

**DOING GOOD WHILE PLAYING THE FIELD**  
**AND MESHING AROUND**

*RIDE THE WAVE, Ansoft Worldwide Workshop*

**Westin Hotel, Westminster, Colorado**

**Friday, November 2, 2001**

**☺tto Buhler, Storage Technology Corporation,**

# OUTLINE

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**; LOGIC SIGNAL EDGE RATES & SIGNAL INTEGRITY**

**; CIRCUIT MODEL OF A TRANSMISSION LINE**

**LOSSY LINE, LOSSLESS LINE**

**PARAMETERS: L, C, R, G,  $Z_0$ , M,  $T_{pd}$ ,  $V_P$**

**; TWO CONDUCTOR OPEN-WIRE PAIR**

**FREQUENCY EFFECTS**

**; FLEX CABLE**

**TWO-WIRE PAIR**

**ETCH FACTOR**

**SHIELD EFFECTS**

## Outline (continued)

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**; QuIP. THE FOUR-WIRE INTERDIGITATED PAIR**

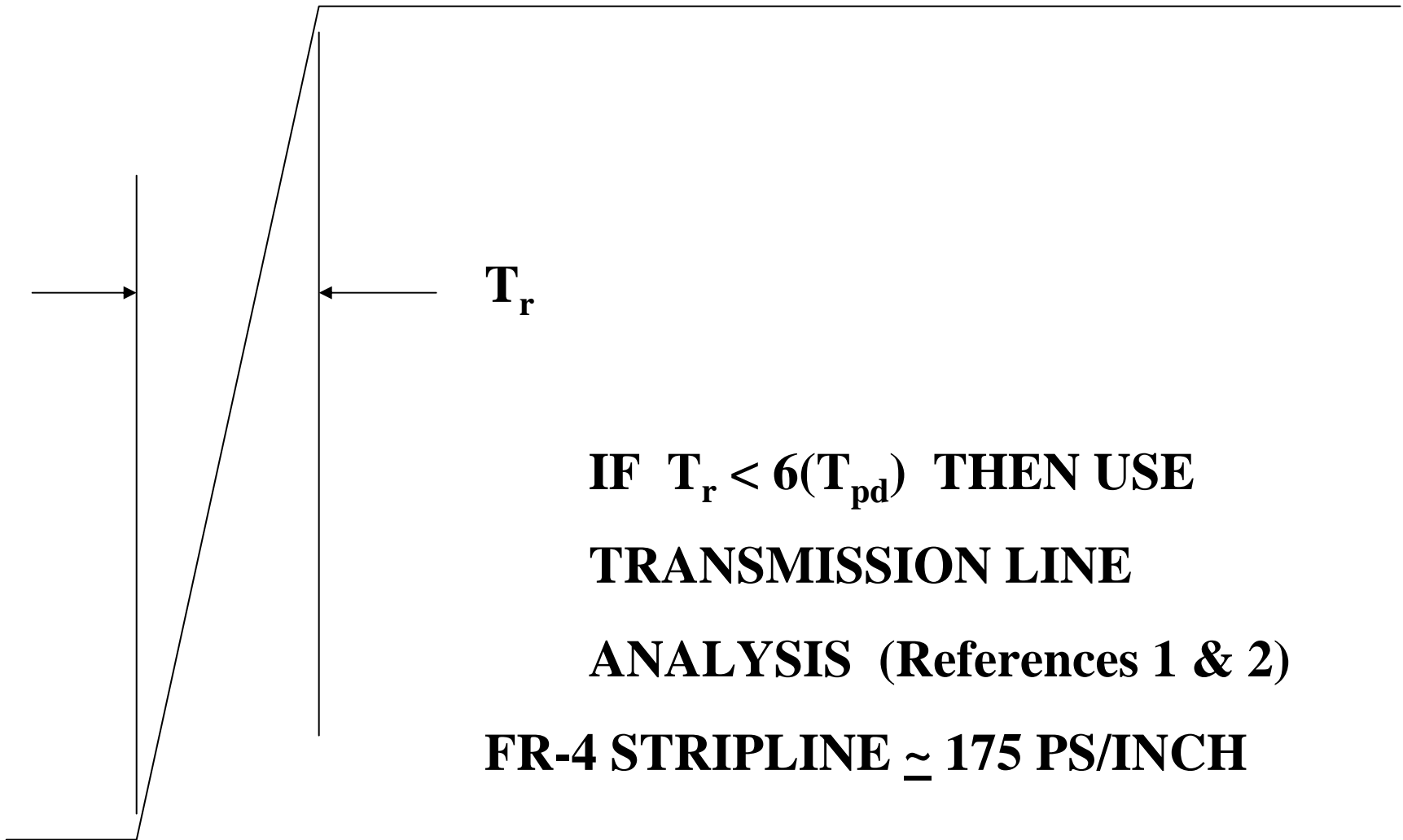
**; FLAT CABLE IMPEDANCE MEASUREMENTS**

**S-G-S-G-S-G-...**

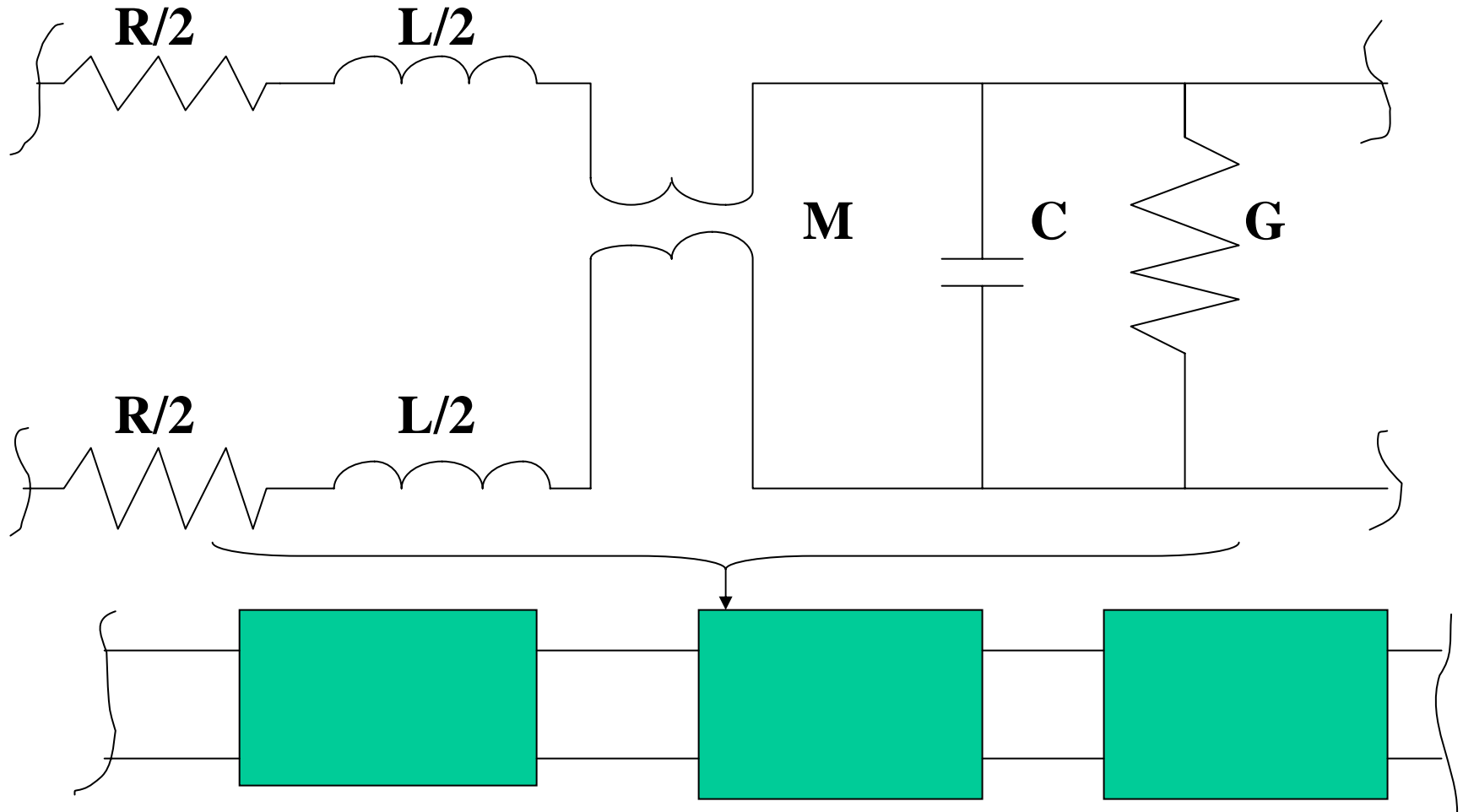
**; EQUATION BASED DESIGN**

**LIMITATIONS**

# LOGIC SIGNAL EDGE RATES & SIGNAL INTEGRITY

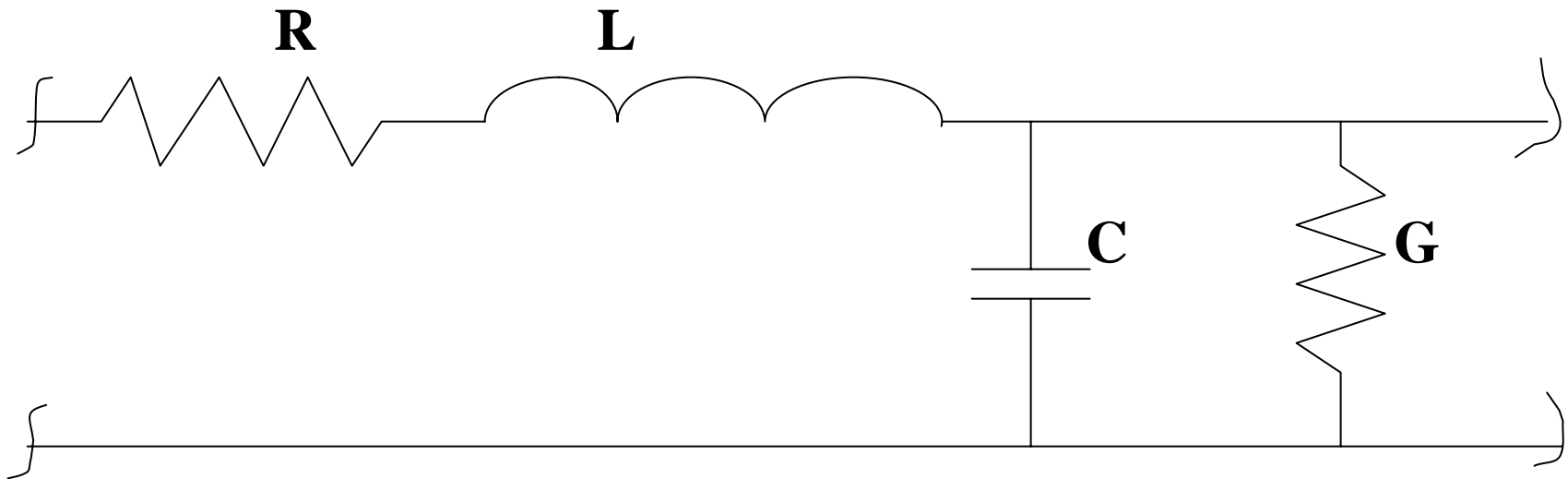


# TRANSMISSION LINE CIRCUIT MODEL



Each box  $T_{pd} < (T_r)/6$

## A SLIGHTLY LESS COMPLICATED LOSSY LINE MODEL



(Reference 3, page 20)

- In many applications, effect of  $G$  is negligible and may be ignored (not as true as frequency increases).
- *FOR THE LOSSLESS LINE;  $R = 0, G = 0$ .*

## **PROPAGATION VELOCITY ( $v_p$ ) & PROP. DELAY ( $t_{pd}$ )**

**; Speed of electromagnetic radiation in vacuum**

$$c = 299,792,458 \text{ meters/second} \quad (\text{Reference 4})$$

**; Speed of electromagnetic radiation in a different medium**

$$v_p = c/(e_r)^{1/2} \quad \text{where } e_r = \text{relative dielectric constant}$$

**; Propagation delay = length/ $v_p$**

$$t_{pd\text{-vacuum}} = 84.723 \text{ ps/inch}$$

$$t_{pd} = (84.723 \text{ ps/inch})(e_r)^{1/2}$$

$$t_{pd\text{-FR4}} = (84.723 \text{ ps/inch})(4.4)^{1/2} = 177.72 \text{ ps/inch}$$

**note:  $e_r$  is a function of humidity, glass/epoxy ratio, f ...**

## L, C, and $Z_0$ for the LOSSLESS LINE

; **LOSSLESS**  $\Rightarrow$   **$R = 0, G = 0$**

;  **$Z_0 = (L/C)^{1/2}$**

;  **$t_{pd} = (LC)^{1/2}$  [ a good sanity check ]**

;  **$\epsilon_{r\text{-effective}} = (t_{pd}/t_{pd\text{-vacuum}})^2$  [ a good sanity check ]**

;  **$C = t_{pd}/Z_0$**

;  **$L = Z_0 t_{pd}$**

; *For a given dielectric constant, the LC product is constant.*

**Be careful with mixed dielectrics, the relative dielectric constant can be difficult to evaluate.**

## A little more on the LOSSLESS LINE

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Since  $C = t_{pd}/Z_0$ , then  $C = [(e_r)^{1/2}t_{pd-vacuum}]/Z_0$

Since  $L = Z_0 t_{pd}$ , then  $L = Z_0 (e_r)^{1/2} t_{pd-vacuum}$

For  $Z_0 = 50 \Omega$  and  $e_r = 4.4$ :

$$C = [(4.4)^{1/2}(84.723 \text{ ps/inch})]/50 = 3.55 \text{ pF/inch}$$

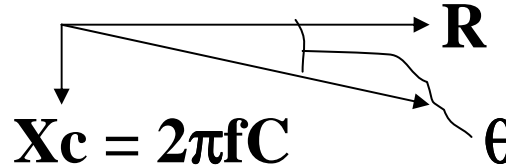
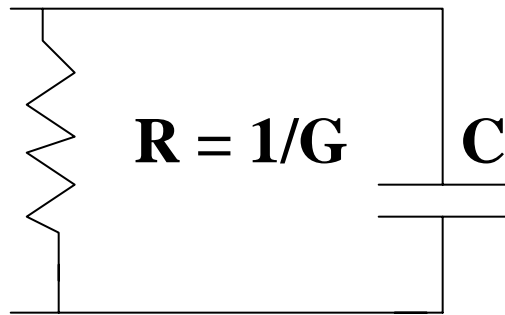
$$L = (50)(4.4)^{1/2}(84.723 \text{ ps/inch}) = 8.89 \text{ nH/inch}$$

**SCALING:** Double all dimensions, and the high frequency

L, C, and  $Z_0$  remain the same.

## GEE, DIELECTRIC LOSS or GOING OFF ON A TANGENT

; Dielectric loss is frequently expressed by the loss tangent.



$$\tan\theta = X_c/R = GX_c$$

$$R = X_c/(\tan\theta)$$

; Over a wide range of frequencies (1 MHz to 1 GHz) the dielectric loss tangent of FR-4 will range from 0.01 to 0.02. It will also vary with temperature and humidity (Reference 5).

## Dielectric Loss (continued)

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**; EXAMPLE: Given that  $C = 2.5$  pF/inch &  $\tan \theta = 0.015$  at 100 MHz and 1 GHz || Find  $G$  at 100 MHz and 1 GHz. Also, how much power is dissipated per inch for a 1 volt rms signal?**

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**@ 100 MHz,  $X_c = 636 \Omega$  ,  $G = \tan\theta/X_c = 0.015/636 = 23.6 \mu\text{Siemen}$**

**$P_d = GE^2 = (23.6 \mu\text{S})(1 \text{ V})^2 = 23.6 \text{ microwatt}$  ,  $R = 42.4 \text{ K}\Omega$**

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**@ 1GHz,  $X_c = 63.6 \Omega$  ,  $G = 0.015/63.6 = 236 \mu\text{S}$ ,  $P_d = 236 \mu\text{watt}$**

**$R = 4.24 \text{ K}\Omega$**

**Note that for constant tan loss, the actual loss is not constant.**

**Higher frequency, higher loss.**

**Higher capacitance (wider) traces will have more loss.**

## D.C. RESISTANCE

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;  $R_{dc} = \rho\lambda/A$ , where  $\rho$  = resistivity ( $1.724 \times 10^{-8} \Omega \cdot m$  for Cu @  $20^\circ C$ )

$\lambda$  = length in meters

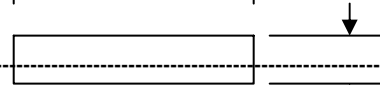
$A$  = cross sectional area in square meters

$R$  = resistance in Ohms

For  $\lambda$  in inches,  $A$  in mils squared, and  $\rho$  in  $\Omega \cdot m$

$$R_{dc} = \rho(\lambda/A)(0.3937 \times 10^8)$$

$$R_{dc} = (0.6787)(\lambda/A), \text{ for copper @ } 20^\circ C$$



$$R_{dc} = (0.6787)(\lambda/A) \quad \text{Cu @ } 20^\circ$$

$$R_{dc} = (0.6787)[\lambda/(w \cdot t)]$$

$w$  and  $t$  are in mils

## RESISTANCE and SKIN EFFECT

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; At “high” frequencies, the current in a conductor tends to flow only on the surface.

] *Skin depth*  $\delta$  may be thought of as the “effective” thickness of a conductor.

;  $\delta_{\text{meters}} = 0.0664/(f)^{1/2}$  for copper  $\delta_{\text{mils}} = 2,614/(f)^{1/2}$

; At what frequency is the skin depth of copper 82.5 mils?

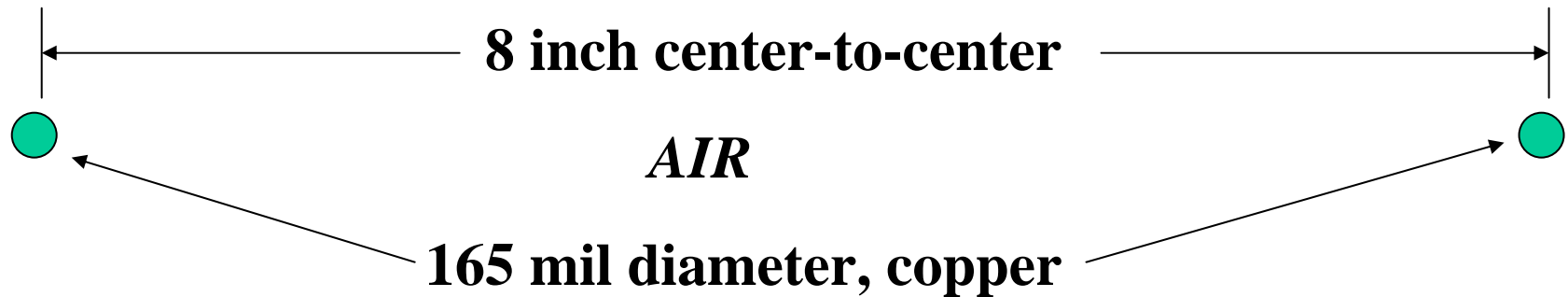
$$f = [2,614/(82.5 \text{ mils})]^2 = 1004 \text{ Hz}$$

; For other materials

$$\delta_{\text{meters}} = \{2/(\omega\mu\sigma)\}^{1/2} \text{ where } \mu = \text{permeability, } \sigma = \text{conductivity}$$

(Reference 6, page 439.)

## TWO-CONDUCTOR OPEN-WIRE PAIR



**; Look at resistance versus frequency (slide 15).**

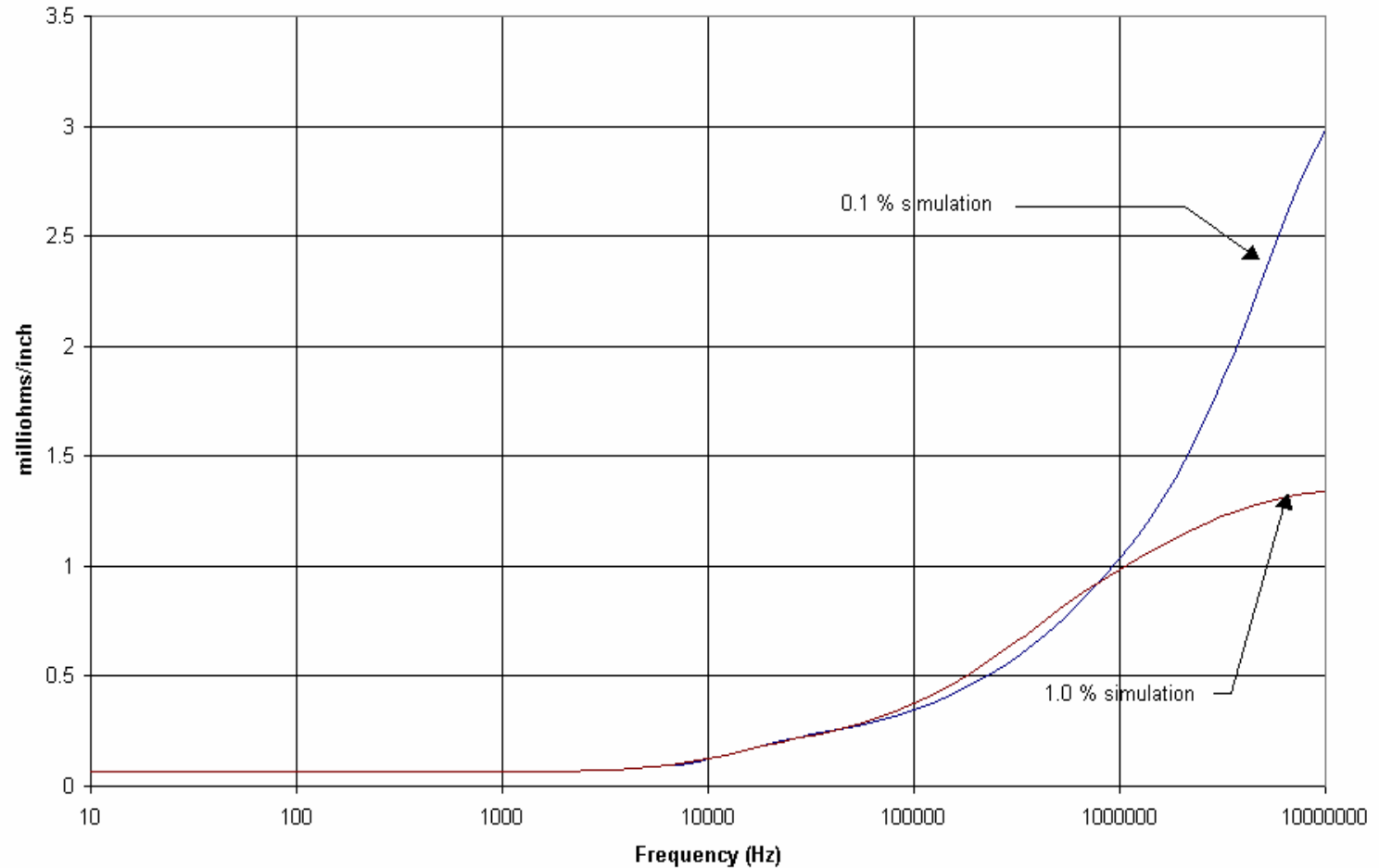
**Why does the 1.0 % field simulation flatten out so much sooner than the 0.1 % field simulation?**

**; Look at inductance versus frequency (slide 17).**

**Why does inductance decrease with increasing frequency?**

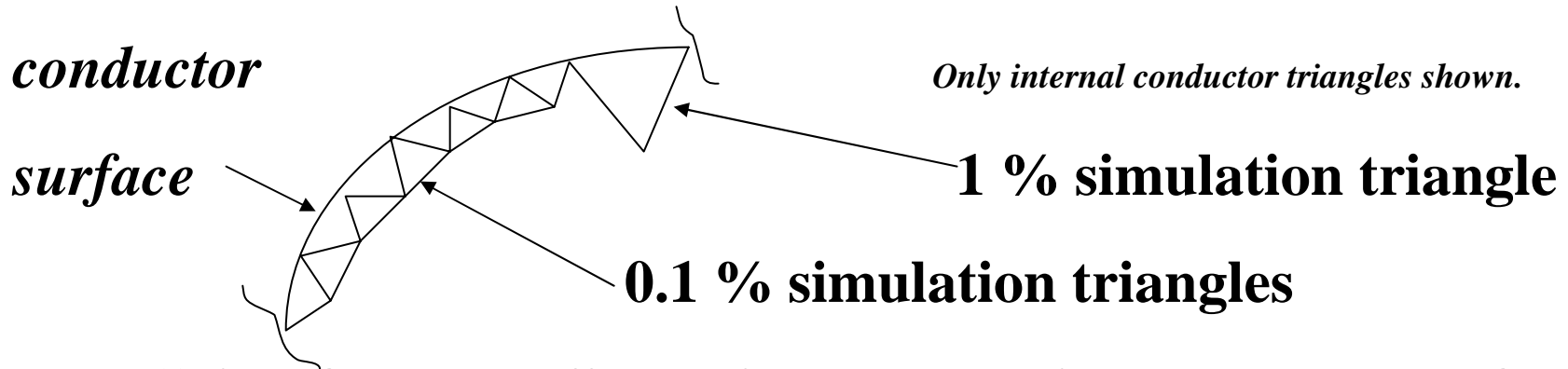
# Open-Wire Pair: Resistance versus Frequency, Simulation

RESISTANCE: Two Wire Pair -- 165 mil dia., 8 inch space



## When one meshes around ...

; When one meshes around at high frequency, one should only expect a skin depth relationship. Granularity determined by accuracy specification ( $\Rightarrow$  triangle size). *External triangles not shown.*

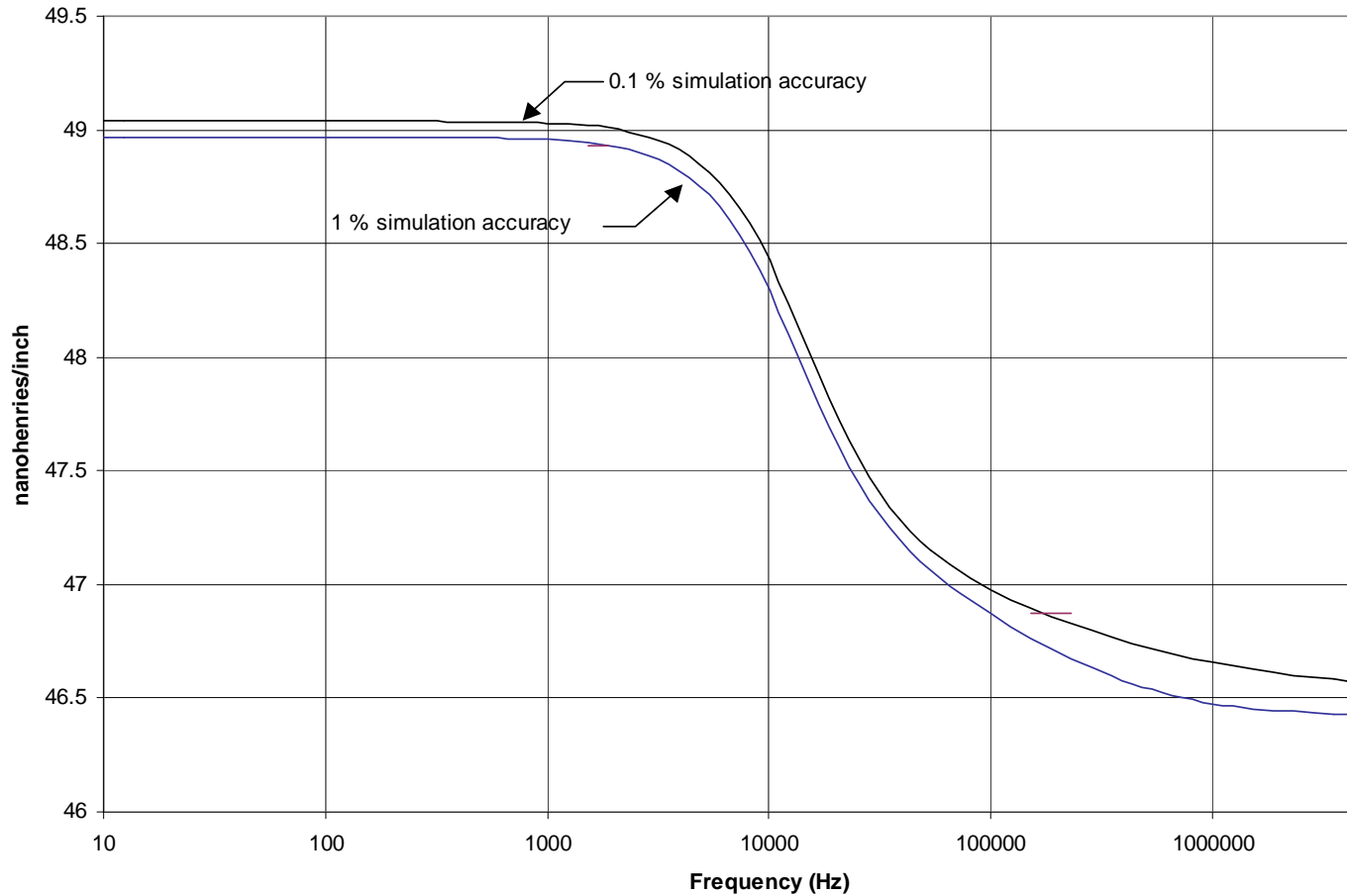


; For “high-frequency” solution, current is only on the surface and even the last interior triangles are gone. Its only a surface relationship.

# Open-Wire Pair: Inductance versus Frequency, Simulation

INDUCTANCE: Two Wire Pair -

165 mil diameter, 8 inch center to center



## INDUCTANCE and SKIN EFFECT

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- ; Reference 6 (pages 196 - 201) and Reference 7.**
- ; At low frequency current inside the conductor creates magnetic flux. This *internal* magnetic flux induces a field in the conductor, thus producing inductance. This *internal inductance* disappears at high frequency due to skin effect ... no internal current. Only the external field survives at high frequency.**
- ; For a *round* conductor, this internal inductance is 1.27 nH/inch for each conductor (2.54 nH/inch for the pair).**
- ; For rectangular conductors we have a *similar* effect but it is not the same value for all geometries.**

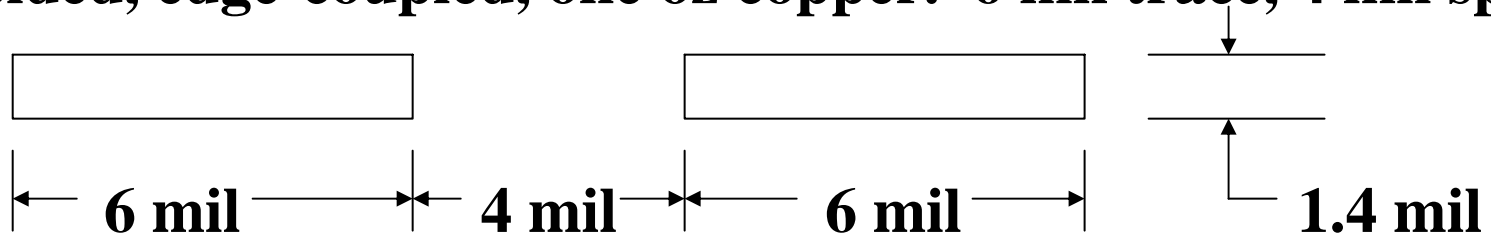
## **Inductance and Skin Effect (continued)**

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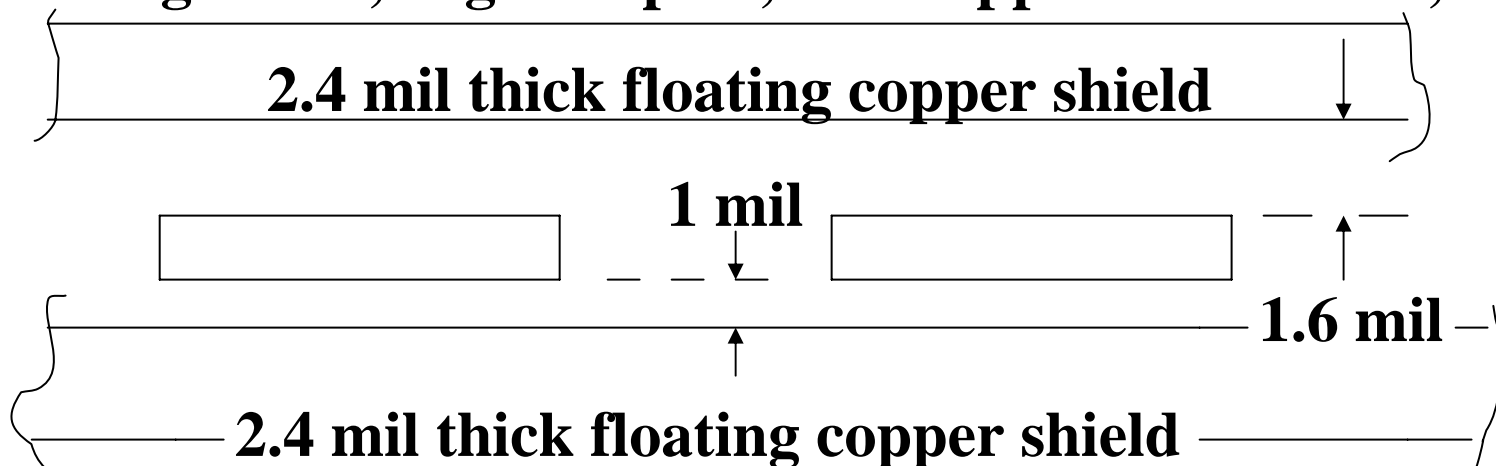
- ; The plot of L versus f for the open-wire pair matches handbook values within 0.25 % (references 7 and 8).**
- ; Consider a 1 oz copper trace (1.4 mil thick). The frequency for a skin depth of 0.7 mil is 13.9 MHz.**
- ; Consider a half ounce copper trace (0.7 mil thick). The frequency for a skin depth of 0.35 mil is 55.8 MHz.**
- ; If we measure  $Z_0$  by measuring open-circuit capacitance and short-circuit inductance [  $Z_0 = (L/C)^{1/2}$  ], what test frequency should we use? (Reference 9)**

## MODELING A FLEX CABLE

- : Provide a low inductance connection from write driver to tape drive write head (valid if write driver rise time  $\gg$  electrical length of interconnect).
- ; Unshielded, edge-coupled, one oz copper. 6 mil trace, 4 mil space.



- ; Floating shield, edge-coupled, 1 oz copper. 6 mil trace, 4 mil space.



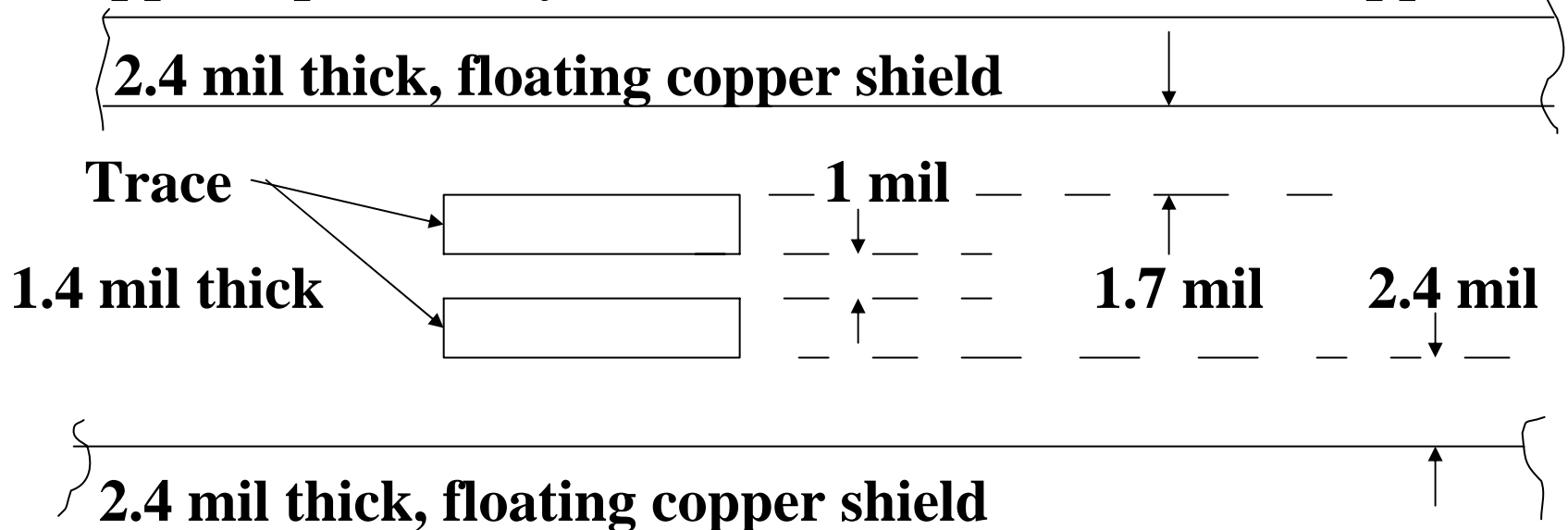
## Modeling A Flex Cable (2)

; The floating shield:

**Increases capacitive coupling between traces.**

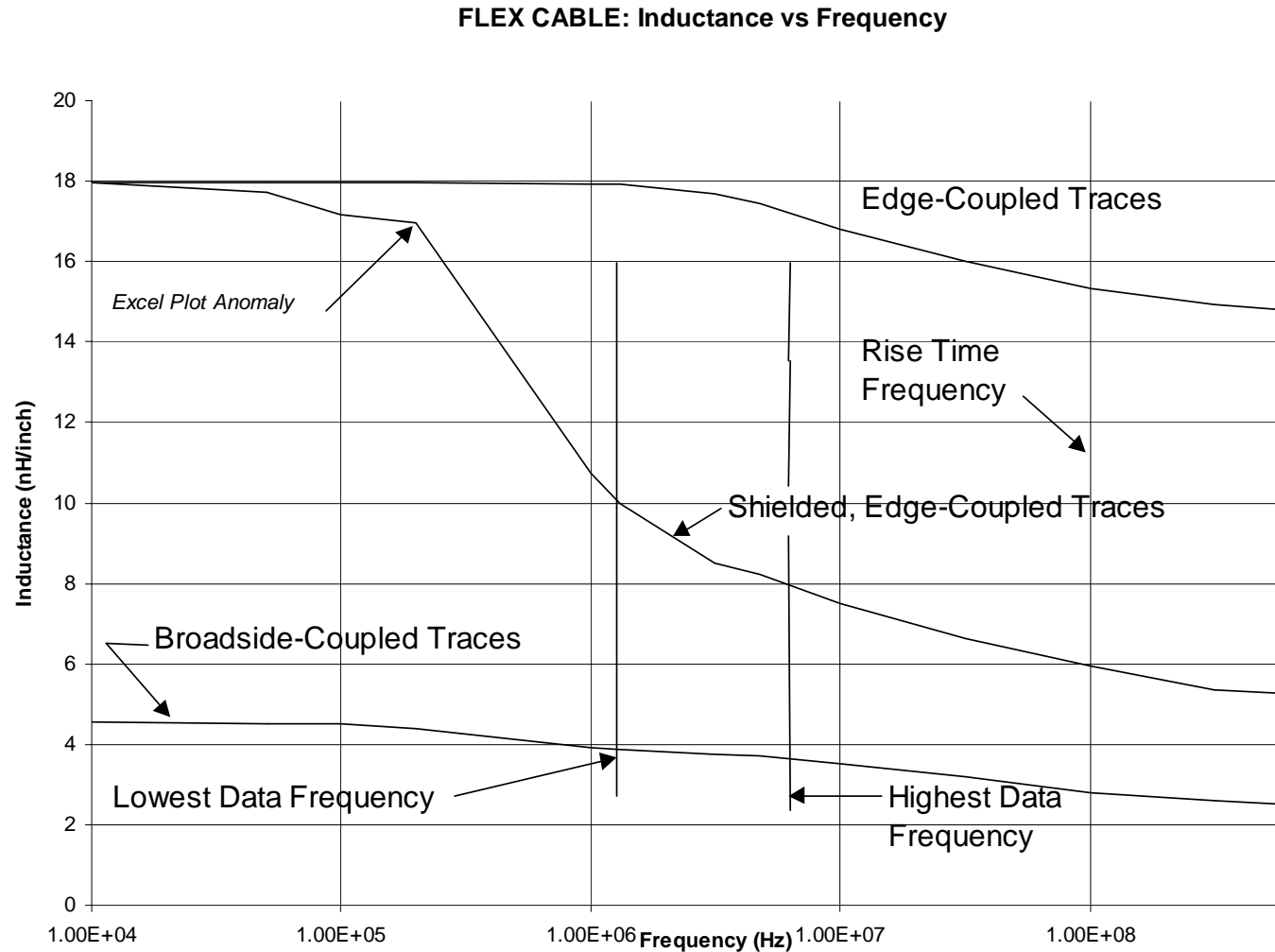
**Decreases inductance -- image plane current in shield reduces net flux and thus reduces inductance.**

; Floating shield, broadside-coupled pair: 10 mil wide traces, 1 oz copper separated by 1 mil. Shield is 2.4 mil thick copper.



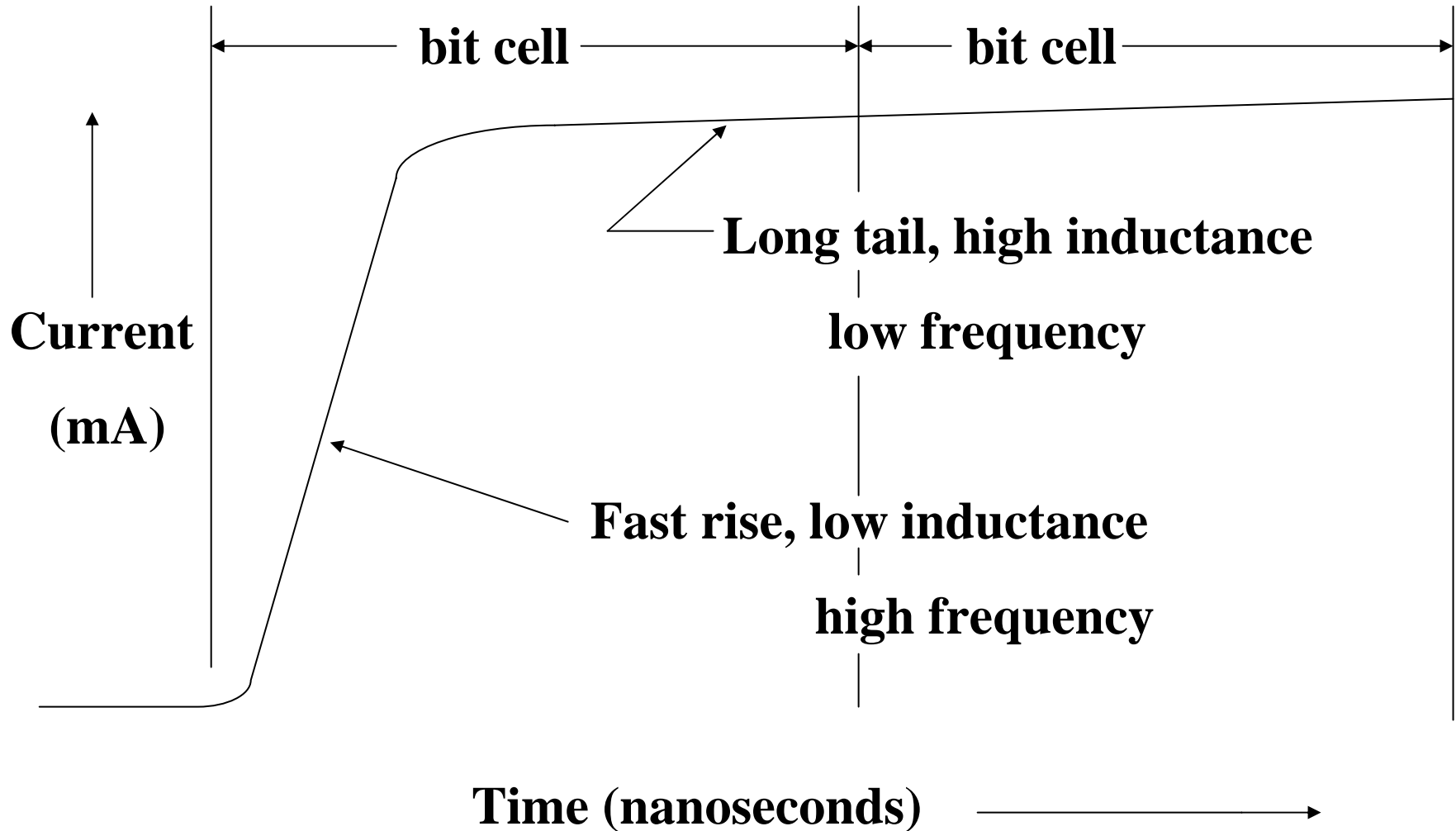
# Modeling A Flex Cable (3)

## Using Maxwell 2D field simulator to extract inductance



# Modeling A Flex Cable (4)

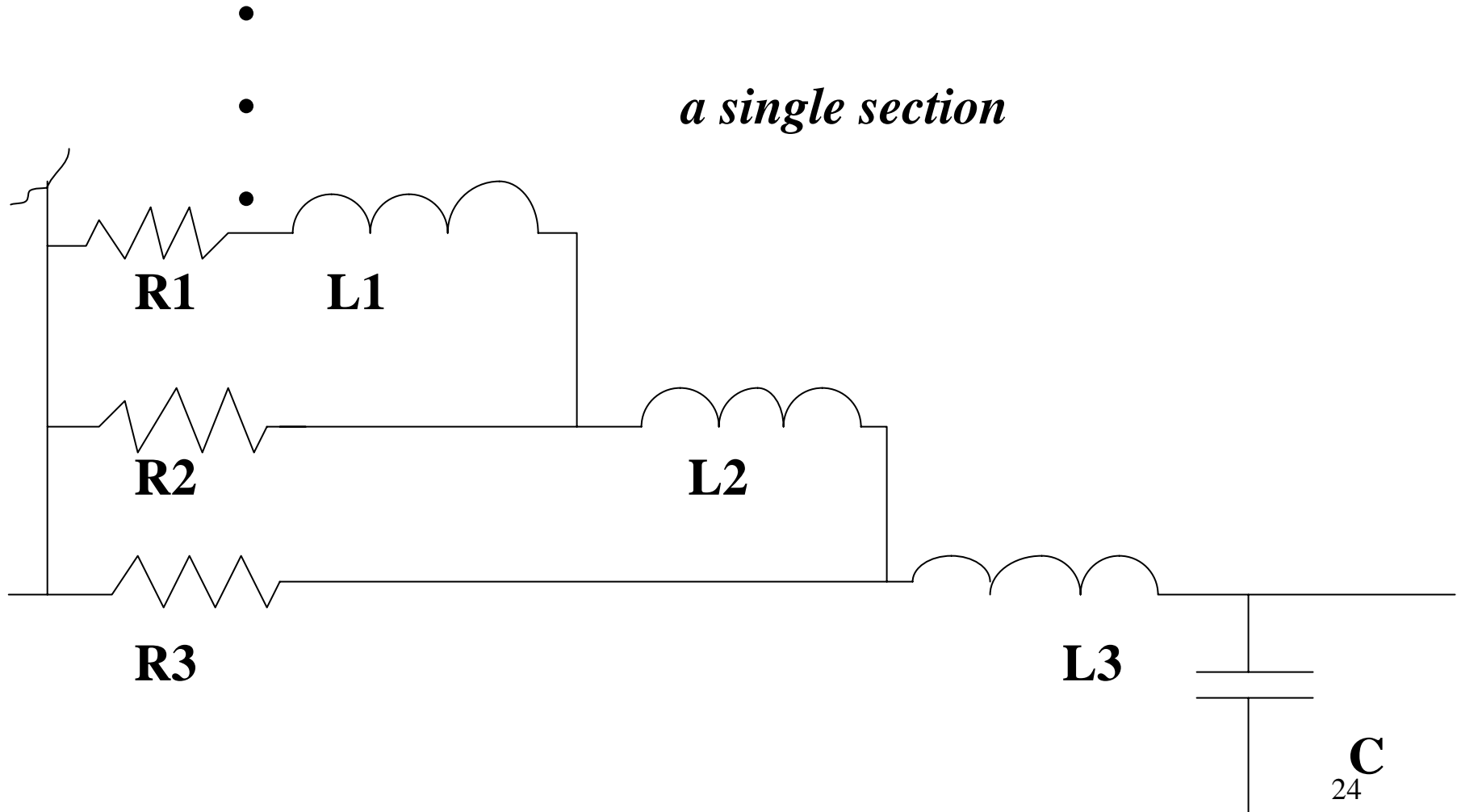
**Effect of frequency dependent inductance on write current:**



*Some patterns will write harder than others*

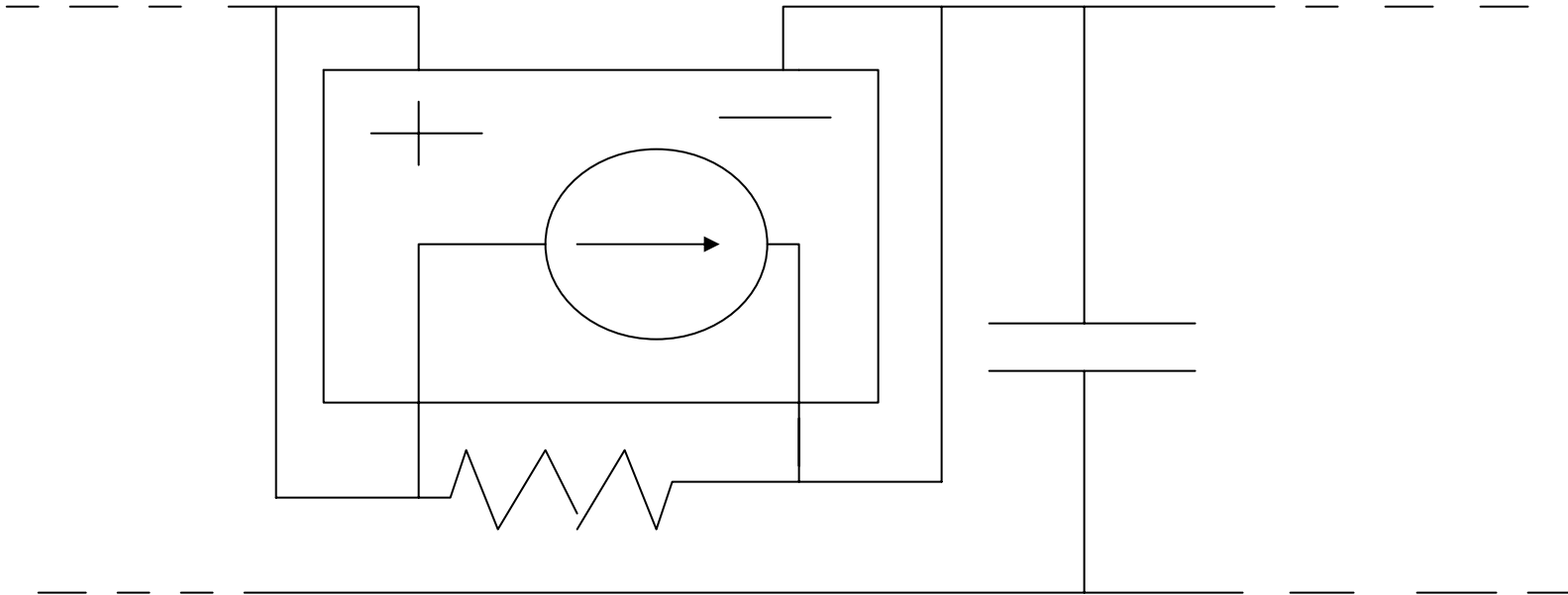
# MODELING FREQUENCY DEPENDENT R & L

; Passive method (Reference 10)



# Modeling Frequency Dependent R & L (continued)

; Active method applied to PSpice (Reference 7)



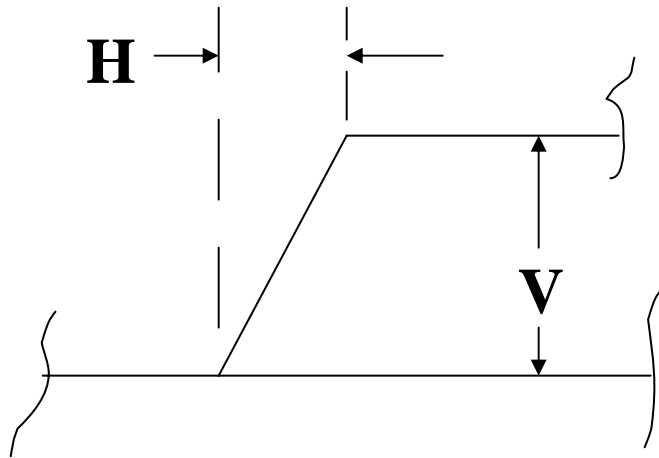
Make the resistor as large as possible, it is for computational stability.

Use the **FREQ** extension table: frequency, Hz     $1/|Z|$ , dB     $\Theta$ , degrees

$$\Theta = \arctan (X_L/R)$$

# ETCH FACTOR

**; The etching process causes trace cross-sections to be trapezoidal instead of rectangular. This can cause impedance deviation in excess of 6% relative to rectangular cross-section. (Reference 2)**



$$\text{Etch Factor} = V/H$$

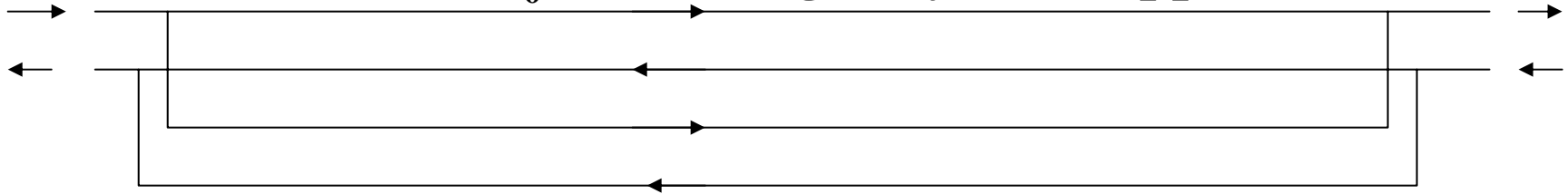
typical etch factors: 1:1 → 8:1

**; Etch factor varies from vendor to vendor, process line to process line. Can change as a process line is updated.**

# QuIP, The Quad Interdigitated Pair

[Four-Wire Interdigitated Pair (Reference 9)]

; How to achieve low  $Z_0$  with a single layer of copper.



; Flat cable experiment [mass termination (i.d.c.)]

Single pair (2 wire):  $Z = 134 \Omega$

QuIP (4 wire, interdigitated):  $Z = 57 \Omega$ , (43 % of 134  $\Omega$ )

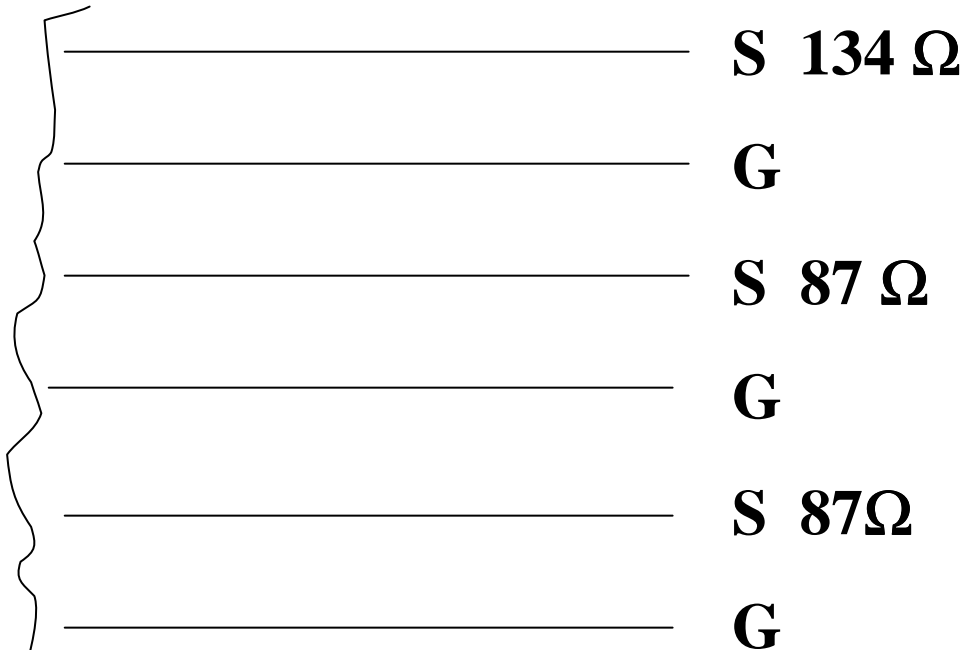
; Maxwell 2D simulation: 0.7 mil thick traces, 3 mil wide,

3 mil space, *air dielectric*, interdigitated

2 trace, 197  $\Omega$  / 4 trace, 85.4  $\Omega$  / 5 trace, 67.8  $\Omega$  / 6 trace, 54.0  $\Omega$

# FLAT CABLE IMPEDANCE MEASUREMENTS

; Mass termination: signal-ground-signal-ground-signal-ground ...



- . *The outer signal line is different*
- . *Than the rest. Terminate different*
- . *Or use for power.*

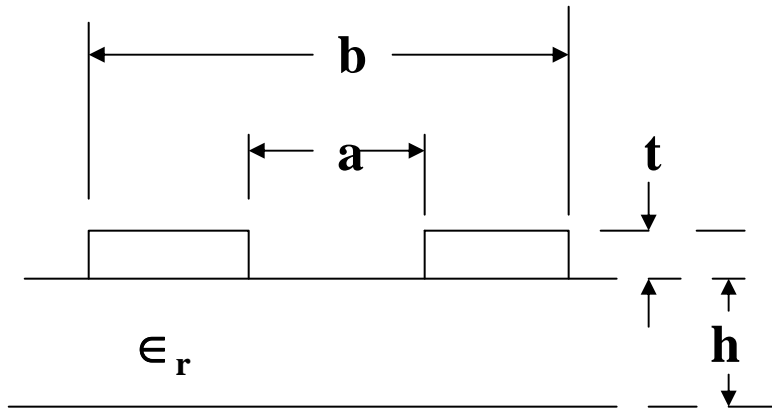
## EQUATION BASED DESIGN

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- ; With the exception of coaxial cable, all transmission line impedance calculations are approximations (admittedly some being better than others). [Reference 11]**
- ; Can be used as a starting point. Verify/finalize with field simulator.**
- ; Can you find your configuration in equation form?**
  - Floating shield, solder mask overlay, QuIP, etch factor, ...**
- ; Is the equation in a *usable form*? Rather than solving for  $Z$  in terms of  $l, w, t, \epsilon_r$ , can you solve for  $w$  in terms of  $Z, l, t, \epsilon_r$ ?**
- ; *Good* equation can be used for initial checkout of simulator.**

**(Learning curve)**

# Equation Based Design [EXAMPLE] (Reference 12, pp 83, 84, 463)



## Coplanar Strips

$$Z_0 = \frac{\eta}{(\epsilon_{\text{eff}})^{1/2}} \frac{K(k)}{K(k')}$$

$$\epsilon_{\text{eff}} = 1 + \frac{\epsilon_r - 1}{2} \frac{K(k') K(k_1)}{K(k) K(k_1')}$$

$$k = a/b$$

$$k' = (1.0 - k^2)^{1/2} \quad k_1' = (1.0 - k_1^2)^{1/2} \quad k_1 = \left\{ \frac{\sinh[(\pi a)/(4h)]}{\sinh[(\pi b)/(4h)]} \right\}$$

$$\frac{K(k)}{K(k')} \approx \frac{1.0}{2\pi} \ln \left\{ \frac{2.0[(1.0 + k)^{1/2} + (4k)^{1/4}]}{[(1.0 + k)^{1/2} - (4k)^{1/4}]} \right\}$$

For  $1.0 \leq K(k)/K(k') \leq \infty$  and  $0.707 \leq k \leq 1.0$

HEY, what about “t”? Doesn’t “t” affect  $Z_0$ ?

## **SOME FIELD SIMULATOR ATTRIBUTES TO CONSIDER**

- ; Can simulator model trapezoidal traces (etch factor)?**
- ; Do you need to model intermediate and low frequencies as well as high frequencies? Losses? Dispersion?**
- ; Do you need to model cables?**
- ; Do you need to evaluate floating shield (intentional or unintentional) effects?**

## **ACKNOWLEDGEMENTS**

**Thanks to Charles Grasso (Ansoft) and Steve Monroe (StorageTek) for running the simulator.**

## REFERENCES

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- 1] Johnson, Howard W. & Martin Graham, High-Speed Digital Design: A Handbook of Black Magic, PTR Prentice Hall, 1993, ISBN 0-13-395724-1.
- 2] Monroe, Steve & Otto Buhler, “Etch Factor and PWB Characteristic Impedance,” 11th Annual Regional Symposium on Electromagnetic Compatibility, Rocky Mountain Chapter of the IEEE EMC Society at the Radisson Inn, Northglenn, Colorado, Wednesday, October 3, 2001.
- 3] Chipman, Robert A., Theory and Problems of Transmission Lines, Schaum’s Outline Series, Mc Graw-Hill, 1968.
- 4] <http://www.physics.nist.gov/constants>
- 5] <http://www.dupont.com>     enter FR-4 in *search*
- 6] Ryder, John D., Networks, Lines and Fields, 2nd ed, Prentice Hall, 1955, p439.

## References (continued)

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- 7] Buhler, Otto and Charles Grasso, “Transmission Line Inductance and Proximity Effect,” 10th Annual Regional Symposium on Electromagnetic Compatibility, Rocky Mountain Chapter of the IEEE EMC Society at the Holiday Inn Denver Northglenn, May 23, 2000.
- 8] Reference Data For Radio Engineers, 5th ed., Howard W. Sams and Company, 1968, page 30-5.
- 9] Buhler, Otto, “Flat Cable Characteristic Impedance Reduction and Measurement Techniques,” 11th Annual Regional Symposium on Electromagnetic Compatibility, Rocky Mountain Chapter of the IEEE EMC Society, at the Radisson Inn, Northglenn, Colorado, Wednesday, October 3, 2001.
- 10] Yen, C., Z. Fazarinc and R. Wheeler, “Time-Domain Skin-Effect Model for Transient Analysis of Lossy Transmission Lines,” Proceedings of the IEEE, vol. 70, no. 7, July 1982, pp 750 - 757.

## References (continued)

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- 11] Bogatin, Eric, “Impedance Calculations,” available as publication ID73 from <http://www.gigatest.com>
- 12] Wadell, Brian C., Transmission Line Design Handbook, Artech House, Inc. 1991. ISBN 0-89006-436-9