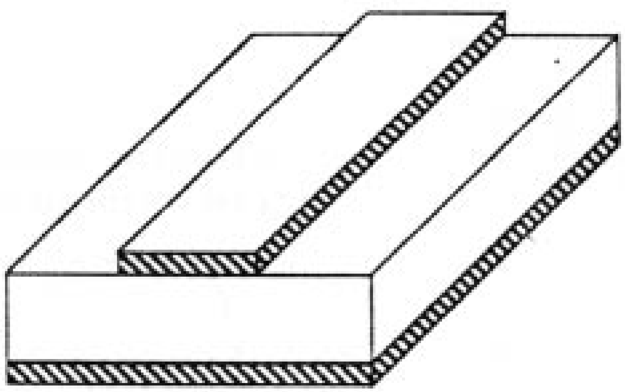
Transmission Lines



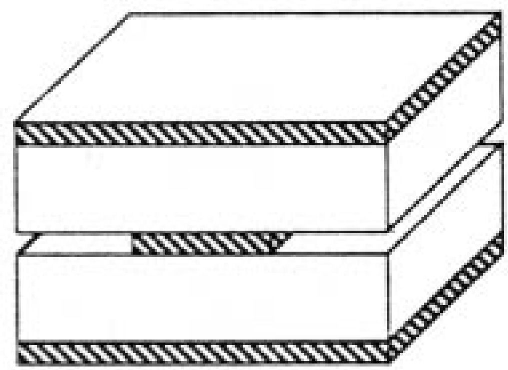
Two-Wire Line



Coaxial Line

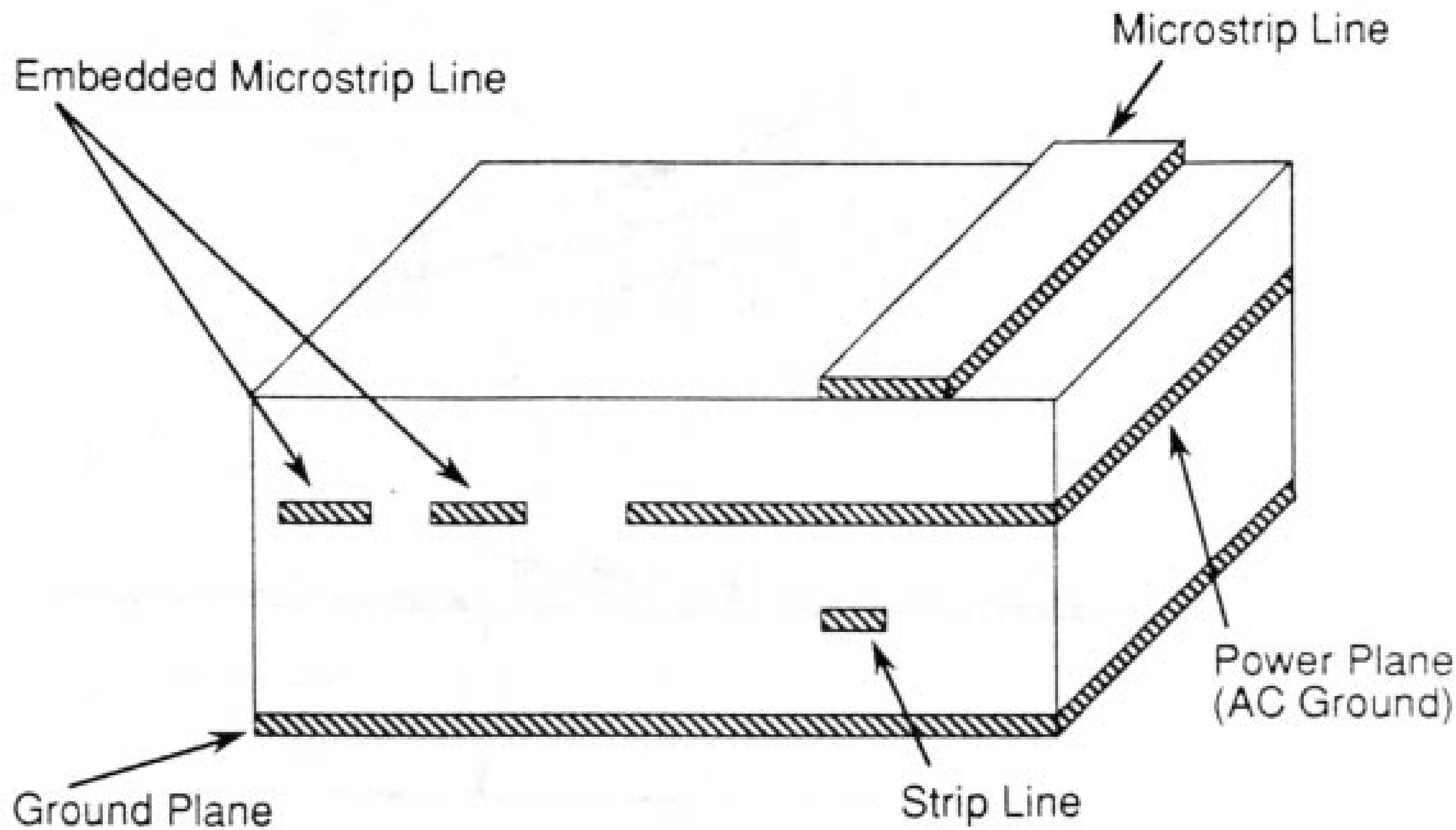


Microstrip Line



Strip Line

Typical Transmission Line Structures



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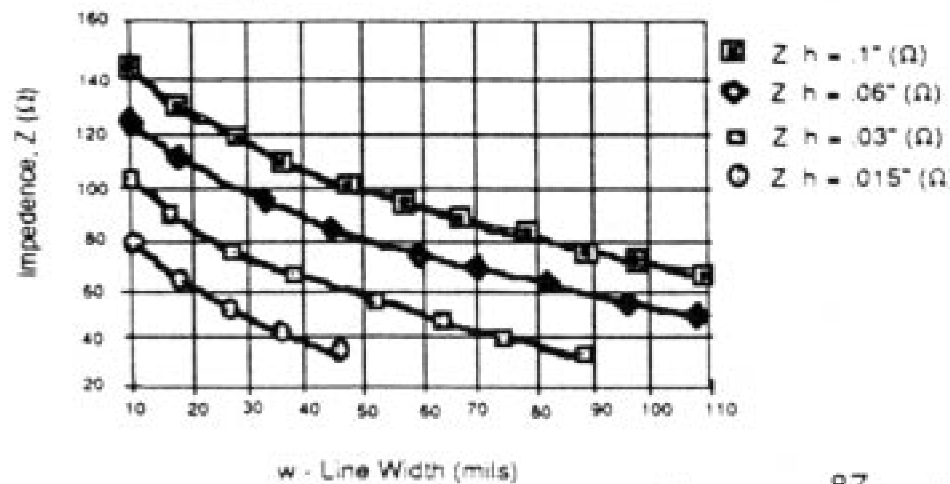
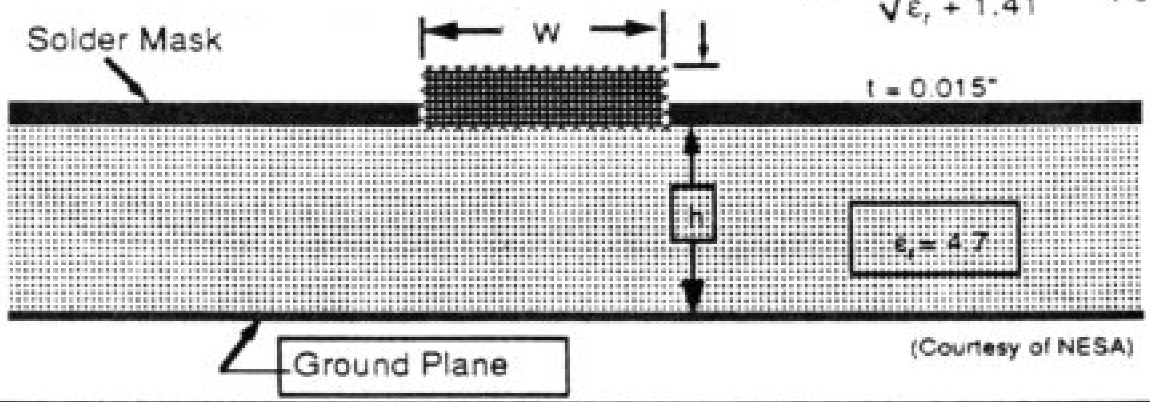
Microstrip Impedance Curves

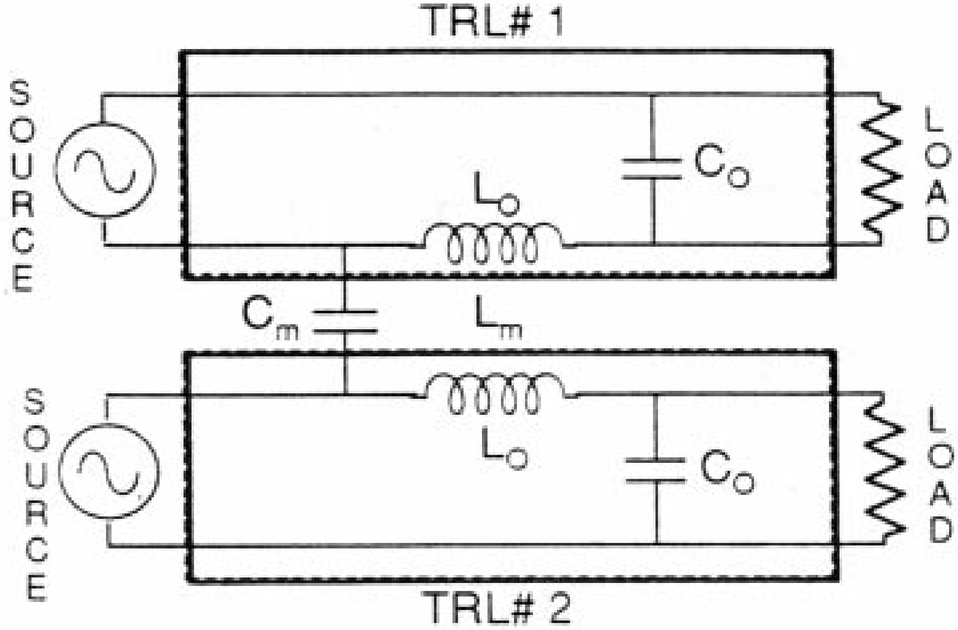


$$Z_O = \frac{87}{\sqrt{\varepsilon_r + 1.41}} \ln\left(\frac{5.98\,h}{0.8\,w + t}\right)$$



(Courtesy of NESA)

Transmission Line Crosstalk Model



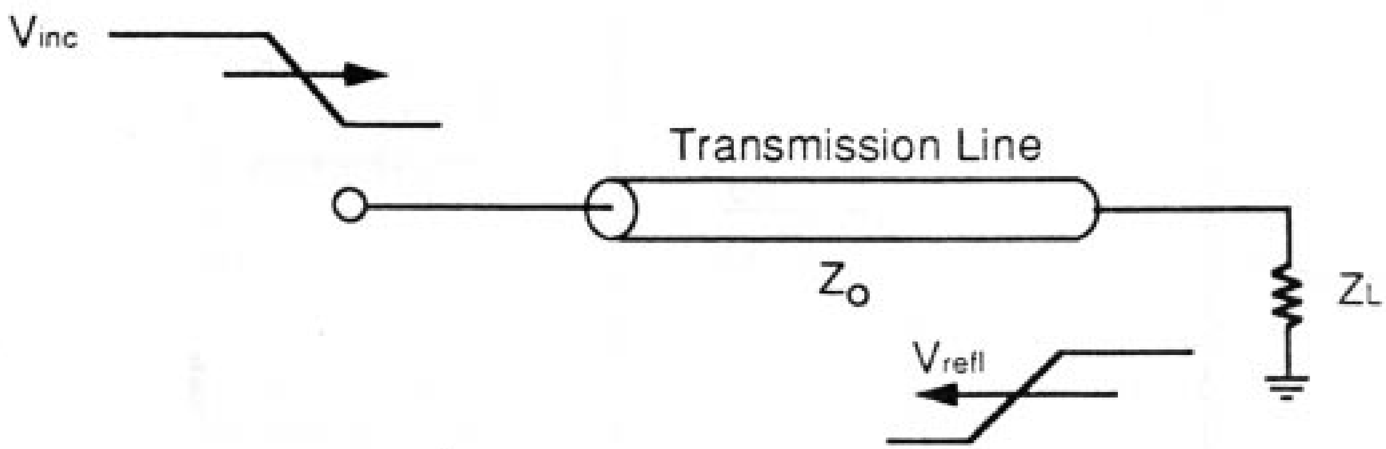
COUPLING COEFFICIENTS, K_f and K_b

$$K_f = -\frac{1}{2}\left[\frac{L_m}{Z_O} - C_m Z_O\right] \qquad K_b = -\frac{1}{4TD}\left[\frac{L_m}{Z_O} + C_m Z_O\right]$$

Time Domain Concepts

- TDR - Time domain reflection
- TDT - Time domain transmission
- Examples

Time Domain Reflection (TDR)



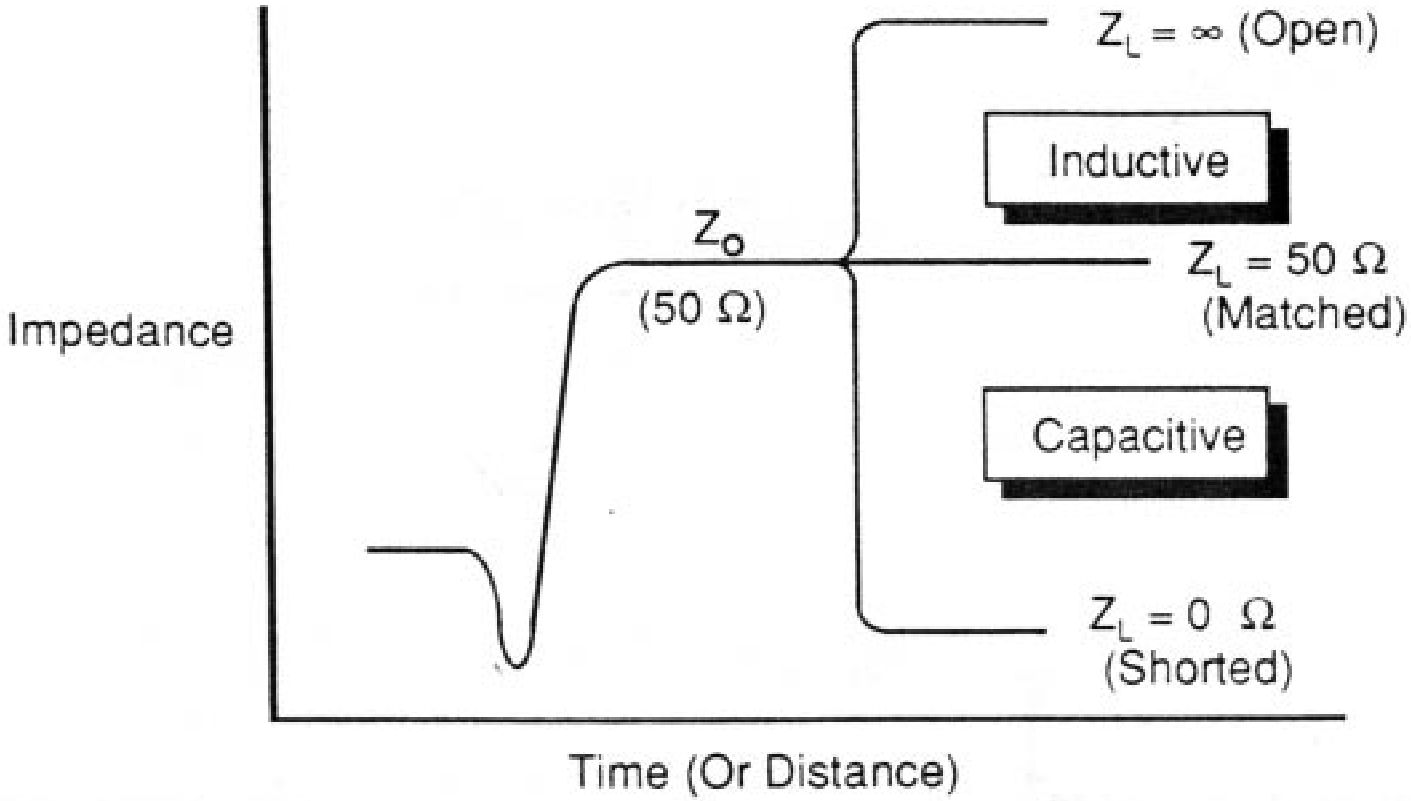
$$\boxed{V_{refl} = \frac{Z_L - Z_o}{Z_L + Z_o} V_{inc}}$$

$$\text{Where } \Gamma = \frac{Z_L - Z_o}{Z_L + Z_o}$$

$\rho = |\Gamma|$ = Reflection Coefficient

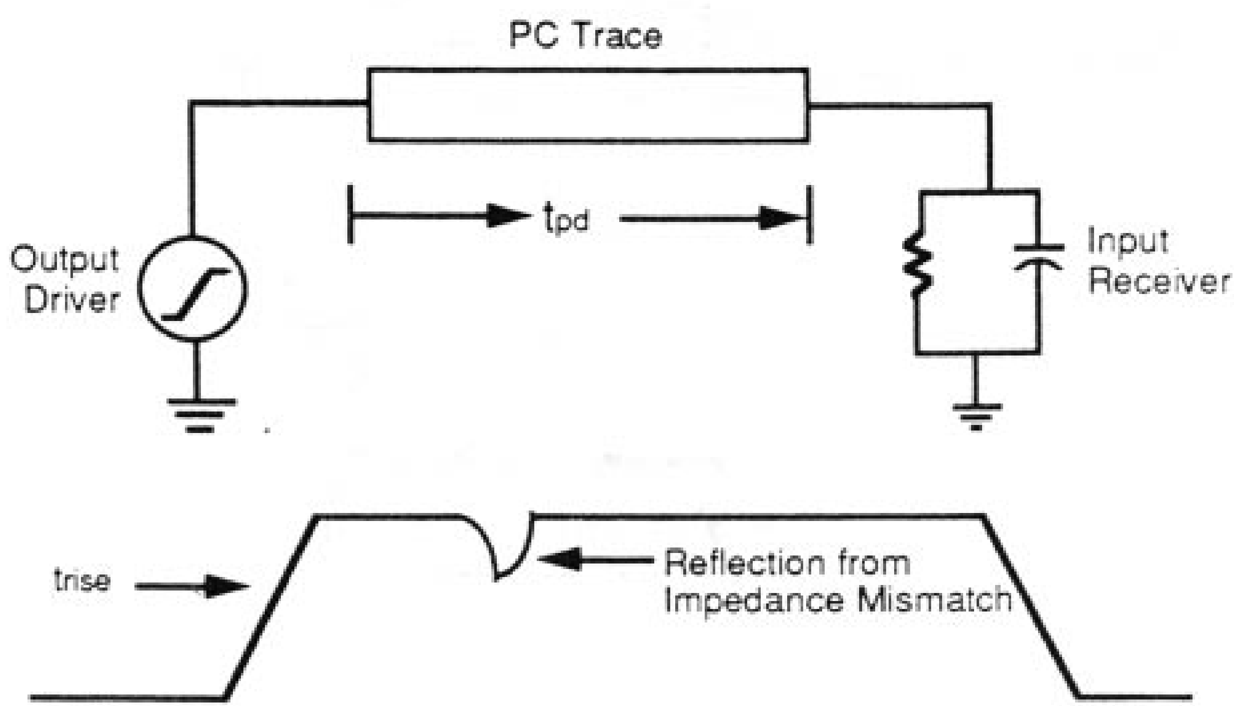
$$\boxed{V_{refl} = \rho * V_{inc}}$$

TDR - Important Conditions



$Z_L = Z_O$ is called an "impedance match"
$Z_L \neq Z_O$ is called an "impedance mismatch"

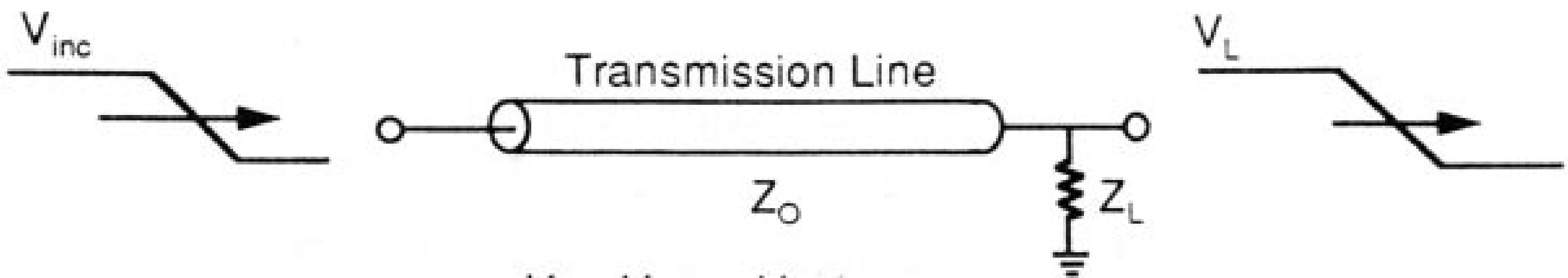
When Does Impedance Mismatch Cause Problems?



trise < 2tpd

$t_{pd} = 1.017\,(0.475\,e_r + 0.67)^{1/2}$ ns/ft

Time Domain Transmission (TDT)



$$V_L = V_{inc} + V_{refl}$$

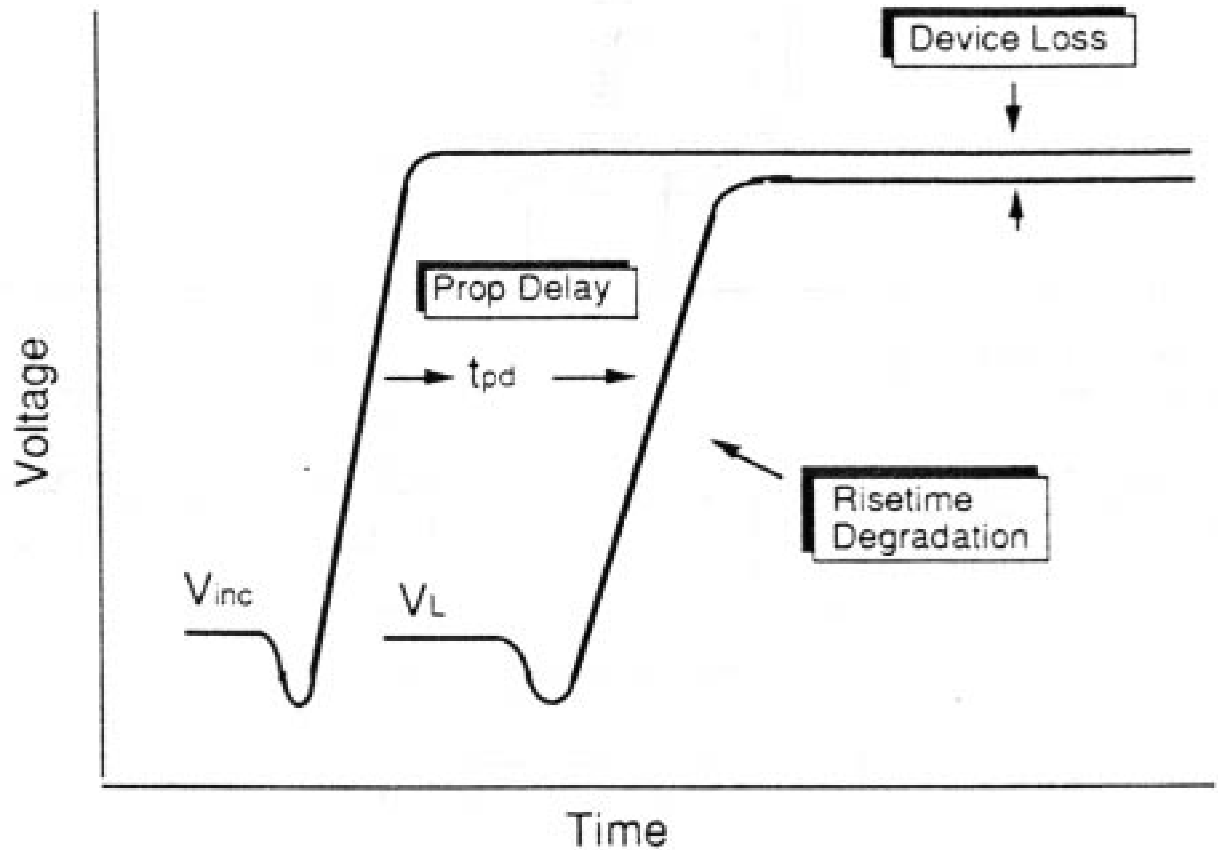
$$= V_{inc} + V_{inc}\frac{Z_L - Z_O}{Z_L + Z_O}$$

$$\boxed{V_L = (1 + \rho)V_{inc}}$$

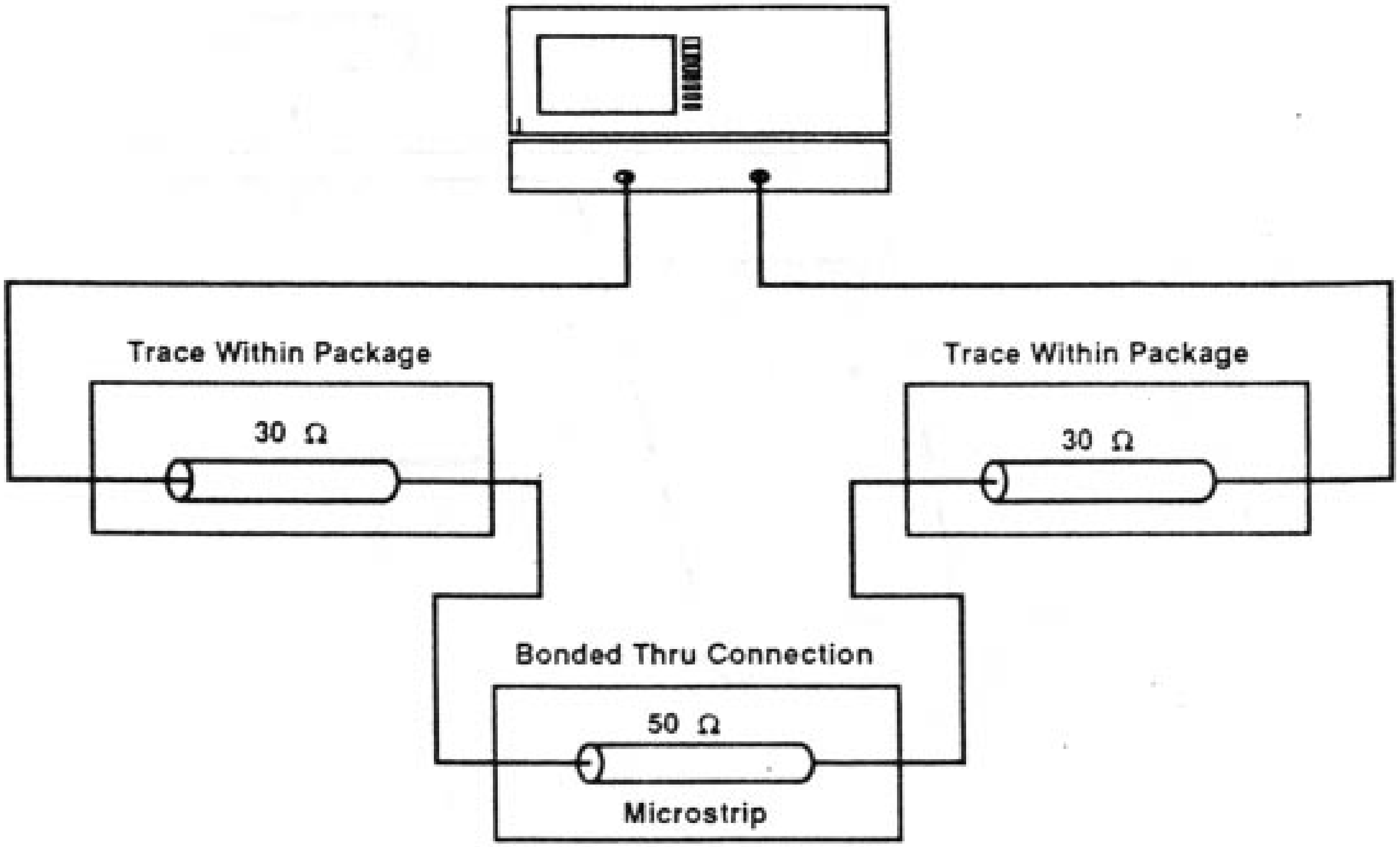
Where

$\tau = (1+\rho) =$ Transmission Coefficient

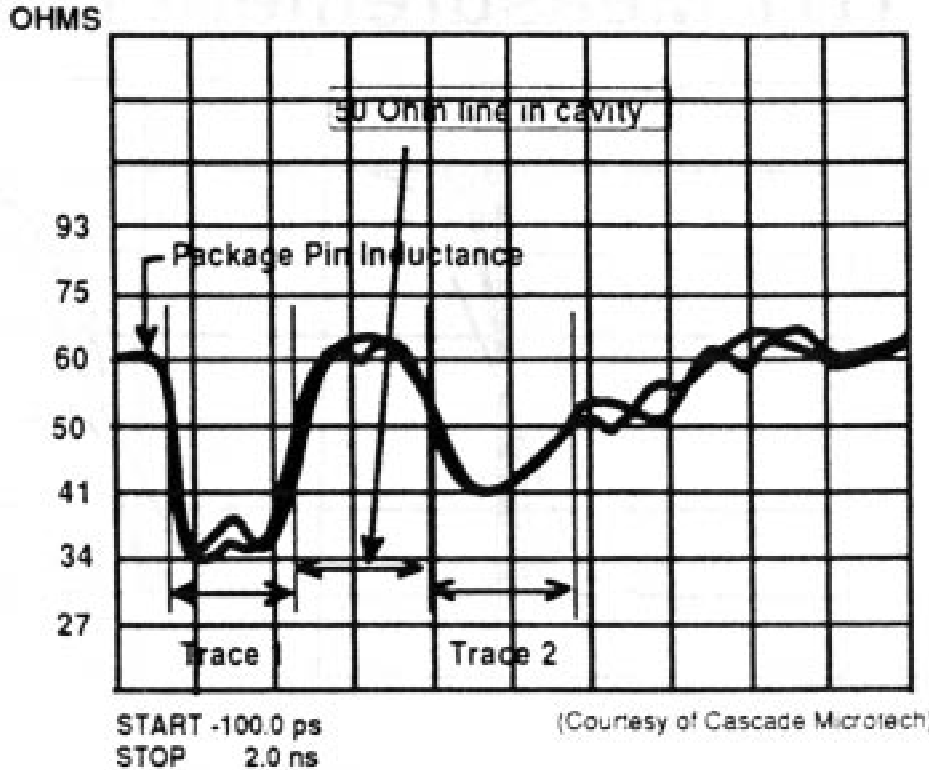
TDT - Important Information



Example Package Measurement



TDR Measurement Example



(Courtesy of Cascade Microtech)

Observations:
- Mismatch between traces and 50 Ω line dominant factor
- Package pin inductance negligible
- Can gain insights into general circuit topology for SPICE from observing TDR of package

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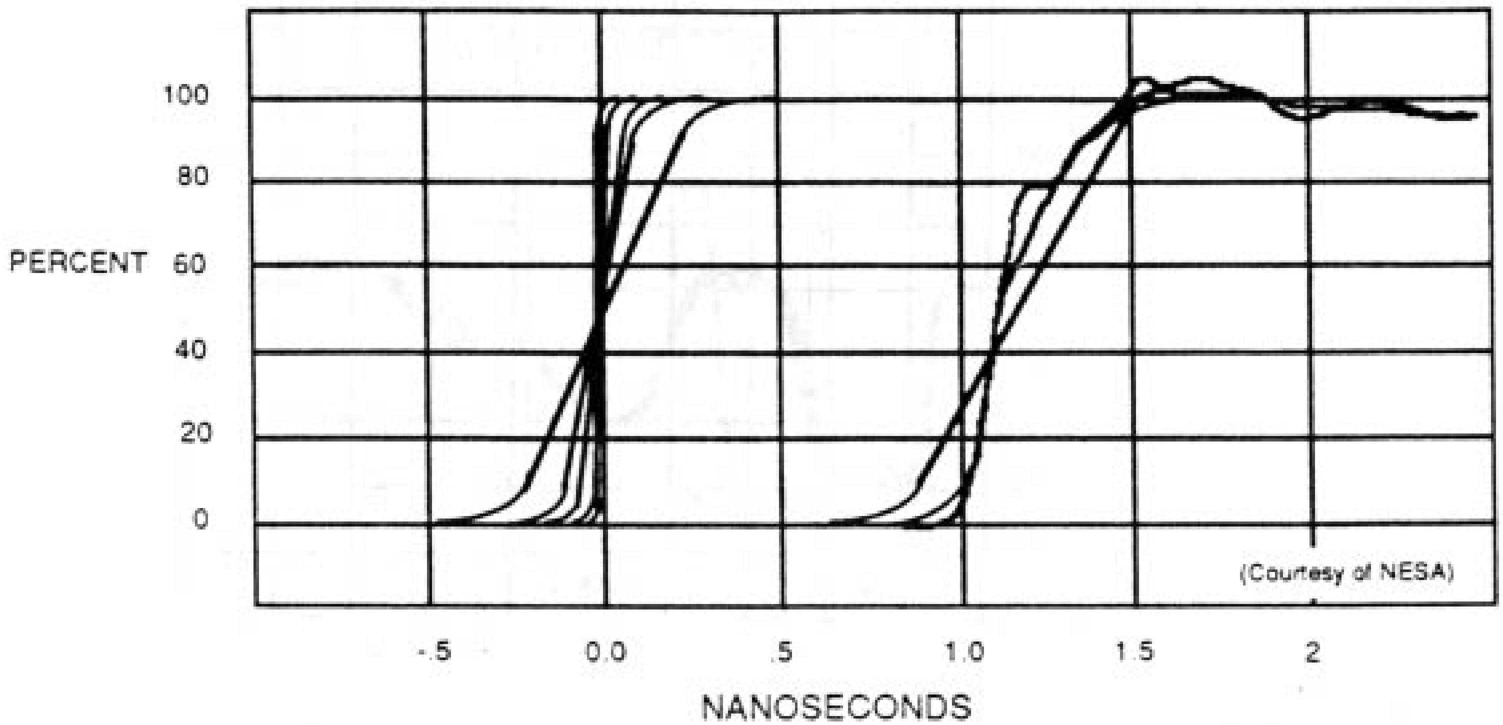
TDT Measurement Example



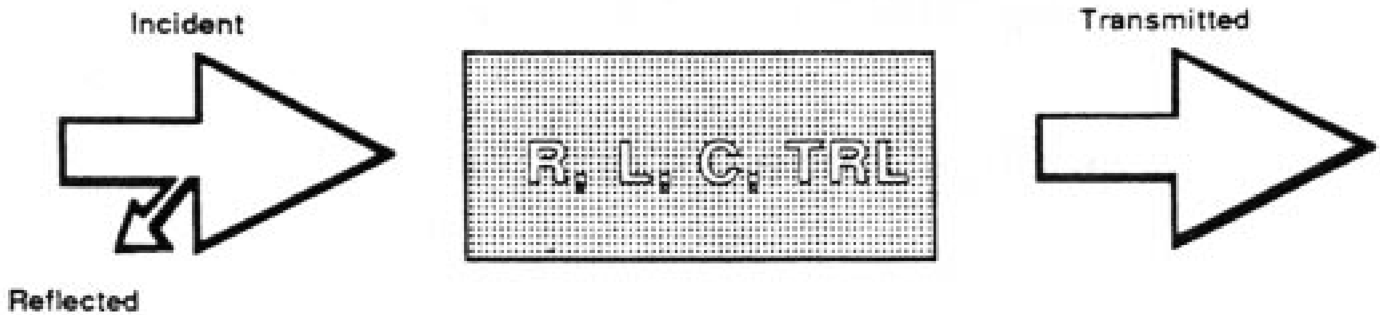
Observations:

- Propagation delay through package is about 1.2 ns
- Loss through package is negligible
- Risetime degradation is about 200 ps

Frequency Domain Concepts

- S_{11} and S_{22} - Reflection parameters
- S_{21} and S_{12} - Transmission parameters
- Measurement examples

High Speed (Microwave) Concepts



NETWORK

Reflection Parameters

$$\Gamma = \frac{V_{Reflected}}{V_{Incident}} = \frac{Z_L - Z_O}{Z_L + Z_O}$$

Reflection Coefficient

Return Loss

S - Parameters

S_{11}, S_{22}

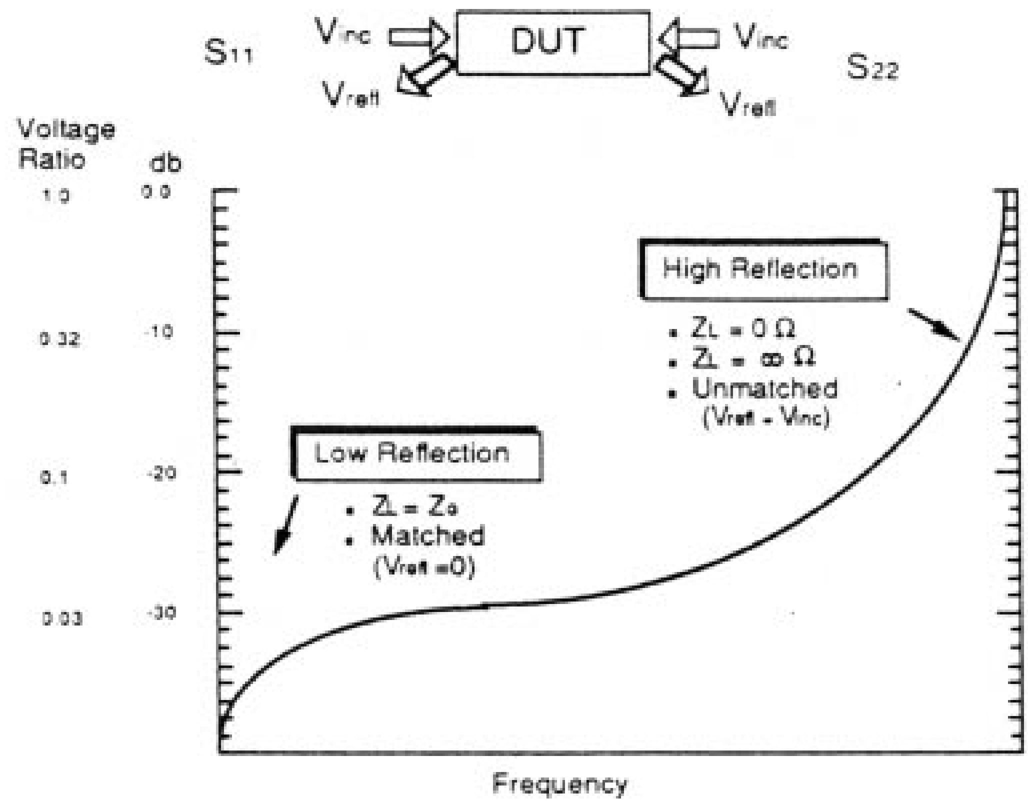
VSWR

Impedance

$\rho = |\Gamma|$

TDR

S_{11} and S_{22} Important Conditions



$$S_{11} = S_{22} = \frac{V_{refl}}{V_{inc}}$$

Transmission Parameters

$$T = \frac{V_{Load}}{V_{Incident}} = \frac{2Z_L}{Z_L + Z_O}$$

Group Delay

Gain/Loss

S - Parameters

S_{21}, S_{12}

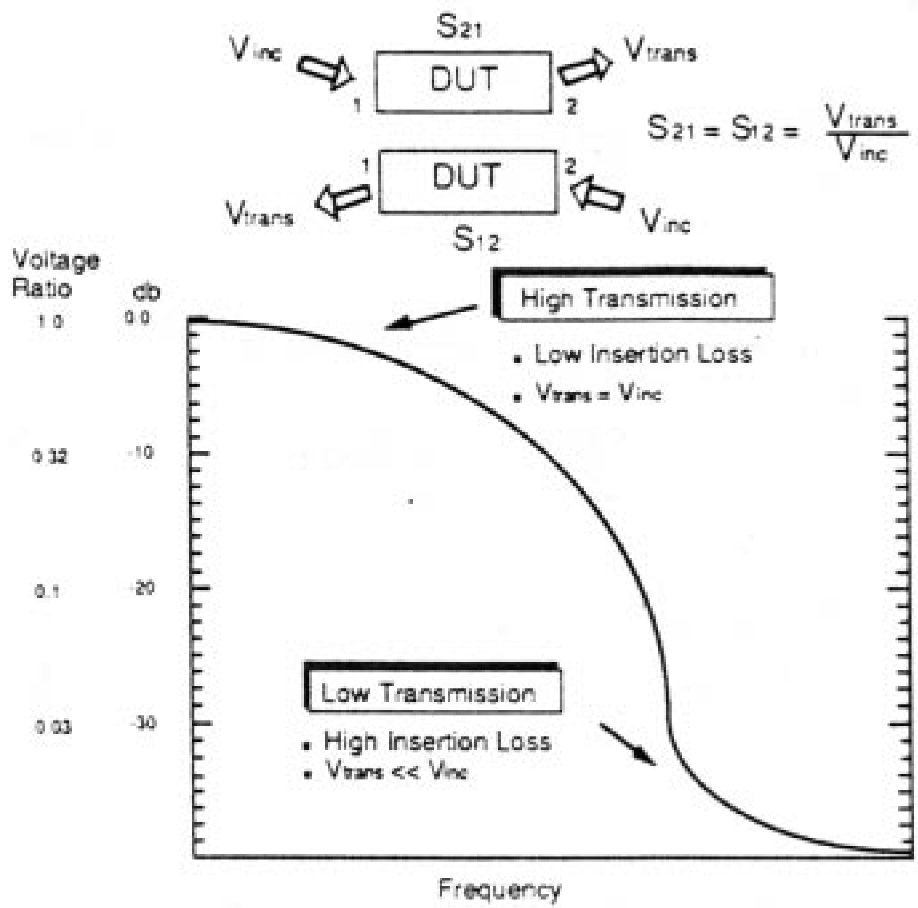
Transmission
Coefficient

Insertion Phase

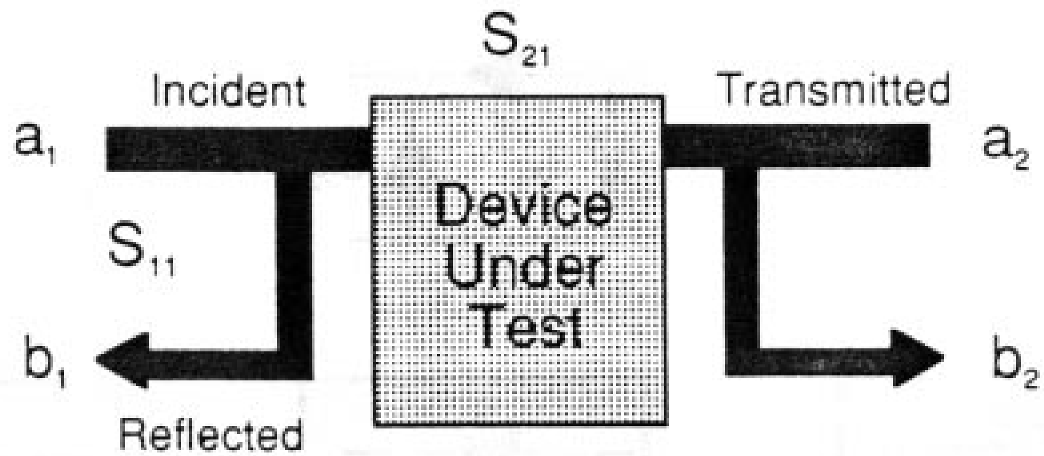
$\tau = | T |$

TDT

S_{21} and S_{12} Important Conditions

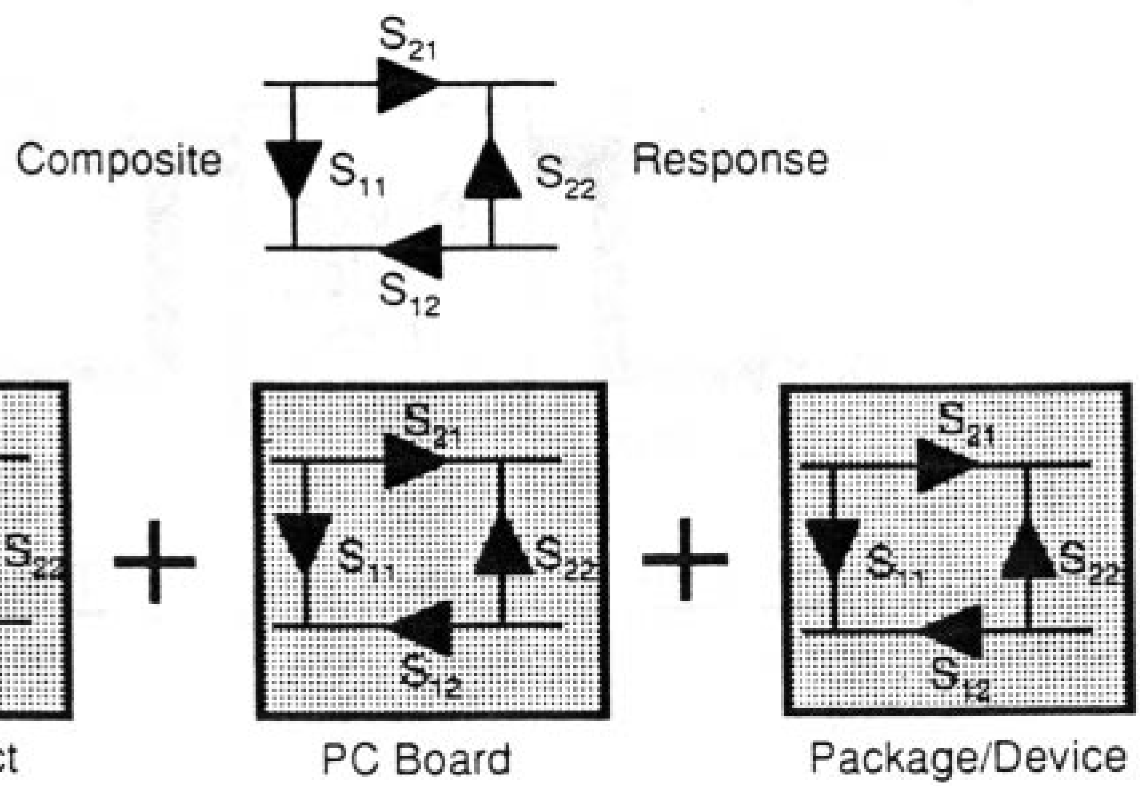


Scattering Parameters

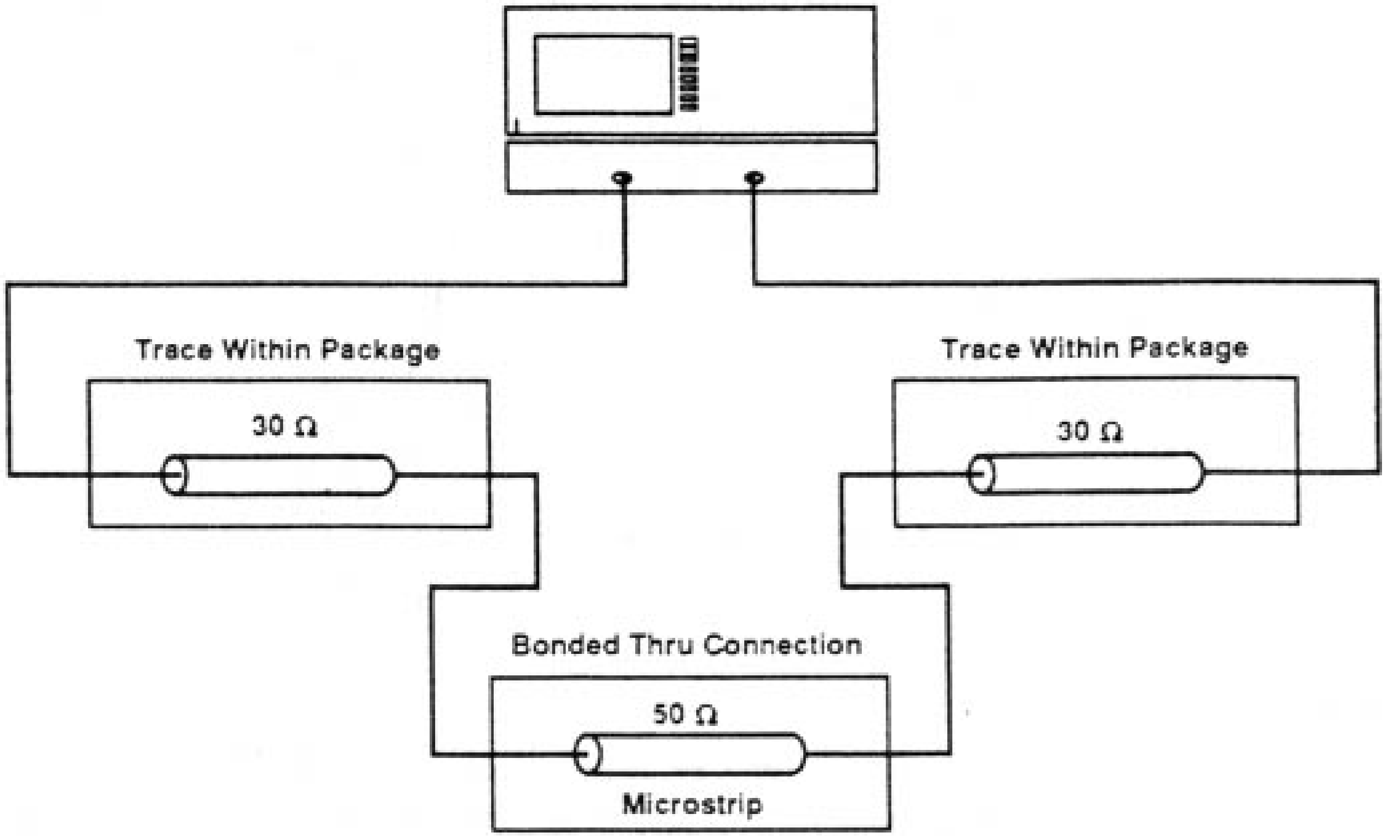


$$S_{11} = \frac{\text{Reflected}}{\text{Incident}} = \frac{b_1}{a_1} \qquad S_{21} = \frac{\text{Transmitted}}{\text{Incident}} = \frac{b_2}{a_1}$$

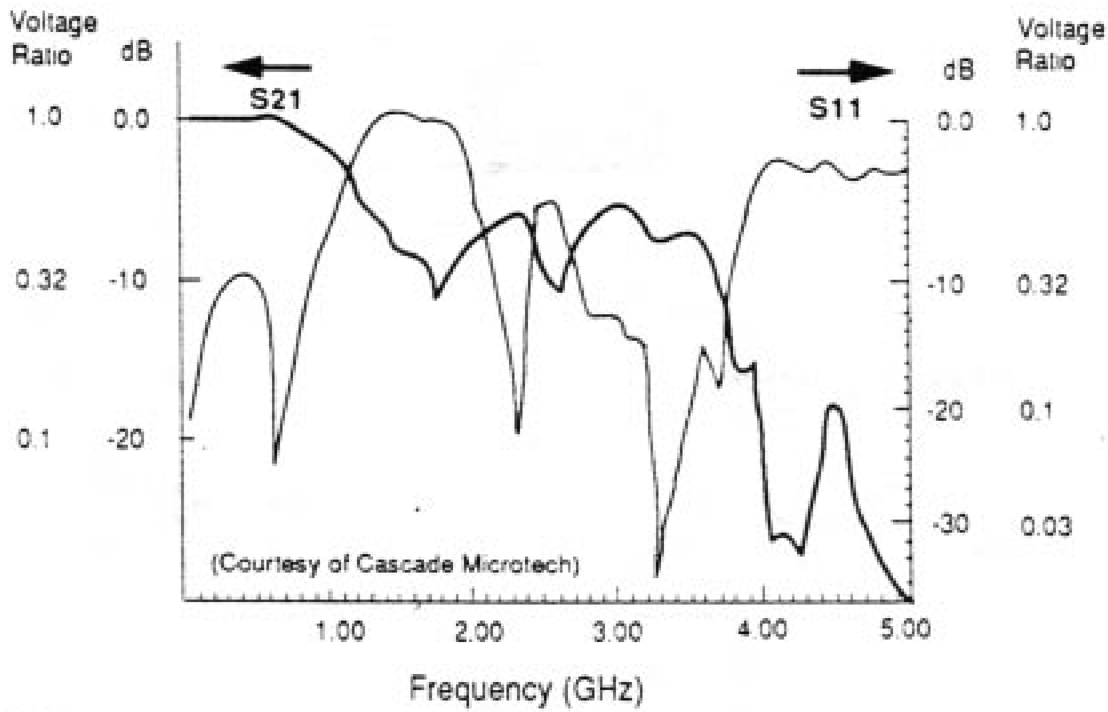
Scattering Parameters



Example Package Measurement



S_{11} and S_{21} Measurement Example



Observations:

- Reflected energy (S_{11}) becomes excessive above 800 MHz
- Bandwidth of package is about 1 GHz (will transmit signals with risetimes as fast as 350 ps without significant distortion assuming interconnect BW = 0.35/tr)

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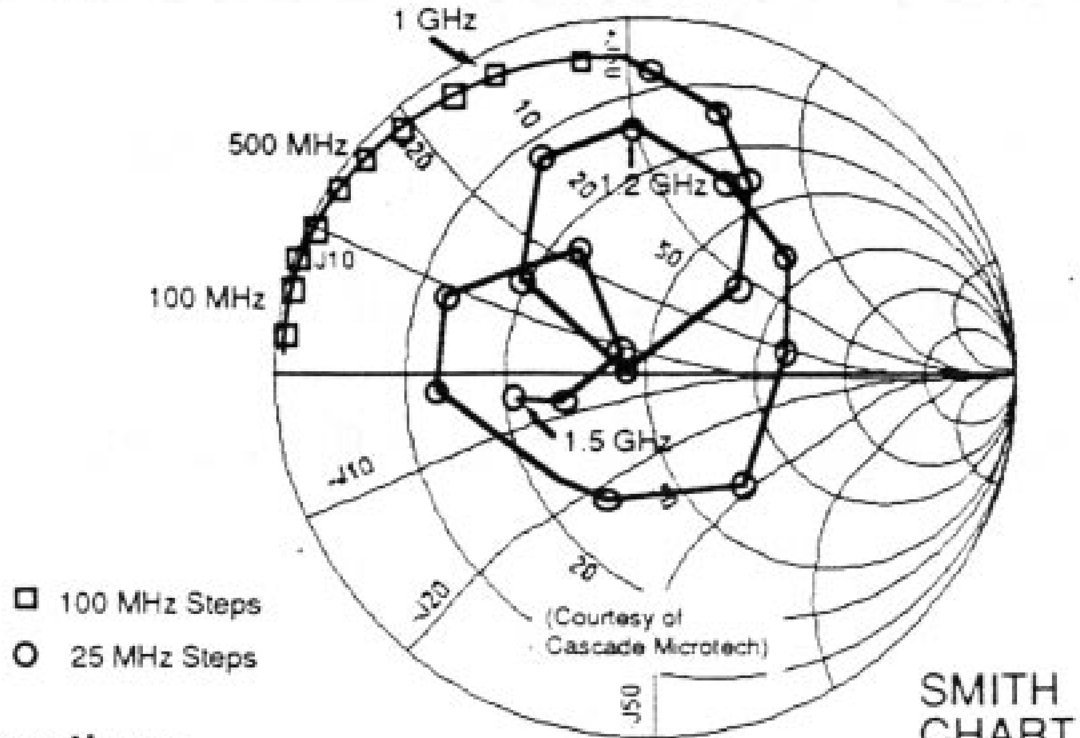
Magnitude and Phase vs Frequency



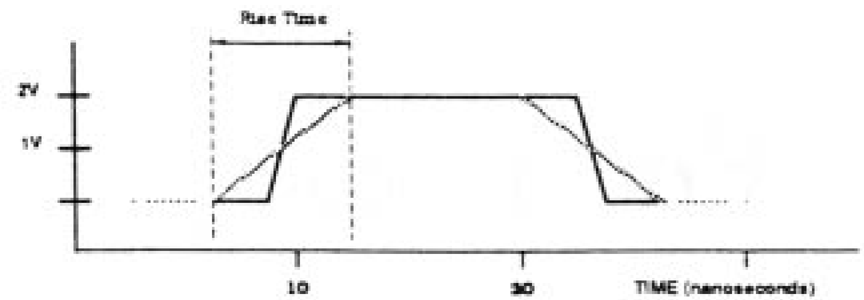
Observations:

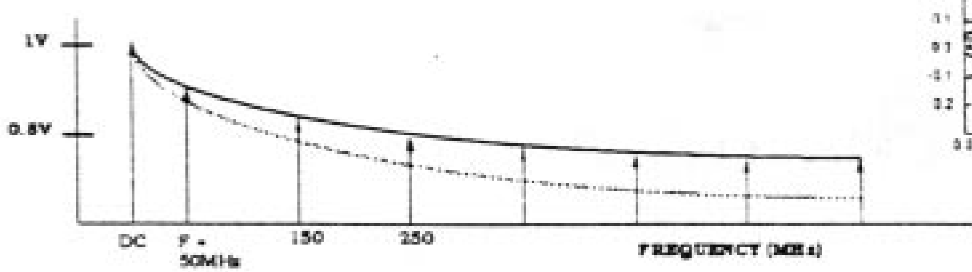
- Major effect of package is inductive
- Package becomes lossy above 1 GHz
- Ability to measure package at higher frequencies reveals several resonances and provides insights as to possible sources of high frequency problem

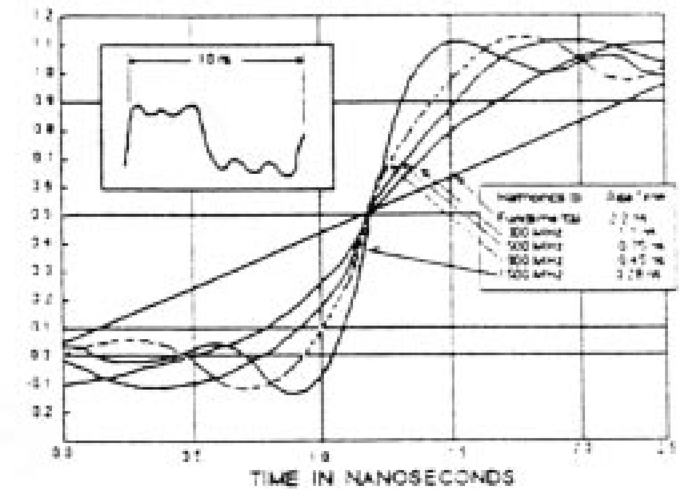
Time and Frequency Relationships

- Risetime and Frequency Relationships
- Measurement BW vs Risetime
- Comparing Measurements in Both Domains

Risetime and Frequency Relationships





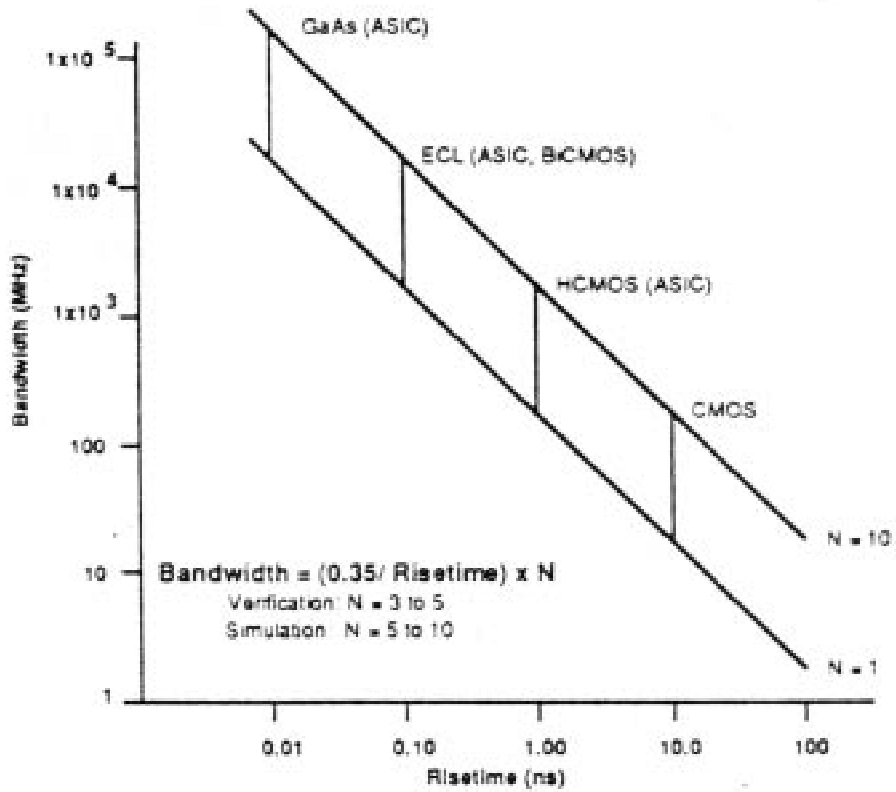


Clock Frequency

=

Bandwidth

Measurement BW vs Risetime



Example: for a pulse risetime of 0.5 ns, what minimum frequency range should be used for hardware verification.

$BW = (0.35/0.5 \times 10^{-9}) \times 5 = 3.5 \times 10^{9}$, or 3.5 GHz

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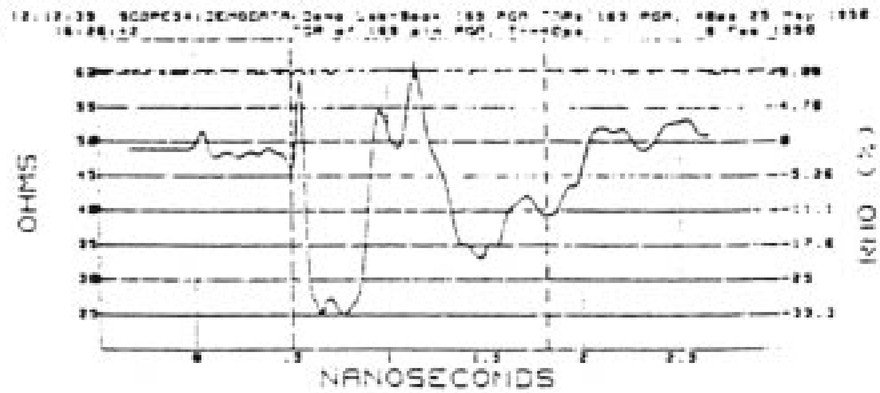
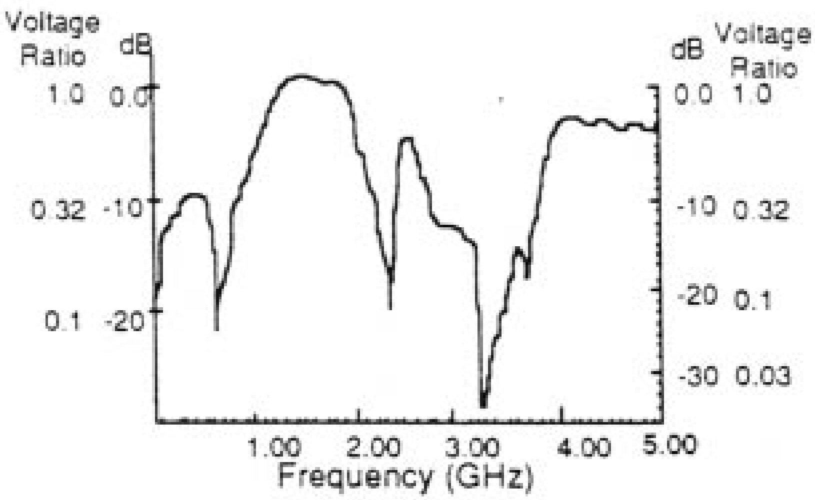
Reflection Parameter Relationships

TDR



Too much impedance variation in the time domain ...

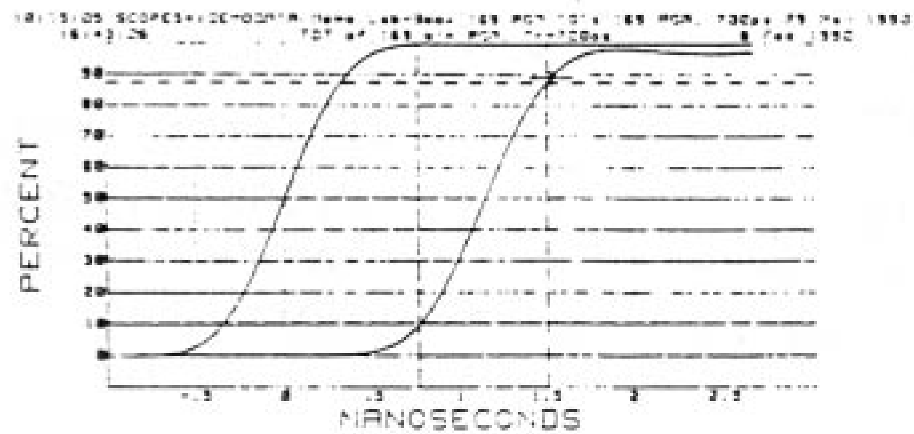
S11



... will appear as reflected energy in the frequency domain

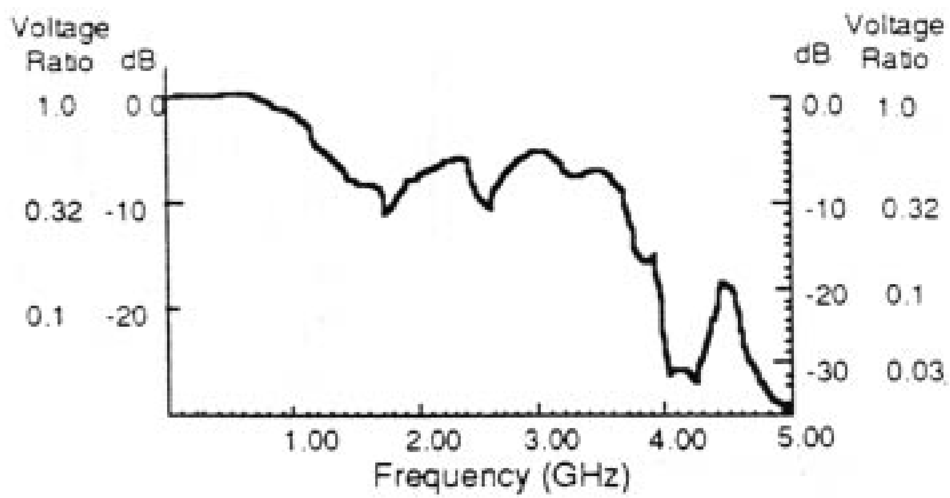
Transmission Parameter Relationships

TDT



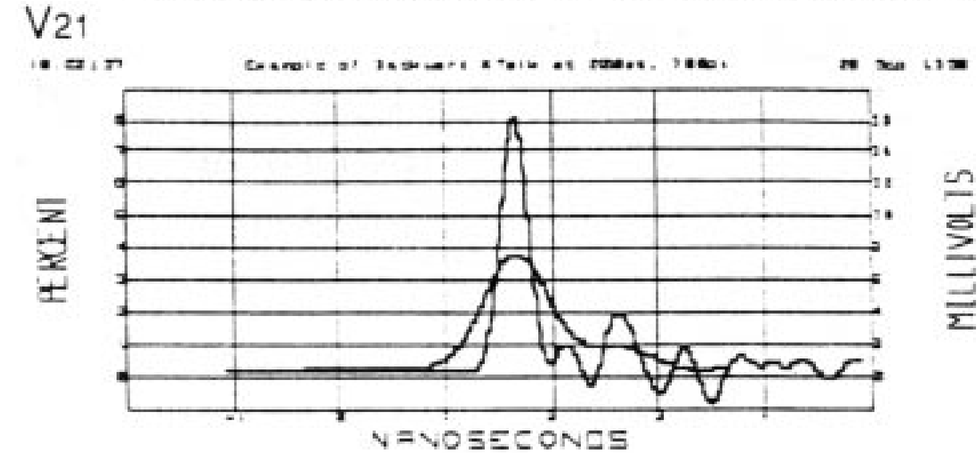
Too much risetime degradation in the time domain ...

S21

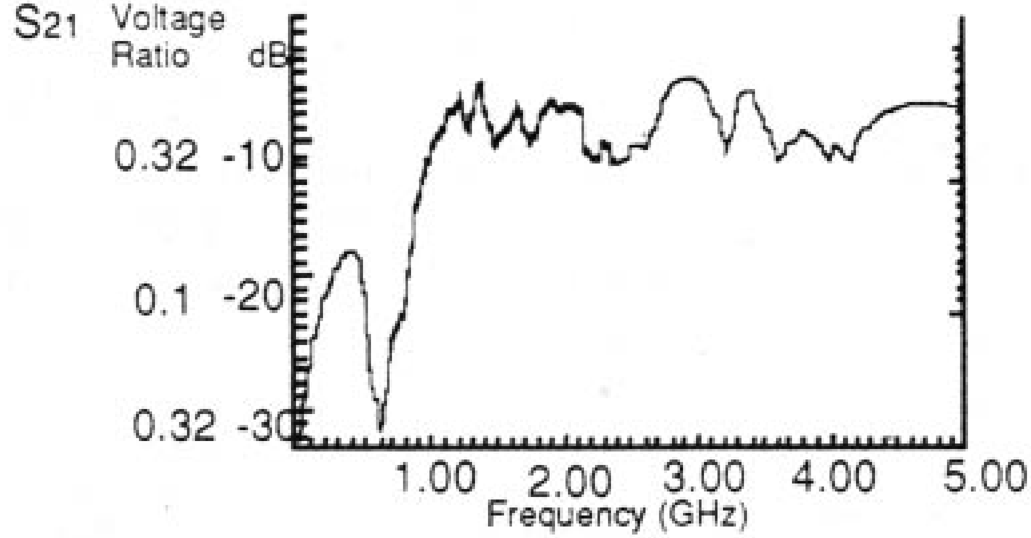


...will appear as inadequate bandwidth in the frequency domain

Crosstalk Parameter Relationship



Risetime dependent crosstalk between two traces in the time domain ...



...will appear as decreased isolation at higher frequencies in the frequency domain

Summary

- Measurements vs information
- Instruments vs measurable parameters

Measurements vs Information

- TDR
  - Impedance of elements within package
  - Visual indication of circuit topology
  - Prediction of signal integrity problems due to impedance mismatch
- TDT
  - Indicates propagation delay of package
  - Can view risetime degradation
  - Shows loss in signal amplitude vs time
- S_{11}
  - Shows reflected energy as a function of frequency
  - Can characterize complex loads vs frequency
  - Can see frequency range over which package is mainly inductive or capacitive (Smith Chart)
- S_{21}
  - Gives bandwidth over which package will operate
  - Can calculate risetimes the package will pass
  - Indicates where package resonates (Smith Chart)

Instrumentation vs Measurable Parameters

Instrumentation	Impedance vs. Time	Transmission vs Time	Impedance vs Frequency	Transmission vs Frequency	Magnitude & Phase vs Freq.	Links to MDS
LCZ Meter	No	No	Yes (<40MHz)	Yes (<40MHz)	Yes (<40MHz)	No
TDR O'scope	Yes	Yes	No	No	No	No
Network Analyzer	Yes w/opt	Yes w/opt	Yes	Yes	Yes	Yes

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