SPEEDING EDGE

THE HOW AND WHY OF OBTAINING ACCURATE IMPEDANCE CALCULATIONS

SESSION W-17

PRESENTED AT SPRING IPC CONFERENCE

LONG BEACH, CALIFORNIA

PRESENTER LEE RITCHEY

WHAT IS IMPEDANCE?

- Impedance is the resistance to the flow of energy in a transmission line.
- At low frequencies, it is primarily the DC resistance of the bulk copper and is relatively small in PCB traces.
- At high frequencies it is primarily reactive and substantially higher than the DC or low frequency value.
- Reactance is both capacitive and inductive.

Bogatin, Eric, "What is Characteristic Impedance?" Printed Circuit Design, January 2000. Very good article.

WHAT IS CONTROLLED IMPEDANCE?

- **Controlling impedance is keeping all sources of impedance mismatch in a transmission line within limits that don't result in malfunctions caused by reflections at impedance changes.**
- **Perfect matching is not necessary. "Good enough" is all that is needed. Good enough can and needs to be calculated by the creator of the design rule set.**
- **Perfect impedance matching wastes time and money and does not contribute to better performance.**

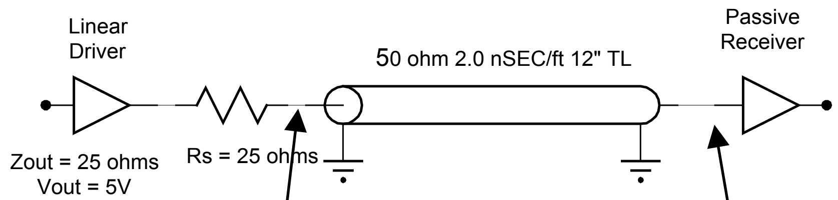
WHY IS CONTROLLED IMPEDANCE NEEDED?

- **Energy in the form of an electromagnetic wave propagates down transmission lines.**

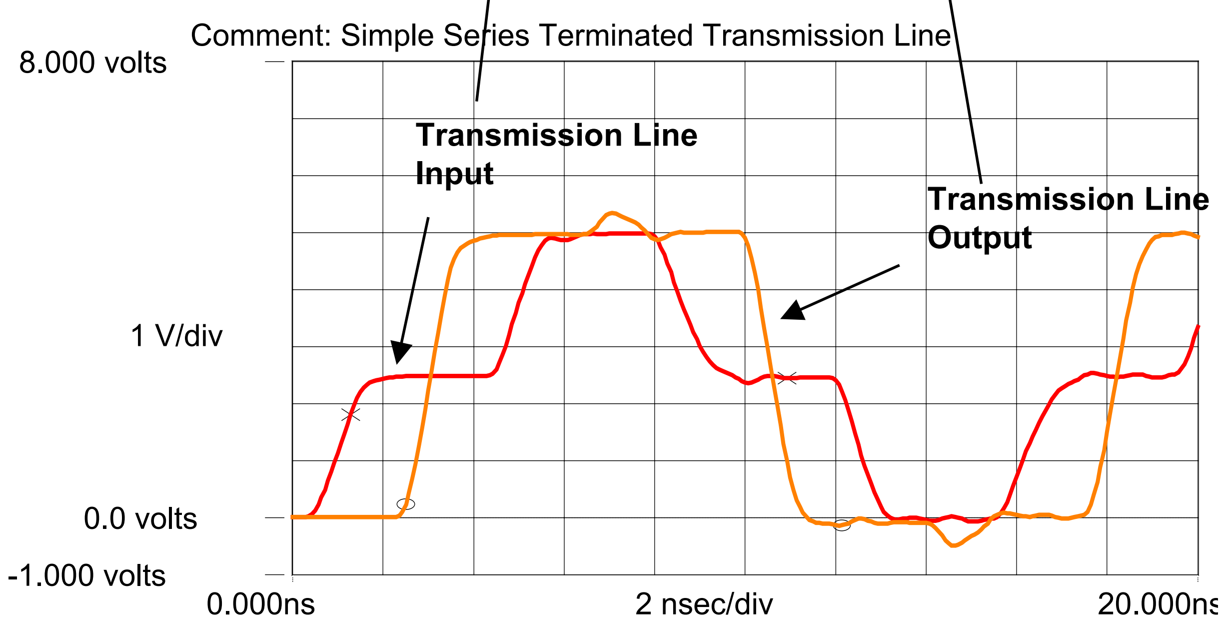
- **At points along the transmission line where there are impedance changes, some of that energy reflects back to the source.**

- **This reflected energy can destructively degrade a signal.**

A SIGNAL WITH CONTROLLED IMPEDANCE

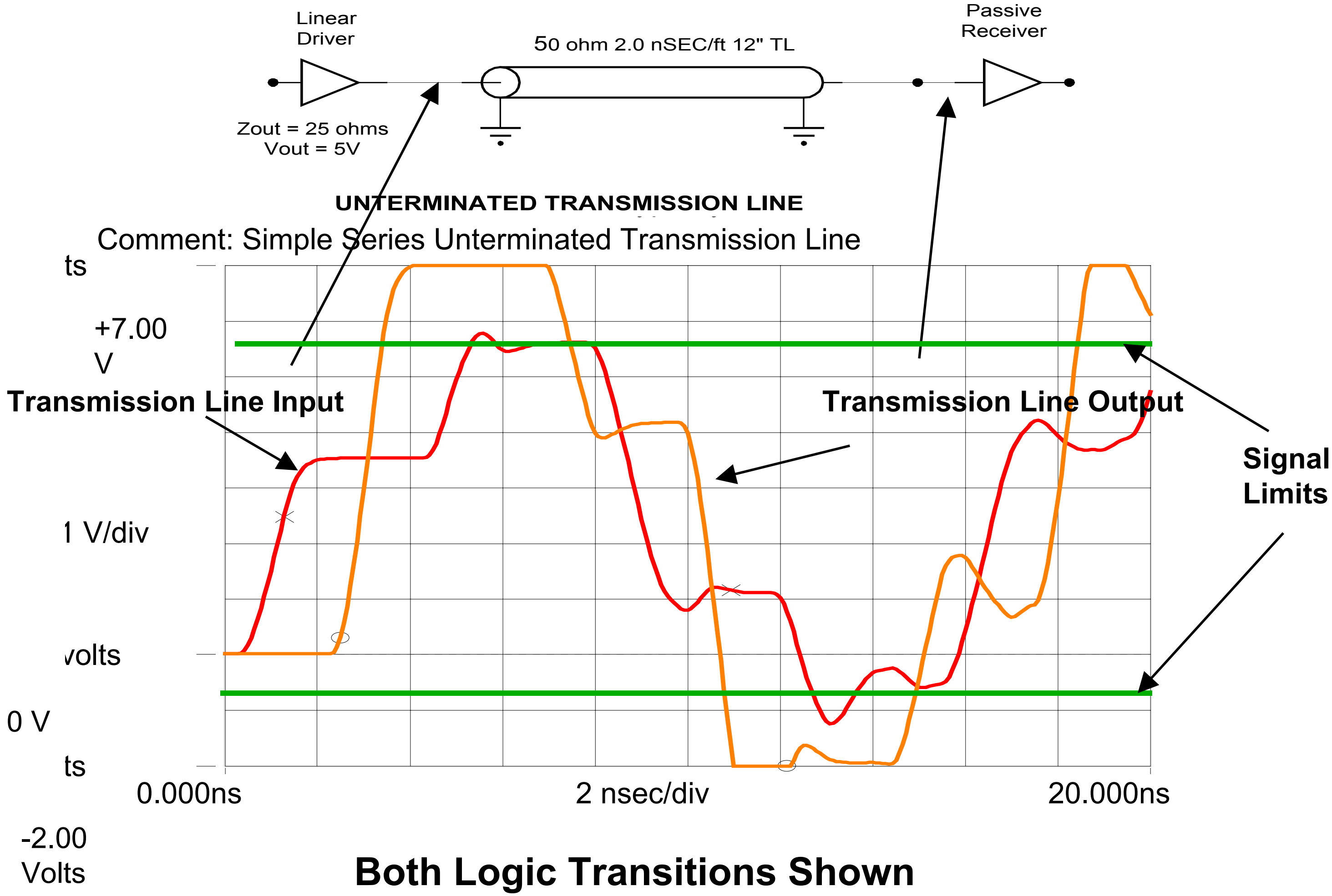


SERIES TERMINATED TRANSMISSION LINE



Both Logic Transitions Shown

A SIGNAL WITHOUT CONTROLLED IMPEDANCE



Both Logic Transitions Shown

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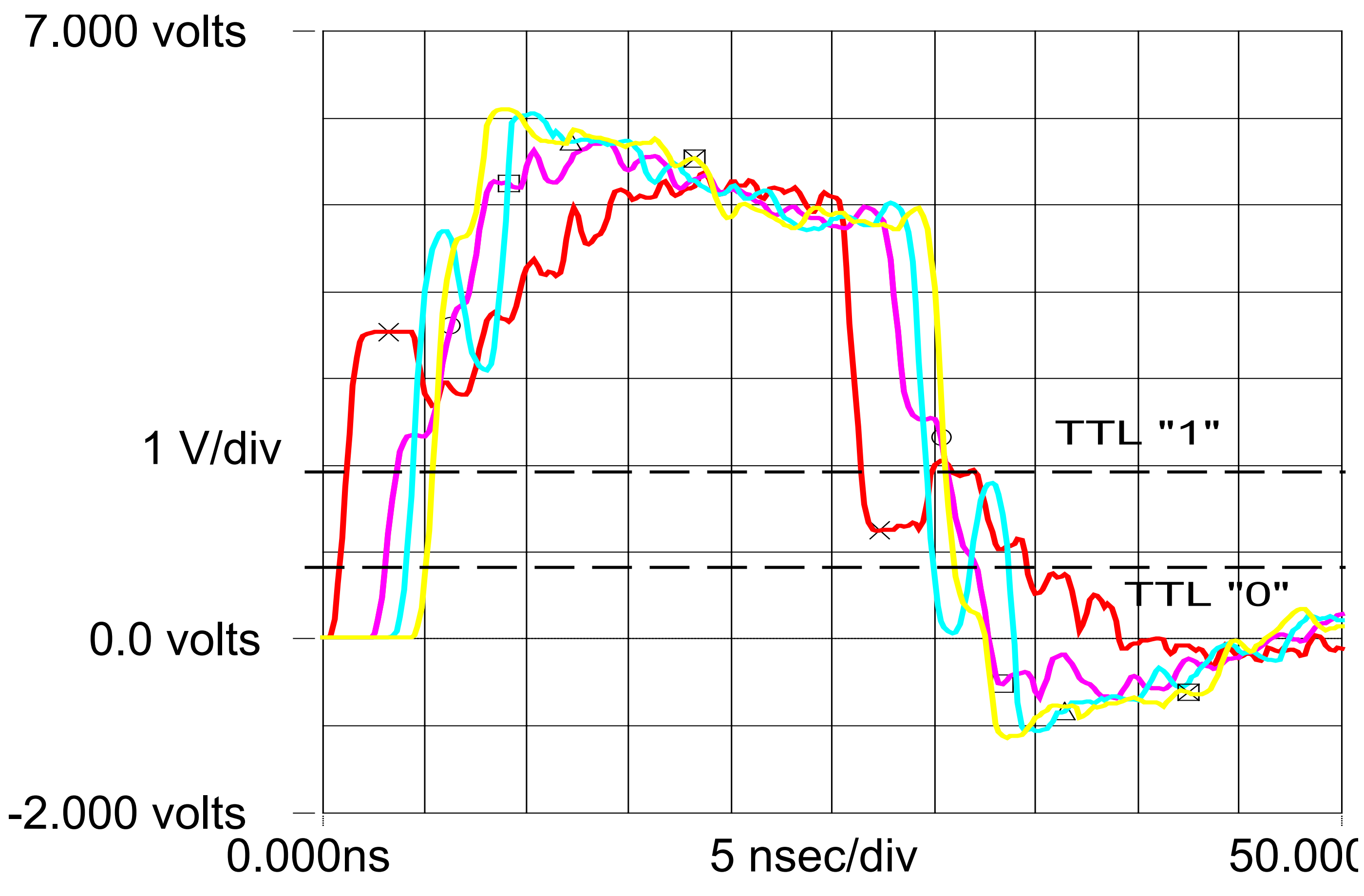
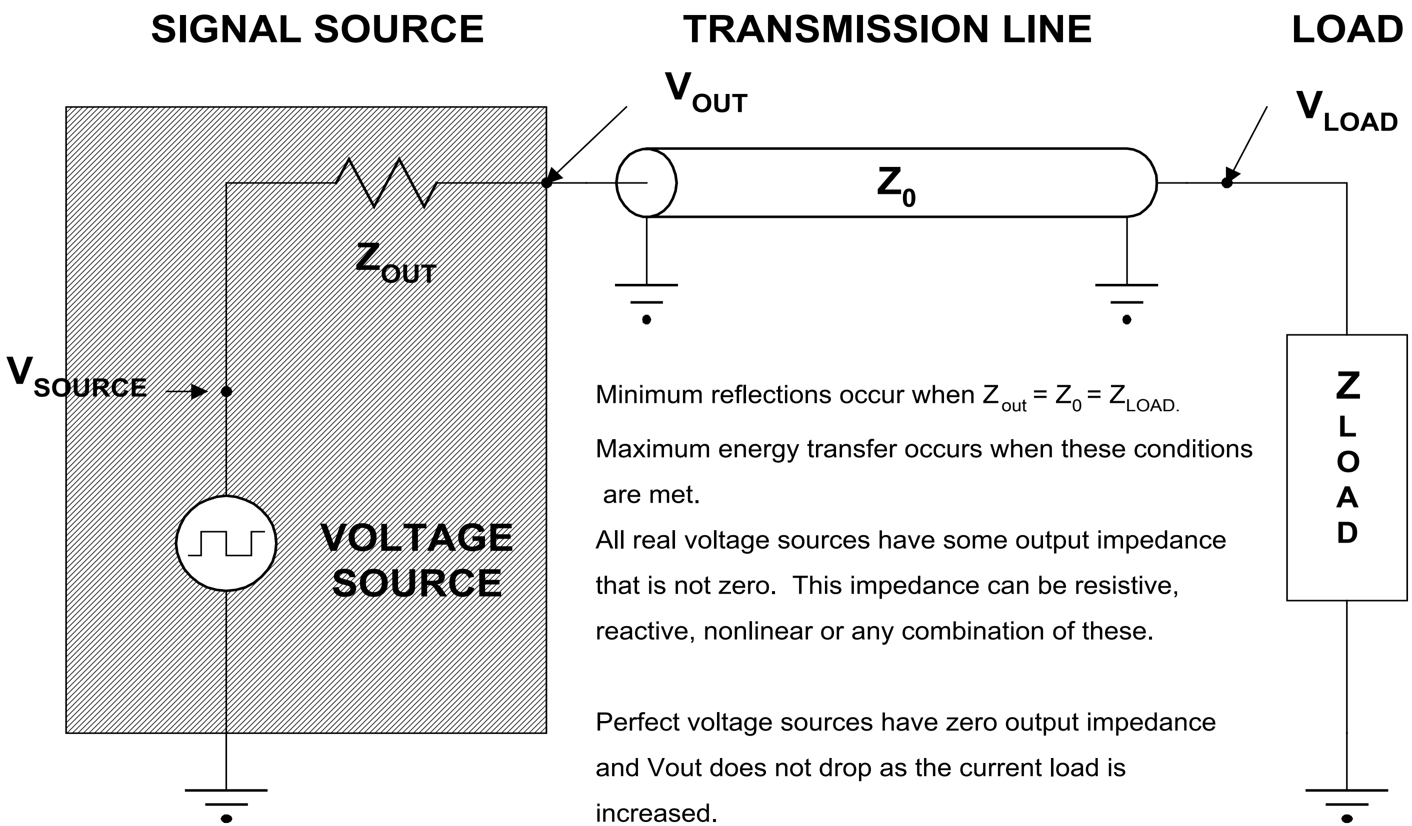
A VERY POORLY MANAGED TRANSMISSION LINE



A TYPICAL CIRCUIT



Minimum reflections occur when $Z_{out} = Z_0 = Z_{LOAD}$.

Maximum energy transfer occurs when these conditions are met.

All real voltage sources have some output impedance that is not zero. This impedance can be resistive, reactive, nonlinear or any combination of these.

Perfect voltage sources have zero output impedance and Vout does not drop as the current load is increased.

TYPICAL TRANSMISSION LINE SYSTEM

THE REFLECTION EQUATION

Z_l = LOAD IMPEDANCE OR DOWNSTREAM IMPEDANCE

Z_O= LINE IMPEDANCE OR UPSTREAM IMPEDANCE

% = AMOUNT OF INCOMING SIGNAL REFLECTED

$$\% = 100 \frac{Z_l - Z_O}{Z_l + Z_O}$$

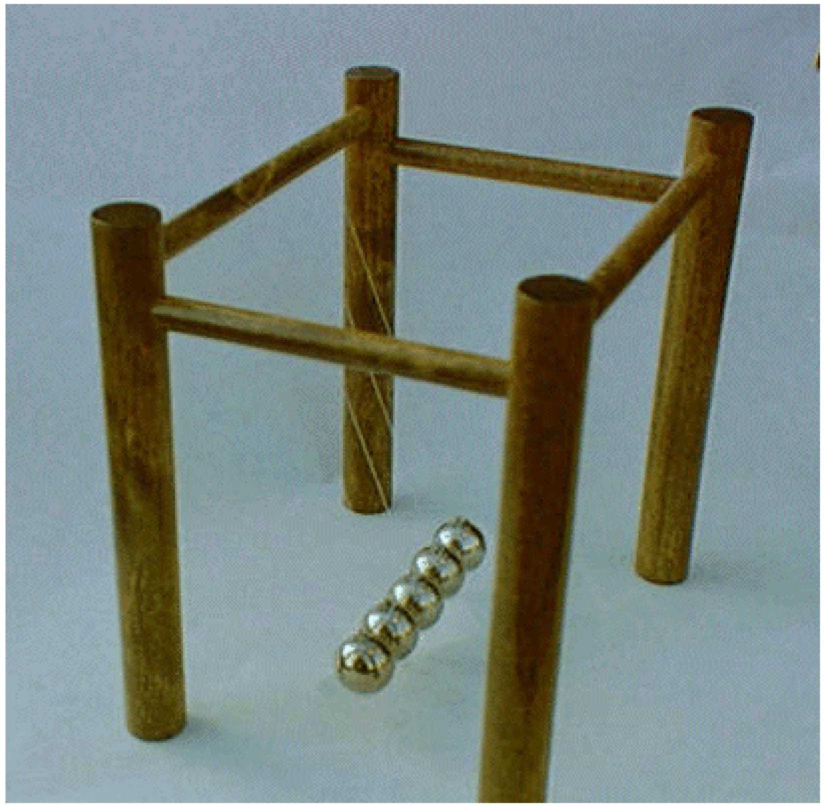
Note: This equation applies to any impedance mismatch. Use Z_o for the signal source side of the mismatch and Z_l for the load side of the mismatch.

WHAT IS A TRANSMISSION LINE?

- A transmission line is any pair of conductors that are used to move *electromagnetic energy* from one place to another.
- In printed circuit boards, this is typically a trace and one or two power planes.
- Other examples of transmission lines:
  - Power lines are transmission lines.
  - Waveguides are transmission lines.
  - TV twin lead is a transmission line.
  - Coaxial cable is a transmission line.
  - Twisted pairs are transmission lines.

Note: All of these have a characteristic impedance and use the same rules for managing signal quality.

A MECHANICAL TRANSMISSION LINE



Mechanical energy is coupled from one end of the line of masses to the other with an acoustic wave that travels at the speed of sound through the masses.

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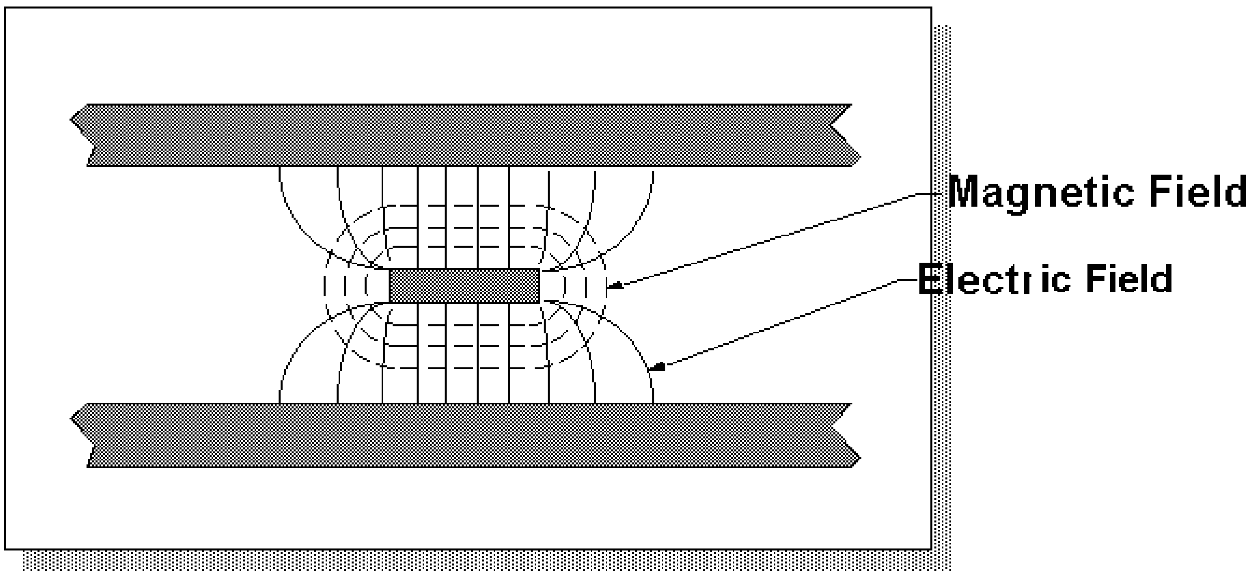
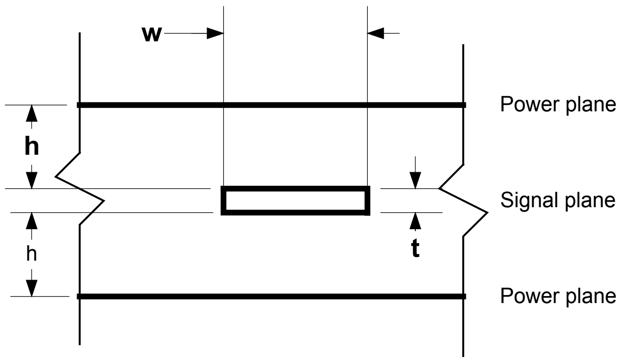
STRIPLINE CIRCUIT WITH ELECTROMAGNETIC FIELDS

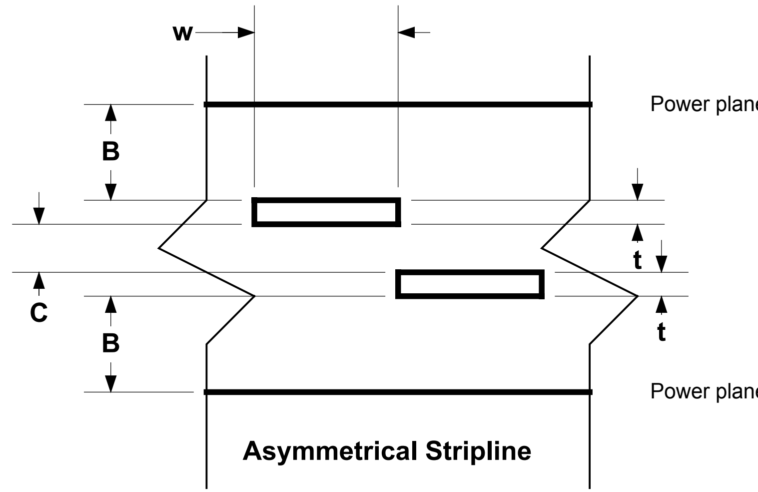


NOTES: Magnetic Field Exists Only When Current is Flowing.
Electric Field Exists Only When There is a Voltage Difference Between Line and Surroundings

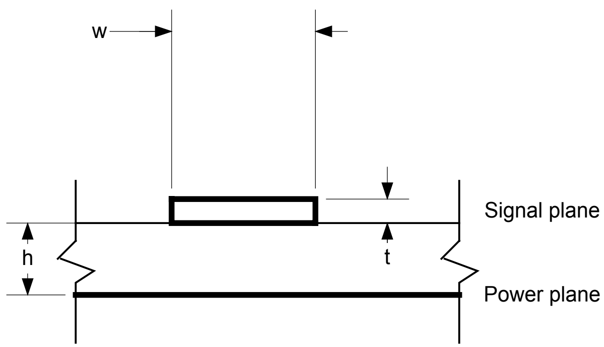
Bogatin, Eric, "What is Characteristic Impedance?" Printed Circuit Design, January 2000. Very good article.



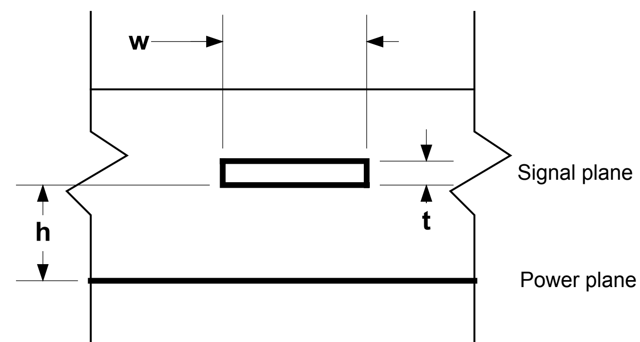
Symmetrical or Balanced Stripline



Asymmetrical Stripline



Surface Microstripline



Buried Microstripline

FOUR BASIC TYPES OF PCB TRANSMISSION LINES

NOTE: VARIABLES ABOVE CORRESPOND TO THOSE USED IN THE IMPEDANCE EQUATIONS IN THIS COURSE.

TRADITIONAL METHODS FOR CALCULATING IMPEDANCE

- **Equations have been developed over time that allow engineers and fabricators to calculate the impedance of PCB transmission lines based on the geometry and the dielectrics being used.**
- **All equations are partial solutions, valid over a limited range of variables.**
- **When equations don’t yield accurate results, iterative adjustments have been made to make the equations fit.**

A PRACTICAL IMPEDANCE EQUATION FOR SURFACE MICROSTRIP

e_r = RELATIVE DIELECTRIC CONSTANT

H = HEIGHT OF TRACE ABOVE PLANE

W = TRACE WIDTH

T = TRACE THICKNESS

Z_O = TRACE IMPEDANCE IN OHMS

ANY DIMENSION SYSTEM IS APPLICABLE

NOTE: VALID FOR 5<w<15 MILS

A more precise calculation can be obtained using a 2D field solver which the author recommends.

$$Z_0 = \frac{79}{\sqrt{e_r + 1.41}} \ln\left(\frac{5.98H}{0.8W + T}\right)$$

e_r value is that obtained from velocity measurements made with a TDR.

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BURIED MICROSTRIP IMPEDANCE EQUATION

Z_O = TRANSMISSION LINE IMPEDANCE (OHMS)

H = HEIGHT OF LINE ABOVE POWER PLANE

W = TRACE WIDTH

T = TRACE THICKNESS

e_r = RELATIVE DIELECTRIC CONSTANT

Valid for 5 < W < 15 mils, valid for any dimension system

Assumes at least 5 mils of dielectric lying on top of trace.

A more precise calculation can be obtained using a 2D field solver which the author recommends.

$$Z_0 = \left(43.037 \ln \frac{H}{W}\right) + 5.048\left(\frac{T}{W}\right) + \frac{106.76}{1.09\sqrt{e_r}}$$

Equation developed by Martin Marietta in mid 1980s.

ASYMMETRIC STRIPLINE IMPEDANCE EQUATION

- Z_0 = TRANSMISSION LINE IMPEDANCE
- B = TRACE TO PLANE SPACING
- C = TRACE PLANE TO TRACE PLANE SPACING
- T = TRACE THICKNESS
- W = TRACE WIDTH
- e_r = relative dielectric constant of insulator
- FOR C = 0, equation applies to centered stripline
- Valid for 5 < W < 15 mils

A more precise calculation can be obtained using a 2D field solver which the author recommends.

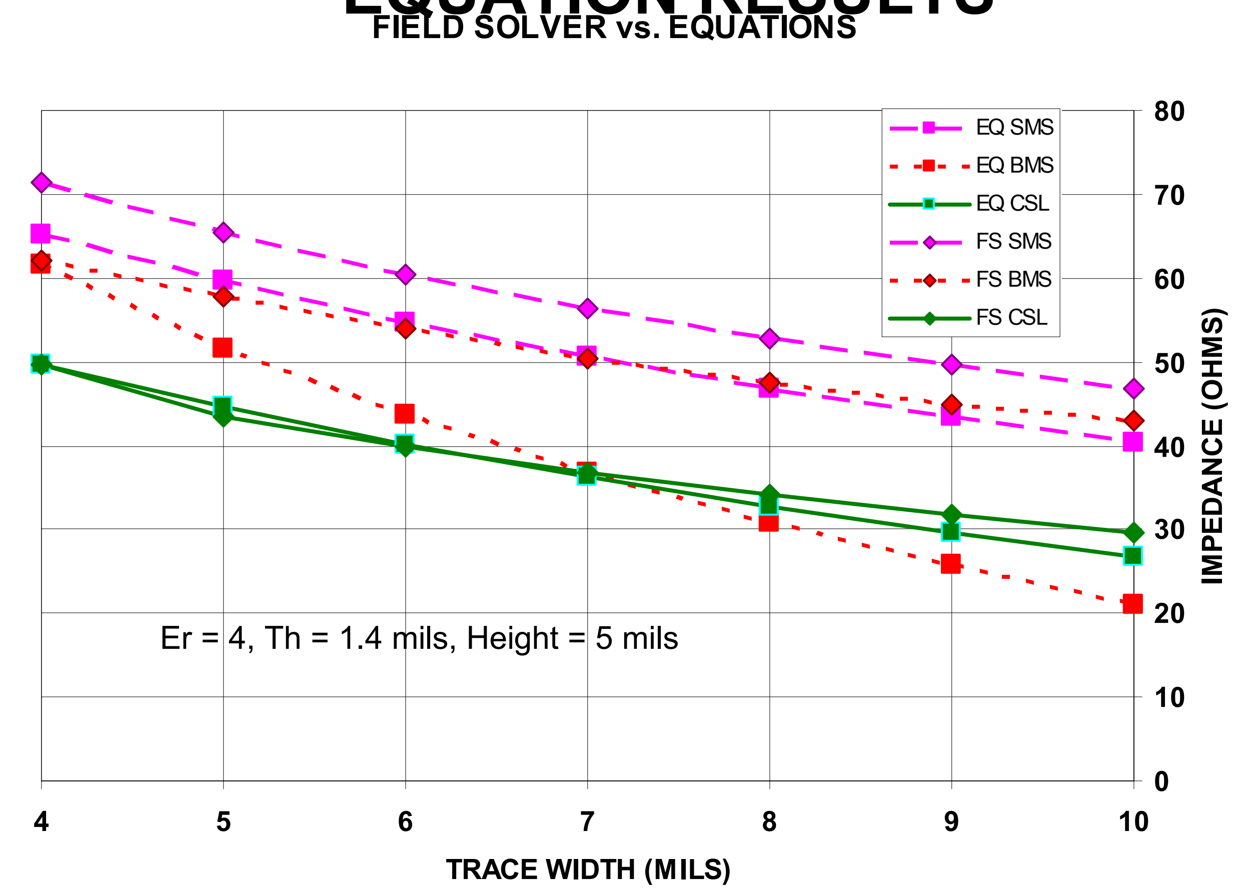
$$Z_0 = 80\left[\frac{1-\dfrac{B}{4(B+C+T)}}{\sqrt{e_r}}\right]\ln\left[\frac{1.9(2B+T)}{(0.8W+T)}\right]$$

Equation developed by DEC in the mid 1980s.

PROBLEMS WITH TRADITIONAL IMPEDANCE CALCULATION METHODS

- **All impedance calculating equations are approximations.**
- **Outside their range of validity, the results are often significantly off.**
- **This coupled with incorrect dielectric constants (e_r) for the insulating materials results in many errors.**
- **Fabricators with significant experience building controlled impedance PCBs know this and compensate empirically for errors.**

COMPARING FIELD SOLVER RESULTS TO EQUATION RESULTS



SMS = Surface microstrip, EMS = embedded microstrip, CSL = centered stripline

R, L, C TRANSMISSION LINE MODEL

O - R - L - R - L - R - L - R - L - O

I I I I

C C C C

I I I I

G G G G

O = END OF LINE

G = GROUND PLANE

C = CAPACITANCE PER UNIT LENGTH

R = RESISTANCE PER UNIT LENGTH

L = INDUCTANCE PER UNIT LENGTH

Model assumes ground is a plane of negligible inductance and resistance.

The following equations permit one to calculate the reactance of capacitors and inductors as a function of frequency.

$$Xc = \frac{1}{2\Pi fC}$$

Xc = Capacitive Reactance

$$X_L = 2\Pi fL$$

X_L = Inductive Reactance

THE IMPEDANCE EQUATION

Z_O = CHARACTERISTIC IMPEDANCE OF LINE

L_O = INDUCTANCE PER UNIT LENGTH

C_O = CAPACITANCE PER UNIT LENGTH

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

As capacitance is added to a transmission line (example: periodic loads) the impedance goes down. Note that impedance is independent of length and frequency.

This equation is useful only when there is a ready means for determining values per unit length.

HOW TO DETERMINE L_o AND C_o

- **L_o is a function of the shape of the transmission line and its proximity to other conductive structures.**
- **C_o is also a function of the shape of the transmission line and its proximity to other conductive structures. It is also a function of the dielectric constant of the insulation between the component parts of the transmission line (e_r).**
- **Maxwell's equations provide a method for calculate these two accurately. 2D and 3D field solvers use Maxwell's equations to calculate Lo and Co.**

The D stands for dimension. 2D is adequate for this job.

SOME 2D FIELD SOLVERS FOR IMPEDANCE CALCULATIONS

- Hyperlynx Linsym- Does whole cross section at once, allows mixed materials. Also differential pairs.
- Ansoft EZ2D- Does single transmission line at a time. Calculates Lo and Co. Can calculate skin effect.
- Polar Instruments Si6000c- Calculates single transmission line at a time. Also does diff. pairs.
- Cadence Spectraquest- Does whole cross section at once. Does differential pairs.
- Mentor Interconnectix ICX- Does whole cross section at once. Does differential pairs.
- Veribest PCB- Same as Cadence Spectraquest.
- Applied Simulation Technologies RLGC
- Linpar

WHAT IS RELATIVE DIELECTRIC CONSTANT, e_r?

- **Relative dielectric constant, e_r, is a measure of the affect an insulator has on the capacitance of a pair of conductors as compared to the same conductor pair in a vacuum.**
- **The dielectric constant of a vacuum is 1. All materials have dielectric constants higher than 1.**
- **The common method for measuring e_r is the parallel plate method at 1 MHz. *A more useful method for transmission line design is signal velocity in the dielectric.***

REASONS AN ACCURATE e_r IS NEEDED

- **The speed with which signals travel on a transmission line is affected by the dielectric used to build it. The higher the e_r, the slower a signal will travel. This affects timing.**

- **The impedance of a transmission is affected by the e_r of the dielectric used to build it. The higher the e_r, the lower the impedance.**

AN EQUATION FOR CALCULATING e_r USING VELOCITY MEASURED WITH A TDR

- C = SPEED OF LIGHT, .0118 INCH/pSEC
- V = MEASURED PROPAGATION VELOCITY

$$\sqrt{e_r} = \frac{C}{V}$$

NOTE: All dielectrics slow electromagnetic waves down according to the above formula.

DIELECTRIC CONSTANTS AND WAVE VELOCITIES OF PCB MATERIALS

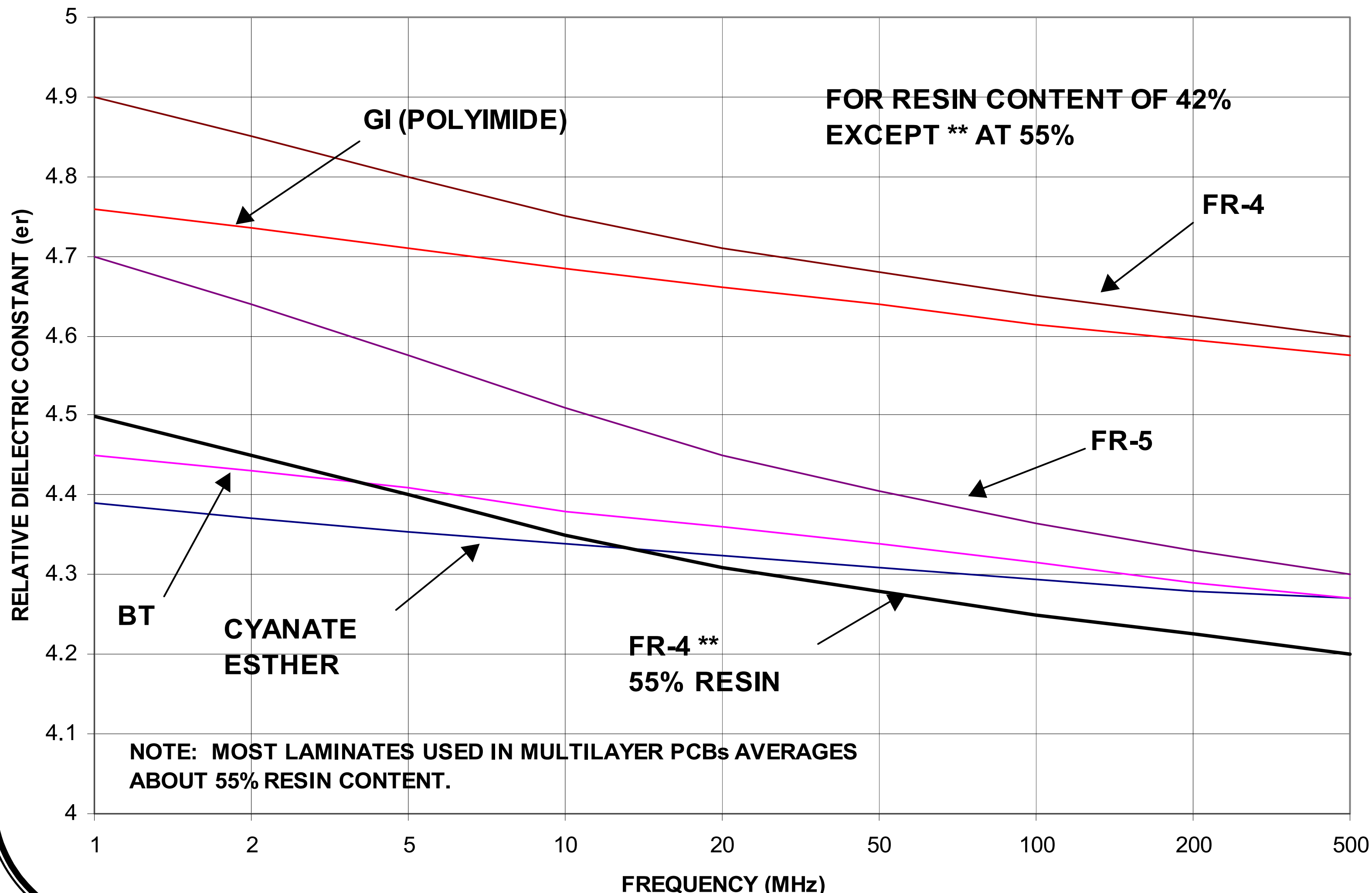
MATERIAL	e_r	VELOCITY (in/nSEC)	VELOCITY (pSEC/in)
AIR	1.0	11.76	84.9
PTFE/GLASS	2.2	7.95	125.8
ROGERS RO 2800	2.9	6.95	143.9
CE/GOREPLY	3.3	5.97	167.0
GETEK	3.9	6.21	161.0
CE/GLASS	3.7	6.12	163.0
SILICON DIOXIDE	3.9	5.97	167.0
BT/GLASS	4.0	5.88	170.0
POLYIMIDE/GLASS	4.1	5.82	172.0
FR-4/GLASS	4.1	5.82	172.0
GLASS CLOTH	6.0	4.70	212.0
ALUMINA	9.0	3.90	256.0
WATER	73.0	0.4	2200.0

Note: e_r values for glass reinforced materials are for 55% resin content.

VALUES MEASURED AT TDR FREQUENCIES USING VELOCITY TECHNIQUE, NOT AT 1 MHz.

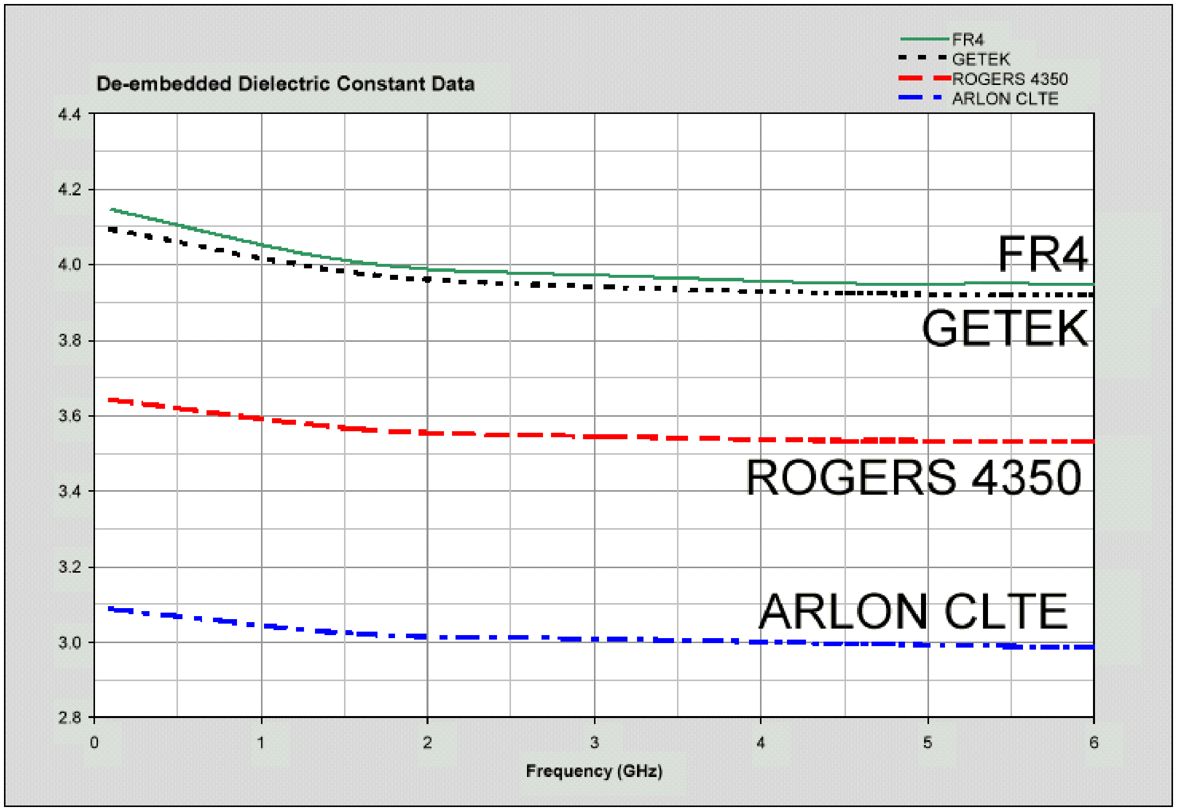
RELATIVE DIELECTRIC CONSTANT vs. FREQUENCY

FOR VARIOUS LAMINATES



Materials Comparison

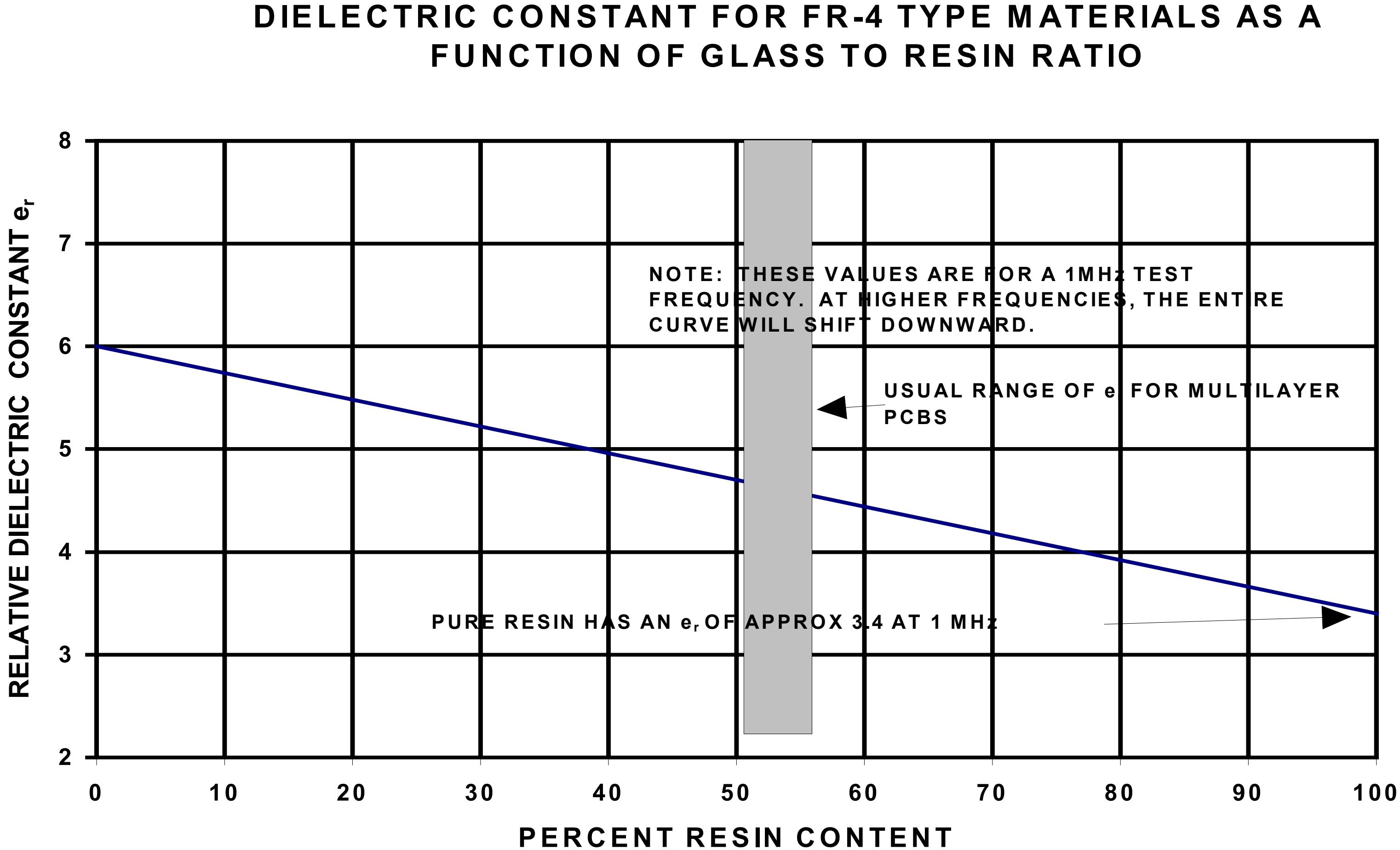
- Dielectric constant (ε_r) vs. frequency



Morgan, Chad & Helster, Dave, "The Impact of PWB Construction on High-Speed Signals"DesignCon99.

Courtesy AMP Circuits and Design 3/99

DIELECTRIC CONSTANT AS A FUNCTION OF GLASS TO RESIN RATIO



SOME PROPERTIES OF HI Tg "FR-4" LAMINATE

Data courtesy of NELCO

Thickness	Construction	Resin Content	er @ 1 MHz	er @ 1 GHz
.002	1 x 106	69.0%	3.84	3.63
.003	1 x 1080	62.0%	4.00	3.80
.004	1 x 2113	54.4%	4.19	4.00
.004	1 x 106 + 1 x 1080	57.7%	4.11	3.91
.004	1 x 2116	43.0%	4.54	4.37
.005	1 x 106 + 1 x 2113	52.8%	4.24	4.05
005	1 x 2116	51.8%	4.26	4.08
.006	1 x 1080 + 1 x 2113	52.2%	4.25	4.06
.006	1 x 106 + 1 x 2116	50.8%	4.29	4.11
.006	2 x 2113	43.5%	4.52	4.35
.007	2 x 2113	49.6%	4.33	4.14
.008	1 x 7628	44.4%	4.49	4.32
.010	2 x 2116	51.8%	4.26	4.08
.014	2 x 7628	38.8%	4.69	4.53

Under construction, the three or four digit number refers to the glass weave type.

SPEEDING EDGE

SOME PROPERTIES OF NELCO 4000-13 LAMINATE

Data courtesy of NELCO

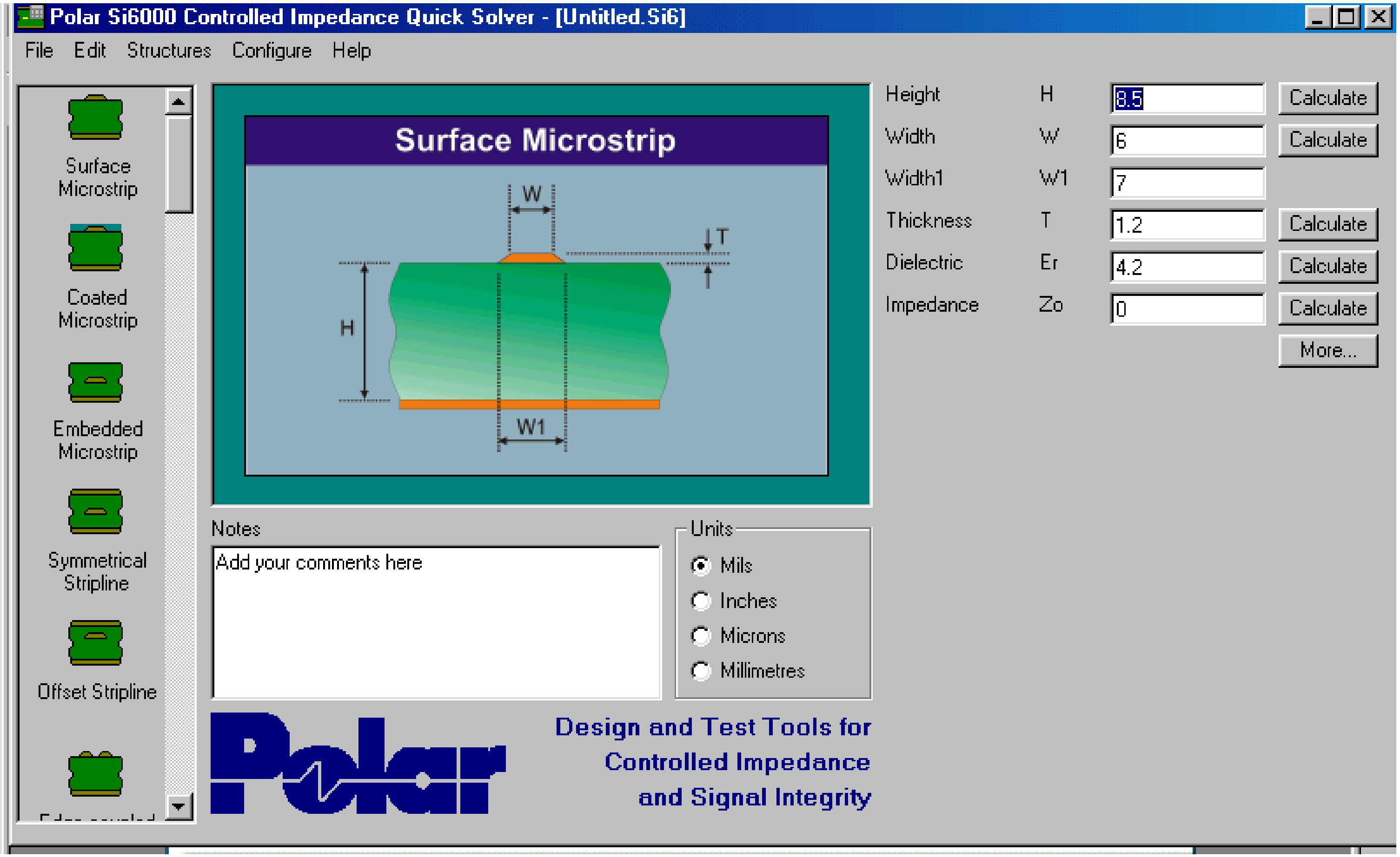
Thickness	Construction	Resin Content	er @ 1 MHz	er @ 1 GHz
.002	1 x 106	68.3%	3.43	3.33
.003	1 x 1080	61.2%	3.61	3.51
.004	1 x 2113	53.8%	3.8	3.7
.004	1 x 106 + 1 x 1080	56.9%	3.72	3.53
.0045	2 X 1080	51.4%	3.86	3.76
.005	2 X 1080	55.2%	3.67	3.57
005	1 x 2116	51.0%	3.87	3.67
.006	1 x 1080 + 1 x 2113	51.4%	3.86	3.66
.006	1 x 106 + 1 x 2116	50.0%	3.80	3.70
.006	2 x 2113	42.7%	3.99	3.88
.007	2 x 2113	48.8%	3.83	3.73
.008	2 X 2116	47.85	3.86	3.75
.010	2 x 2116	51.0%	3.87	3.77
.011	2 x 106 + 1 x 7628	47.7%	3.86	3.76

Under construction, the three or four digit number refers to the glass weave type.

WHAT FREQUENCY TO USE WHEN DETERMINING THE VALUE OF e_r?

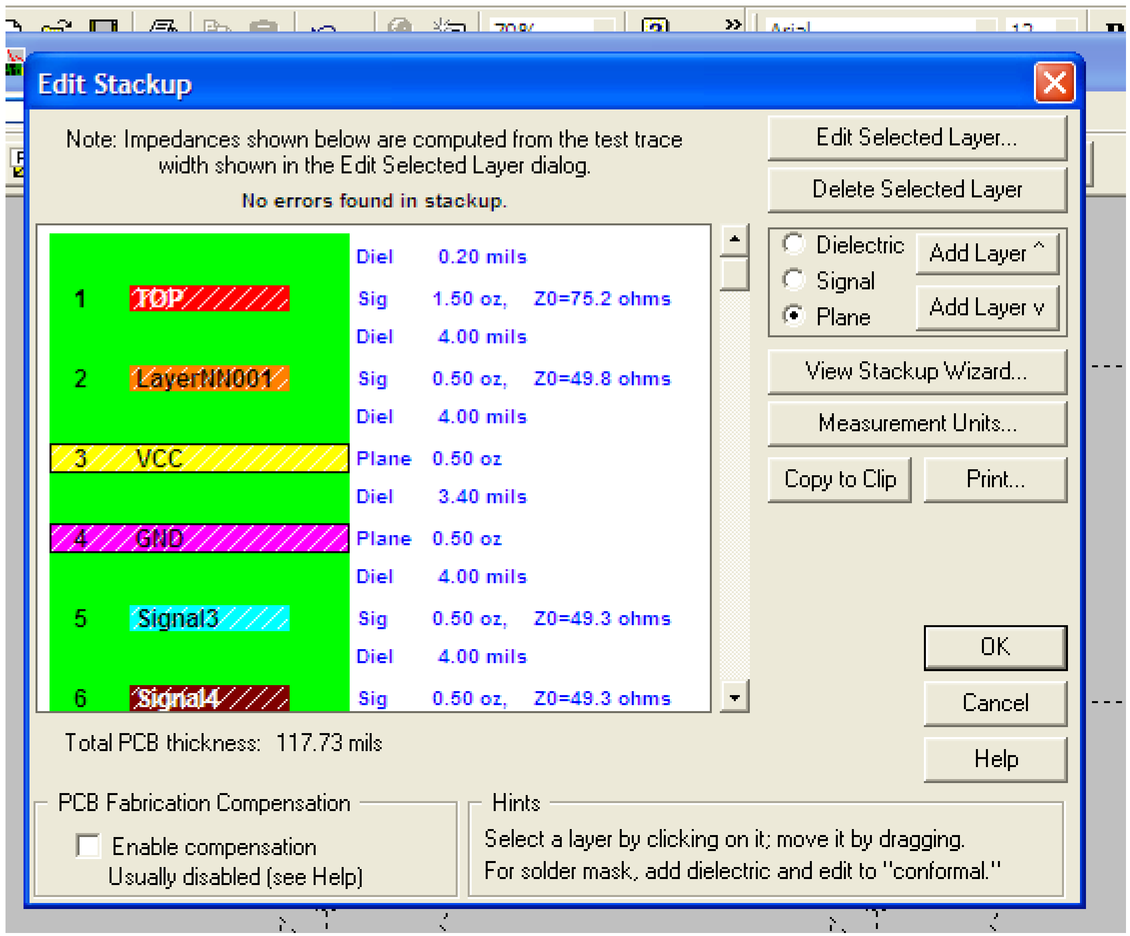
- As can be seen from earlier data, the relative dielectric constant of virtually all laminates varies with frequency.
- Traditionally, the 1 MHz value has been used to calculate impedance. Why? Because that was the only frequency at which it was specified for most materials.
- Impedance matching needs to be done for the frequencies that make up the switching edges.
- The first harmonic of a switching edge is approximately, F in GHz = 0.35/tr, where tr, the rise time, is in nanoseconds.
- As a practical matter, most switching edges are so fast that the 1 GHz value of e_r will yield good values for Z

THE CONTROL SCREEN FOR THE POLAR INSTRUMENTS Si6000b 2D FIELD SOLVER



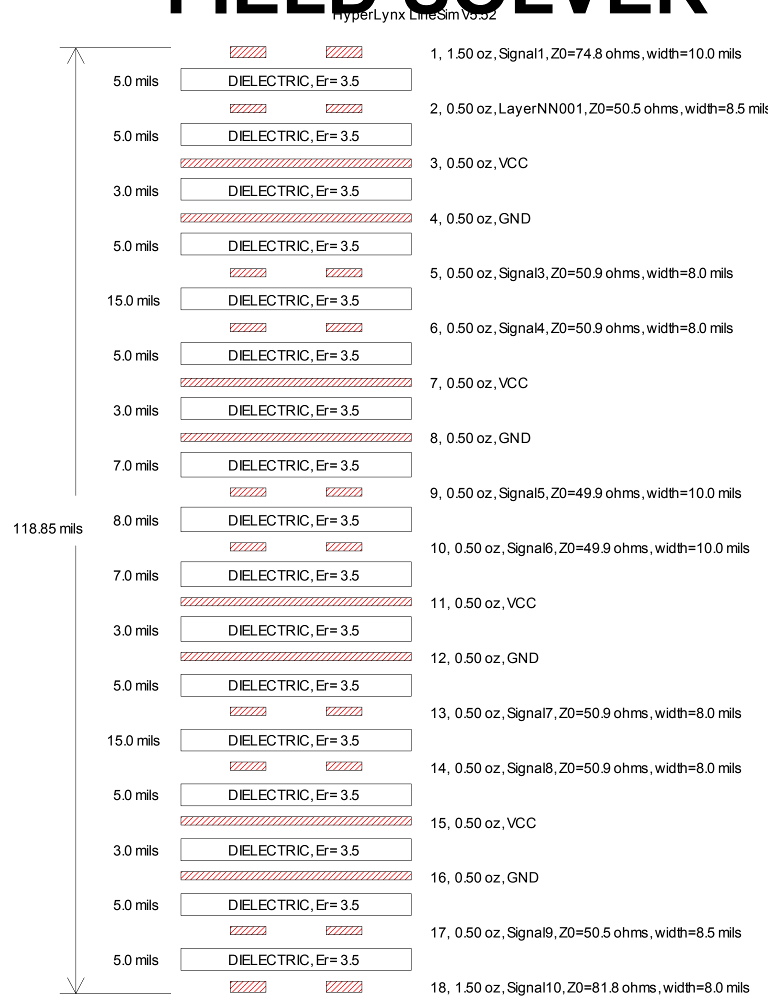
COURTESY POLAR INSTRUMENTS

THE CONTROL SCREEN FOR THE HYPERLYNX 6.0 FIELD SOLVER



COURTESY OF HYHPERLYNX

A STACKUP USING A MULTILAYER FIELD SOLVER



SOME RESULTS

Layer		STACKUP		TRACE WIDTH	Zo HP	Zo Polar	Zo F.S	Zo HL STK
1		---------------						
		5						
2		---------------		8.6	51.1	49.9	52.2	54.3
		5.7						
3	---------------	---------------	--------------					
		2						
4	---------------	---------------	--------------					
		5.7						
5		---------------		9.3	49.5	47.7	48.8	50.8
		18						
6		---------------		9.5	50.4	48.7	48.3	48.2
		5.2						
7	---------------	---------------	--------------					
		1.5						
8	---------------	---------------	--------------					
		6.3						
9		---------------		9.3	51	49	51.1	49.8
		8.5						
10		---------------		9.5	51.1	49.3	51.1	50
		6.6						
11	---------------	---------------	--------------					
		1.5						
12	---------------	---------------	--------------					
		5.1						
13		---------------		9.4	53	47.9	52	52.2
		17.5						
14		---------------		9.4	51	49.3	52	49.5
		5.5						
15	---------------	---------------	--------------					
		1.5						
16	---------------	---------------	--------------					
		5.2						
17		---------------		8.5	52	49.9	52	51.6
		5.5						
18		---------------			409.1	391.7		

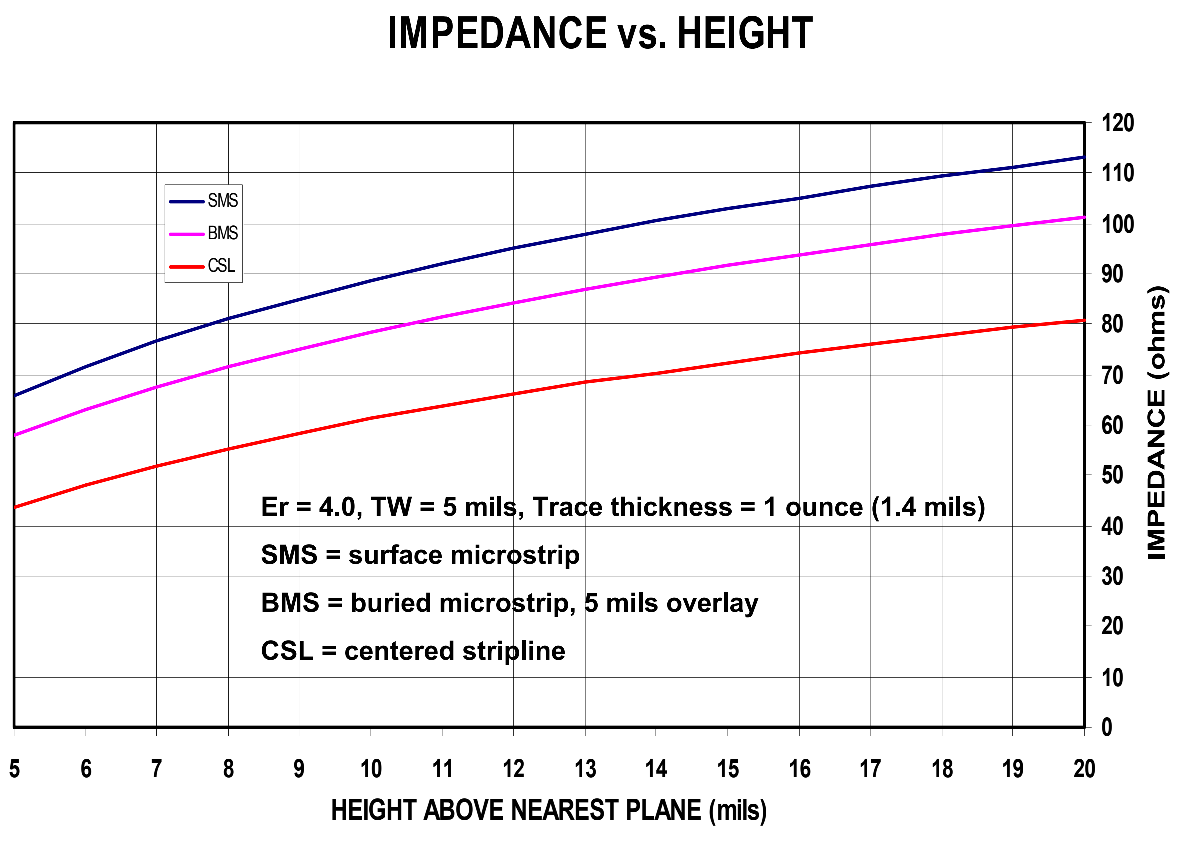
1. All impedances in ohms
2. Assumes dielectric constant of 3.5
3. Trace widths measured at bottom of trace
4. HP is Hewlett Packard 5474A TDR with 60 pSec edge.
5. Polar is Polar Instruments Cits 500 TDR with 175 pSec edge.
6. F.S. is Hyperlynx field solver.
7. HL STK is Hyperlynx equation based stackup editor.
8. Trace widths in mils.
9. All dimensions measured by Multek using destructive testing.

Note 1: Polar Instruments Cits 500 reads, on average, 2 ohms lower than HP TDR.
Note 2: Field solver agrees with actual measured values within accuracy of tools.

PCB made from Neldo 4000-13SI, approximately 58% resin

IMPEDANCE vs. HEIGHT ABOVE NEAREST PLANE

OR WHY NOT 100 OHMS INSTEAD OF 50 OHMS



Even with the narrowest production trace width, stripline layers cannot achieve high impedances. In all cases, high impedances require very thick dielectrics, making PCBs excessively thick, as well and subject to severe cross talk.

CONCLUSIONS

- **Accurate materials data exists that yields accurate impedance calculations.**
- **Impedance predicting equations have limited ranges over which they are accurate.**
- **Impedance predicting tools, field solvers, exist that yield accurate impedance calculations.**
- **In order to get accurate results from fabrication, the exact laminate styles must be specified on the fabrication drawing and not substituted to make use of stock on hand.**
- **Right the first time is possible. Just takes good data and good methods.**

SOME LAMINATE MANUFACTURERS WITH ACCURATE MATERIALS DATA

- NELCO- WWW.PARKNELCO.COM
- ISOLA- WWW.ISOLA.COM

Note: This is not a complete list. The author has worked with these materials for some time and is certain that the materials data accurately represents the materials.

WAYS TO CONTACT ME

- **Lee Ritchey- 707-568-3983**
- **FAX- 707-568-3504**
- **E-mail- leeritchey@earthlink.net**
  www.speedingedge.com
- **Most effective method is to send me an E-mail with your question.**
- **Second most effective is a FAX.**

SOME USEFUL ARTICLES

Neusch, Martin. "Primer on High Performance Laminates." EP &P June 1997.

Ritchey, Lee, "A Survey and Tutorial of Dielectric Materials used in the Manufacture of Printed Circuit Boards." Circuitree, November 1999.

Ritchey, Lee W. "Who Cares about Tg?" Speeding Edge, January 14, 1999.

Bogatin, Eric, "What is Characteristic Impedance?" Printed Circuit Design, January 2000. Very good article.

Morgan, Chad & Helster, Dave, "The Impact of PWB Construction on High-Speed Signals"DesignCon99.