Transmission Lines, Micro Strips, Striplines and Non-ideal Interconnect

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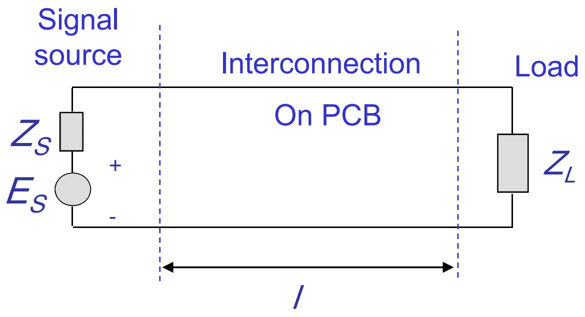
Today's Topics

- Transmission Lines in PCB
  - Basic Principle? What is Transmission Line?
  - Types of Transmission Lines in PCB
  - Transmission Lines Basics
    - Telegraphic Equations
    - Equivalent Circuit of Transmission Lines
    - Reflection Coefficients
    - Lattice Diagram and Design Example
- Non Ideal Interconnect
  - Capacitance, Inductance and Resistance
    - Resistance, AC Resistance,Capacitance and Inductance
    - Frequency Dependent Dielectric Losses (Lecture on PCB Materials)
    - Serpentine traces
    - ISI (Intersymbol Interference)
    - Effect of 90^{o} Bend in trace

When Circuit Behaves as Transmission Line?



If $l > \lambda/8$ then interconnection should be considered transmission line.

Also relevant on-chip if frequency at GHz.

Analog or RF:

Sinusoidal signal wavelength

$\lambda = v_p/f$

E.g. $f = 2\text{GHz}$, $v_p = 1.5\cdot10^8$ m/sec

$\lambda = 7.5$ cm

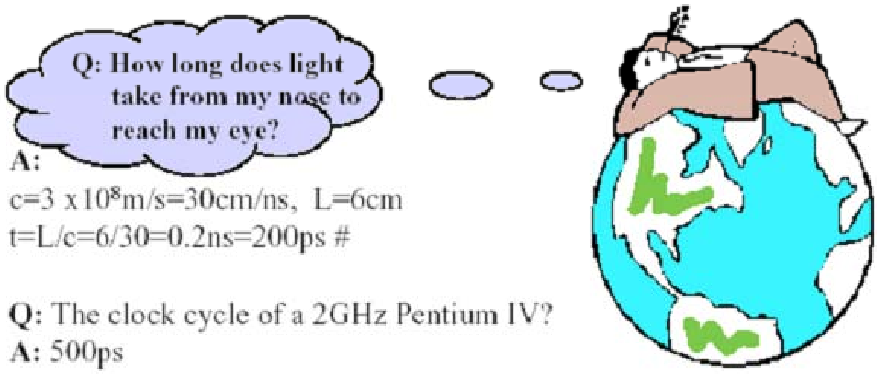
Commercial standard 802.11a WLAN: $f = 5.8\text{GHz}$,

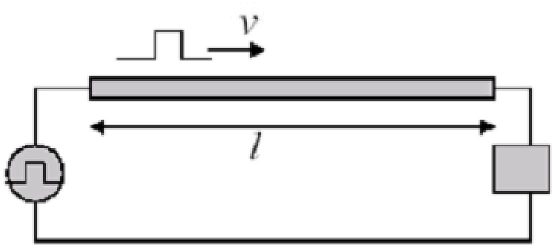
$\lambda = 2.6$ cm

For length > $\lambda/8$ or $\lambda/8$ transmission line problem arises

When Circuit Behaves as Transmission Line?

Digital





Unequal potential on the conductor!

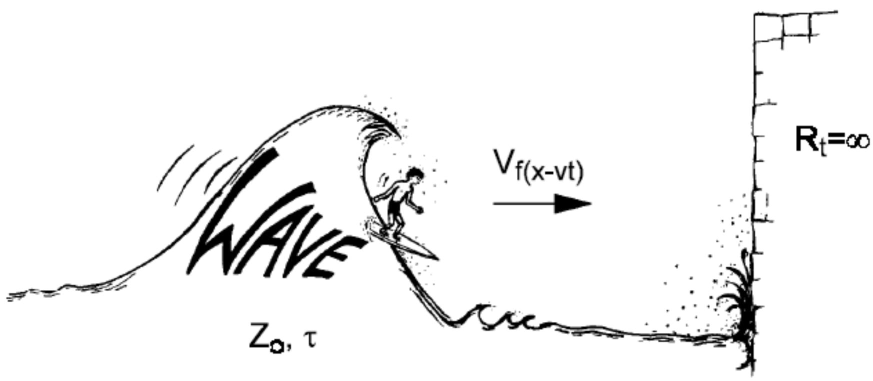
$$t_{of} > 0.5t_{rise} \quad \textit{For squrewave}$$

$$\textit{where}\; t_{of} = \frac{l}{v}, \textit{called time of flight}$$

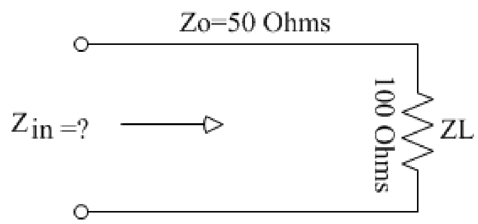
$$l_{trans-line} > \lambda/10 \quad \textit{For Sinewave}$$

What is Transmission Line?

- When the edge rate (rise and fall time) of digital signal is small compared to propagation delay, the conductor do not behave a *simple short* circuit.
- Electrical signal will travel down the conductor (Transmission line) as water travel down in square pipe.
- Important transmission line parameters are *Characteristic impedance* (Z_O) and *Propagation delay* (t_d).



Why Transmission Lines Important?



Calculate the impedance Z_{in} looking into 1 m long 50 Ω transmission line. The line is terminated with Z_L = 100 Ω resistance. The line operates at 30 MHz and the velocity factor is 0.8. Assume the line to be lossless.

$$Z = Z_0 \frac{Z_L + jZ_0 \tan\theta}{Z_0 + jZ_L \tan\theta} \qquad (1)$$

$$\lambda = \frac{V}{f} = \frac{V_f C}{f} = \frac{0.8 \times 300 \times 10^6 \text{m}}{30 \times 10^6} = 8\text{m}$$

$$\theta = \frac{1\text{m}}{8\text{m}} \times 360^\circ = 45^\circ$$

$$Z = 50\Omega \frac{100\Omega + j(50\Omega)(\tan 45^\circ)}{50\Omega + j(100\Omega)(\tan 45^\circ)}$$

$$Z = 50\Omega \frac{100\Omega + j50\Omega}{50\Omega + j100\Omega} = \frac{100\Omega + j50}{1 + j2}$$

$$Z = \frac{(100 + j50)(1 - j2)}{(1 + j2)(1 - j2)}$$

$$Z = 200\Omega - j150/5 = 40 - j30$$

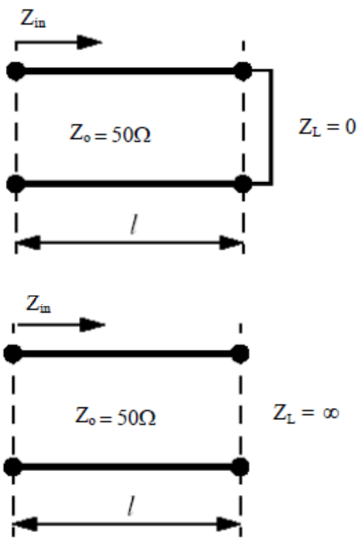
$$Z = 40 - j30\Omega$$

If the length of line changes Z_{in} Changes.

Notes: Show Tline Simulation Ulticad.

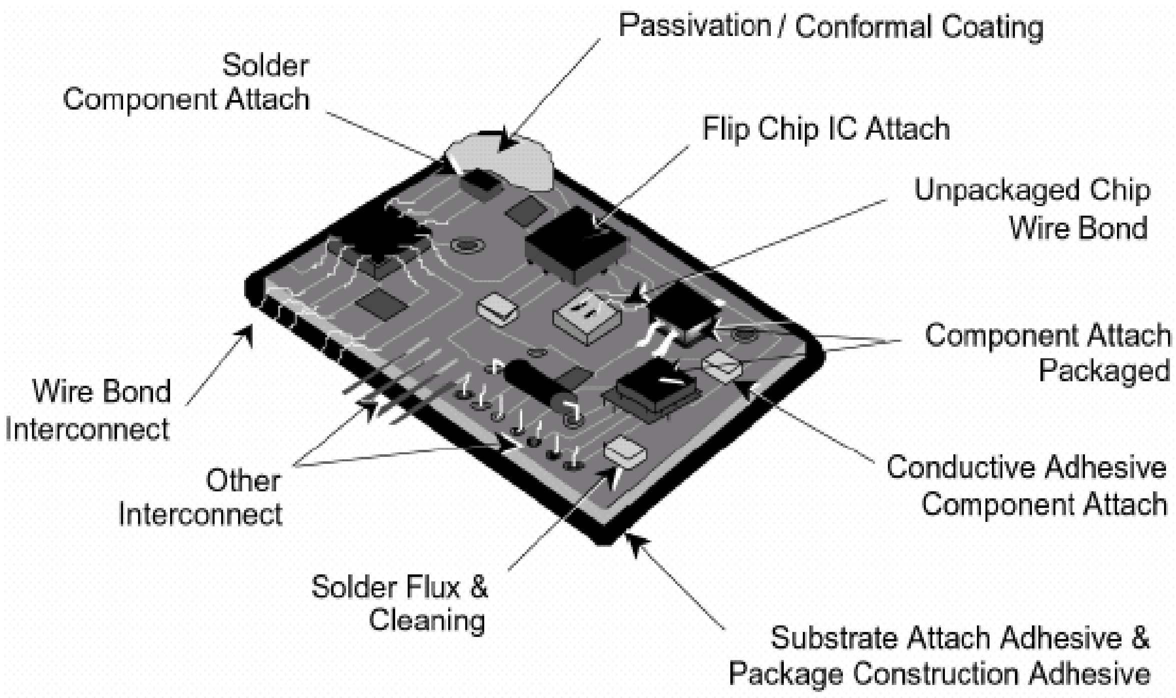
Why Transmission Lines?

$$Z = Z_0 \frac{Z_L + jZ_0 \tan\theta}{Z_0 + jZ_L \tan\theta} \qquad (1)$$

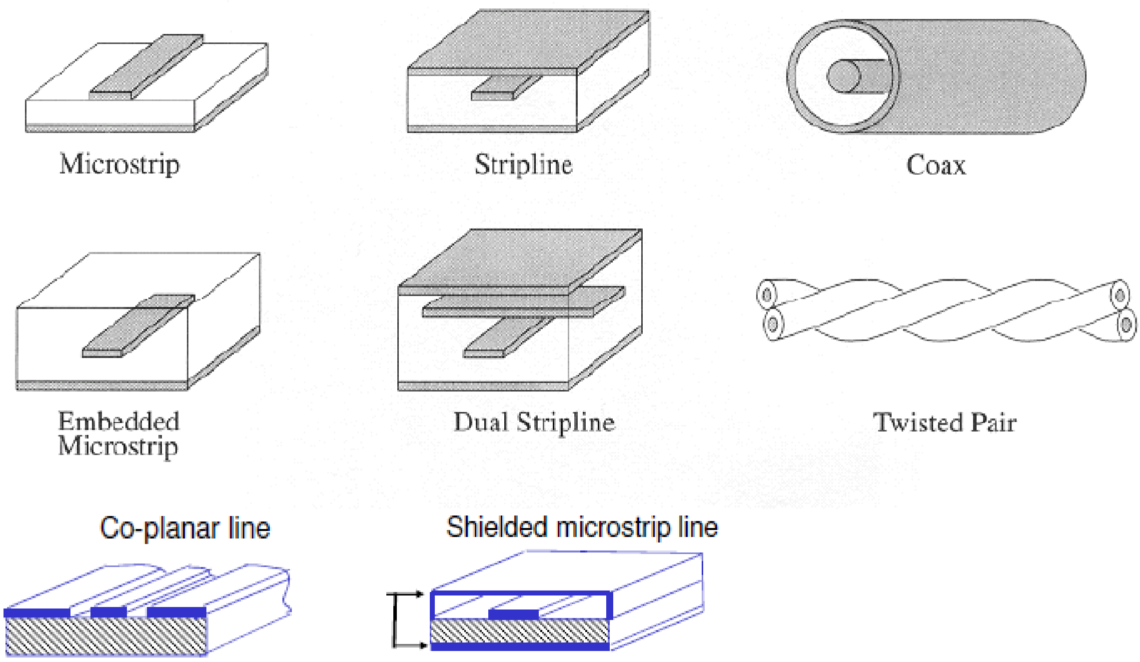


Z_L	l/λ	θ	
∞	1/6	60°	$-28.87j$
0	1/6	60°	$86.6j$
∞	1/4	90°	0
0	1/4	90°	∞
∞	1/2	180°	∞
0	1/2	180°	0
∞	1/3	120°	$28.87j$
0	1/3	120°	$-86.60j$

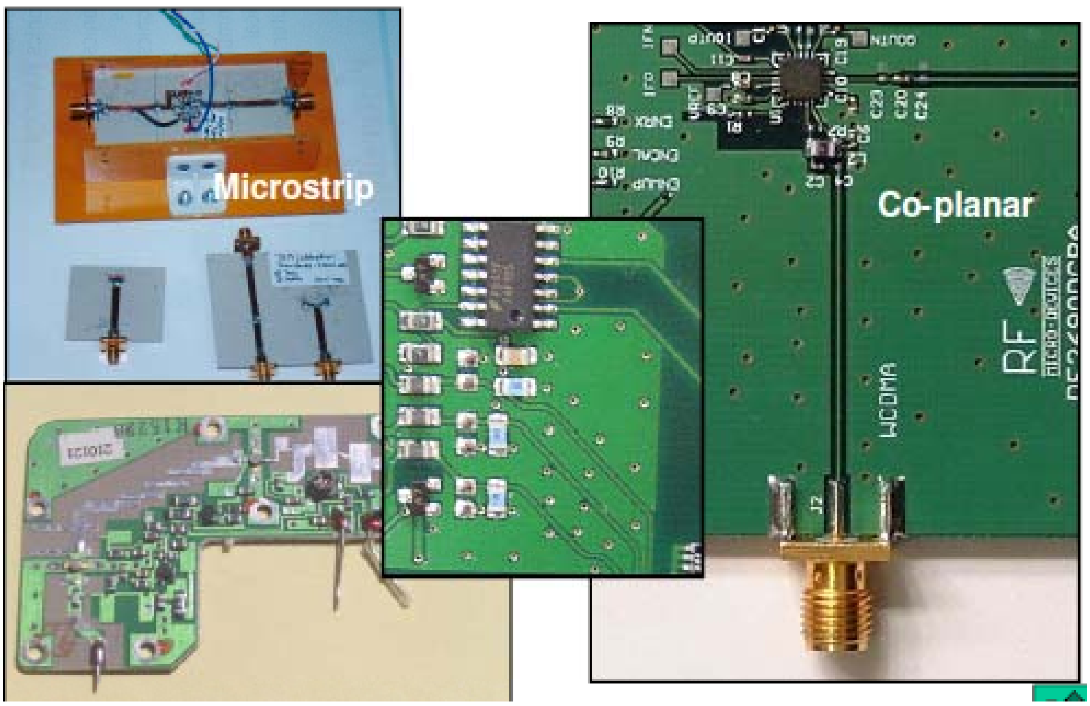
Transmission Lines in PCB



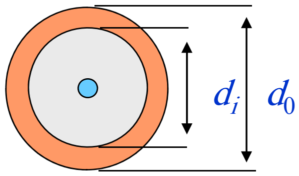
Some Basic Transmission Lines



Some Basic Transmission Lines



Some Basic Transmission Lines

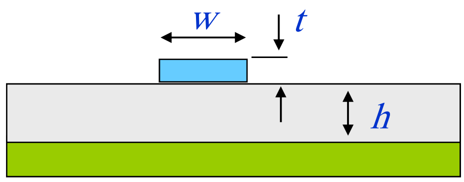


Coaxial cable

$$Z_0 = \left(60/\sqrt{\varepsilon_r}\right)\ln\frac{d_0}{d_i} \quad [\Omega]$$

$$L_l = 200\ln\frac{d_0}{d_i} \quad [\text{nH/m}]$$

$$v_p = \frac{3\times10^8}{\sqrt{\varepsilon_r}} \quad [\text{m/s}]$$



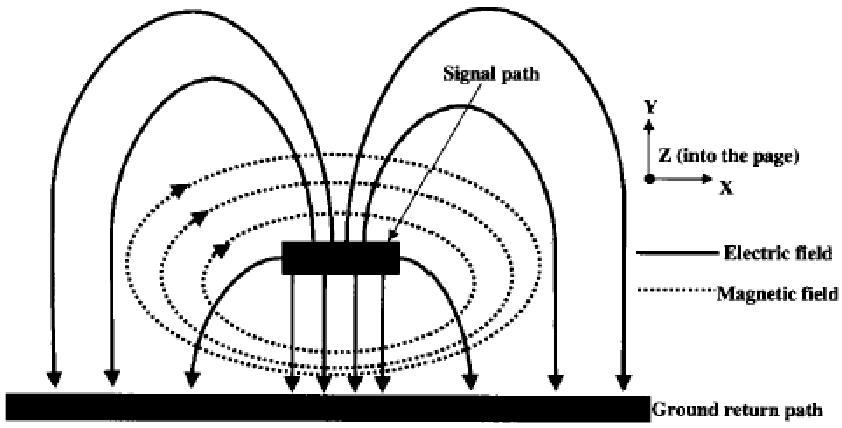
Microstrip line

$$Z_0 \approx \left(87/\sqrt{\varepsilon_r + 1.41}\right)\ln\frac{6h}{0.8w+t} \quad [\Omega]$$

$$v_p = \frac{3\times10^8}{\sqrt{\varepsilon_{\text{eff}}}} \quad [\text{m/s}]$$

Usually, software tools are needed for those calculations

Capacitance and Inductance in Microstrip Line



Cross section of a microstrip depicting the electric and magnetic fields assuming that an electrical signal is propagating down the line into the page.

Signal current

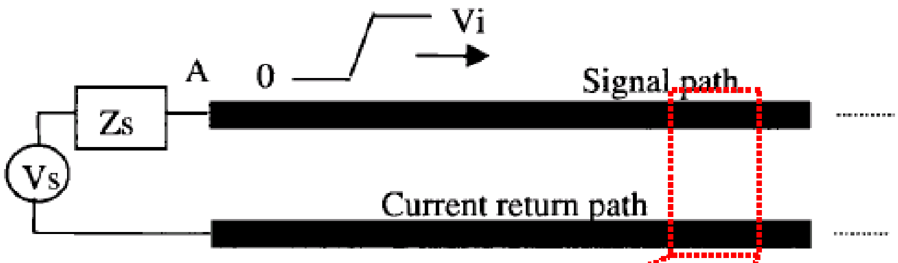
$\otimes$

$\odot$

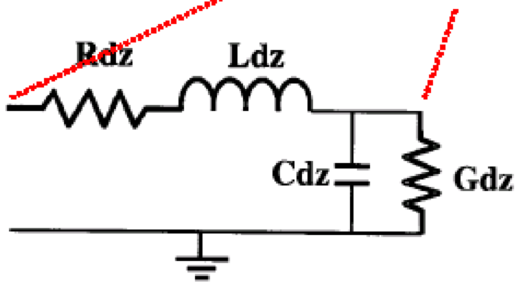
Return or image current

Important: Always have a current return path!

Equivalent Circuit Model

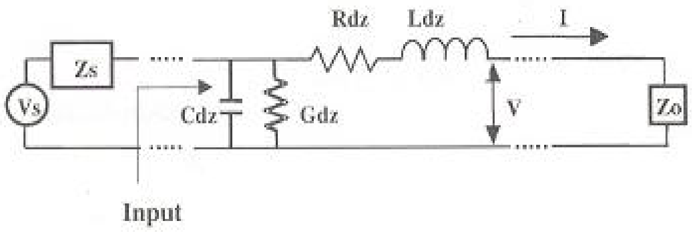


Typical method of portraying a digital signal propagating on a transmission line.

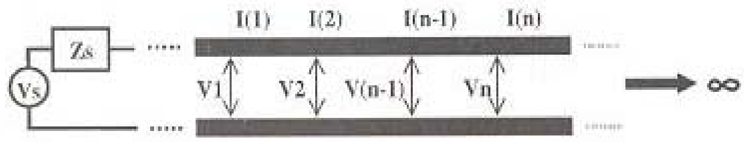


Equivalent circuit model of a differential section of a transmission line of length *dz* (*RLCG* model).

Characteristic Impedance (Z_o)



(a)



(b)

Method of deriving a transmission lines characteristic impedance: (*a*) differential section; (*b*) infinitely long transmission line.

$$Z_o = \frac{V_x^+}{I_x^+}$$

Characteristic Impedance (Z_o)

$j\omega L(\Delta z) + R(\Delta z) = Z\Delta z$ (series impedance for length of line Δz)

$j\omega C(\Delta z) + G(\Delta z) = Y\Delta z$ (parallel admittance for length of line Δz)

Then

$$Z(\text{input}) = Z_o = \frac{(Z_o + Z\,\Delta z)(1/Y\,\Delta z)}{Z_o + Z\,\Delta z + 1/Y\,\Delta z}$$ (assuming the load is equal to the characteristic impedance)

$$Z_o\left(Z\,\Delta z + Z_o + \frac{1}{Y\,\Delta z}\right) = (Z_o + Z\,\Delta z)\frac{1}{Y\,\Delta z}$$

$$\Rightarrow Z_o Z\,\Delta z + Z_o^2 + \frac{Z_o}{Y\,\Delta z} = \frac{Z_o}{Y\,\Delta z} + \frac{Z\,\Delta z}{Y\,\Delta z}$$

$$\Rightarrow Z_o(Z\,\Delta z + Z_o) = \frac{Z}{Y}$$

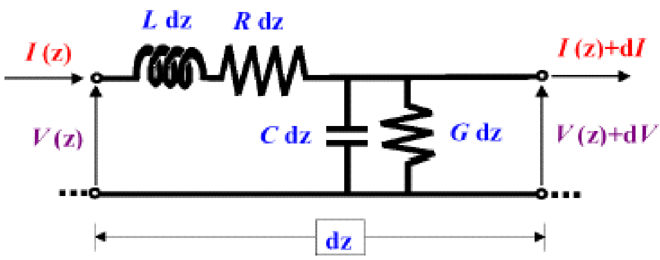
$$\Rightarrow Z_o Y(Z\,\Delta z + Z_o) = Z$$

$$\Rightarrow \lim_{\Delta z \to 0}[Z] = Z_o^2 Y$$

Therefore,

$$Z_o = \sqrt{\frac{Z}{Y}} = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \qquad (2.1)$$

The Telegraphers Equations



$$\left\{\begin{aligned} \frac{dV}{dz} &= -(j\omega L + R)I \\ \frac{dI}{dz} &= -(j\omega C + G)V \end{aligned}\right.$$

The First order equation

$$\left\{\begin{aligned} \frac{d^2V}{dz^2} &= -(j\omega L + R)\frac{dI}{dz} \\ &= (j\omega L + R)(j\omega C + G)V \\ \frac{d^2I}{dz^2} &= -(j\omega C + G)\frac{dV}{dz} \\ &= (j\omega C + G)(j\omega L + R)I \end{aligned}\right.$$

The second order (or uncoupled) equation

Equivalent Circuit Model for Spice Simulation

RULE OF THUMB: Choosing a Sufficient Number of *RLCG* Segments

When using a distributed *RLCG* model for modeling transmission lines, the number of *RLCG* segments should be determined as follows:

$$\text{segments} \geq 10\left(\frac{x}{T_r v}\right)$$

where x is the length of the line, v the propagation velocity of the transmission line, and T_r the rise (or fall) time. Each parasitic in the model should be scaled by the number of segments. For example, if the parasitics are known per unit meter, the maximum values used for a single segment must be

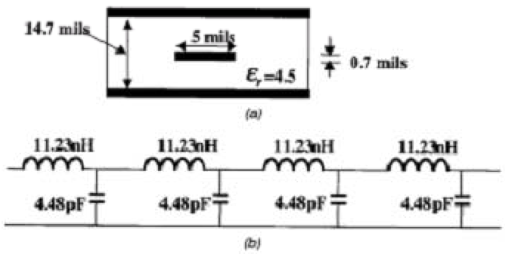
$$C_{\text{segment}} = \frac{(x)(C/\text{meter})}{\text{segments}}$$

$$L_{\text{segment}} = \frac{(x)L/\text{meter}}{\text{segments}}$$

$$R_{\text{segment}} = \frac{(x)R/\text{meter}}{\text{segments}}$$

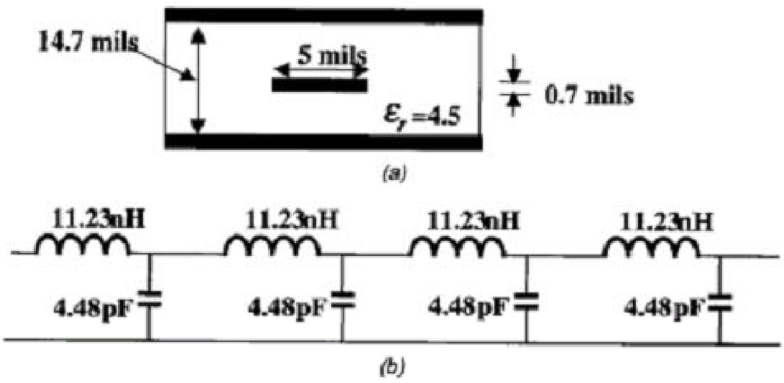
$$G_{\text{segment}} = \frac{(x)G/\text{meter}}{\text{segments}}$$

$$\text{TD}_{\text{segment}} = \sqrt{L_{\text{segment}}C_{\text{segment}}} \leq \frac{T_r}{10}$$



Creating a transmission line model: (*a*) cross section; (*b*) equivalent circuit.

Example: Transmission Line Model for SPICE



Creating a transmission line model: (*a*) cross section; (*b*) equivalent

Q: Create an equivalent circuit model of a loss-free 50 ohm transmission line 5 inch long (1 inch=2.54cm, 1mil=0.001 inch) for cross section shown above. Assume the driver has a minimum rise time of 2.4ns. Dielectric constant is 4.5.

Example (contd.,)

SOLUTION: Initially, the inductance and capacitance of the transmission line must be calculated. Since no field solver is available, the equations presented above will be used.

$$Z_o \approx \frac{60}{\sqrt{\varepsilon_r}} \ln \frac{4H}{0.67\pi(T + 0.8W)} = \frac{60}{\sqrt{\varepsilon_r}} \ln \frac{4(14.7)}{0.67\pi[0.7 + 0.8(5)]} = 50\ \Omega$$

$$\text{TD} = \frac{x\sqrt{\varepsilon_r}}{c} = 5\ \text{in.}(0.0254\ \text{m/in.})\frac{\sqrt{4.5}}{3 \times 10^8\ \text{m/s}} = 898\ \text{ps}$$

$$v = \frac{c}{\sqrt{\varepsilon_r}} = \frac{3 \times 10^8\ \text{m/s}}{\sqrt{4.5}} = 1.41 \times 10^8\ \text{m/s}$$

Example (contd.,)

If the transmission line is a microstrip, the same procedure is used to calcula the velocity, but with the effective dielectric constant as calculated in equatic (2.6).

Since $Z_o = \sqrt{L/C}$ and $\text{TD} = \sqrt{LC}$, we have two equations and two u knowns. Solve for L and C.

$$L_{\text{total}} = (\text{TD})(Z_o) = (898 \times 10^{-12})(50\ \Omega) = 44.9\ \text{nH}$$

$$C_{\text{total}} = \frac{\text{TD}}{Z_o} = \frac{898 \times 10^{-12}\ \text{s}}{50\ \Omega} = 17.9\ \text{pF}$$

The L and C values above are the total inductance and capacitance for th 5-in. line.

$$\text{segments} \geq 10\left(\frac{X}{T_r v}\right) = 10\left[\frac{5\ \text{in.}(0.0254\ \text{m/in.})}{2.5\ \text{ns}(1.41 \times 10^8\ \text{m/s})}\right] = 3.6$$

Because 3.6 is not a round number, we will use four segments in the model

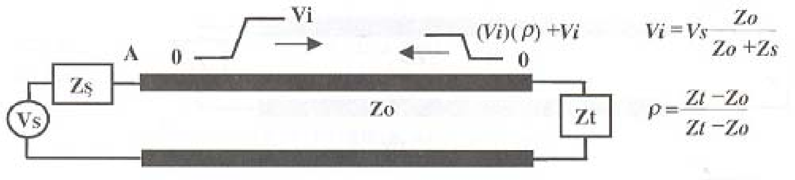
$$C_{\text{segment}} = \frac{C_{\text{total}}}{\text{segments}} = \frac{17.9\ \text{pF}}{4} = 4.48\ \text{pF}$$

$$L_{\text{segment}} = \frac{L_{\text{total}}}{\text{segments}} = \frac{44.9\ \text{nH}}{4} = 11.23\ \text{nH}$$

Double check to ensure that the rule of thumb is satisfied.

$$\text{TD}_{\text{segment}} = \sqrt{L_{\text{segment}} C_{\text{segment}}} = \sqrt{(4.48\ \text{pF})(11.23\ \text{nH})} = 0.224\ \text{ns} \leq \frac{T_r}{10}$$

Transmission Line Reflection



Incident signal being reflected from an unmatched load.

Incident voltage

$$V_i = V_s \frac{Z_0}{Z_s + Z_0}$$

Reflection Coefficient

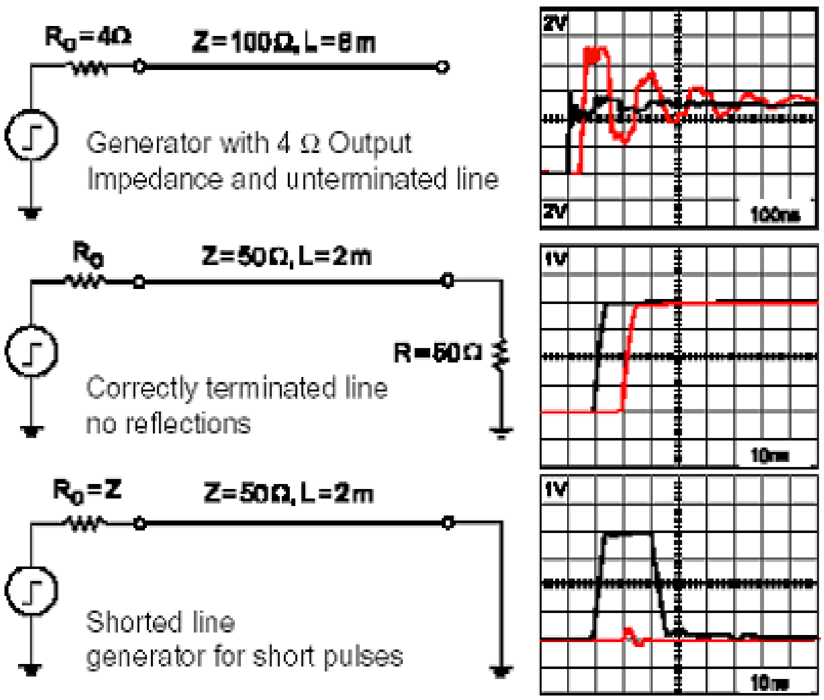
$$\rho = \frac{V_{reflected}}{V_{incident}} = \frac{Z_t - Z_0}{Z_t + Z_0}$$

Reflection Coefficient

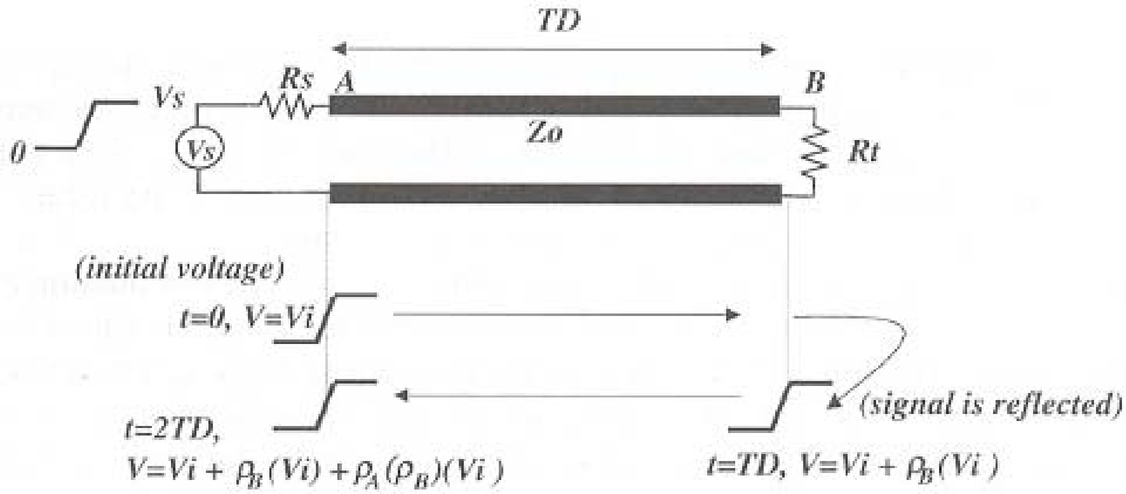
$$\rho = \frac{\alpha - Z_o}{\alpha + Z_o} = 1$$

$$\rho = \frac{Z_o - Z_o}{Z_o + Z_o} = 0$$

$$\rho = \frac{0 - Z_o}{0_s + Z_o} = -1$$

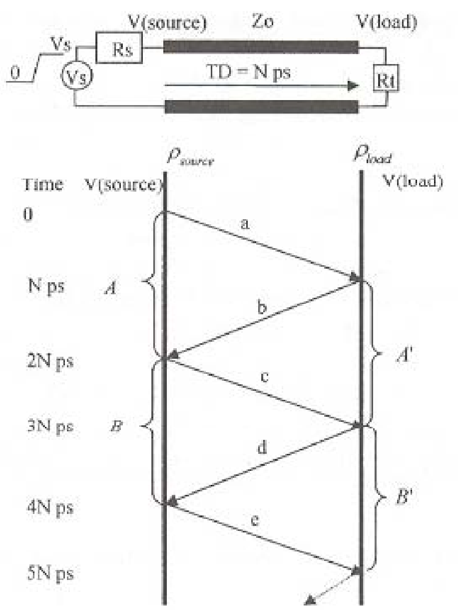


Transmission Line with Reflection



Example of transmission line with reflections.

Lattice Diagram to calculate Multiple Reflection



$a = V_{initial}$

$b = a\ \rho_{load}$

$c = b\ \rho_{source}$

$d = c\ \rho_{load}$

$e = d\ \rho_{source}$

$f = e\ \rho_{load}$

$A = a$

$B = a + b + c$

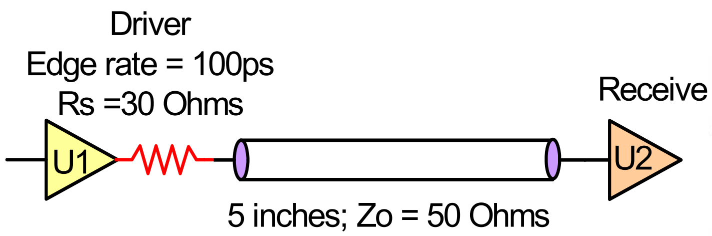
$C = a + b + c + d + e$

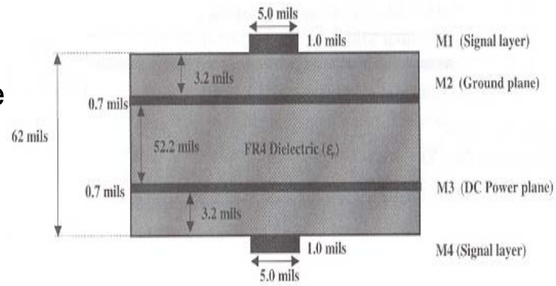
$A' = a + b$

$B' = a + b + c + d$

$C' = a + b + c + d + e + f$

Typical Case: Source Termination





- Calculate the time it takes from U1 to U2?
- Determine the wave shape seen at U2?

$$\varepsilon_e = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + \frac{12H}{W}\right]^{-\frac{1}{2}} + F - 0.217(\varepsilon_r - 1)\frac{T}{\sqrt{WH}}$$

$$\varepsilon_r(FR4) = 4 \;\; ,W/H = 5/3.2 \;\Rightarrow F = 0$$

$$\varepsilon_e = \frac{4+1}{2} + \frac{4-1}{2}\left[1 + \frac{12(3.2)}{5}\right]^{-\frac{1}{2}} + 0 - 0.217(4-1)\frac{1.0}{\sqrt{5.0(3.2)}}$$

$$\varepsilon_e = 2.84$$

$$v = \frac{c}{\sqrt{\varepsilon_r}} = \frac{3.0\times 10^8\, m/s}{\sqrt{2.84}} = 1.78\times 10^8\, m/s$$

$$TD = \frac{length\,\sqrt{\varepsilon_r}}{c} =$$

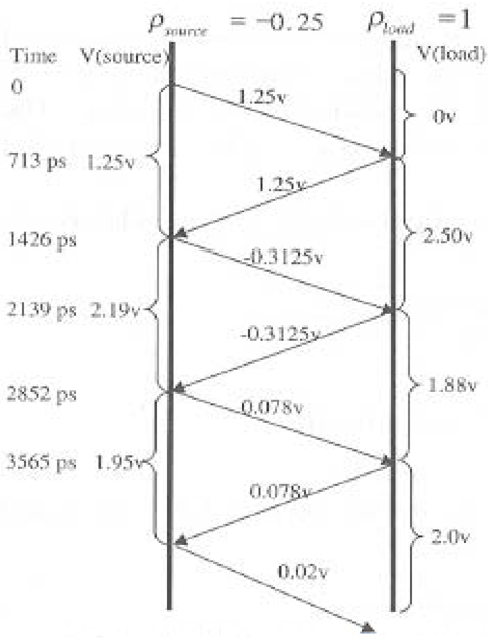
$$\frac{5.0in}{1.78\times 10^8\, m/s}\left(\frac{0.0254\,m}{1.0in}\right) = 713\;ps$$

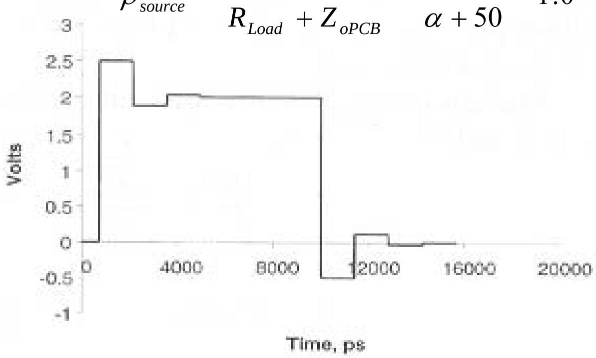
Wave shape at U2

$$V_{initial} = V_{in}\frac{Z_{oPCB}}{Z_{oPCB} + R_s} = 2.0\left(\frac{50}{50+30}\right) = 1.25\;V$$

$$\rho_{source} = \frac{R_S - Z_{oPCB}}{R_s + Z_{oPCB}} = \frac{30-50}{30+50} = -0.25$$

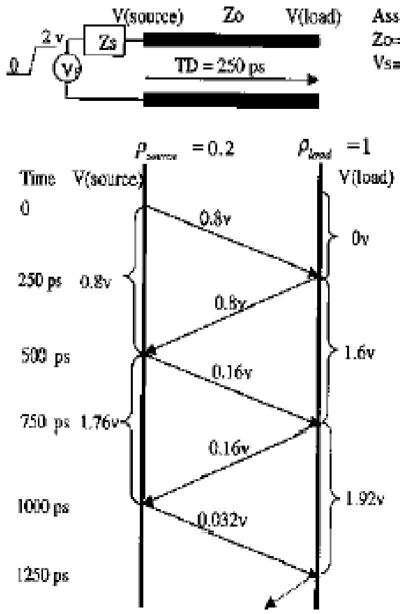
$$\rho_{source} = \frac{R_{Load} - Z_{oPCB}}{R_{Load} + Z_{oPCB}} = \frac{\alpha - 50}{\alpha + 50} = 1.0$$





- We assume input Cap of receiver is very small 2-3Pf.
- There might be problem to ESD diodes.

Under Driven Transmission Line



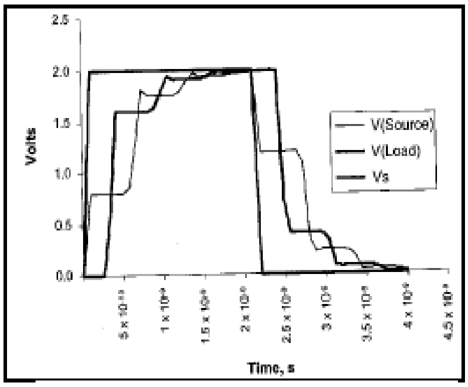
Assume Zs=75 ohms
Zo=50 ohms
Vs=0-2 volts

$$V_{initial} = Vs\frac{Zo}{Zs+Zo} = (2)\left(\frac{50}{75+50}\right) = 0.8$$

$$\rho_{source} = \frac{Zs-Zo}{Zs+Zo} = \frac{75-50}{75+50} = 0.2$$

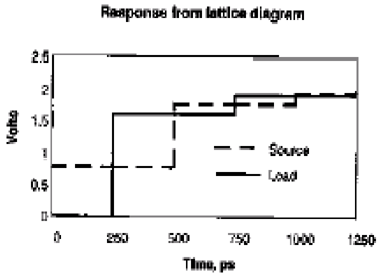
$$\rho_{load} = \frac{Zl-Zo}{Zl+Zo} = \frac{\infty-50}{\infty+50} = 1$$

$\rho_{source} = 0.2$ $\rho_{load} = 1$



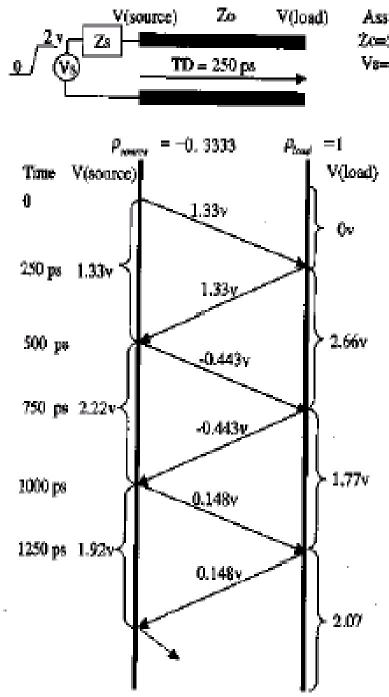
The simulation result

Response from lattice diagram



Lattice Diagram used to Calculate Multiple Reflection for Under driven Transmission Line

Over Driven Transmission Line



Assume Zs=25 ohms
Zo=50 ohms
Vs=0-2 volts

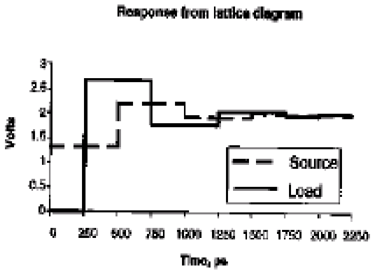
$$V_{initial} = Vs\frac{Zo}{Zs+Zo} = (2)\left(\frac{50}{25+50}\right) = 1.3333$$

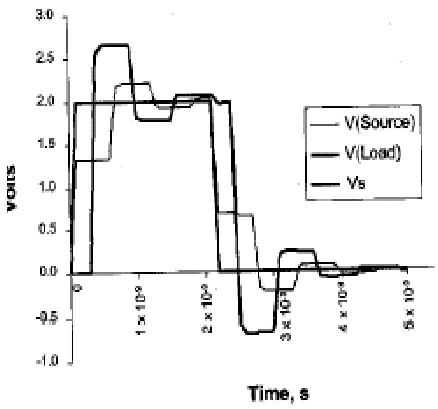
$$\rho_{source} = \frac{Zs-Zo}{Zs+Zo} = \frac{25-50}{25+50} = -0.33333$$

$$\rho_{load} = \frac{Zl-Zo}{Zl+Zo} = \frac{\infty-50}{\infty+50} = 1$$

$\rho_{source} = -0.3333$ $\rho_{load} = 1$

Response from lattice diagram

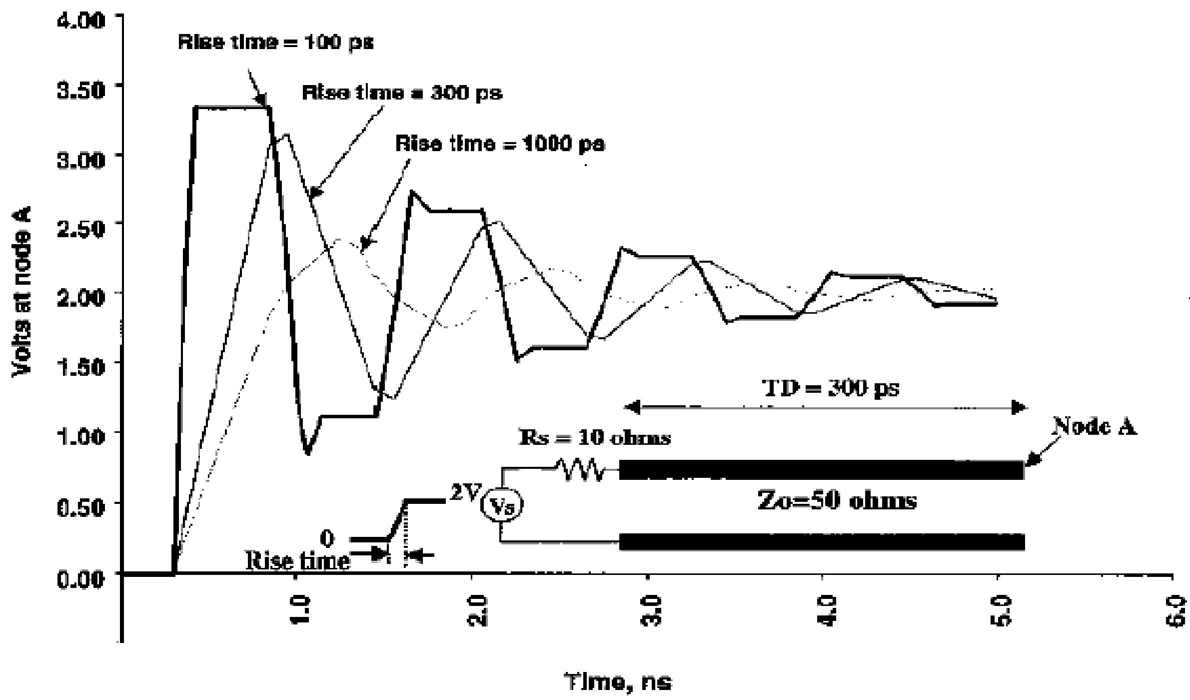




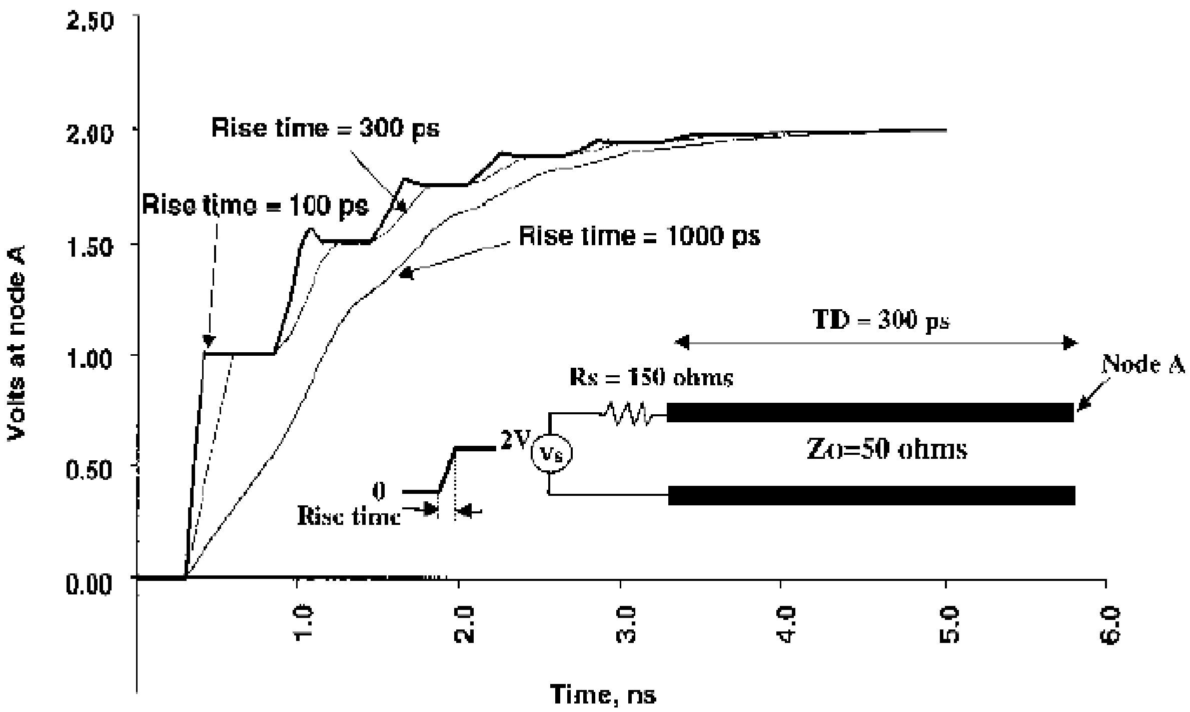
The simulation result

Lattice Diagram used to Calculate Multiple Reflection for Over driven Transmission Line

Effect of Slow Edge Rate: Overdriven Case

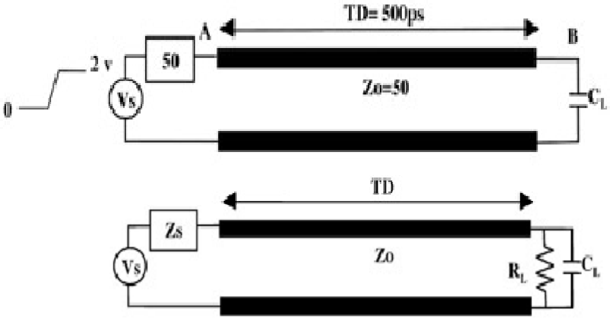


Effect of Slow Edge Rate: Underdriven Case



Real world Case: Capacitive Load

The input of CMOS is capacitive in nature.



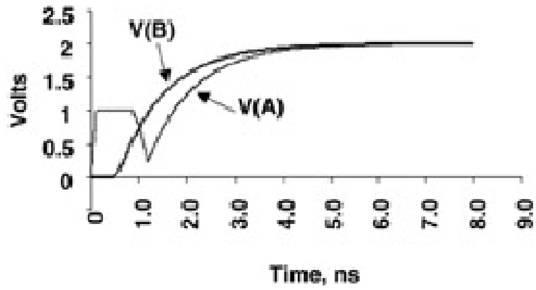
$$V_{Cap} = 2V_i(1 - e^{-(t-TD)/\tau}) \quad \because t > TD$$

$$\tau = CZ_0$$

Equations for RC load

$$V_{Cap} = 2V_i \frac{R_L}{R_L + Z_0}(1 - e^{-(t-TD)/\tau_1}) \because t > TD$$

$$\tau_1 = \frac{C_L Z_0 R_L}{R_L + Z_0}$$

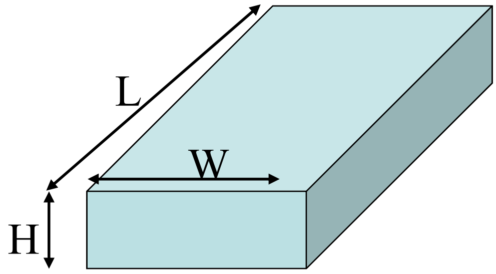


Non Ideal Interconnect

- Non Ideal Interconnect
  - Resistance, Capacitance and Inductance
    - Resistance
    - AC Resistance (Skin Effect)
    - Capacitance
    - Inductance
  - Frequency Dependent Dielectric Losses
  - Serpentine traces
  - ISI (Intersymbol Interference)
  - Effect of 90^o Bend in trace

DC Resistance

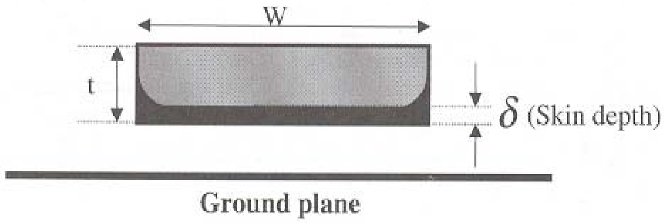
At low or DC frequencies, a current flowing through a non-ideal conductor is uniformly distributed over the conductor cross section.



Material	Resistivity [Ω-m]
Silver (Ag)	1.6×10^{-8}
Copper (Cu)	1.7×10^{-8}
Gold (Au)	2.2×10^{-8}
Aluminium (Al)	2.7×10^{-8}
Tungsten (W)	5.5×10^{-8}

$$R = \frac{\rho L}{A} = \frac{\rho L}{HW}$$

AC Resistance

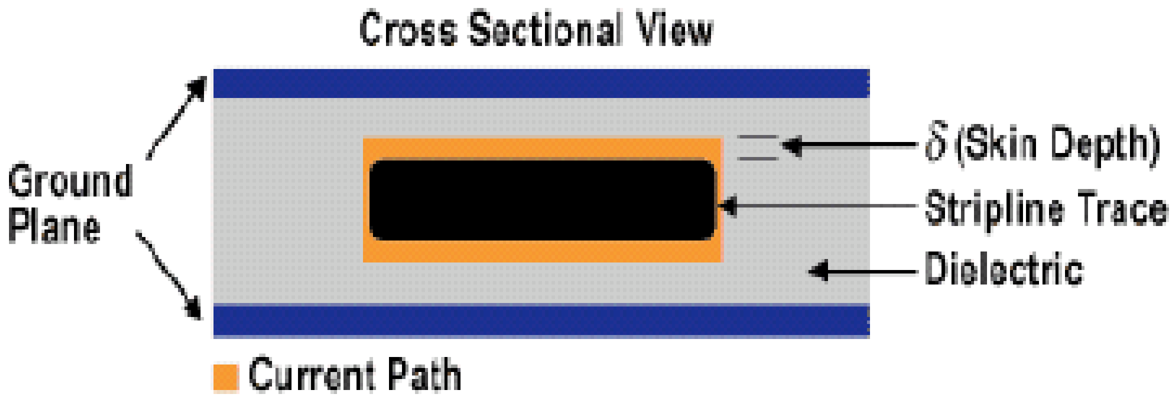


Current distribution on a microstrip transmission line. 63% of the current is concentrated in the darkly shaded area due to the skin effect.

$$R_{ac,signal} \approx \frac{\rho}{w\delta} = \frac{\sqrt{\rho \pi \mu f}}{w} \quad (\Omega / m)$$

Resistance thus increases as square root of frequency!

AC Resistance



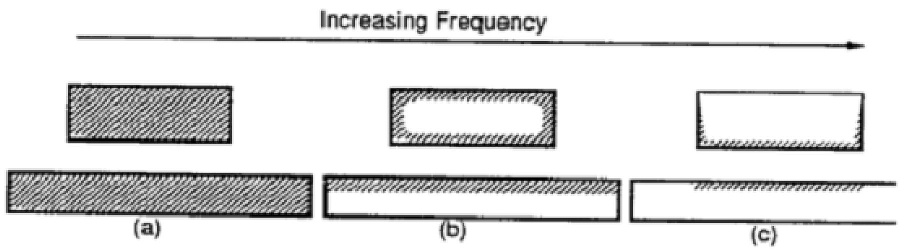
$$\delta = \sqrt{\frac{\rho}{\pi F \mu}}$$

Resistivity

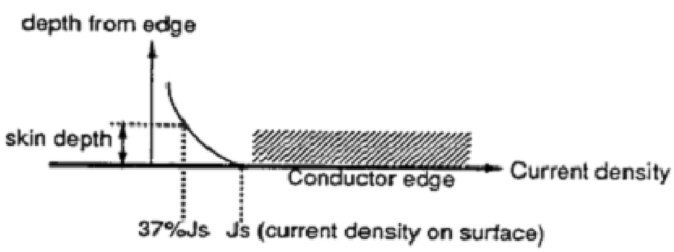
Permeability of Free Space

Frequency

AC Resistance: Skin Effect



$$\delta_s = \sqrt{\frac{\rho}{\pi \mu f}}$$



The skin effect. As the frequency increases, the current becomes more concentrated a → b → c.

At high frequencies, current concentrated at the surface of the conductor, called skin effect.

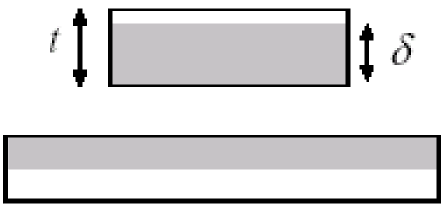
Total Resistance

Model 1.

$$R_{\text{total}} \approx \sqrt{R_{\text{ac}}^2 + R_{\text{dc}}^2}$$

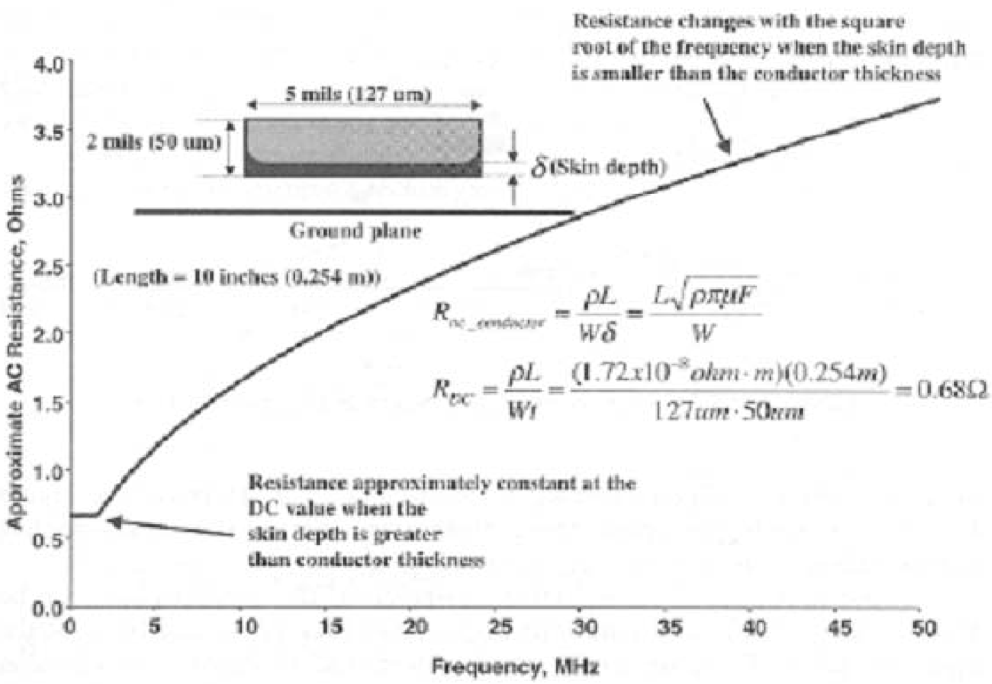
Model 2.

$$R_{tot} = \begin{cases} R_{dc} & f \le f_o \\ R_{dc}\sqrt{f / f_o} & f \ge f_o \end{cases} \quad (\Omega / m)$$



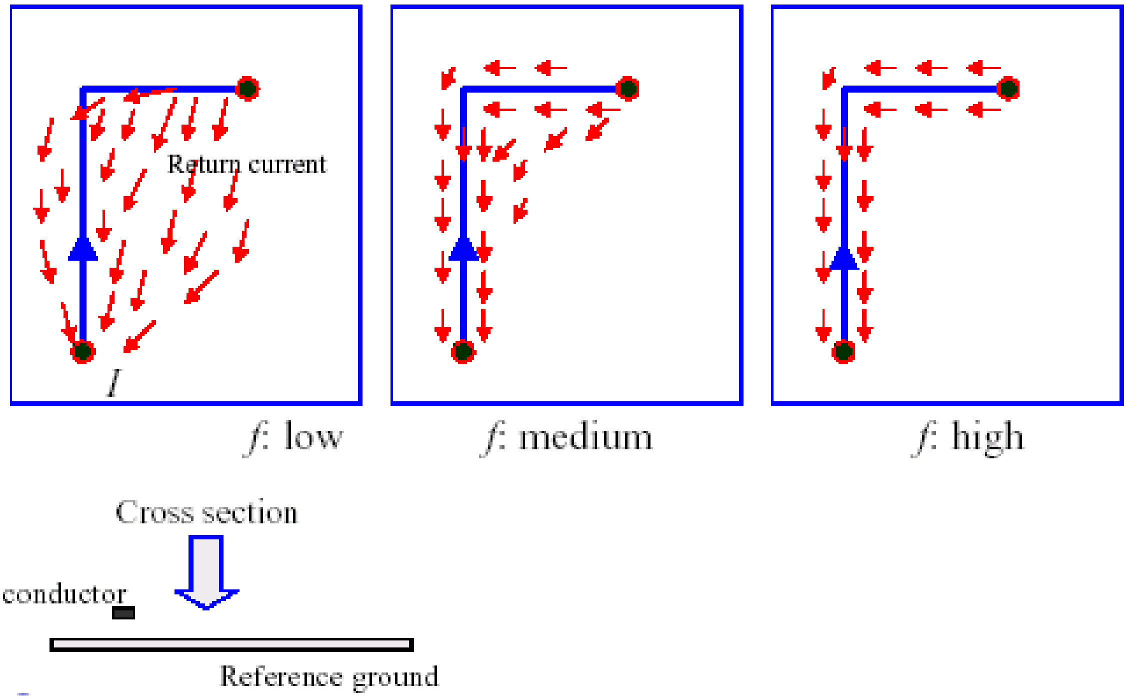
Where $f_o = \rho / (\mu \pi t^2)$ is referred to as the break frequency at the equivalent skin depth (i.e., when the skin depth $\delta = t$)

AC Resistance as a function of Frequency

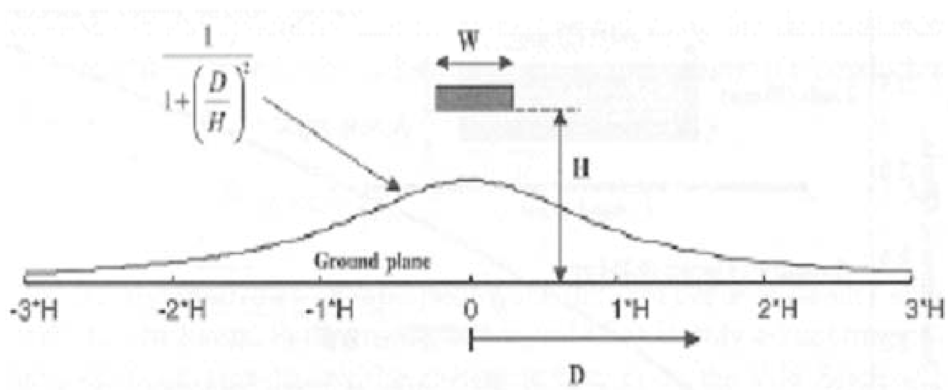


Ac resistance as a function of frequency.

Resistance of Reference Ground Plane



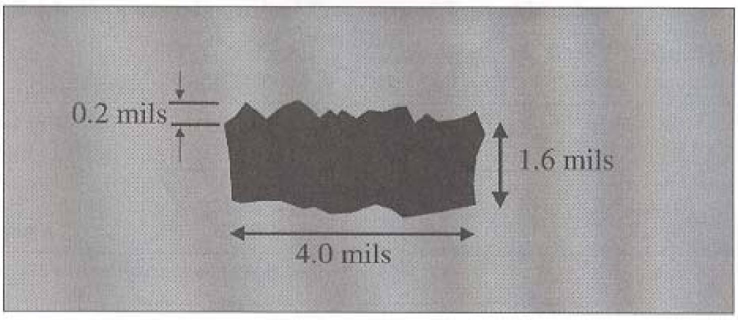
Current Density Distribution in GND Plane



Current density distribution in the ground plane.

$$\boxed{I(D) \approx \frac{I_o}{\pi H} \frac{1}{1 + (D/H)^2}}$$

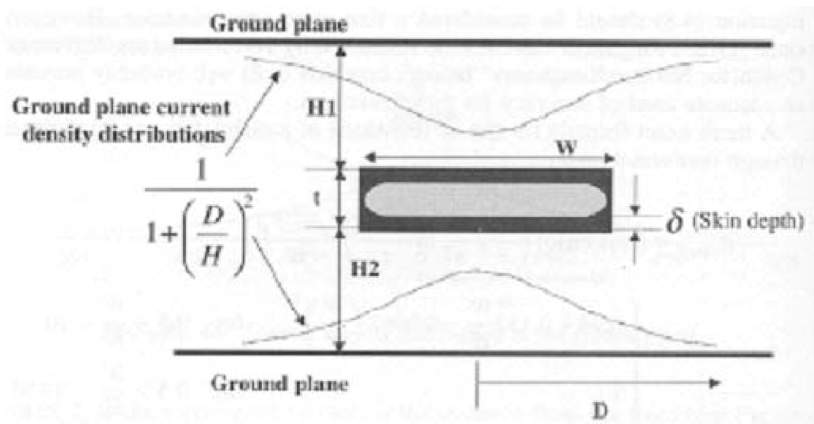
Effective of Conductor Roughness



Cross section of a stripline in a typical PCB, showing surface roughness.

Conductor surface roughness increases AC resistance by 10~50% when the roughness is a significant percent of skin depth.
Careful in RF/HF Design!

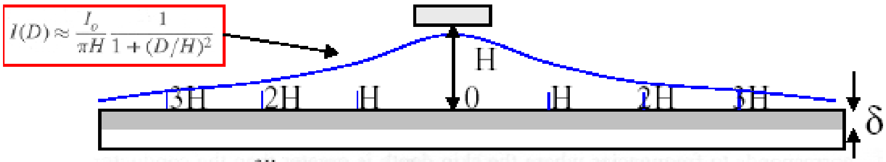
Current Density Distribution in a Striplines



Current density distribution in a stripline.

$$R_{ac\ signal} = \frac{(R_{H1\ ac\ microstripline})(R_{H2\ ac\ microstripline})}{R_{H1\ ac\ microstripline} + R_{H2\ ac\ microstripline}} \quad (\Omega / m)$$

AC Resistance of Ground Ref Plane 3H Rule



$$\int_{-3H}^{3H} \frac{I_o}{\pi H}\frac{1}{1+(D/H)^2} = \frac{2I_o}{\pi}\tan^{-1}(3) \approx 0.795 I_o$$

$$= 79.5\% \text{ of the total current}$$

shows that 79.5% of the current is contained within a distance of $\pm 3H$ ($6H$ total width) away from the center of the conductor. Thus, the ground return path resistance can be approximated by a conductor of cross section $A_{\text{ground}} = \delta \times 6H$. Substituting this result into equation (4.1) yields

$$R_{\text{ac ground}} \approx \frac{\rho}{A_{\text{ground}}} = \frac{\rho}{6\delta H} = \frac{\rho}{6H}\sqrt{\frac{\pi\mu F}{\rho}}$$

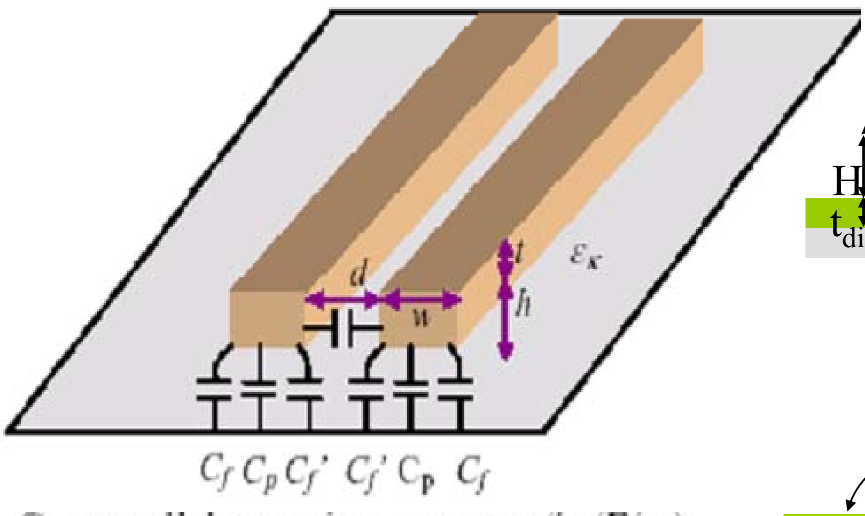
$$= \frac{\sqrt{\rho\pi\mu F}}{6H} \quad \Omega/\text{m}$$

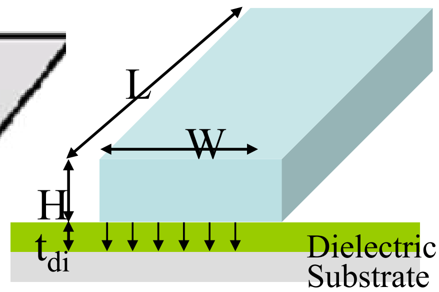
The total ac resistance is the sum of the conductor and ground plane resistance:

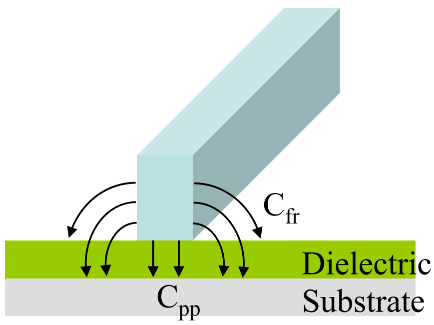
$$R_{\text{ac microstrip}} = R_{\text{ac signal}} + R_{\text{ac ground}}$$

$$\approx \frac{\sqrt{\rho\pi\mu F}}{W} + \frac{\sqrt{\rho\pi\mu F}}{6H} = \sqrt{\rho\pi\mu F}\left(\frac{1}{W}+\frac{1}{6H}\right) \quad \Omega/\text{m}$$

Capacitance of Microstrip







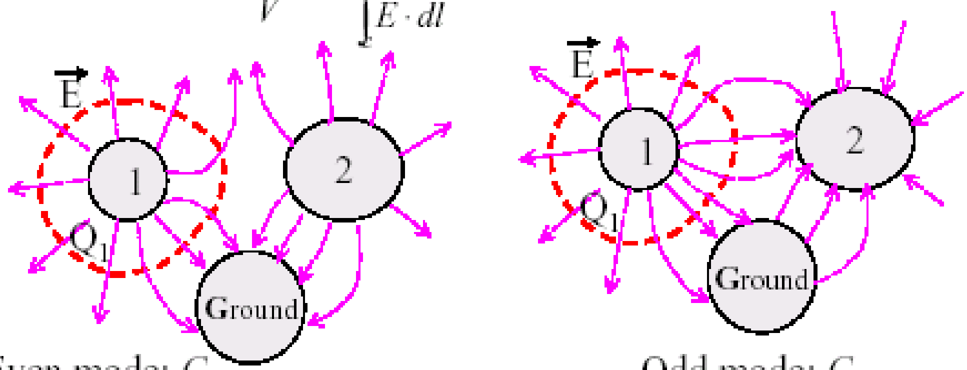
C_p : parallel capacitor, $= \varepsilon_o \varepsilon_r w/h$ (F/m)

C_f' and C_f: fringing capacitors with and without an adjacent wire

Capacitance of Microstrip

The capacitance between two conductors is defined as

$$C = \frac{Q}{V} = \frac{\iint_S \varepsilon \vec{E} \cdot d\vec{S}}{\int_l \vec{E} \cdot d\vec{l}} \qquad (F)$$



Even mode: C_e Odd mode: C_o

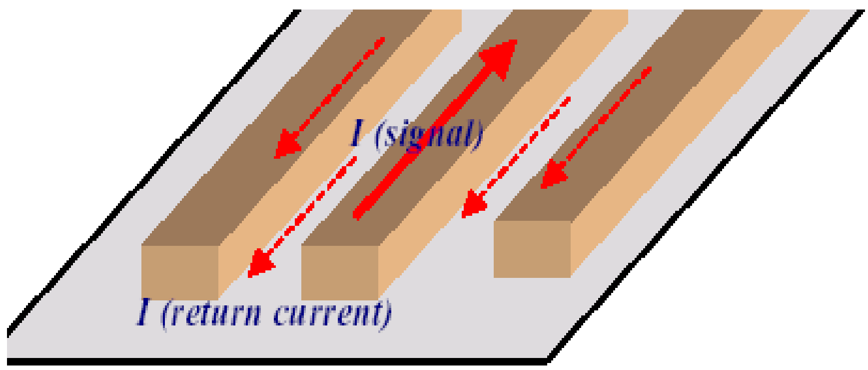
$$\begin{bmatrix} Q_1 \\ Q_2 \end{bmatrix} = \begin{bmatrix} C_1 + C_m & -C_m \\ -C_m & C_2 + C_m \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \end{bmatrix}$$

Inductance

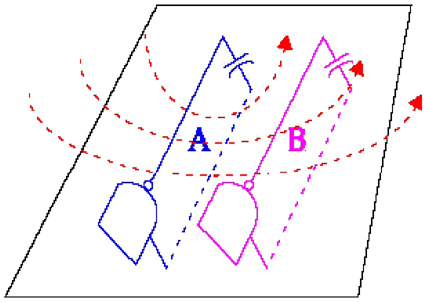
Inductance is measured by the magnetic flux induced by a loop current,

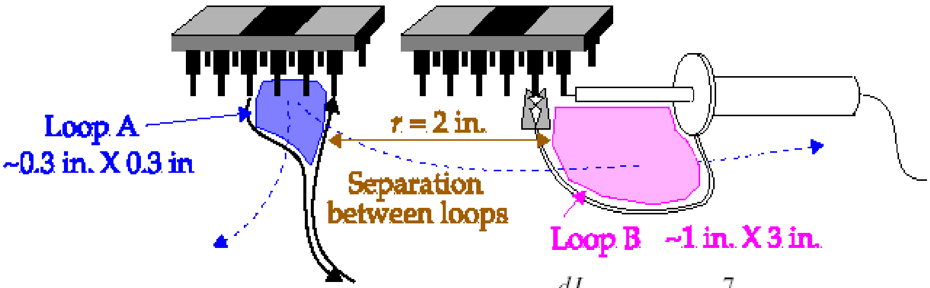
$$L = \frac{\iint_s \vec{B} \cdot d\vec{S}}{i} = \frac{\oint_c \vec{A} \cdot d\vec{l}}{i} \qquad (H)$$

but where is the return loop ?



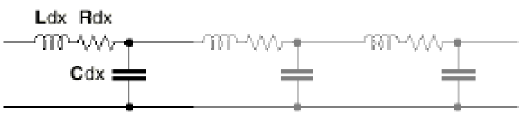
Inductance: Return Loops

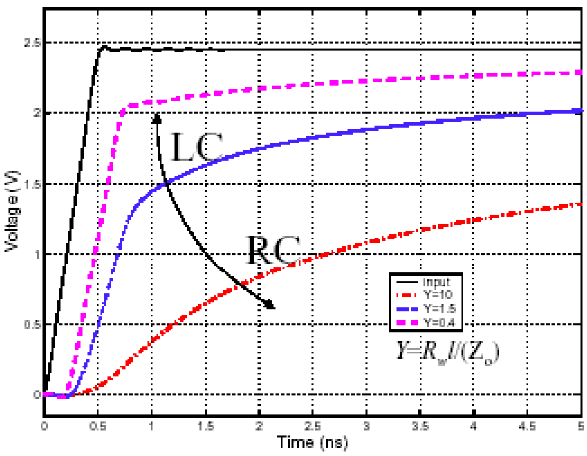




$$\frac{dI}{dt} = 7.0 \times 10^{7} A/s$$

Effect of L, R and C





LC line:

$$t_{wire} = t_{tof} = \frac{l}{v} = l\sqrt{L_w C_w}$$

RC line:

$$t_{wire} = t_{tof} = \frac{1}{2} L_w C_w l^2$$

Total line delay:

$$t_{wire} = \left(t_{tof}{}^{1.6} + t_{RC}{}^{1.6}\right)^{1/1.6}$$

Note: above equation doesn't include driver delay.

If $R_w l < Z_o$, LC delay dominates; otherwise, RC delay dominates.

Effect of Serpentine Traces

Rule of Thumb.

- Make minimum spacing between parallel sections (s) at least 3H to 4H, where H is the height of signal conductor above the reference GND plane. This will minimize the coupling between parallel sections.
- Minimize the length of serpentine sections (Lp) to reduce the coupling.
- Embedded traces has fewer serpentine effects.
- Do not serpentine CLK traces

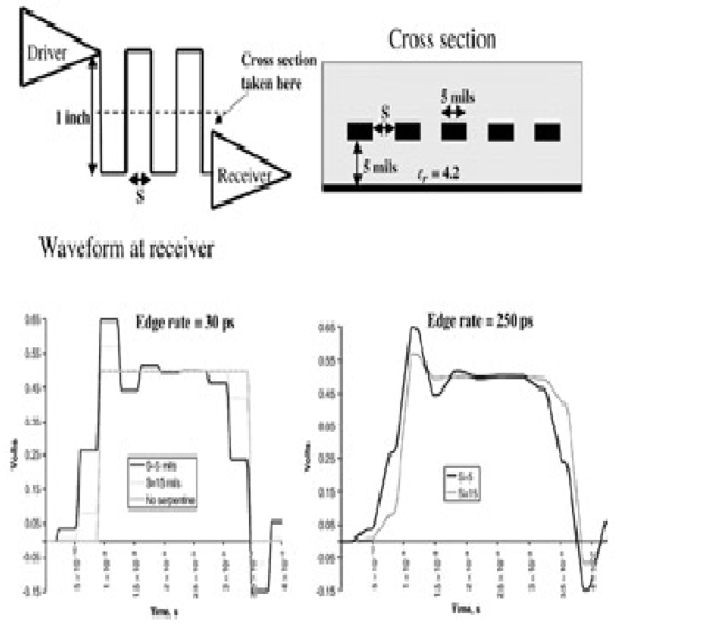


Figure 4.14: Effect of a serpentine trace on signal integrity and timing.

Inter-symbol Distortion (ISI)

Rule of Thumb ISI.

- Minimize reflection by minimizing Z discontinuities
- Keep Interconnects as short as possible.
- Avoid tightly couples serpentine traces
- Avoid undershoot, overshoot and ringing
- Minimize the cross-talk.

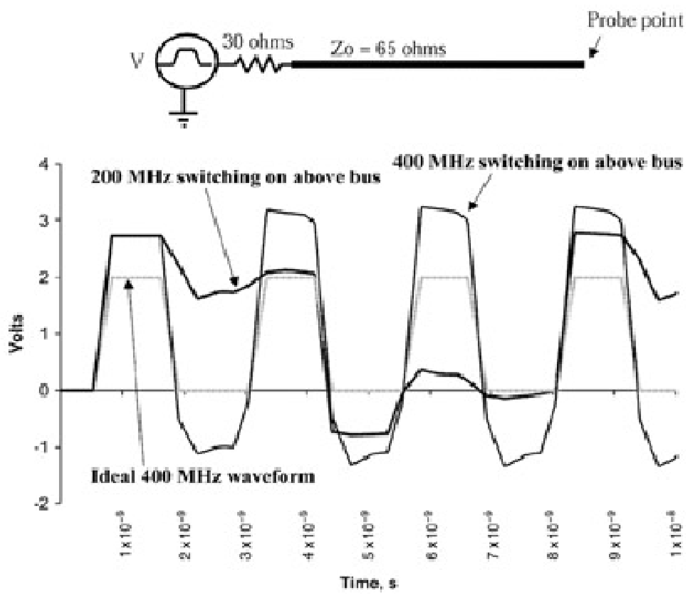
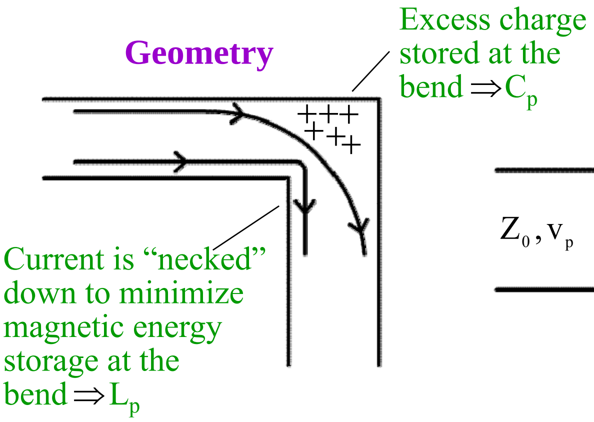
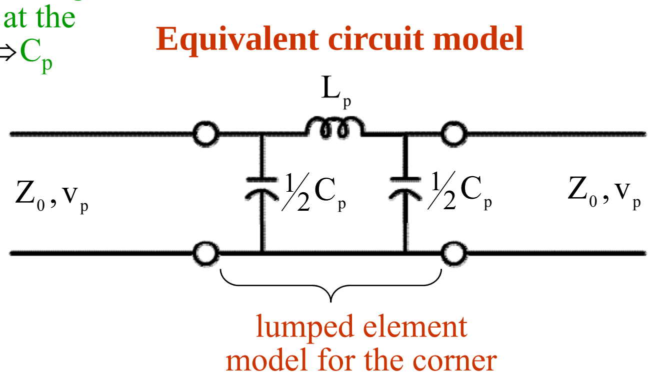


Figure 4.16: Effect of ISI on signal integrity.

Impedance Discontinuity: Capacitive



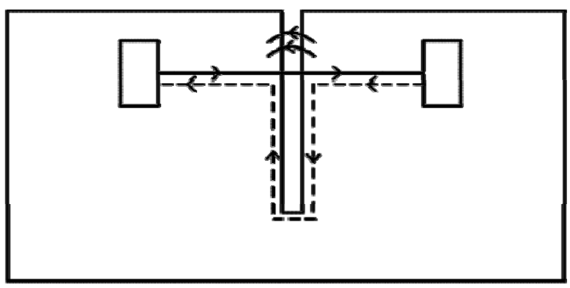


- Path 1 – conduction current around the bend to the load and return on the reference to the source → L_p
- Path 2 – displacement current die to the excess charge at the corner → C_p, to return plane and back to the source

Split C_p in the model for symmetry

Impedance Discontinuity: Inductive

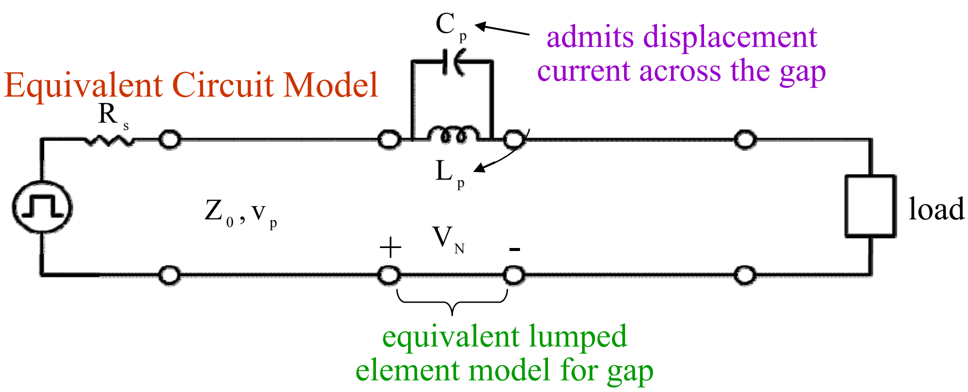
Slot in GND plane



•This give rise to long return path, which increases the loop area and hence higher inductance.

•Some of current propagates across the gap through gap capacitance..

•These both Inductance and Capacitance slows down the signal propagation and results in noise



Summery

- Transmission Lines in PCB
  - What is Transmission Line?
  - Types of Transmission Lines in PCB
  - Transmission Lines Basics
    - Telegraphic Equations
    - Equivalent Circuit of Transmission Lines
    - Reflection Coefficients
    - Lattice Diagram and Design Example
- Non Ideal Interconnect
  - Capacitance, Inductance and Resistance
    - Resistance, AC Resistance,Capacitance and Inductance
    - Frequency Dependent Dielectric Losses (Lecture on PCB Materials)
    - Serpentine traces
    - ISI (Intersymbol Interference)
    - Effect of 90^o Bend in trace

Wakeup Please lets have Some Food….