Interconnections and Signal Integrity

José Schutt-Ainé
SemChip

DAC Tutorial

22, June 2001

Future System Needs and Functions

Auto

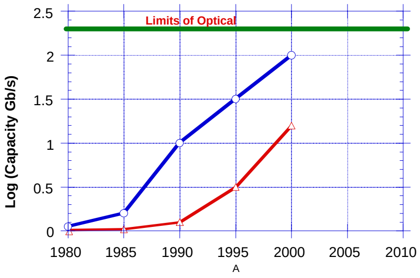
Digital Wireless

MEMS

Analog, RF

Consumer

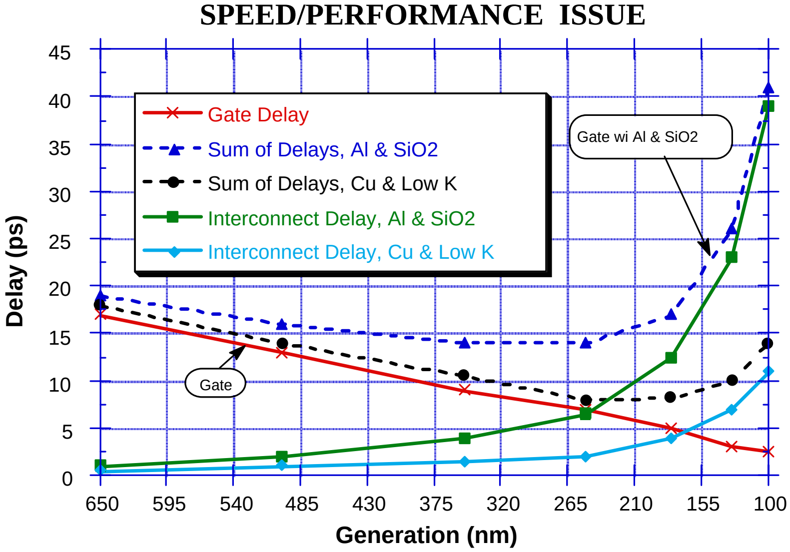
Computer



High bandwidth

High-speed Digital

The Interconnect Bottleneck



Al 3.0 μΩ -cm
Cu 1.7 μΩ -cm
SiO2 κ = 4.0
Low κ κ = 2.0
Al & Cu .8μ Thick
Al & Cu Line 43μ Long

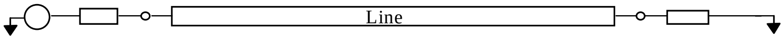
Semiconductor Technology Trends

	1997	**2003**	**2006**	**2012**
Chip size (mm^2)	300	430	520	750
Number of transistors (million)	11	76	200	1400
Interconnect width (nm)	200	100	70	35
Total interconnect length (km)	2.16	2.84	5.14	24

The Interconnect Bottleneck

Technology Generation	MOSFET Intrinsic Switching Delay	Response Time
1.0 um	~ 10 ps	~ 1 ps
0.01 um	~ 1 ps	~ 100 ps

Chip-Level Interconnect Delay

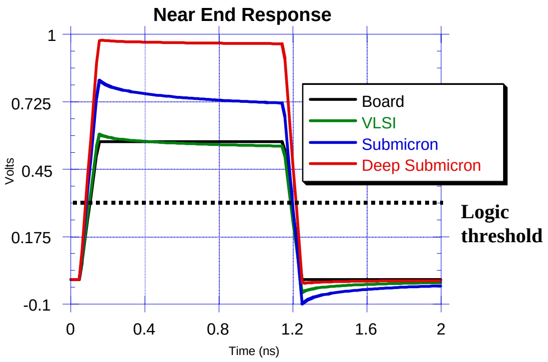


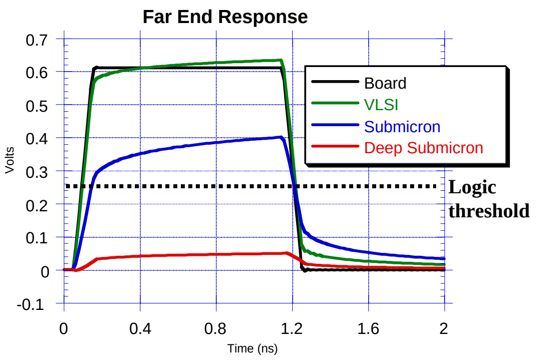
Pulse Characteristics:

rise time: 100 ps
fall time: 100 ps
pulse width: 4ns

Line Characteristics

length : 3 mm
near end termination: 50 Ω
far end termination 65 Ω

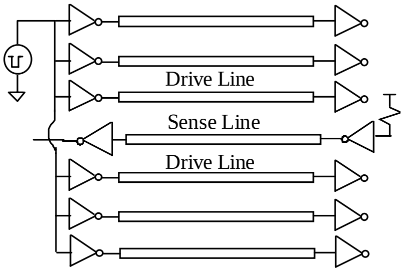


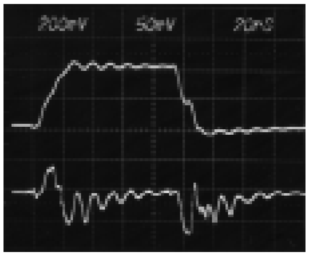


Interconnect Bottleneck

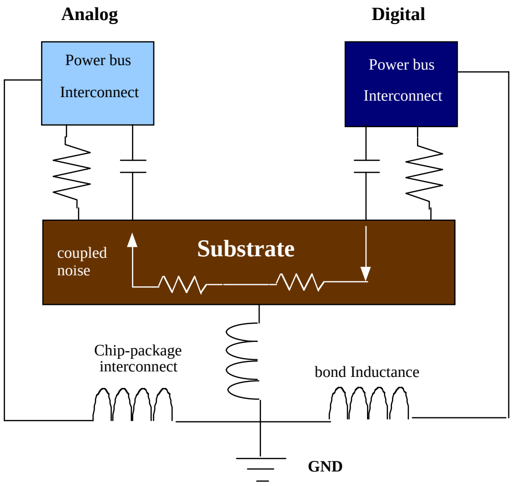
Signal Integrity

Crosstalk
Reflection
Delta I Noise
Dispersion
Distortion
Ground Bounce
Attenuation
Loss
Radiation



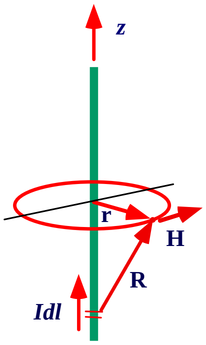


Mixed Signal Noise



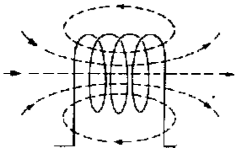
- **Simultaneous switching and inductance (L_{eff})**
- **L_{eff} is f(current magnitude and direction)**
- **Interactions between noise generated by power/ground and signal paths**

INDUCTANCE



$$\text{Inductance} = \frac{\text{Total flux linked}}{\text{Current}}$$

INDUCTANCE

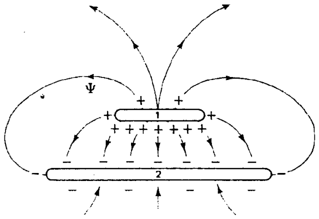


$$L = \frac{N\Phi}{I}$$

N : number of turns

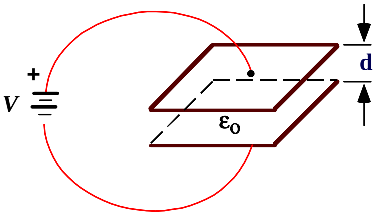
Φ : flux per turn

CAPACITANCE



$$\text{Capacitance} = \frac{\text{Total charge}}{\text{Voltage}}$$

CAPACITANCE



$$C = \frac{\varepsilon_o A}{d}$$

A : area

ε_o : permittivity

Package Inductance & Capacitance

Component	Capacitance (pF)	Inductance (nH)
68 pin plastic DIP pin[†]	4	35
68 pin ceramic DIP pin [††]	7	20
68 pin SMT chip carrier[†]	2	7

[†] No ground plane; capacitance is dominated by wire to wire component.

[††] With ground plane; capacitance and inductance are determined by the distance between the lead frame and the ground plane, and the lead length.

Package Inductance & Capacitance

Component	Capacitance (pF)	Inductance (nH)
68 pin PGA pin[††]	4	35
256 pin PGA pin [††]	7	20
Wire bond	1	1
Solder bump	0.5	0.1

[†] No ground plane; capacitance is dominated by wire to wire component.

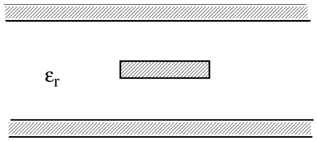
[††] With ground plane; capacitance and inductance are determined by the distance between the lead frame and the ground plane, and the lead length.

CONDUCTIVITY OF DIELECTRIC MATERIALS

Material	Conductivity ($\Omega^{-1}\,m^{-1}$)
Germanium	2.2
Silicon	0.0016
Glass	10^{-10} - 10^{-14}
Quartz	0.5×10^{-17}

Loss TANGENT : $\tan\delta = \dfrac{\sigma}{\omega\,\varepsilon}$

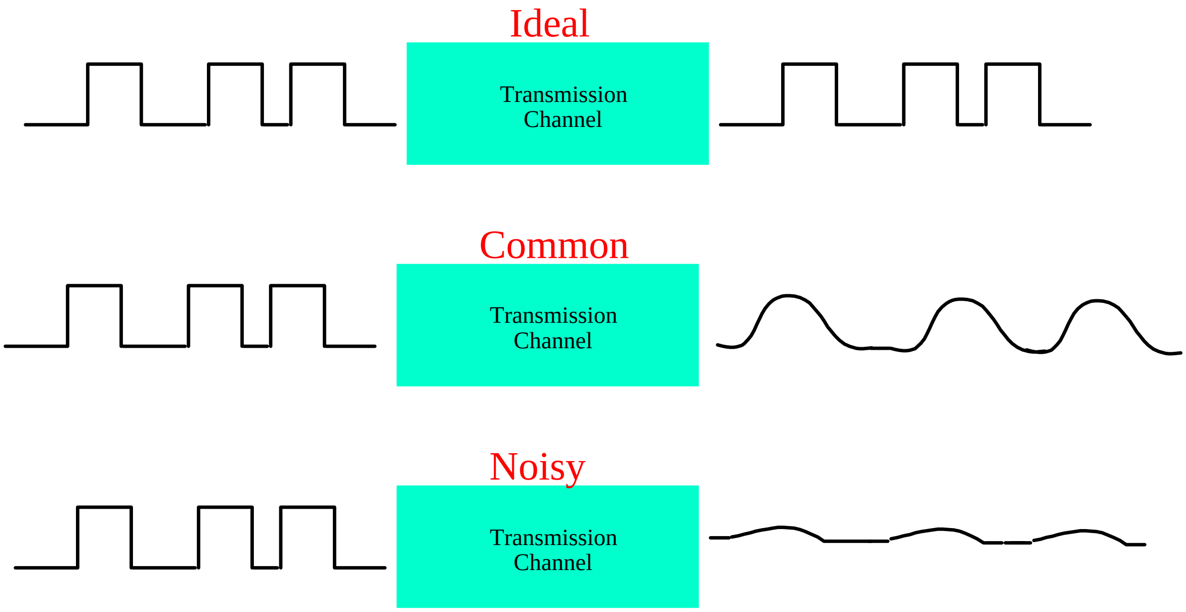
Propagation Speeds



$$v = \frac{c}{\sqrt{\varepsilon_r}}$$

Dielectric	ε_r	v (cm/ns)
Polymide	2.5-3.5	16-19
Silicon Dioxide	3.9	15
Epoxy Glass (PC board)	5	13
Alumina (ceramic)	9.5	10

Signal Integrity



Ideal

Transmission Channel

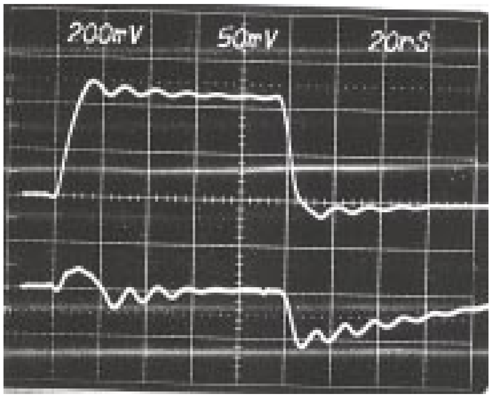
Common

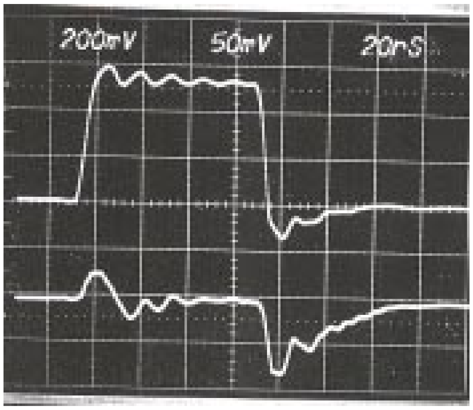
Transmission Channel

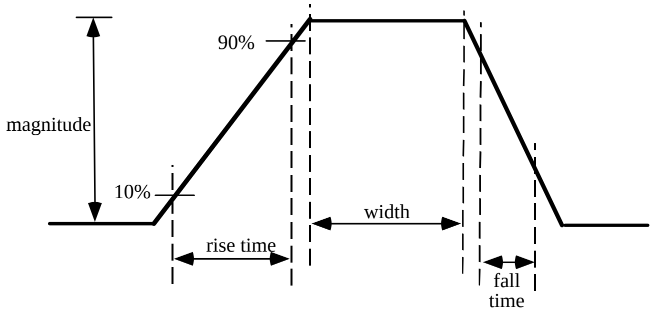
Noisy

Transmission Channel

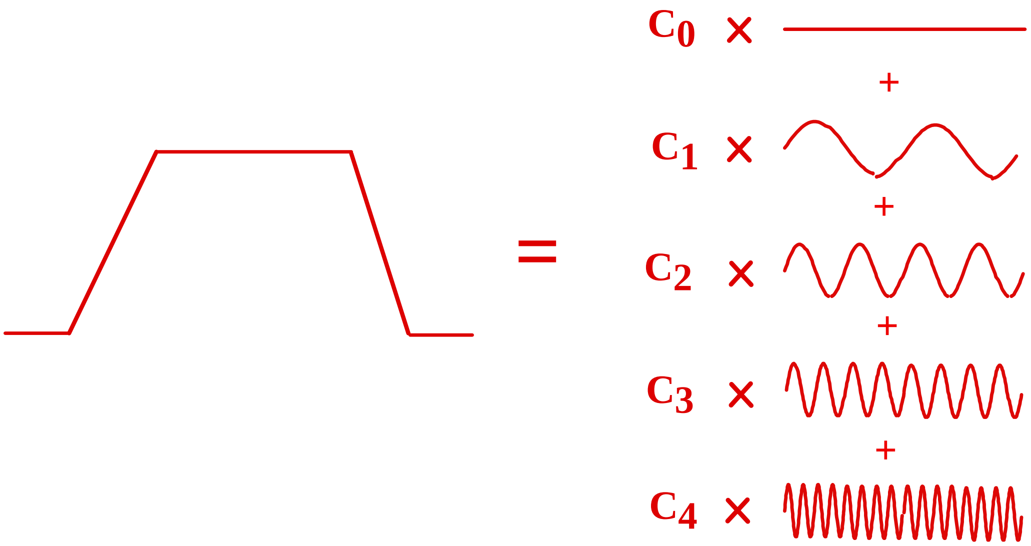
Signal Degradation



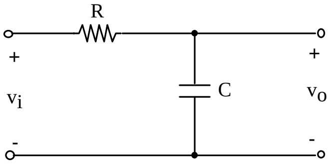




Frequency Components of Digital Signal



RC Network

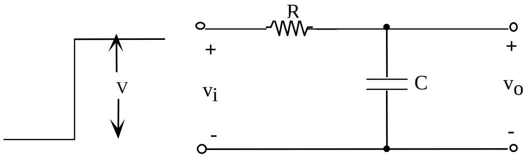


A is in the steady state gain of the network; $\mathbf{A = \frac{v_o(f)}{v_i(f)}}$

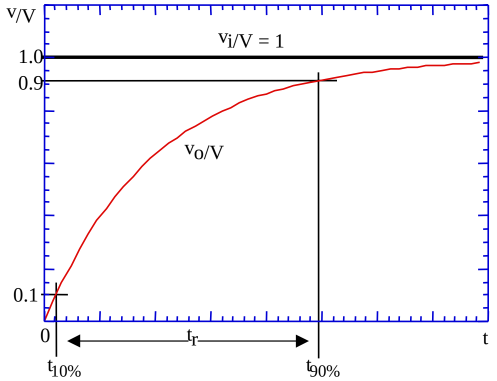
$$|A| = \frac{1}{\sqrt{1 + (f/f_2)^2}} \qquad f_2 = \frac{1}{2\pi RC}$$

The gain falls to 0.707 of its low-frequency value at the frequency f_2. f_2 is the *upper 3-dB frequency* or the 3-dB bandwidth of the RC network.

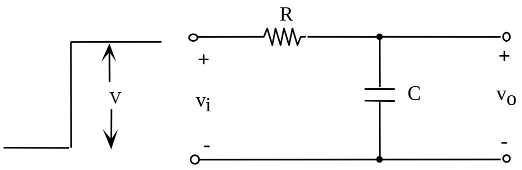
RC Network



$$v_o = V(1 - e^{-t/RC})$$



RC Network

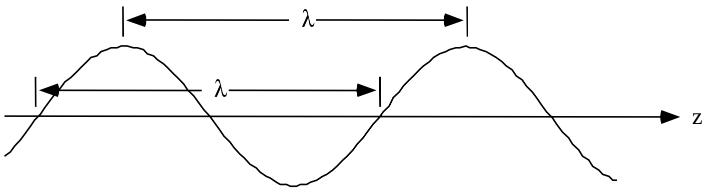


Rise time : $t_r = t_{90\%} - t_{10\%}$

$$t_r = 2.2RC = \frac{2.2}{2\pi f_2} = \frac{0.35}{f_2}$$

<u>Rule of thumb</u> : A 1-ns pulse requires a circuit with a 3-dB bandwidth of the order of 2 GHz.

WAVE PROPAGATION



Wavelength : λ

$$\lambda = \frac{\text{propagation velocity}}{\text{frequency}}$$

Why Transmission Lines ?

In Free Space

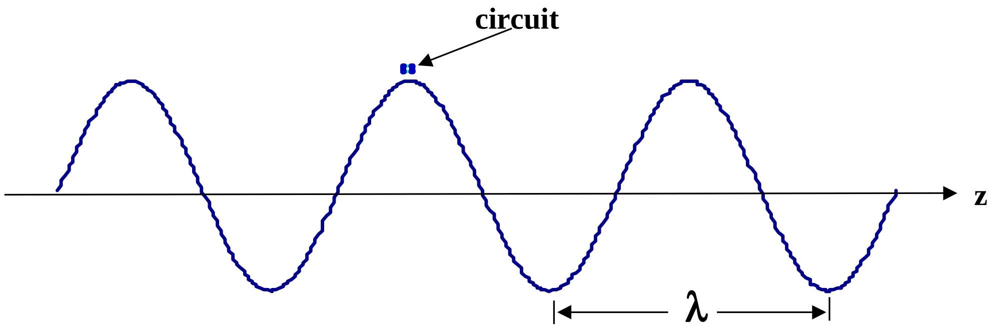
At 10 KHz : $\lambda = 30$ km

At 10 GHz : $\lambda = 3$ cm

Transmission line behavior is prevalent when the structural dimensions of the circuits are comparable to the wavelength.

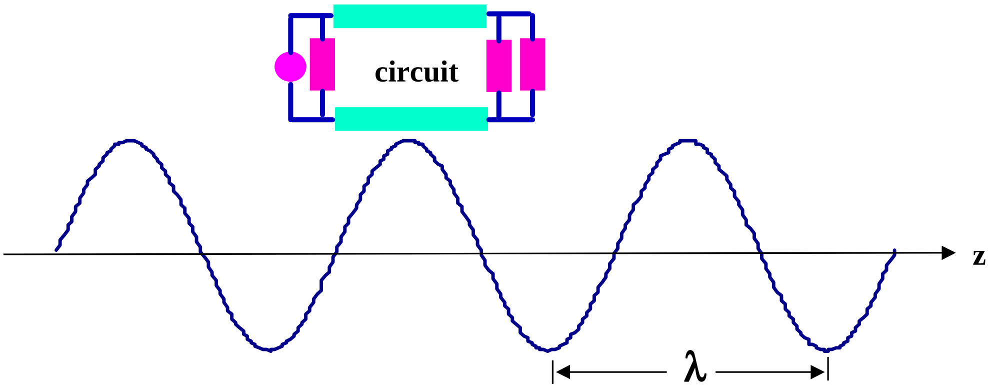
Transmission Line Model

Let d be the largest dimension of a circuit



If d << λ, a lumped model for the circuit can be used

Transmission Line Model



If d ≈ λ, or d > λ then use transmission line model

Frequency Dependence of Lumped Circuit Models

At higher frequencies, a lumped circuit model is no longer accurate for interconnects and one must use a distributed model. Transition frequency depends on the dimensions and relative magnitude of the interconnect parameters.

$$f \approx \frac{0.3 \times 10^9}{10d\sqrt{\varepsilon_r}} \qquad t_r \approx \frac{0.35}{f}$$

Lumped Circuit or Transmission Line?

A) Determine frequency or bandwidth of the signal

-**Microwave**: f = operating frequency

-**Digital**: $f = \dfrac{0.35}{\text{rise time}}$

B) Determine propagation velocity in medium, v,

next calculate wavelength $\lambda = \dfrac{v}{f}$

Lumped Circuit or Transmission Line?

C) Compare wavelength with dimensions (feature size) d.

Case 1: If $\lambda >> d$ use lumped circuit equivalent

Total inductance = L x length

Total capacitance = C x length

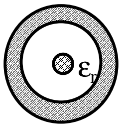
Case 2: If $\lambda \approx 10d$ or $\lambda < 10d$, use transmission-line model

Frequency Dependence of Lumped Circuit Models

	Dimension	Frequency	Rise time
Printed circuit line (epoxy, glass)	10 in	>55 MHz	<7 ns
Package lead frame (ceramic)	1 in	>400 MHz	<0.9 ns
VLSI interconnection* (silicon)	100 μm	>8 GHz	<50 ps

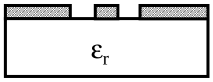
* Using RC criterion for distributed effect

Types of Transmission Lines

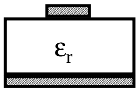


Coaxial line

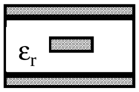
Waveguide



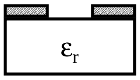
Coplanar line



Microstrip

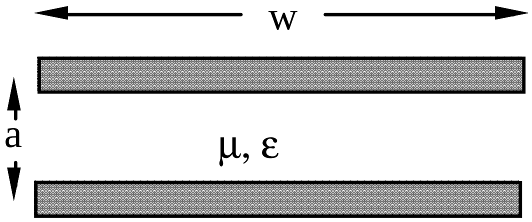


Stripline



Slot line

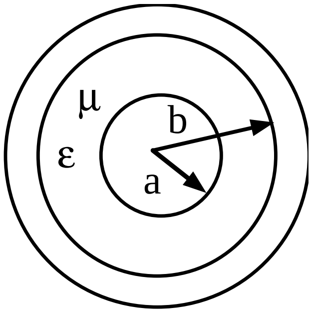
Parallel-plate Transmission Line



$$L = \frac{\mu a}{w}$$

$$C = \frac{\varepsilon w}{a}$$

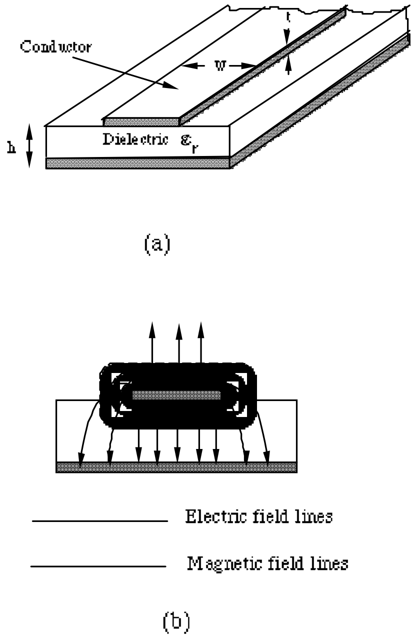
Coaxial Transmission Line



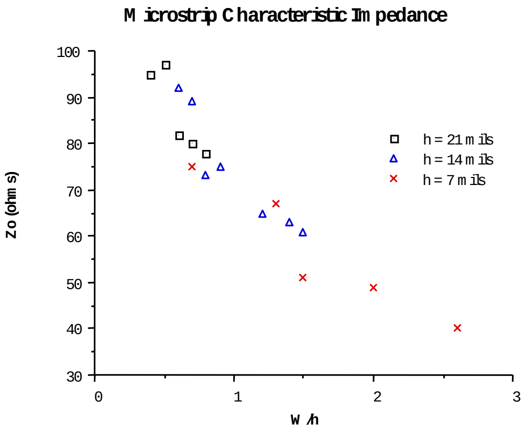
$$L = \mu \ln \frac{b}{a}$$

$$C = \frac{2\pi\varepsilon}{\ln(b/a)}$$

Microstrip

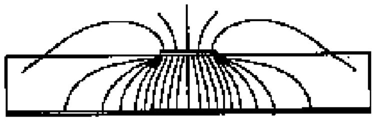


Microstrip

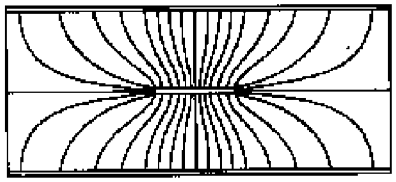


dielectric constant : 4.3.

Electric Field Configuration



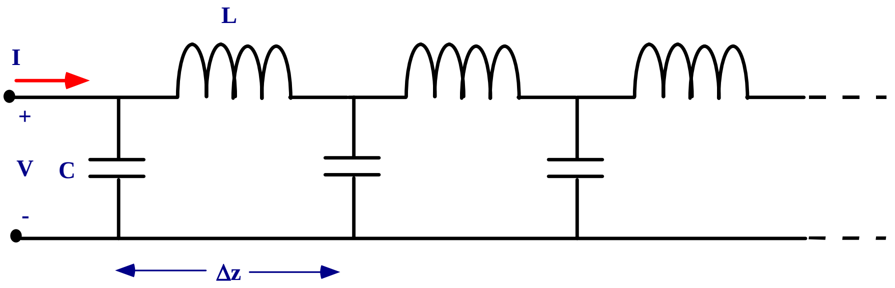
Microstrip

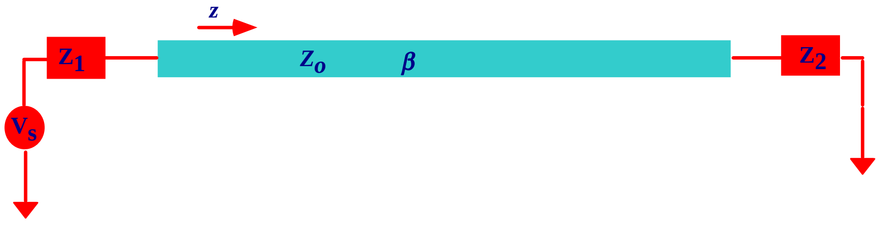


Stripline

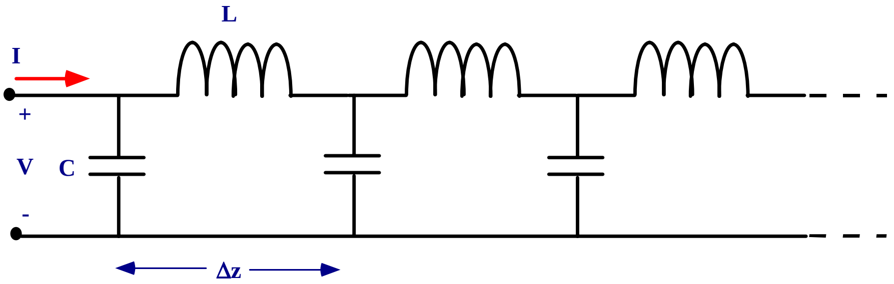
<u>Consequence</u>: Wave propagation in stripline is closer to the TEM mode of propagation and the propagation of velocity is approximately $c/\sqrt{\varepsilon_r}$.

TEM PROPAGATION





Telegrapher’s Equations



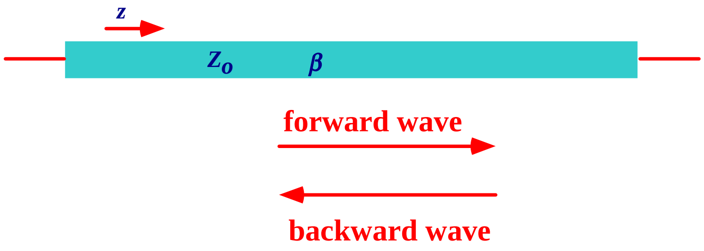
$$-\frac{\partial V}{\partial z} = L\frac{\partial I}{\partial t}$$

$$-\frac{\partial I}{\partial z} = C\frac{\partial V}{\partial t}$$

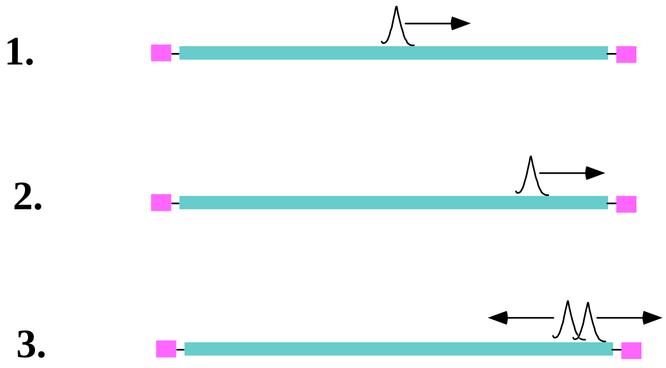
***L*: Inductance per unit length.**

***C*: Capacitance per unit length.**

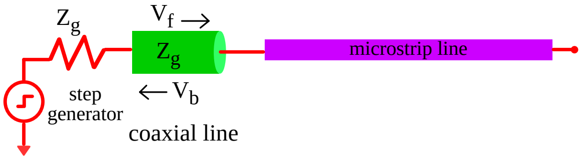
Transmission Line Solutions

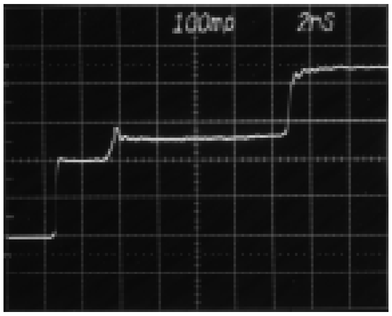


Reflection in Transmission Lines

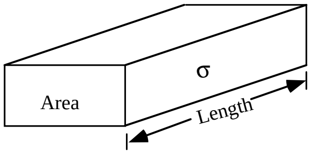


Time Domain Reflectometry





Metallic Conductors



Resistance : R

$$R = \frac{\text{Length}}{\sigma \ \text{Area}}$$

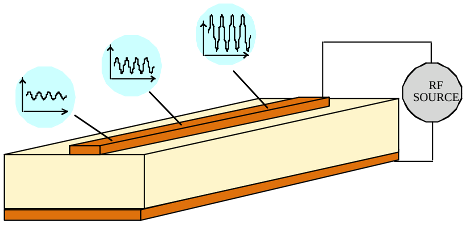
Package level:
W=3 mils
R=0.0045 Ω/mm

Submicron level:
W=0.25 microns
R=422 Ω/mm

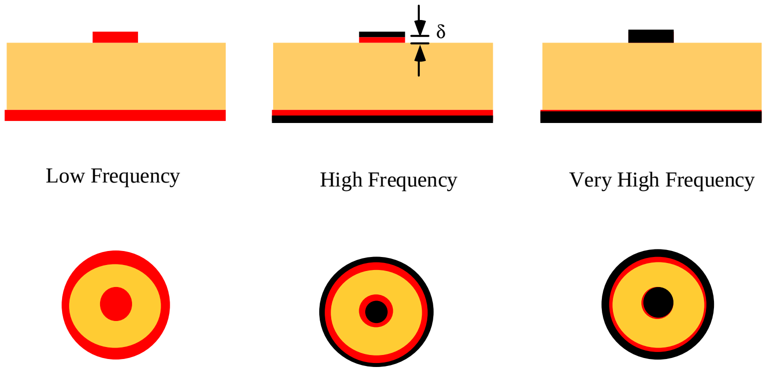
Metallic Conductors

Metal	$\sigma\ (\Omega^{-1}\,\mathrm{m}^{-1} \times 10^{-7})$
Silver	6.1
Copper	5.8
Gold	3.5
Aluminum	1.8
Tungsten	1.8
Brass	1.5
Solder	0.7

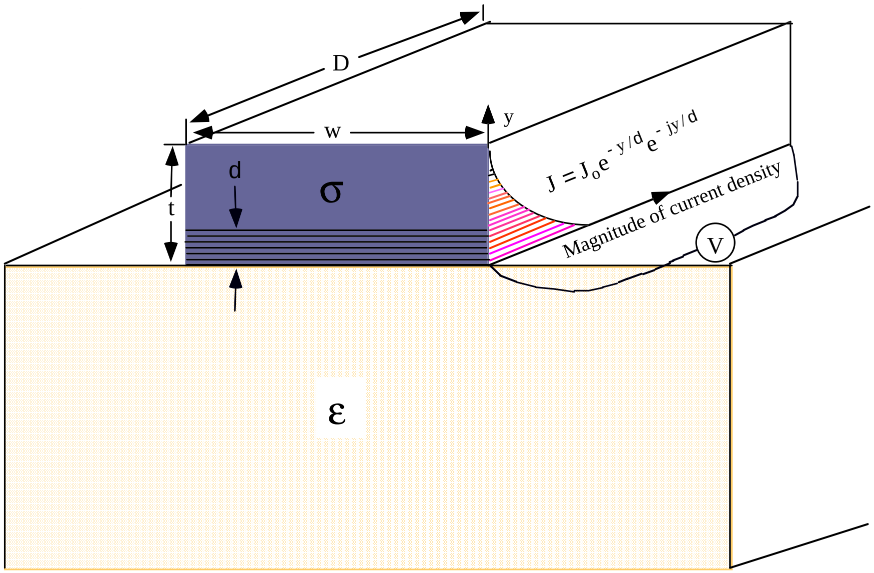
Loss in Transmission Lines



Skin Effect in Transmission Lines

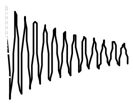


Skin Effect in Microstrip



Skin Effect

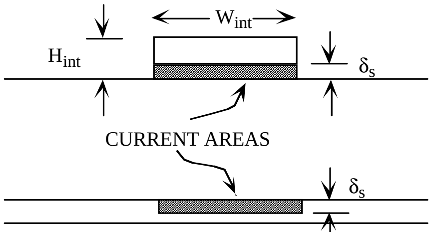
The electric field in a material medium propagates as



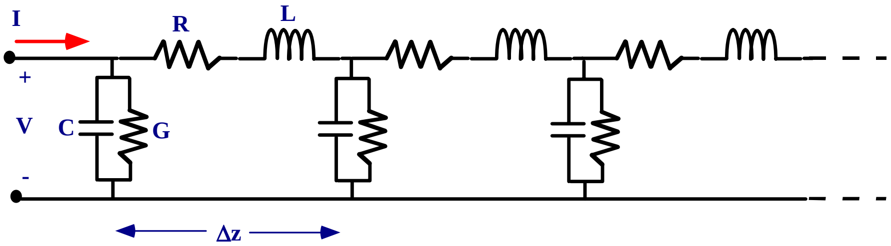
$$E_o e^{-\gamma z} = E_o e^{-\alpha z} e^{-j\beta z}$$

where $\gamma = \alpha + j\beta$. We also have

$$\boldsymbol{\gamma = \omega \sqrt{\mu\varepsilon\left(1 + j\frac{\sigma}{\omega\varepsilon}\right)}\,.}$$



Lossy Transmission Line

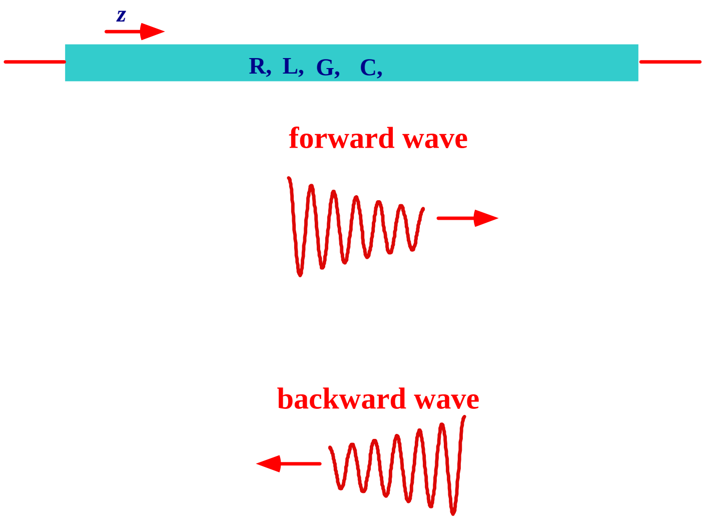


Telegraphers Equation

$$-\frac{\partial V}{\partial z} = (R + j\omega L)I = ZI$$

$$-\frac{\partial I}{\partial z} = (G + j\omega C)V = YV$$

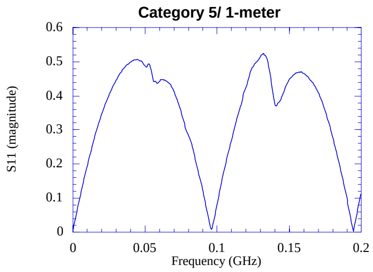
Lossy Transmission Line

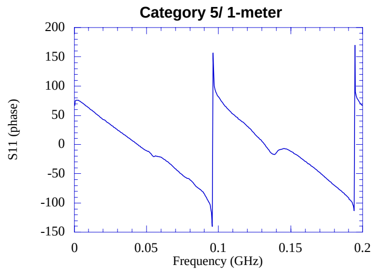


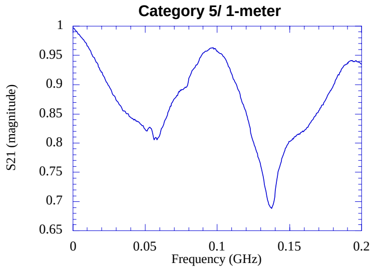
Network Analyzer

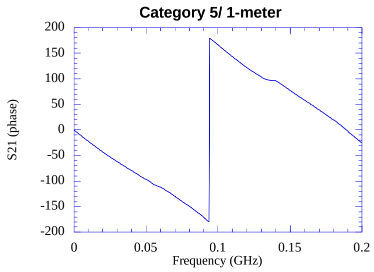
S Parameters of Transmission Lines

Short line

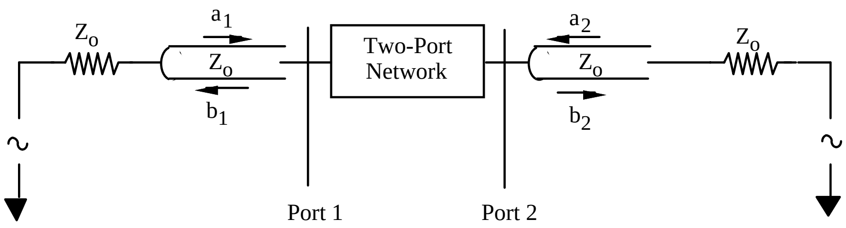








Two-Port Characterization



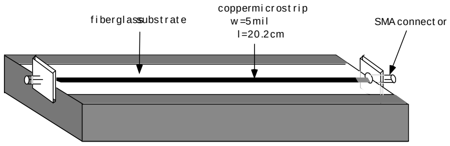
$$b_1 = S_{11}\, a_1 + S_{12}\, a_2$$
$$b_2 = S_{21}\, a_1 + S_{22}\, a_2$$

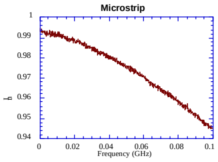
$$S_{11} = \frac{b_1}{a_1}\Big|_{a_2=0} \qquad S_{21} = \frac{b_2}{a_1}\Big|_{a_2=0}$$

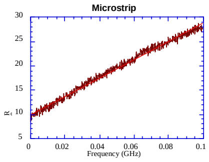
$$S_{12} = \frac{b_1}{a_2}\Big|_{a_1=0} \qquad S_{22} = \frac{b_2}{a_2}\Big|_{a_1=0}$$

Microstrip Characterization

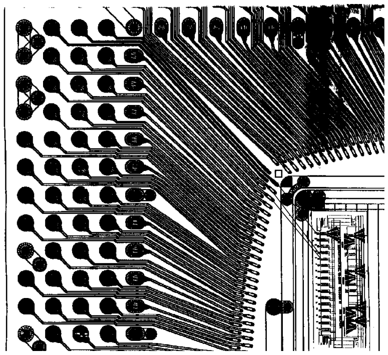
- Network analyzer measurement of S parameters
- Use de-embedding scheme
- Use extraction algorithm

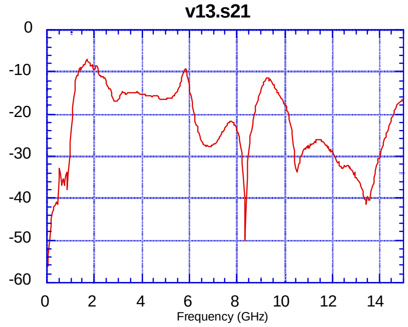


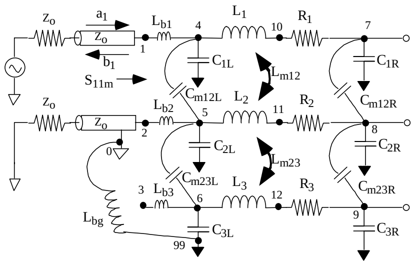




Package Level Characterization







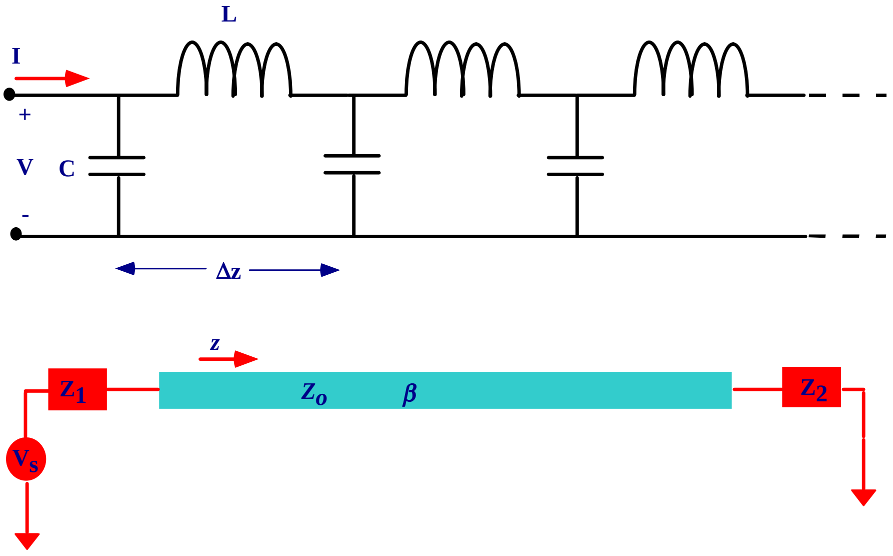
Crosstalk Noise and Coupled Transmission Lines

José Schutt-Ainé
SemChip

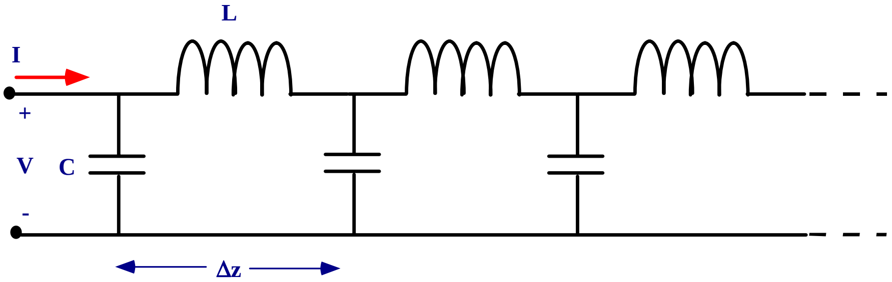
DAC Tutorial

22, June 2001

TEM PROPAGATION



Telegrapher's Equations



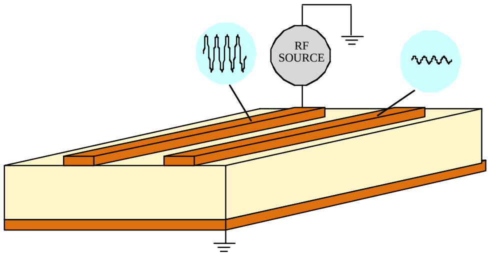
$$-\frac{\partial V}{\partial z} = L\frac{\partial I}{\partial t}$$

$$-\frac{\partial I}{\partial z} = C\frac{\partial V}{\partial t}$$

***L*: Inductance per unit length.**

***C*: Capacitance per unit length.**

Crosstalk and Coupled Line Analysis



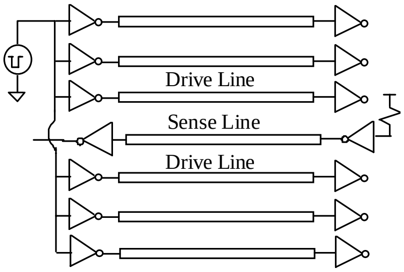
Crosstalk Noise

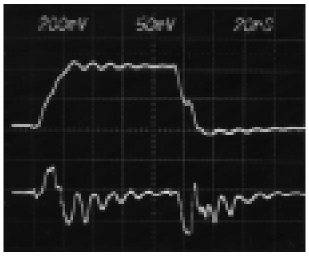
Signal Integrity

Crosstalk
Reflection
Delta I Noise

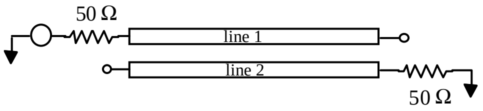
Dispersion
Distortion
Ground Bounce

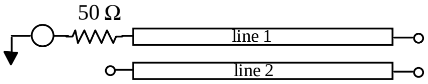
Attenuation
Loss
Radiation

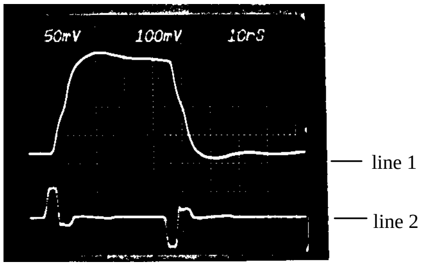


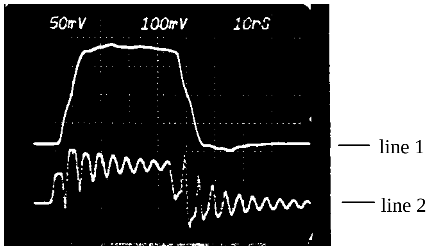


Crosstalk noise depends on termination

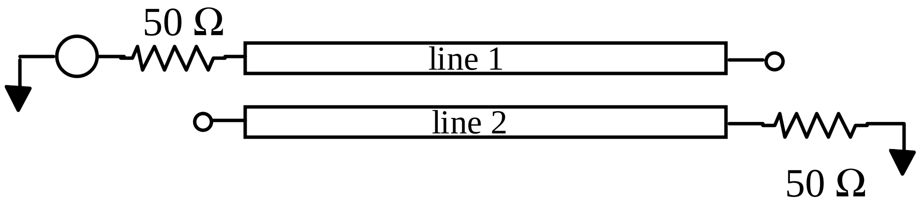




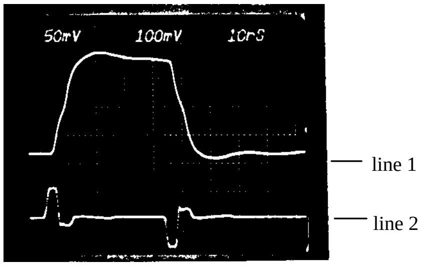




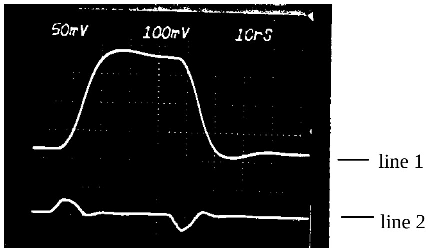
Crosstalk depends on signal rise time



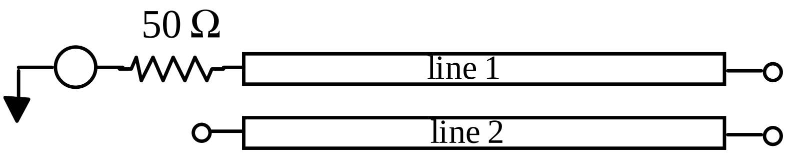
t_r = 1 ns



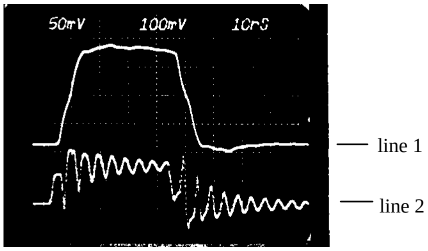
t_r = 7 ns



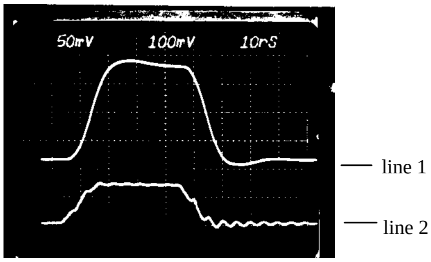
Crosstalk depends on signal rise time



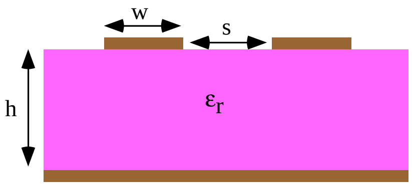
t_r = 1 ns

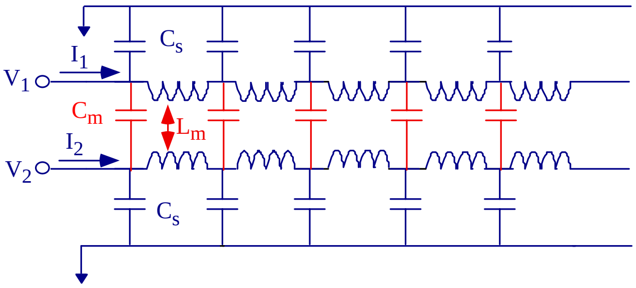


t_r = 7 ns



Coupled Transmission Lines





Telegraphers Equations for Coupled Transmission Lines

Maxwellian Form

$$-\frac{\partial V_1}{\partial z} = L_{11}\frac{\partial I_1}{\partial t} + L_{12}\frac{\partial I_2}{\partial t}$$

$$-\frac{\partial V_2}{\partial z} = L_{21}\frac{\partial I_1}{\partial t} + L_{22}\frac{\partial I_2}{\partial t}$$

$$-\frac{\partial I_1}{\partial z} = C_{11}\frac{\partial V_1}{\partial t} + C_{12}\frac{\partial V_2}{\partial t}$$

$$-\frac{\partial I_2}{\partial z} = C_{21}\frac{\partial V_1}{\partial t} + C_{22}\frac{\partial V_2}{\partial t}$$

Telegraphers Equations for Coupled Transmission Lines

Physical form

$$-\frac{\partial V_1}{\partial z} = L_s\frac{\partial I_1}{\partial t} + L_m\frac{\partial I_2}{\partial t}$$

$$-\frac{\partial V_2}{\partial z} = L_m\frac{\partial I_1}{\partial t} + L_s\frac{\partial I_2}{\partial t}$$

$$-\frac{\partial I_1}{\partial z} = C_s\frac{\partial V_1}{\partial t} + C_m\frac{\partial V_1}{\partial t} - C_m\frac{\partial V_2}{\partial t}$$

$$-\frac{\partial I_2}{\partial z} = -C_m\frac{\partial V_1}{\partial t} + C_m\frac{\partial V_2}{\partial t} + C_s\frac{\partial V_2}{\partial t}$$

Relations Between Physical and Maxwellian Parameters

$$L_{11} = L_{22} = L_s$$

$$L_{12} = L_{21} = L_m$$

$$C_{11} = C_{22} = C_s + C_m$$

$$C_{12} = C_{21} = - C_m$$

Even Mode

$$-\frac{\partial V_e}{\partial z} = \left(L_{11} + L_{12}\right)\frac{\partial I_e}{\partial t}$$

$$-\frac{\partial I_e}{\partial z} = \left(C_{11} + C_{12}\right)\frac{\partial I_e}{\partial t}$$

Add voltage and current equations

V_e : Even mode voltage $V_e = \frac{1}{2}\left(V_1 + V_2\right)$

I_e : Even mode current $I_e = \frac{1}{2}\left(I_1 + I_2\right)$

$$Z_e = \sqrt{\frac{L_{11} + L_{12}}{C_{11} + C_{12}}} = \sqrt{\frac{L_s + L_m}{C_s}}$$

Impedance

$$v_e = \frac{1}{\sqrt{(L_{11} + L_{12})(C_{11} + C_{12})}} = \frac{1}{\sqrt{(L_s + L_m)C_s}}$$

velocity

Odd Mode

$$-\frac{\partial V_d}{\partial z} = (L_{11} - L_{12})\frac{\partial I_d}{\partial t}$$

$$-\frac{\partial I_d}{\partial z} = (C_{11} - C_{12})\frac{\partial I_d}{\partial t}$$

Subtract voltage and current equations

V_d : Odd mode voltage $\quad V_d = \frac{1}{2}(V_1 - V_2)$

I_d : Odd mode current $\quad I_d = \frac{1}{2}(I_1 - I_2)$

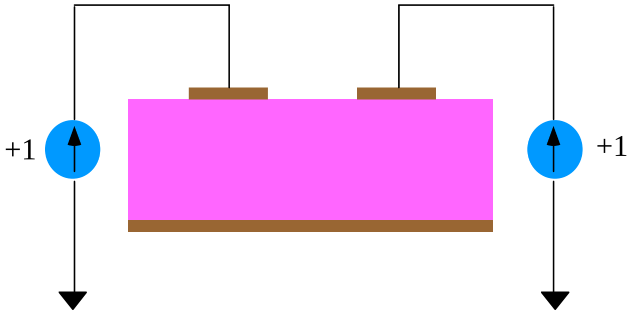
$$Z_d = \sqrt{\frac{L_{11} - L_{12}}{C_{11} - C_{12}}} = \sqrt{\frac{L_s - L_m}{C_s + 2C_m}}$$

Impedance

$$v_d = \frac{1}{\sqrt{(L_{11} - L_{12})(C_{11} - C_{12})}} = \frac{1}{\sqrt{(L_s - L_m)(C_s + 2C_m)}}$$

velocity

Even Mode



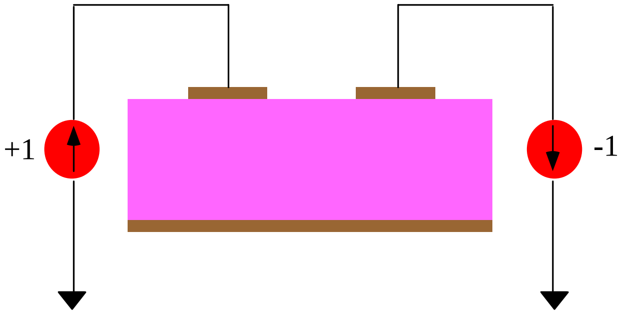
$$Z_e = \sqrt{\frac{L_s + L_m}{C_s}}$$

Impedance

$$v_e = \frac{1}{\sqrt{(L_s + L_m)C_s}}$$

velocity

Odd Mode



$$Z_d = \sqrt{\frac{L_s - L_m}{C_s + 2C_m}}$$

Impedance

$$v_d = \frac{1}{\sqrt{(L_s - L_m)(C_s + 2C_m)}}$$

velocity

PHYSICAL SIGNIFICANCE OF EVEN- AND ODD-MODE IMPEDANCES

* Z_e and Z_d are the wave resistance seen by the even and odd mode travelling signals respectively.

* The impedance of each line is no longer described by a single characteristic impedance; instead, we have

$$V_1 = Z_{11} I_1 + Z_{12} I_2$$
$$V_2 = Z_{21} I_1 + Z_{22} I_2$$

EVEN AND ODD-MODE IMPEDANCES

Z_{11}, Z_{22} : Self Impedances

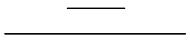
Z_{12}, Z_{21} : Mutual Impedances

For symmetrical lines,

$Z_{11} = Z_{22}$ and $Z_{12} = Z_{21}$

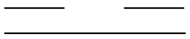
EXAMPLE

(Microstrip)



$\varepsilon_r = 4.3$
$Z_s = 56.4\ \Omega$

Single Line
Dielectric height = 6 mils
Width = 8 mils

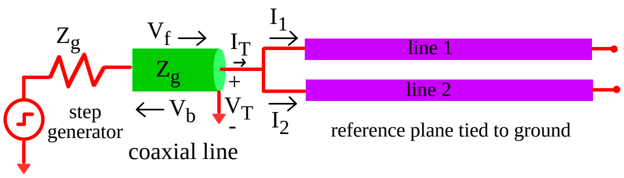


$\varepsilon_r = 4.3$

Coupled Lines
Height = 6 mils
Width = 8 mils
Spacing = 12 mils

$Z_e = 68.1\ \Omega$ $Z_d = 40.8\ \Omega$
$Z_{11} = 54.4\ \Omega$ $Z_{12} = 13.6\ \Omega$

Even Mode

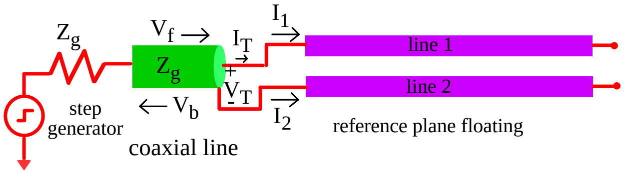


$$I_{tdr} = \left[\frac{a_e(t,0)}{Z_e} + \frac{a_d(t,0)}{Z_d}\right] + \left[\frac{a_e(t,0)}{Z_e} - \frac{a_d(t,0)}{Z_d}\right]$$

$$V_{tdr} = a_e(t,0) - a_d(t,0) \qquad a_d(t,0) = 0$$

$$\frac{V_{tdr}}{I_{tdr}} = \frac{Z_e}{2} \qquad Z_e = 2\left(\frac{1+\rho_e}{1-\rho_e}\right) Z_g \qquad v_e = \frac{2l}{\tau_e}$$

Odd Mode



$$V_{tdr} = a_e(t,0) + a_d(t,0) - [a_e(t,0) - a_d(t,0)] = V_f + V_b$$

$$I_{tdr} = \left[\frac{a_e(t,0)}{Z_e} + \frac{a_d(t,0)}{Z_d}\right] \qquad I_{tdr} = -\left[\frac{a_e(t,0)}{Z_e} - \frac{a_d(t,0)}{Z_d}\right]$$

$$a_e(t,0) = 0, \qquad \frac{V_{tdr}}{I_{tdr}} = 2Z_d$$

$$Z_d = \frac{1}{2}\left(\frac{1+\rho_d}{1-\rho_d}\right) Z_g, \qquad v_d = \frac{2l}{\tau_d}$$

EXTRACT INDUCTANCE AND CAPACITANCE COEFFICIENTS

$$L_s = \frac{1}{2}\left[\frac{Z_e}{v_e} + \frac{Z_d}{v_d}\right]$$

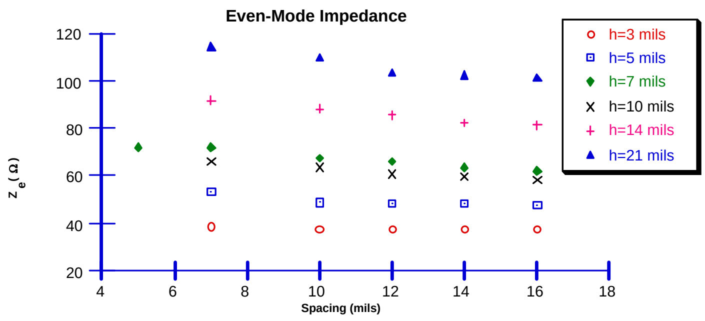
$$C_s = \frac{1}{Z_e v_e}$$

$$L_m = \frac{1}{2}\left[\frac{Z_e}{v_e} - \frac{Z_d}{v_d}\right]$$

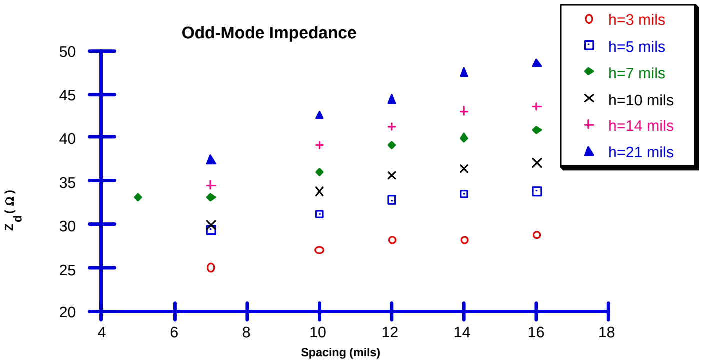
$$C_m = \frac{1}{2}\left[\frac{1}{Z_e v_e} - \frac{1}{Z_d v_d}\right]$$

$$Z_d < Z_s < Z_e$$

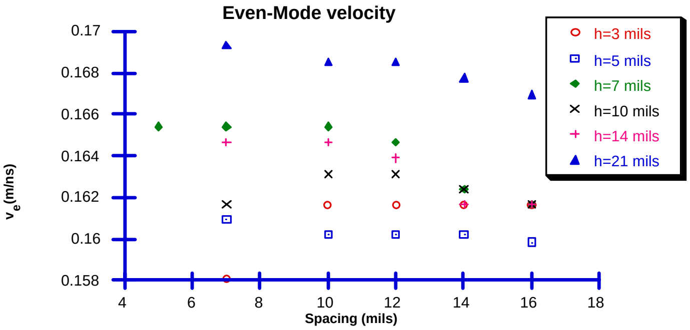
Measured even-mode impedance



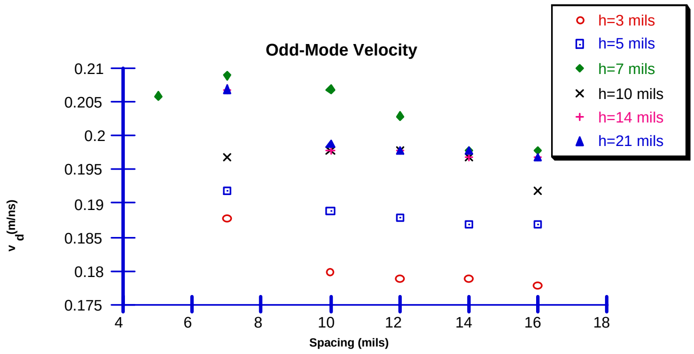
Measured odd-mode impedance



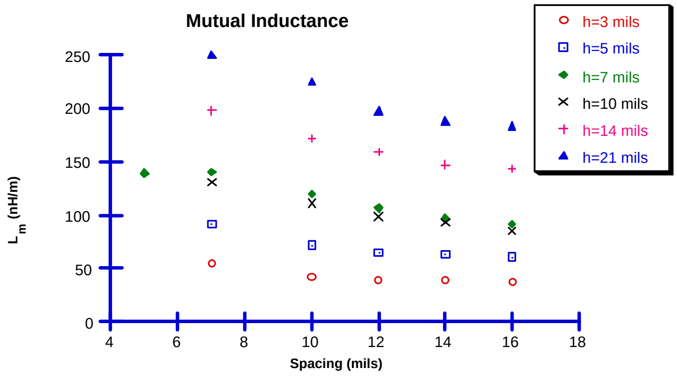
Measured even-mode velocity



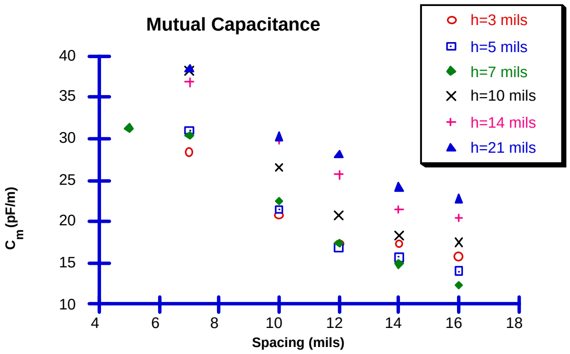
Measured odd-mode velocity



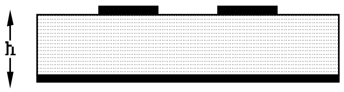
Measured mutual inductance

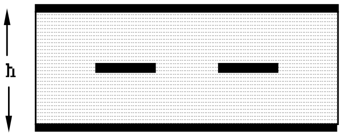


Measured mutual capacitance



Modal Velocities in Stripline and Microstrip

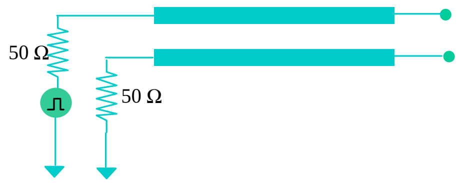




<u>Microstrip</u> : Inhomogeneous structure, odd and even-mode velocities must have different values.

<u>Stripline</u> : Homogeneous configuration, odd and even-mode velocities have approximately the same values.

Microstrip vs Stripline



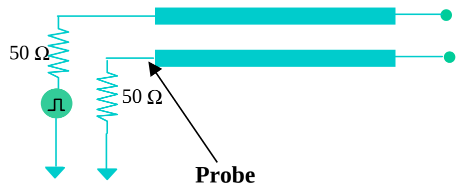
Microstrip (h =8 mils)

$w = 8$ mils
$\varepsilon_r = 4.32$
$L_s = 377$ nH/m
$C_s = 82$ pF/m
$L_m = 131$ nH/m
$C_m = 23$ pF/m
$v_e = 0.155$ m/ns
$v_d = 0.178$ m/ns

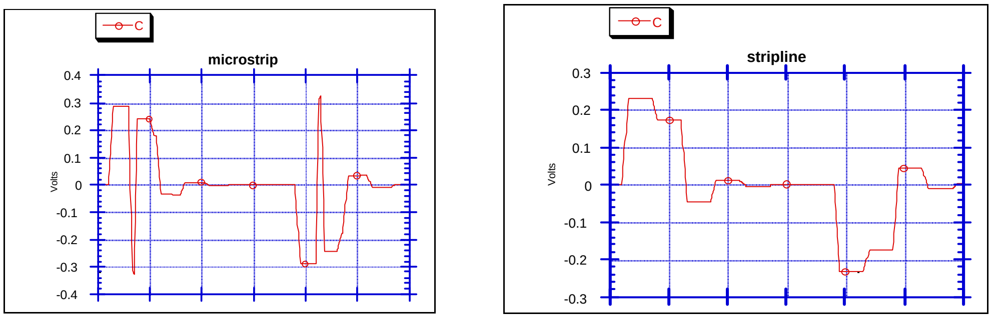
Stripline (h =16 mils)

$w = 8$ mils
$\varepsilon_r = 4.32$
$L_s = 466$ nH/m
$C_s = 86$ pF/m
$L_m = 109$ nH/m
$C_m = 26$ pF/m
$v_e = 0.142$ m/ns
$v_d = 0.142$ m/ns

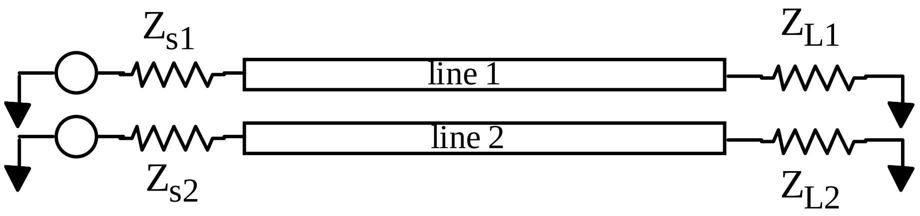
Microstrip vs Stripline



Sense line response at near end



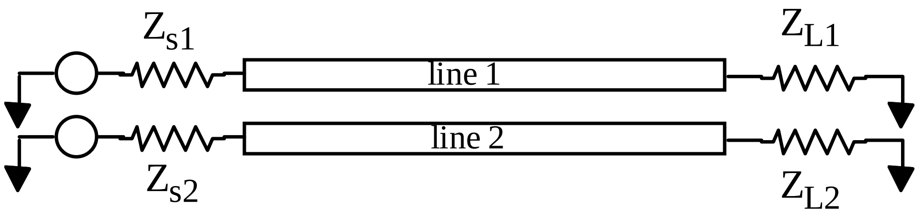
General Solution for Voltages



$$V_1(z) = \underbrace{A_e e^{-\frac{j\omega z}{v_e}} + B_e e^{+\frac{j\omega z}{v_e}}}_{even} + \underbrace{A_d e^{-\frac{j\omega z}{v_d}} + B_d e^{+\frac{j\omega z}{v_d}}}_{odd}$$

$$V_2(z) = \underbrace{A_e e^{-\frac{j\omega z}{v_e}} + B_e e^{+\frac{j\omega z}{v_e}}}_{even} - \underbrace{A_d e^{-\frac{j\omega z}{v_d}} - B_d e^{+\frac{j\omega z}{v_d}}}_{odd}$$

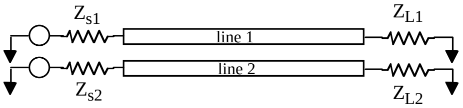
General Solution for Currents

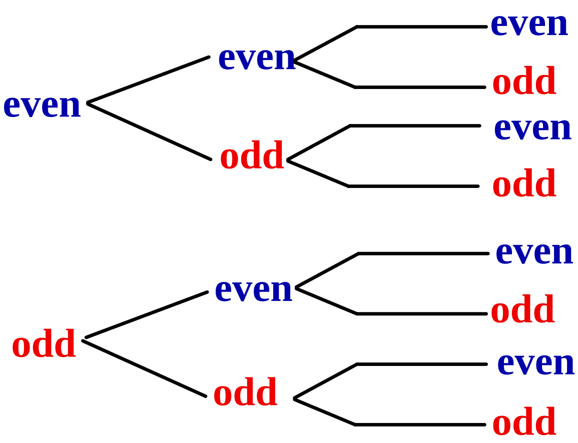


$$I_1(z) = \underbrace{\frac{1}{Z_e}\left[A_e e^{-\frac{j\omega z}{v_e}} - B_e e^{+\frac{j\omega z}{v_e}}\right]}_{even} + \underbrace{\frac{1}{Z_d}\left[A_d e^{-\frac{j\omega z}{v_d}} - B_d e^{+\frac{j\omega z}{v_d}}\right]}_{odd}$$

$$I_2(z) = \underbrace{\frac{1}{Z_e}\left[A_e e^{-\frac{j\omega z}{v_e}} - B_e e^{+\frac{j\omega z}{v_e}}\right]}_{even} - \underbrace{\frac{1}{Z_d}\left[A_d e^{-\frac{j\omega z}{v_d}} - B_d e^{+\frac{j\omega z}{v_d}}\right]}_{odd}$$

Coupling of Modes (asymmetric load)





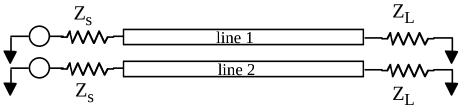
even
even
even
odd
odd
even
odd

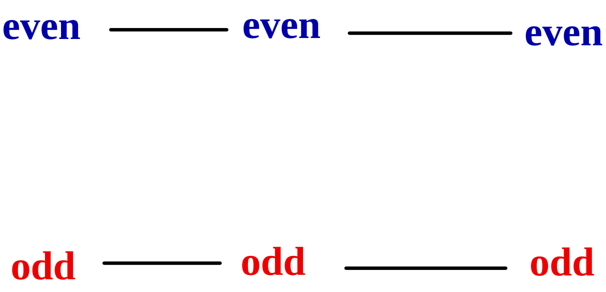
odd
even
even
odd
odd
even
odd

First reflection

Second reflection

Coupling of Modes (symmetric load)



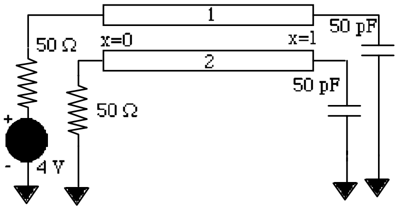


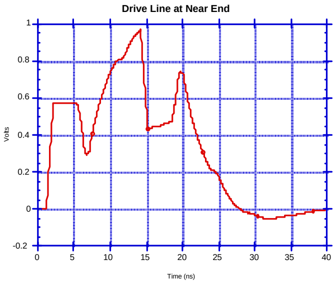
even even even

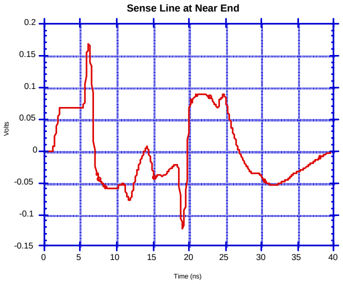
odd odd odd

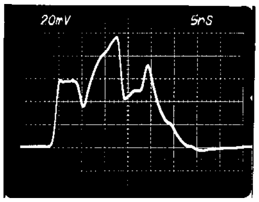
First reflection

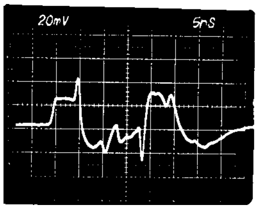
Second reflection



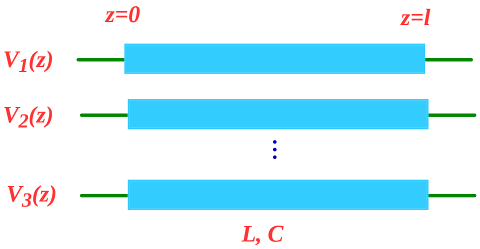








TELGRAPHER’S EQUATION FOR N COUPLED TRANSMISSION LINES



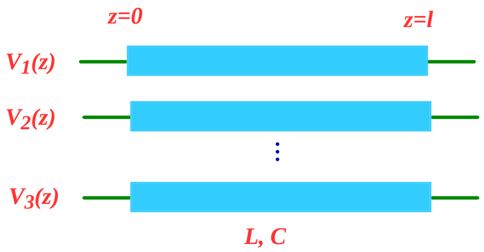
$$-\frac{\partial V}{\partial z} = L\frac{\partial I}{\partial t}$$

$$-\frac{\partial I}{\partial z} = C\frac{\partial V}{\partial t}$$

V and I are the line voltage and line current VECTORS respectively (dimension n).

N-LINE SYSTEM

$$V = \begin{bmatrix} V_1 \\ V_2 \\ \cdot \\ \cdot \\ V_n \end{bmatrix}$$

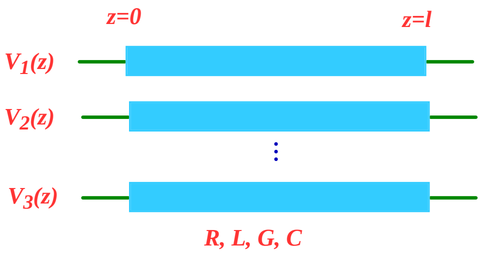


$$I = \begin{bmatrix} I_1 \\ I_2 \\ \cdot \\ \cdot \\ I_n \end{bmatrix}$$

L and *C* are the inductance and capacitance MATRICES respectively

$$L = \begin{bmatrix} L_{11} & L_{12} & \cdot & \cdot \\ L_{21} & L_{22} & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & L_{nn} \end{bmatrix} \qquad C = \begin{bmatrix} C_{11} & C_{12} & \cdot & \cdot \\ C_{21} & C_{22} & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & C_{nn} \end{bmatrix}$$

COUPLED LOSSY TRANSMISSION LINES

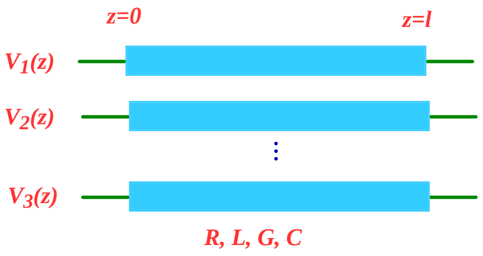


Time Domain

$$-\frac{\partial V}{\partial z} = RI + L\frac{\partial I}{\partial t}$$

$$-\frac{\partial I}{\partial z} = GV + C\frac{\partial V}{\partial t}$$

COUPLED LOSSY TRANSMISSION LINES



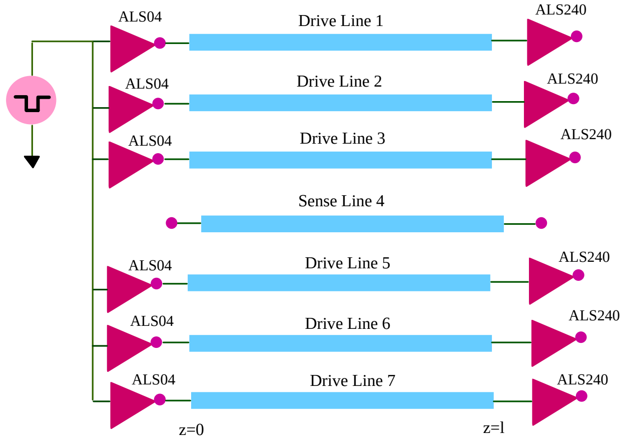
Frequency Domain

$$-\frac{\partial V}{\partial z} = ZI$$

$$-\frac{\partial I}{\partial z} = YV$$

$$Z = R + j\omega L \qquad Y = G + j\omega C$$

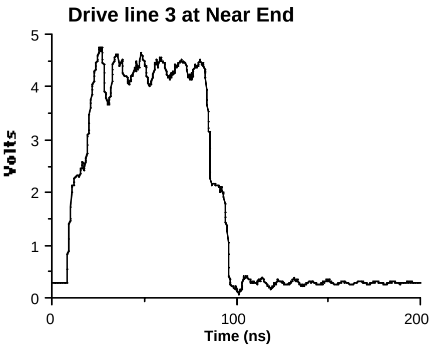
7-Line Coupled-Microstrip System

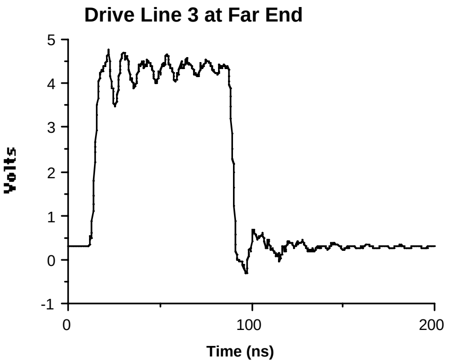


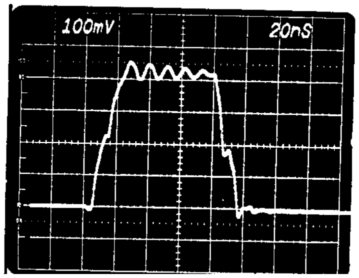
L_s = 312 nH/m; C_s = 100 pF/m;

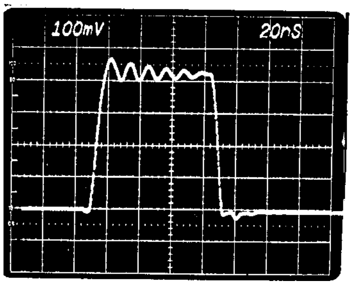
L_m = 85 nH/m; C_m = 12 pF/m.

Drive Line 3

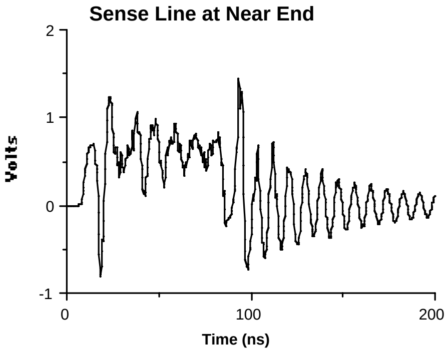

Drive line 3 at Near End

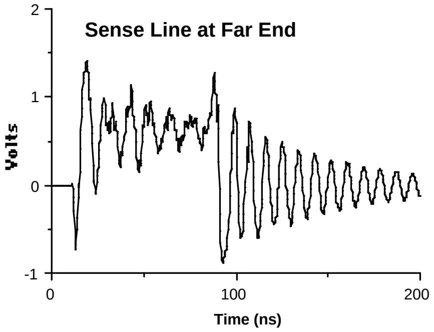

Drive Line 3 at Far End





Sense Line


Sense Line at Near End


Sense Line at Far End