ECE 546
Lecture - 08
Nonideal Conductors and Dielectrics

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Material Medium

$$\nabla \times \vec{E} = -\frac{\partial \mu \vec{H}}{\partial t}$$

or

$$\nabla \times \vec{E} = -j\omega\mu\vec{H}$$

$$\nabla \times \vec{H} = \vec{J} + \frac{\partial \varepsilon \vec{E}}{\partial t}$$

$$\nabla \times \vec{H} = \vec{J} + j\omega\varepsilon\vec{E}$$

$$\vec{J} = \sigma\vec{E}$$

σ: conductivity of material medium ($\Omega^{-1}m^{-1}$)

$$\nabla \times \vec{H} = \sigma\vec{E} + j\omega\varepsilon\vec{E} = \vec{E}\left(\sigma + j\omega\varepsilon\right) = j\omega\varepsilon\left(1 + \frac{\sigma}{j\omega\varepsilon}\right)\vec{E}$$

since $\varepsilon \to \varepsilon\left(1 + \frac{\sigma}{j\omega\varepsilon}\right)$ then $\nabla^2\vec{E} = -\omega^2\mu\varepsilon\left(1 + \frac{\sigma}{j\omega\varepsilon}\right)\vec{E}$

Wave in Material Medium

$$\nabla^2 \vec{E} = -\omega^2 \mu\varepsilon\left(1 + \frac{\sigma}{j\omega\varepsilon}\right)\vec{E} = \gamma^2 \vec{E}$$

$$\gamma^2 = -\omega^2 \mu\varepsilon\left(1 + \frac{\sigma}{j\omega\varepsilon}\right)$$

γ is complex propagation constant

$$\gamma = j\omega\sqrt{\mu\varepsilon}\sqrt{1 + \frac{\sigma}{j\omega\varepsilon}} = \alpha + j\beta$$

α: associated with attenuation of wave

β: associated with propagation of wave

Wave in Material Medium

Solution: $\vec{E} = \hat{x}E_o e^{-\gamma z} = \hat{x}E_o e^{-\alpha z} e^{-j\beta z}$ **decaying exponential**

$$\alpha = \omega\sqrt{\frac{\mu\varepsilon}{2}}\left[\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2}-1\right]^{1/2}$$

$$\beta = \omega\sqrt{\frac{\mu\varepsilon}{2}}\left[\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2}+1\right]^{1/2}$$

Complex intrinsic impedance

$$\eta = \sqrt{\frac{j\omega\mu}{\sigma + j\omega\varepsilon}}$$

Magnetic field

$$\vec{H} = \hat{y}\frac{E_o}{\eta}e^{-\alpha z}e^{-j\beta z}$$

Wave in Material Medium

$\frac{\sigma}{\omega\varepsilon}$ is the loss tangent

Two special cases can be distinguished:

$\frac{\sigma}{\omega\varepsilon} \ll 1$: poor conductor

$$\alpha \simeq \frac{\sigma}{2}\sqrt{\frac{\mu}{\varepsilon}}\left(1-\frac{\sigma^2}{8\omega^2\varepsilon^2}\right) \simeq \frac{\sigma}{2}\sqrt{\frac{\mu}{\varepsilon}}$$

$$\beta \simeq \omega\sqrt{\mu\varepsilon}\left(1+\frac{\sigma^2}{8\omega^2\varepsilon^2}\right) \simeq \omega\sqrt{\mu\varepsilon}$$

$$\eta \simeq \sqrt{\frac{\mu}{\varepsilon}}\left[1-\frac{3\sigma^2}{8\omega^2\varepsilon^2}+j\frac{\sigma}{2\omega\varepsilon}\right]$$

Wave in Material Medium

$\frac{\sigma}{\omega\varepsilon} \gg 1$ **: good conductor**

$$\gamma = \sqrt{j\omega\mu(\sigma + j\omega\varepsilon)} \simeq \sqrt{j\omega\mu\sigma} = \sqrt{\omega\mu\sigma}\, e^{j\pi/4}$$

$$\gamma \simeq \sqrt{\pi f \mu\sigma}\,(1+j)$$

$$\alpha = \sqrt{\pi f \mu\sigma} \qquad \beta = \sqrt{\pi f \mu\sigma}$$

$$\eta = \sqrt{\frac{\pi f \mu}{\sigma}}\,(1+j)$$

Skin Depth

$$\vec{E} = \hat{x}E_o e^{-\gamma z} = \hat{x}E_o e^{-\alpha z} e^{-j\beta z}$$ ← **Wave decay**

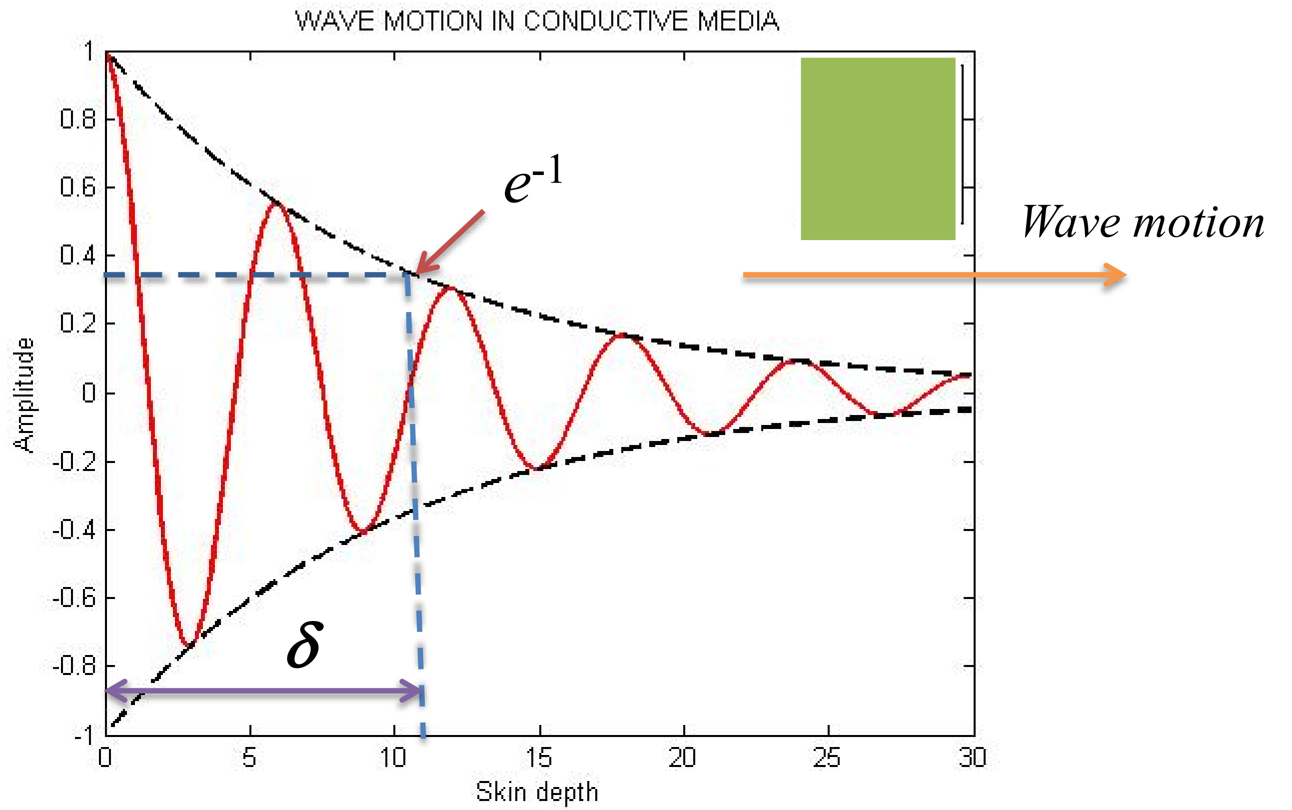
The decay of electromagnetic wave propagating into a conductor is measured in terms of the *skin depth*

Definition: skin depth δ is distance over which amplitude of wave drops by *1/e*.

$$\delta = \frac{1}{\alpha}$$

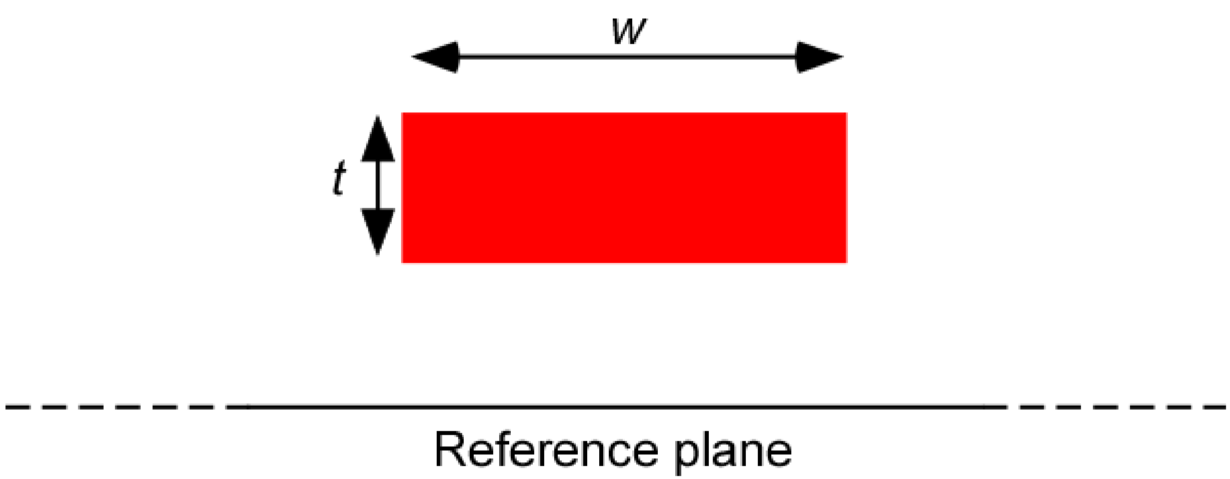
For good conductors: $$\delta = \sqrt{\frac{2}{\omega\mu\sigma}}$$

Skin Depth



For perfect conductor, $\delta = 0$ and current only flows on the surface

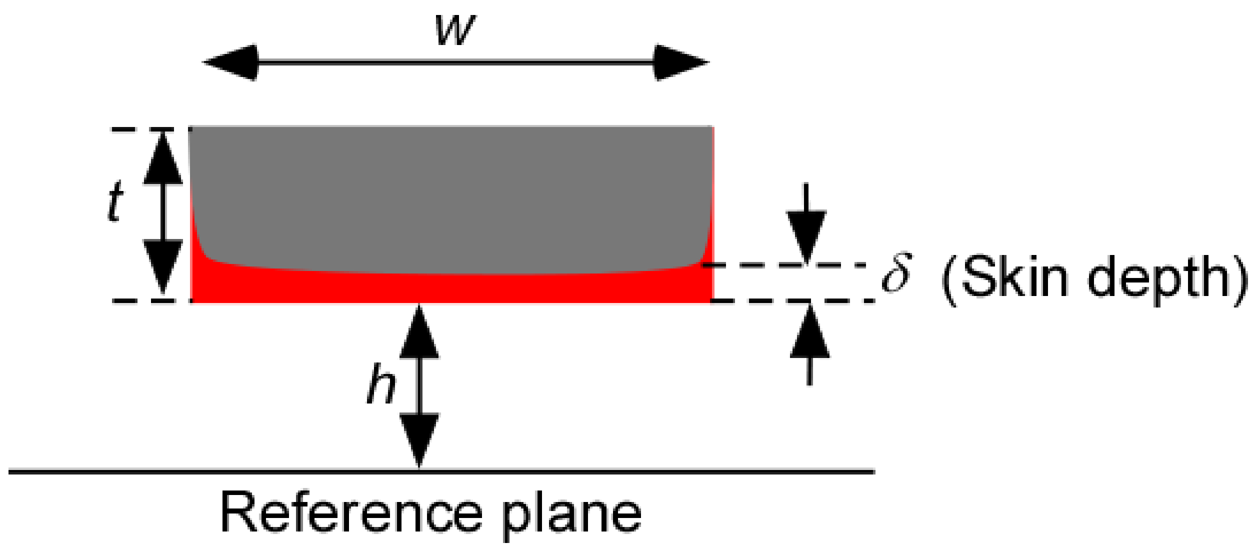
DC Resistance



$$R_{dc} = \frac{l}{\sigma w t}$$

l: conductor length
σ: conductivity

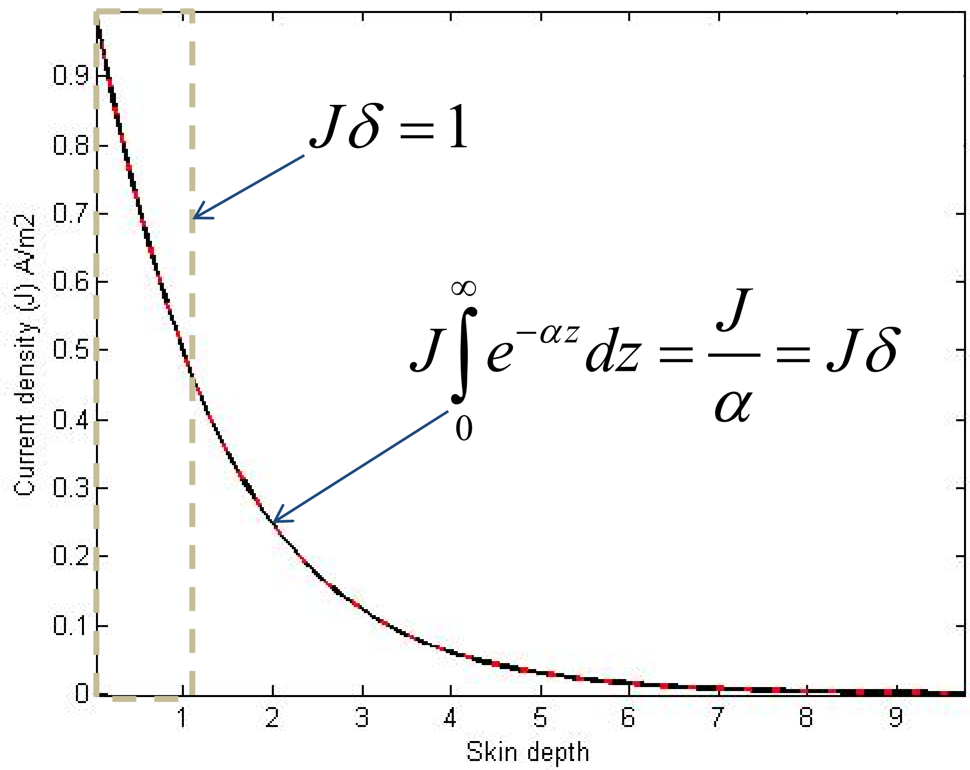
AC Resistance



$$R_{ac} = \frac{l}{\sigma w \delta} = \frac{l}{\sigma w \sqrt{2/\omega\mu\sigma}} = \frac{l}{w}\sqrt{\frac{\pi\mu f}{\sigma}}$$

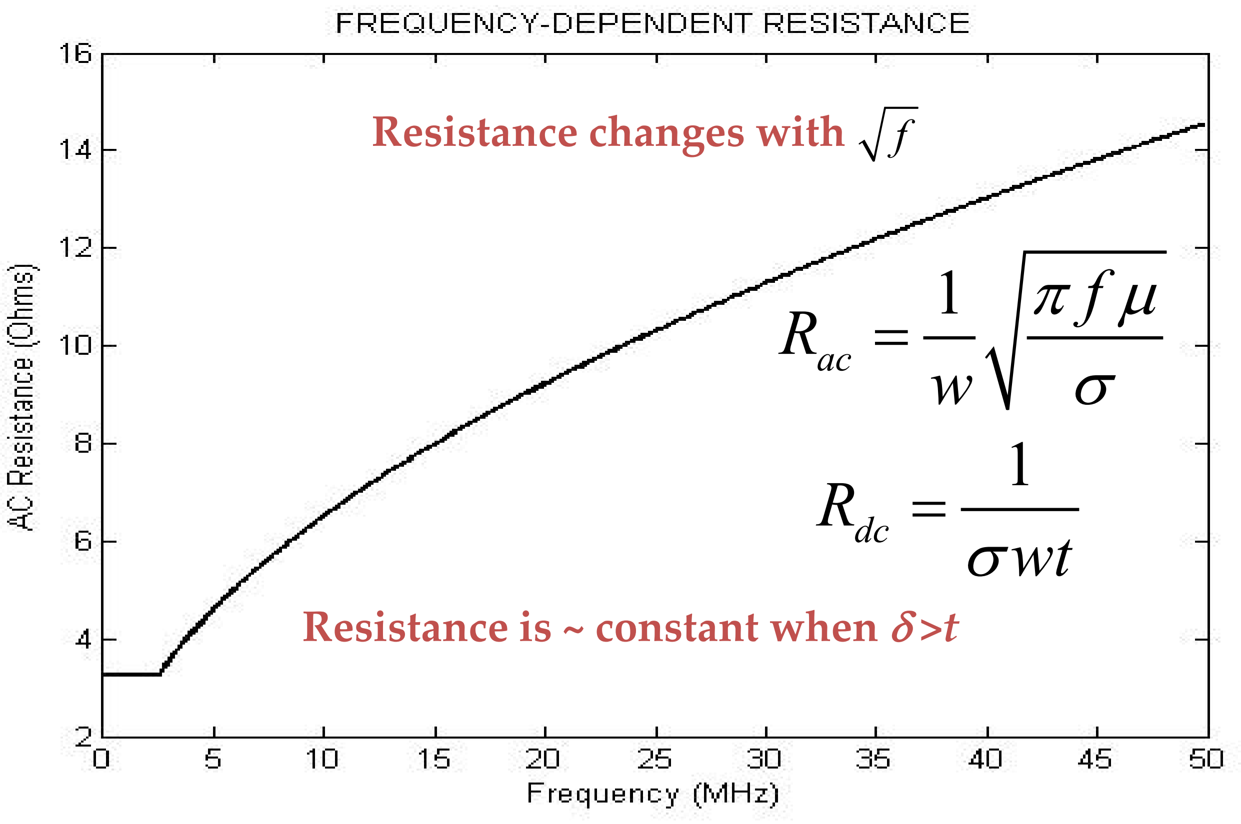
***l*: conductor length**
σ: conductivity
***f*: frequency**

Frequency-Dependent Resistance

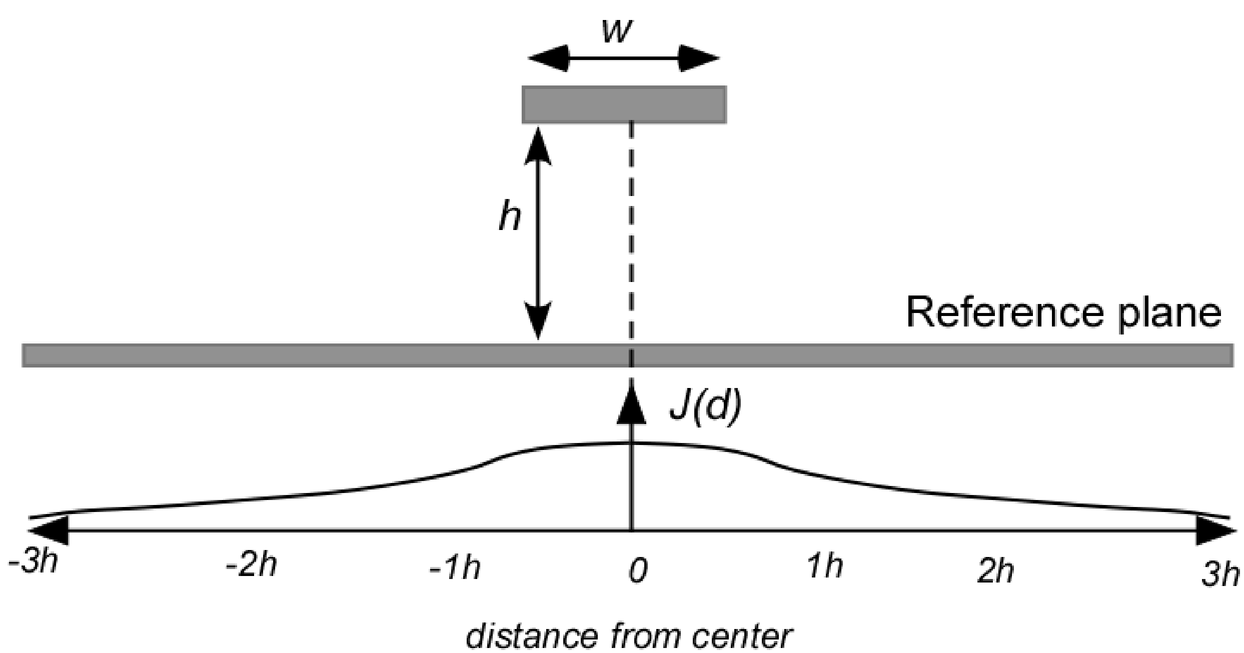


Approximation is to assume that all the current is flowing uniformly within a skin depth

Frequency-Dependent Resistance

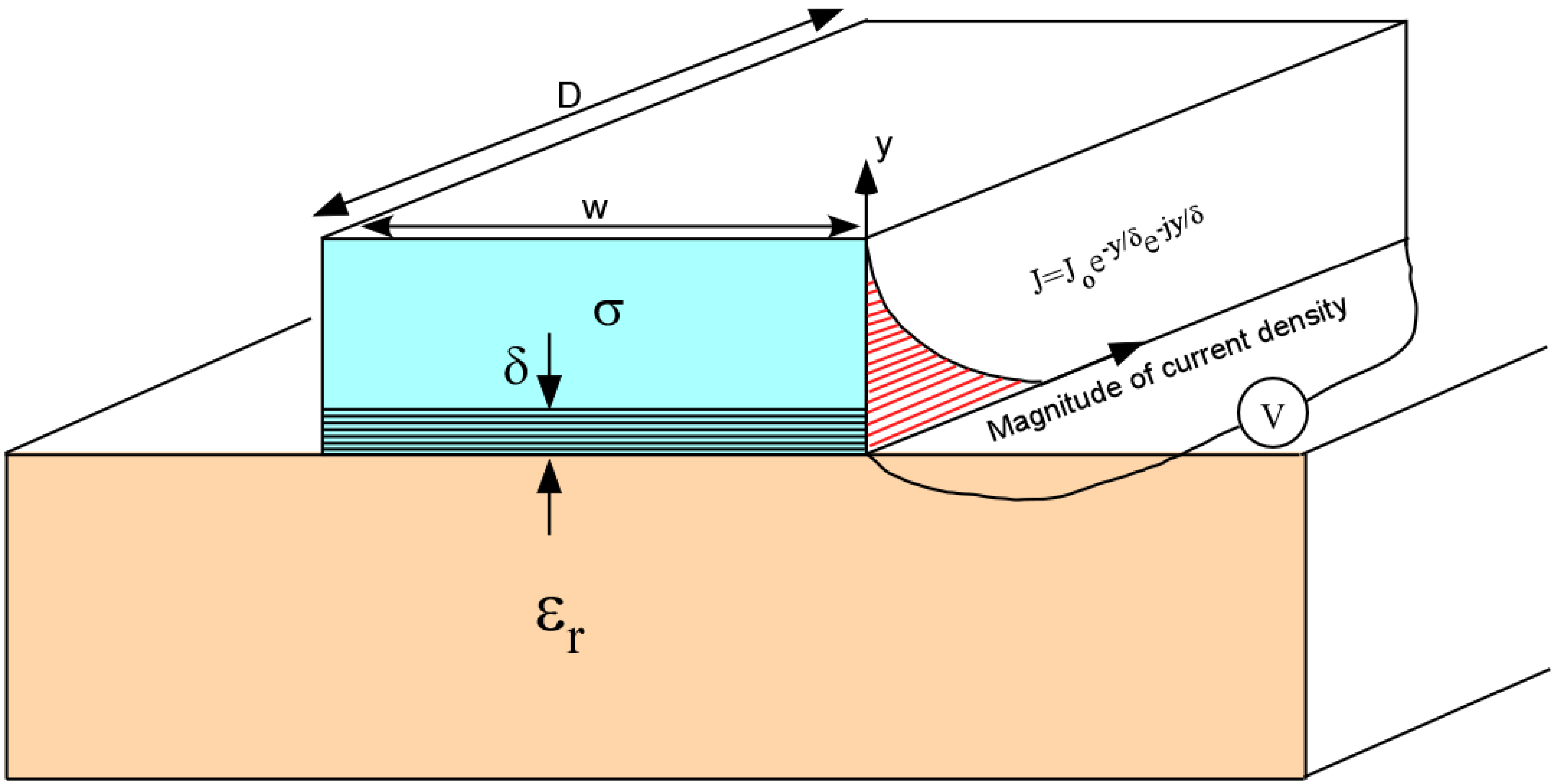


Reference Plane Current



$$R_{ac,ground} \approx \frac{l}{6h}\sqrt{\frac{\pi\mu f}{\sigma}}$$

Skin Effect in Microstrip



H. A. Wheeler, "Formulas for the skin effect," Proc. IRE, vol. 30, pp. 412-424,1942

Skin Effect in Microstrip

Current density varies as

$$J = J_o e^{-y/\delta} e^{-jy/\delta}$$

Note that the phase of the current density varies as a function of *y*

$$I = \int_0^\infty J_o w e^{-y/\delta} e^{-jy/\delta} dy = \frac{J_o w \delta}{1+j}$$

$$\sigma E_o = J_o \Rightarrow E_o = \frac{J_o}{\sigma}$$

The voltage measured over a section of conductor of length *D* is:

$$V = E_o D = \frac{J_o D}{\sigma}$$

Skin Effect in Microstrip

The skin effect impedance is

$$Z_{skin} = \frac{V}{I} = \frac{J_o D}{\sigma} \frac{(1+j)}{J_o w \delta} = \frac{D}{w}(1+j)\sqrt{\pi f \mu \rho}$$

where $\rho = \dfrac{1}{\sigma}$ is the bulk resistivity of the conductor

$$Z_{skin} = R_{skin} + jX_{skin}$$

with

$$R_{skin} = X_{skin} = \frac{D}{w}\sqrt{\pi f \mu \sigma}$$

➔ Skin effect has reactive (inductive) component

Internal Inductance

The internal inductance can be calculated directly from the ac resistance

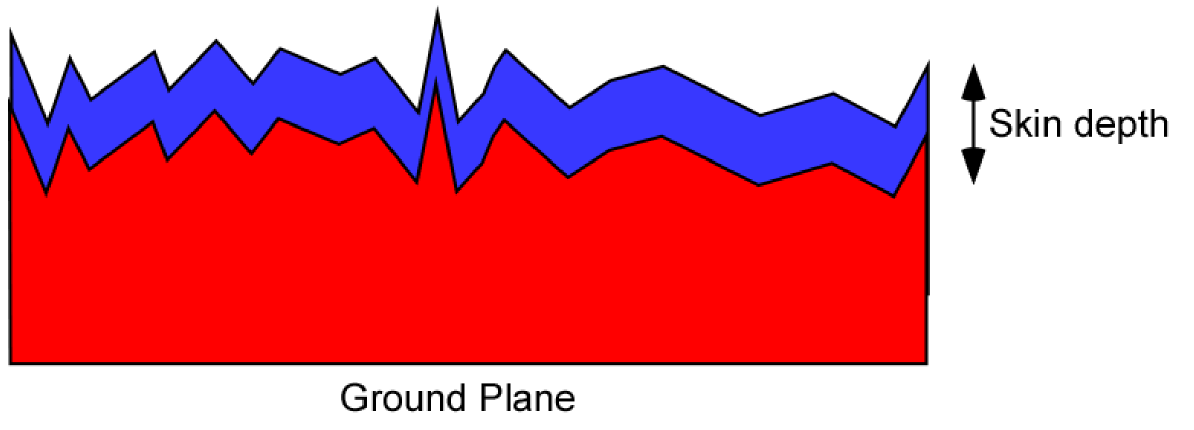
$$L_{\text{internal}} = \frac{R_{ac}}{\omega} = \frac{R_{skin}}{\omega}$$

➔ Skin effect resistance goes up with frequency

➔ Skin effect inductance goes down with frequency

Surface Roughness

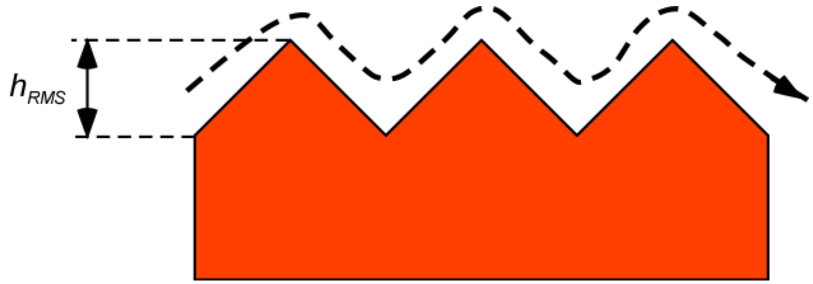
Copper surfaces are rough to facilitate adhesion to dielectric during PCB manufacturing



When the *tooth* height is comparable to the skin depth, roughness effects cannot be ignored

Surface roughness will increase ohmic losses

Hammerstad Model



$$R_H(f) = \begin{cases} K_H R_s \sqrt{f} & \text{when } \delta < t \\ R_{dc} & \text{when } \delta \geq t \end{cases}$$

$$L_H(f) = \begin{cases} L_{external} + \dfrac{R_H(f)}{2\pi f} & \text{when } \delta < t \\[2ex] L_{external} + \dfrac{R_H(f_{\delta=t})}{2\pi f_{\delta=t}} & \text{when } \delta \geq t \end{cases}$$

Hammerstad Model

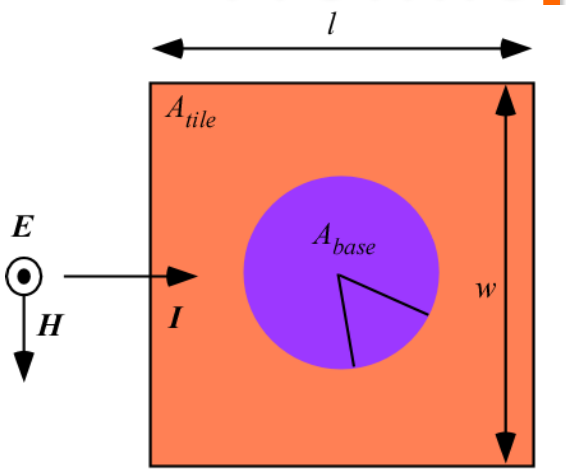
$$K_H = 1 + \frac{2}{\pi}\arctan\left[1.4\left(\frac{h_{RMS}}{\delta}\right)^2\right]$$

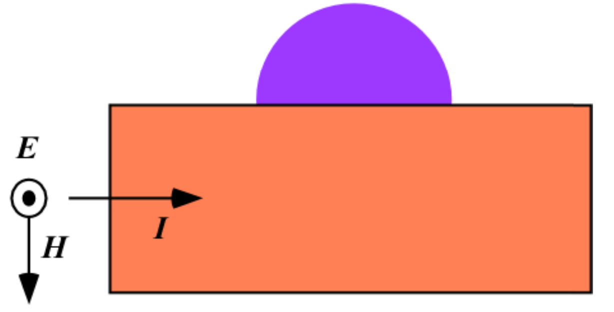
h_{RMS}: root mean square value of surface roughness height

δ: skin depth

$f_{\delta=t}$: frequency where the skin depth is equal to the thickness of the conductor

Hemispherical Model





$$R_{hemi}(f) = \begin{cases} K_{hemi} R_s \sqrt{f} & \text{when } \delta < t \\ R_{dc} & \text{when } \delta \geq t \end{cases}$$

$$L_{hemi}(f) = \begin{cases} L_{external} + \dfrac{R_{hemi}(f)}{2\pi f} & \text{when } \delta < t \\ L_{external} + \dfrac{R_{hemi}(f_{\delta=t})}{2\pi f_{\delta=t}} & \text{when } \delta \geq t \end{cases}$$

Hemispherical Model

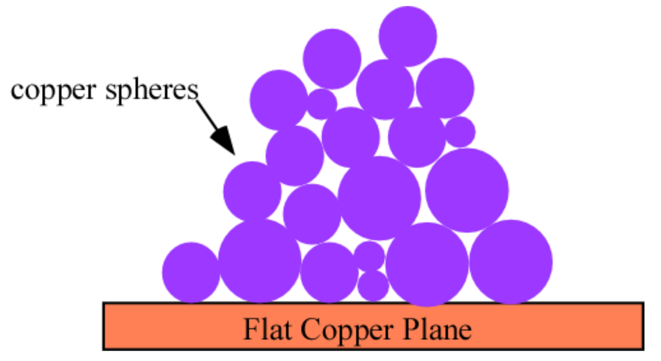
$$K_{hemi} = \begin{cases} 1 & \text{when } K_s \le 1 \\ K_s & \text{when } K_s > 1 \end{cases}$$

$$K_s = \frac{\left|\mathrm{Re}\left[\eta\left(3\pi/4k^2\right)\left(\alpha(1)+\beta(1)\right)\right]\right| + \left(\mu_o\omega\delta/4\right)\left(A_{tile}-A_{base}\right)}{\left(\mu_o\omega\delta/4\right)A_{tile}}$$

$$\alpha(1) = -\frac{2j}{3}(kr)^3 \frac{1-(\delta/r)(1+j)}{1+(\delta/2r)(1+j)}$$

$$\beta(1) = -\frac{2j}{3}(kr)^3 \frac{1-\left(4j/k^2r\delta\right)\left(1/(1-j)\right)}{1+\left(2j/k^2r\delta\right)\left(1/(1-j)\right)}$$

Huray Model



$$R_{Huray}(f) = \begin{cases} K_{Huray} R_s \sqrt{f} & \text{when } \delta < t \\ R_{dc} & \text{when } \delta \geq t \end{cases}$$

$$L_{Huray}(f) = \begin{cases} L_{external} + \dfrac{R_{Huray}(f)}{2\pi f} & \text{when } \delta < t \\ L_{external} + \dfrac{R_{Huray}(f_{\delta=t})}{2\pi f_{\delta=t}} & \text{when } \delta \geq t \end{cases}$$

Huray Model

$$K_{Huray} = \frac{P_{flat} + P_{N\_spheres}}{P_{flat}}$$

$$P_{N\_spheres} = -\sum_{n=1}^{N} \mathrm{Re}\left[\frac{1}{2}\eta\left|H_o\right|^2 \frac{3\pi}{k^2}\alpha(1) + \beta(1)\right]_n$$

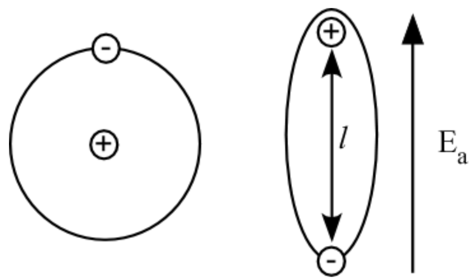
$$P_{flat} = \left(\mu_o \omega \delta / 4\right) A_{tile} \qquad \eta = \sqrt{\mu_o / \varepsilon_o \varepsilon'}$$

H_o: magnitude of applied H field.

$$\alpha(1) = -\frac{2j}{3}(kr)^3 \frac{1-(\delta/r)(1+j)}{1+(\delta/2r)(1+j)}$$

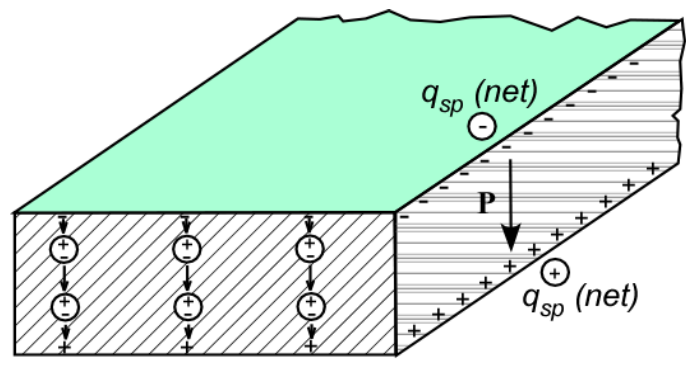
$$\beta(1) = -\frac{2j}{3}(kr)^3 \frac{1-\left(4j/k^2 r\delta\right)\left(1/(1-j)\right)}{1+\left(2j/k^2 r\delta\right)\left(1/(1-j)\right)}$$

Dielectrics and Polarization



No field

Applied field



Field causes the formation of dipoles → polarization

Bound surface charge density $-q_{sp}$ on upper surface and $+q_{sp}$ on lower surface of the slab.

Dielectrics and Polarization

$$\vec{D} = \varepsilon_o \vec{E}_a + \vec{P} = \varepsilon_o \vec{E}_a + \varepsilon_o \chi_e \vec{E}_a = \varepsilon_o \left(1 + \chi_e\right) \vec{E}_a = \varepsilon_s \vec{E}_a$$

$\vec{P}$: polarization vector

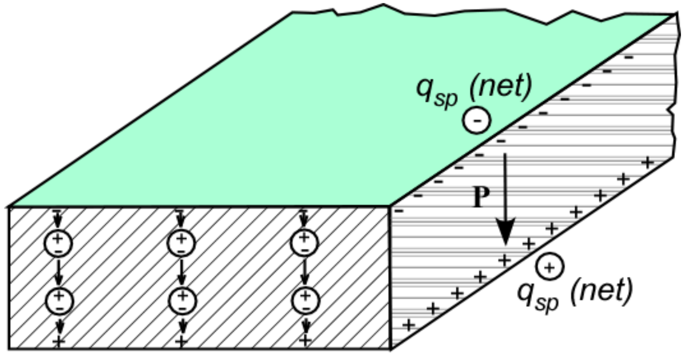
$\vec{D}$: electric flux density

$\vec{E}_a$: applied electric field

χ_e : electric susceptibility

ε_o : free-space permittivity

ε_s : static permittivity



Dielectric Constant

Material	ε_r
Air	1.0006
Styrofoam	1.03
Paraffin	2.1
Teflon	2.1
Plywood	2.1
RT/duroid 5880	2.20
Polyethylene	2.26
RT/duroid 5870	2.35
Glass-reinforced teflon (microfiber)	2.32-2.40
Teflon quartz (woven)	2.47
Glass-reinforced teflon (woven)	2.4-2.62
Cross-linked polystyrene (unreinforced)	2.56
Polyphenelene oxide (PPO)	2.55
Glass-reinforced polystyrene	2.62
Amber	3
Rubber	3
Plexiglas	3.4

Dielectric Constants

Material	ε_r
Lucite	3.6
Fused silica	3.78
Nylon (solid)	3.8
Quartz	3.8
Bakelite	4.8
Formica	5
Lead glass	6
Mica	6
Beryllium oxide (BeO)	6.8-7.0
Marble	8
Flint glass	10
Ferrite (FqO,)	12-16
Silicon (Si)	12
Gallium arsenide (GaAs)	13
Ammonia (liquid)	22
Glycerin	50
Water	81

AC Variations

When a material is subjected to an applied electric field, the centroids of the positive and negative charges are displaced relative to each other forming a linear dipole.

When the applied fields begin to alternate in polarity, the permittivities are affected and become functions of the frequency of the alternating fields.

AC Variations

Reverses in polarity cause incremental changes in the static conductivity σ_s ➔ heating of materials using microwaves (e.g. food cooking)

When an electric field is applied, it is assumed that the positive charge remains stationary and the negative charge moves relative to the positive along a platform that exhibits a friction (damping) coefficient *d*.

Complex Permittivity

$$\varepsilon_r^{'} = 1 + \frac{\frac{N_e Q^2}{\varepsilon_o m}\left(\omega_o^2 - \omega^2\right)}{\left(\omega_o^2 - \omega^2\right)^2 + \left(\omega \frac{d}{m}\right)^2}$$

$$\varepsilon_r^{''} = \frac{N_e Q^2}{\varepsilon_o m}\left[\frac{\omega \frac{d}{m}}{\left(\omega_o^2 - \omega^2\right)^2 + \left(\omega \frac{d}{m}\right)^2}\right]$$

$$\omega_o = \sqrt{\frac{s}{m}}$$

N_e : dipole density

Q : dipole charge

ε_o: free space permittivity

s : spring (tension) factor

m : mass

d : damping coefficient

ω_o: natural frequency

ω: applied frequency

Complex Permittivity

$$\nabla \times \vec{H} = \vec{J}_i + \vec{J}_c + j\omega\dot{\varepsilon}\vec{E} = \vec{J}_i + \sigma_s\vec{E} + j\omega\left(\varepsilon' - j\varepsilon''\right)\vec{E}$$

$$\nabla \times \vec{H} = \vec{J}_i + \left(\sigma_s + \omega\varepsilon''\right)\vec{E} + j\omega\varepsilon'\vec{E} = \vec{J}_i + \sigma_e\vec{E} + j\omega\varepsilon'\vec{E}$$

$$\sigma_e = \text{equivalent conductivity} = \sigma_s + \omega\varepsilon'' = \sigma_s + \sigma_a$$

$$\sigma_a = \text{alternating field conductivity} = \omega\varepsilon''$$

$$\sigma_s = \text{static field conductivity}$$

σ_e: total conductivity composed of the static portion σ_s and the alternative part σ_a caused by the rotation of the dipoles

Complex Permittivity

$$\vec{J}_t = \vec{J}_i + \vec{J}_{ce} + \vec{J}_{de} = \vec{J}_i + \sigma_e \vec{E} + j\omega\varepsilon' \vec{E}$$

$\vec{J}_t$: total electric current density

$\vec{J}_i$: impressed (source) electric current density

$\vec{J}_{ce}$: effective electric conduction current density

$\vec{J}_{de}$: effective displacement electric current density

$$\vec{J}_t = \vec{J}_i + \sigma_e \vec{E} + j\omega\varepsilon' \vec{E} = \vec{J}_i + j\omega\varepsilon' \left(1 - j\frac{\sigma_e}{\omega\varepsilon'}\right)\vec{E} = \vec{J}_i + j\omega\varepsilon'\left(1 - j\tan\delta_e\right)\vec{E}$$

$$\tan\delta_e = \text{effective electric loss tangent} = \frac{\sigma_e}{\omega\varepsilon'} = \frac{\sigma_s + \sigma_a}{\omega\varepsilon'} = \frac{\sigma_s}{\omega\varepsilon'} + \frac{\sigma_a}{\omega\varepsilon'}$$

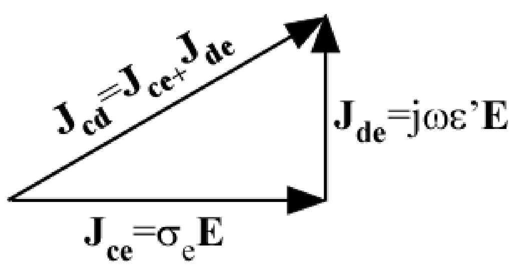
Complex Permittivity

$$\tan\delta_e = \frac{\sigma_s}{\omega\varepsilon'} + \frac{\varepsilon''}{\varepsilon'} = \tan\delta_s + \tan\delta_a = \frac{\varepsilon_e''}{\varepsilon_e'}$$

$$\tan\delta_s = \text{static electric loss tangent} = \frac{\sigma_s}{\omega\varepsilon'}$$

$$\tan\delta_a = \text{alternating electric loss tangent} = \frac{\sigma_a}{\omega\varepsilon'} = \frac{\varepsilon''}{\varepsilon'}$$

$$\vec{J}_{cd} = \vec{J}_{ce} + \vec{J}_{de} = \sigma_e\vec{E} + j\omega\varepsilon'\vec{E} = j\omega\varepsilon'\left(1 - j\frac{\sigma_e}{\omega\varepsilon'}\right)\vec{E} = j\omega\varepsilon'\left(1 - j\tan\delta_e\right)\vec{E}$$



Dielectric Properties

Good Dielectrics: $\frac{\sigma_e}{\omega\varepsilon'} \ll 1$

$$\vec{J}_{cd} = j\omega\varepsilon'\left(1 - j\frac{\sigma_e}{\omega\varepsilon'}\right)\vec{E} \simeq j\omega\varepsilon'\vec{E}$$

Good Conductors: $\frac{\sigma_e}{\omega\varepsilon'} \gg 1$

$$\vec{J}_{cd} = j\omega\varepsilon'\left(1 - j\frac{\sigma_e}{\omega\varepsilon'}\right)\vec{E} \simeq \sigma_e\vec{E}$$

Dielectric Properties

Good Dielectrics: $\dfrac{\sigma_e}{\omega\varepsilon'} \ll 1$

$$\vec{J}_{cd} = j\omega\varepsilon'\left(1 - j\frac{\sigma_e}{\omega\varepsilon'}\right)\vec{E} \simeq j\omega\varepsilon'\vec{E}$$

Good Conductors: $\dfrac{\sigma_e}{\omega\varepsilon'} \gg 1$

$$\vec{J}_{cd} = j\omega\varepsilon'\left(1 - j\frac{\sigma_e}{\omega\varepsilon'}\right)\vec{E} \simeq \sigma_e\vec{E}$$

Kramers-Kronig Relations

There is a relation between the real and imaginary parts of the complex permittivity:

$$\varepsilon_r^{'}(\omega) = 1 + \frac{2}{\pi}\int_0^{\infty}\frac{\omega'\varepsilon_r^{''}(\omega')}{(\omega')^2-\omega^2}d\omega'$$

$$\varepsilon_r^{''}(\omega) = \frac{2\omega}{\pi}\int_0^{\infty}\frac{1-\varepsilon_r^{'}(\omega')}{(\omega')^2-\omega^2}d\omega'$$

Debye Equation

$$\dot{\varepsilon}_r(\omega) = \varepsilon_r^{'}(\omega) - j\varepsilon_r^{''}(\omega) = \varepsilon_{r\infty}^{'} + \frac{\varepsilon_{rs}^{'} - \varepsilon_{r\infty}^{'}}{1 + j\omega\tau_e}$$

Kramers-Kronig Relations

τ_e is a relaxation time constant:

$$\tau_e = \tau \frac{\varepsilon_{rs}^{'} + 2}{\varepsilon_{r\infty}^{'} + 2}$$

$$\varepsilon_r^{'}(\omega) = \varepsilon_{r\infty}^{'} + \frac{\varepsilon_{rs}^{'} - \varepsilon_{r\infty}^{'}}{1 + (\omega\tau_e)^2}$$

$$\varepsilon_r^{''}(\omega) = \frac{\left(\varepsilon_{rs}^{'} - \varepsilon_{r\infty}^{'}\right)\omega\tau_e}{1 + (\omega\tau_e)^2}$$

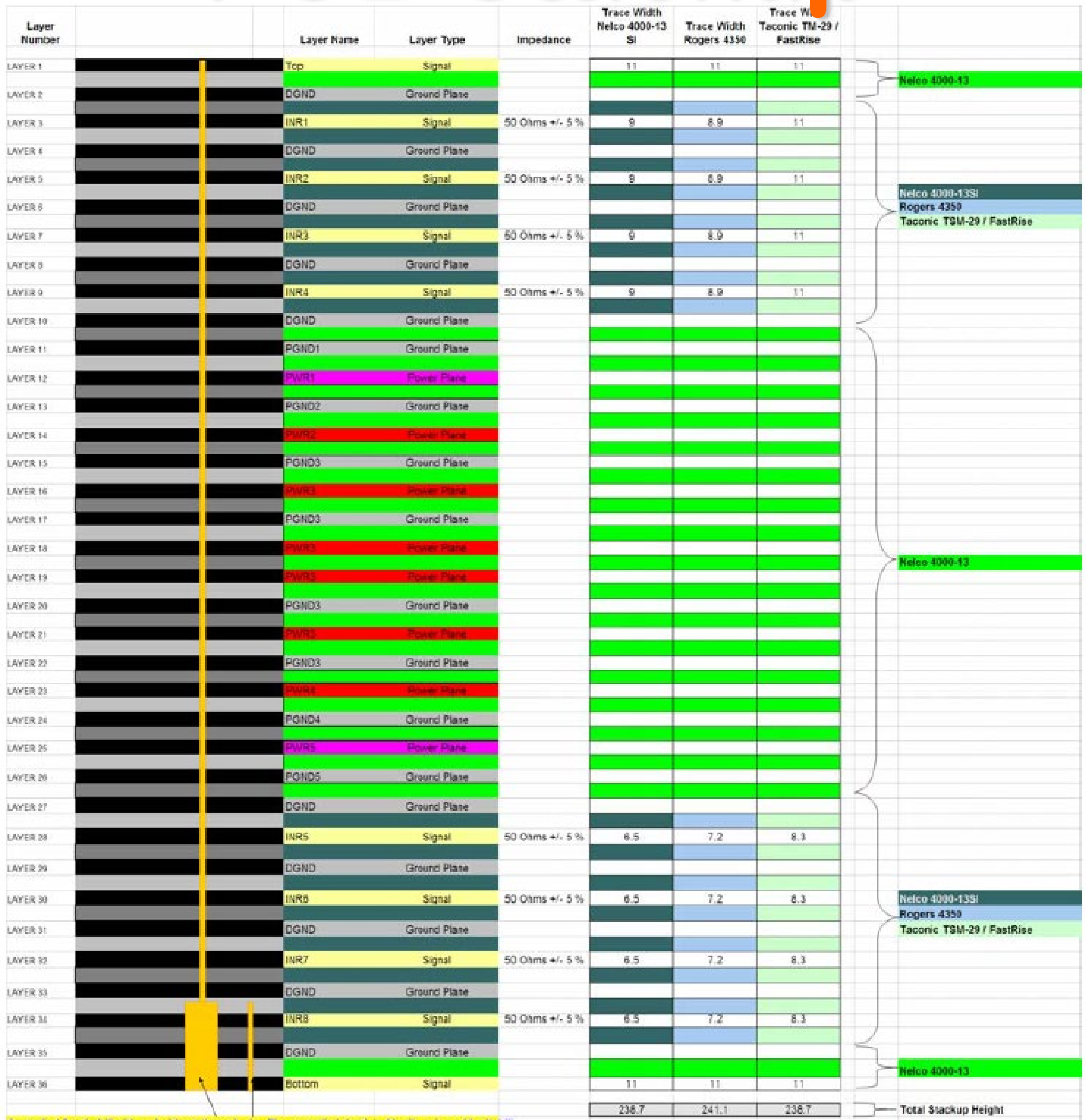
Dielectric Materials

Material	ε_r'	$\tan\delta$
Air	1.0006	
Alcohol (ethyl)	25	0.1
Aluminum oxide	8.8	6×10^{-4}
Bakelite	4.74	22×10^{-3}
Carbon dioxide	1.001	
Germanium	16	
Glass	4*7	1×10^{-3}
Ice	4.2	0.1
Mica	5.4	6×10^{-4}
Nylon	3.5	2×10^{-2}
Paper	3	8×10^{-3}
Plexiglas	3.45	4×10^{-2}
Polystyrene	2.56	5×10^{-5}
Porcelain	6	14×10^{-3}

Dielectric Materials

Material	ε_r'	$\tan\delta$
Pyrex glass	4	6×10^{-4}
Quartz (fused)	3.8	7.5×10^{-4}
Rubber	2.5-3	2×10^{-3}
Silica (fused)	3.8	7.5×10^{-4}
Silicon	11.8	
Snow	3.3	0.5
Sodium chloride	5.9	1×10^{-4}
Soil (dry)	2.8	7×10^{-2}
Styrofoam	1.03	1×10^{-4}
Teflon	2.1	3×10^{-4}
Titanium dioxide	100	15×10^{-4}
Water (distilled)	80	4×10^{-2}
Water (sea)	81	4.64
Water (dehydrated)	1	0
Wood (dry)	1.5-4	1×10^{-2}

PCB Stackup



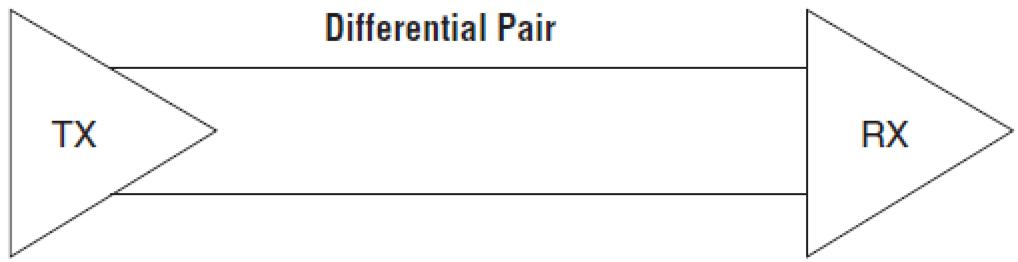
Layer Number	Layer Name	Layer Type	Impedance	Trace Width Nelco 4000-13 SI	Trace Width Rogers 4350	Trace Width Taconic TM-29 / FastRise
LAYER 1	Top	Signal		11	11	11
LAYER 2	DGND	Ground Plane				
LAYER 3	INR1	Signal	50 Ohms +/- 5 %	9	8.9	11
LAYER 4	DGND	Ground Plane				
LAYER 5	INR2	Signal	50 Ohms +/- 5 %	9	8.9	11
LAYER 6	DGND	Ground Plane				
LAYER 7	INR3	Signal	50 Ohms +/- 5 %	9	8.9	11
LAYER 8	DGND	Ground Plane				
LAYER 9	INR4	Signal	50 Ohms +/- 5 %	9	8.9	11
LAYER 10	DGND	Ground Plane				
LAYER 11	PGND1	Ground Plane				
LAYER 12	PWR1	Power Plane				
LAYER 13	PGND2	Ground Plane				
LAYER 14	PWR2	Power Plane				
LAYER 15	PGND3	Ground Plane				
LAYER 16	PWR3	Power Plane				
LAYER 17	PGND3	Ground Plane				
LAYER 18	PWR3	Power Plane				
LAYER 19	PWR3	Power Plane				
LAYER 20	PGND3	Ground Plane				
LAYER 21	PWR3	Power Plane				
LAYER 22	PGND3	Ground Plane				
LAYER 23	PWR4	Power Plane				
LAYER 24	PGND4	Ground Plane				
LAYER 25	PWR5	Power Plane				
LAYER 26	PGND5	Ground Plane				
LAYER 27	DGND	Ground Plane				
LAYER 28	INR5	Signal	50 Ohms +/- 5 %	6.5	7.2	8.3
LAYER 29	DGND	Ground Plane				
LAYER 30	INR6	Signal	50 Ohms +/- 5 %	6.5	7.2	8.3
LAYER 31	DGND	Ground Plane				
LAYER 32	INR7	Signal	50 Ohms +/- 5 %	6.5	7.2	8.3
LAYER 33	DGND	Ground Plane				
LAYER 34	INR8	Signal	50 Ohms +/- 5 %	6.5	7.2	8.3
LAYER 35	DGND	Ground Plane				
LAYER 36	Bottom	Signal		11	11	11
Total Stackup Height				236.7	241.1	236.7

Controlled Depth drill with and without through via. The controlled depth is 20 mils using a 29-mil drill.

Source: H. Barnes et al, "ATE Interconnect Performance to 43 Gps Using Advanced PCB Materials", DesignCon 2008

Differential Signaling

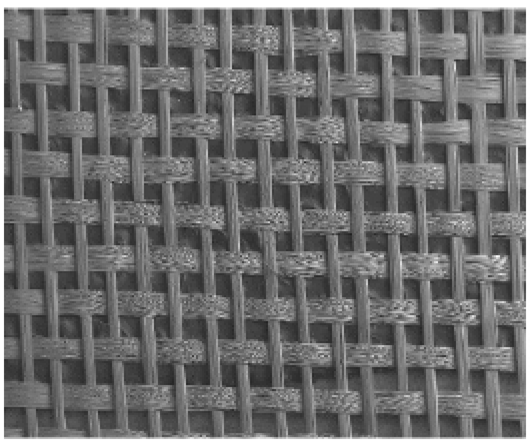
Differential signaling is widely used in the industry today. High-speed serial interfaces such as PCI-E, XAUI, OC768, and CEI use differential signaling for transmitting and receiving data in point-to-point topology between a driver (TX) and receiver (RX) connected by a differential pair.



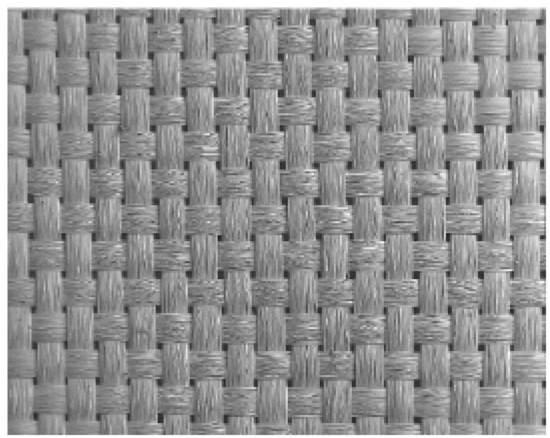
The skew (time delay) between the two traces of the differential pair should be zero. Any skew between the two traces causes the differential signal to convert into a common signal.

Fiber Weave Effect

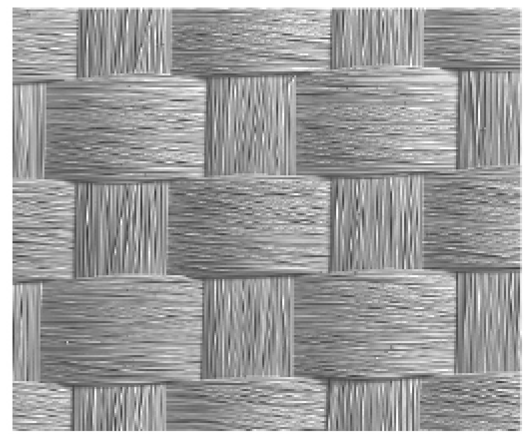
Fiberglass weave pattern causes signals to propagate at different speeds in differential pairs



1080



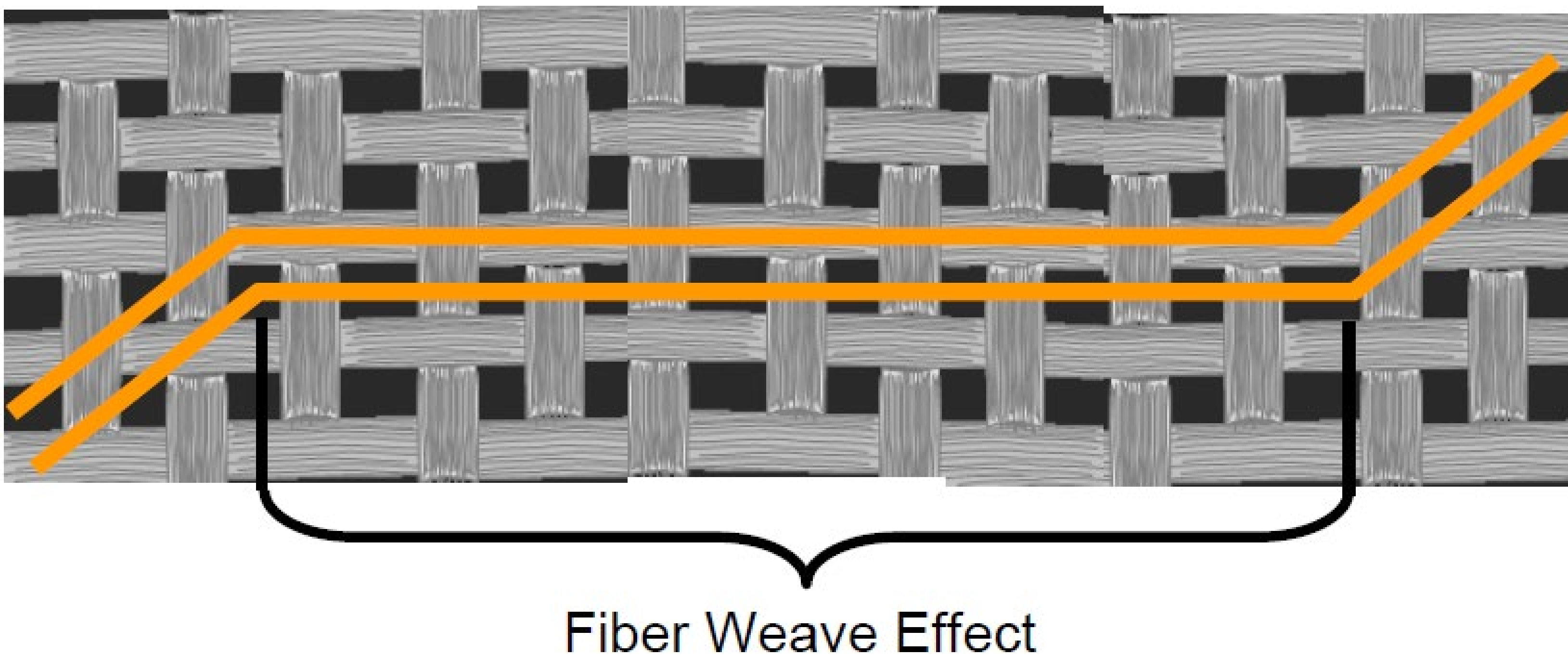
2116



7628

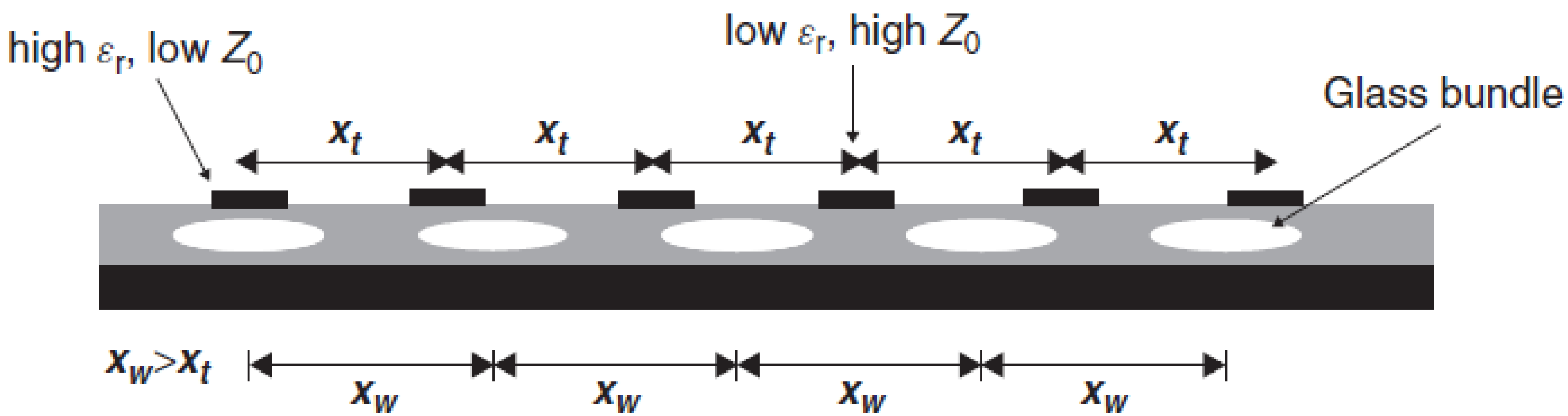
Source: S. McMorrow, C. Heard, "The Impact of PCB Laminate Weave on the Electrical Performance of Differential Signaling at Multi-Gigabit Data Rates", DesignCon 2005.

Fiber Weave Effect



Source: Lambert Simonovich, "Practical Fiber Weave Effect Modeling",
White Paper-Issue 3, March 2, 2012.

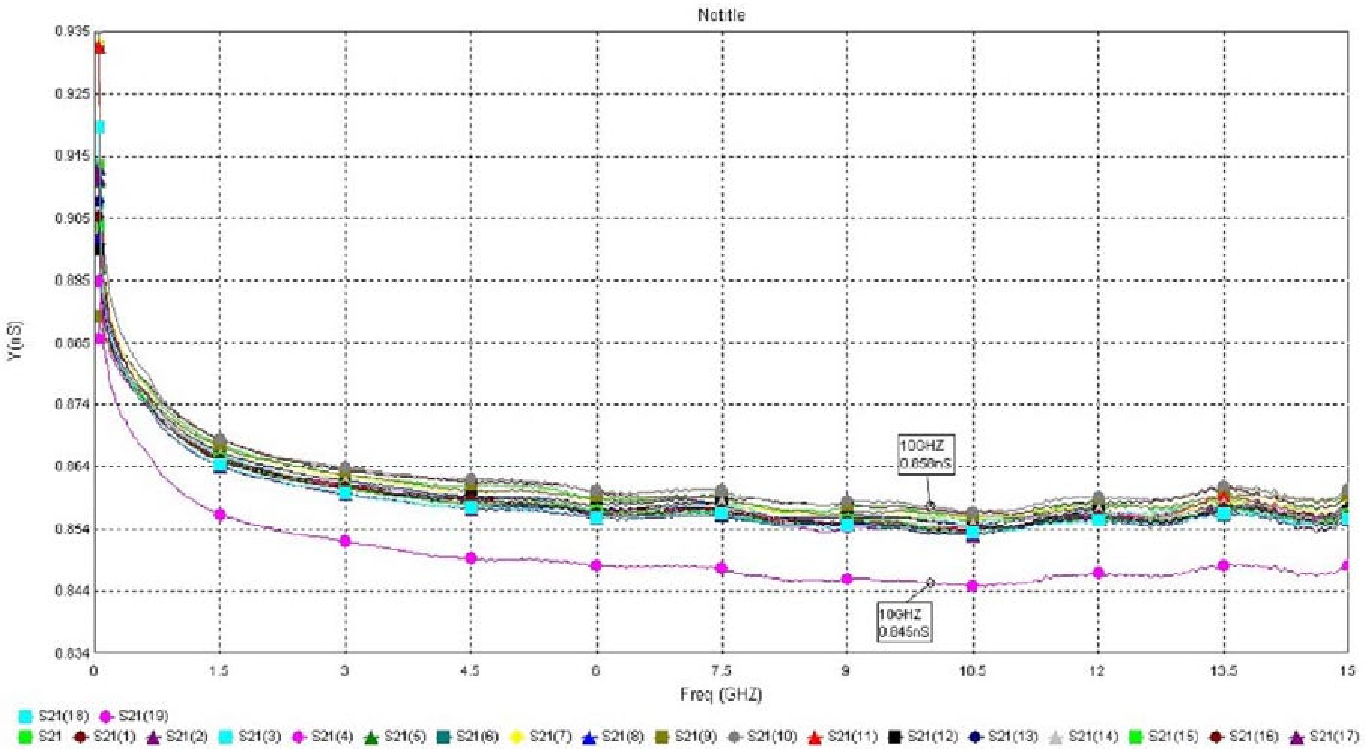
Fiber Weave Effect



Source: S. Hall and H. Heck , Advanced Signal Integrity for High-Speed Digital Designs, J. Wiley, IEEE , 2009.

Fiber Weave Effect

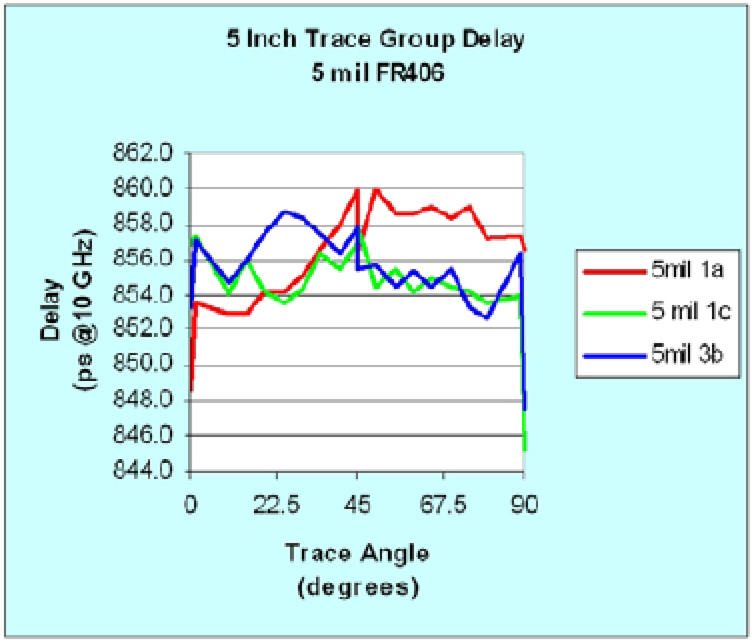
Group delay variation

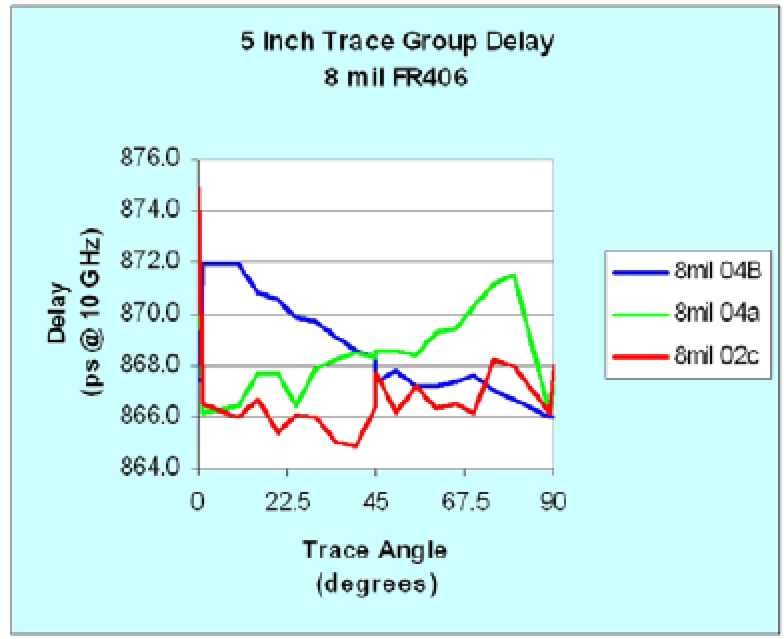


Source: S. McMorrow, C. Heard, "The Impact of PCB Laminate Weave on the Electrical Performance of Differential Signaling at Multi-Gigabit Data Rates", DesignCon 2005.

Fiber Weave Effect

Group delay variation: effect of angle

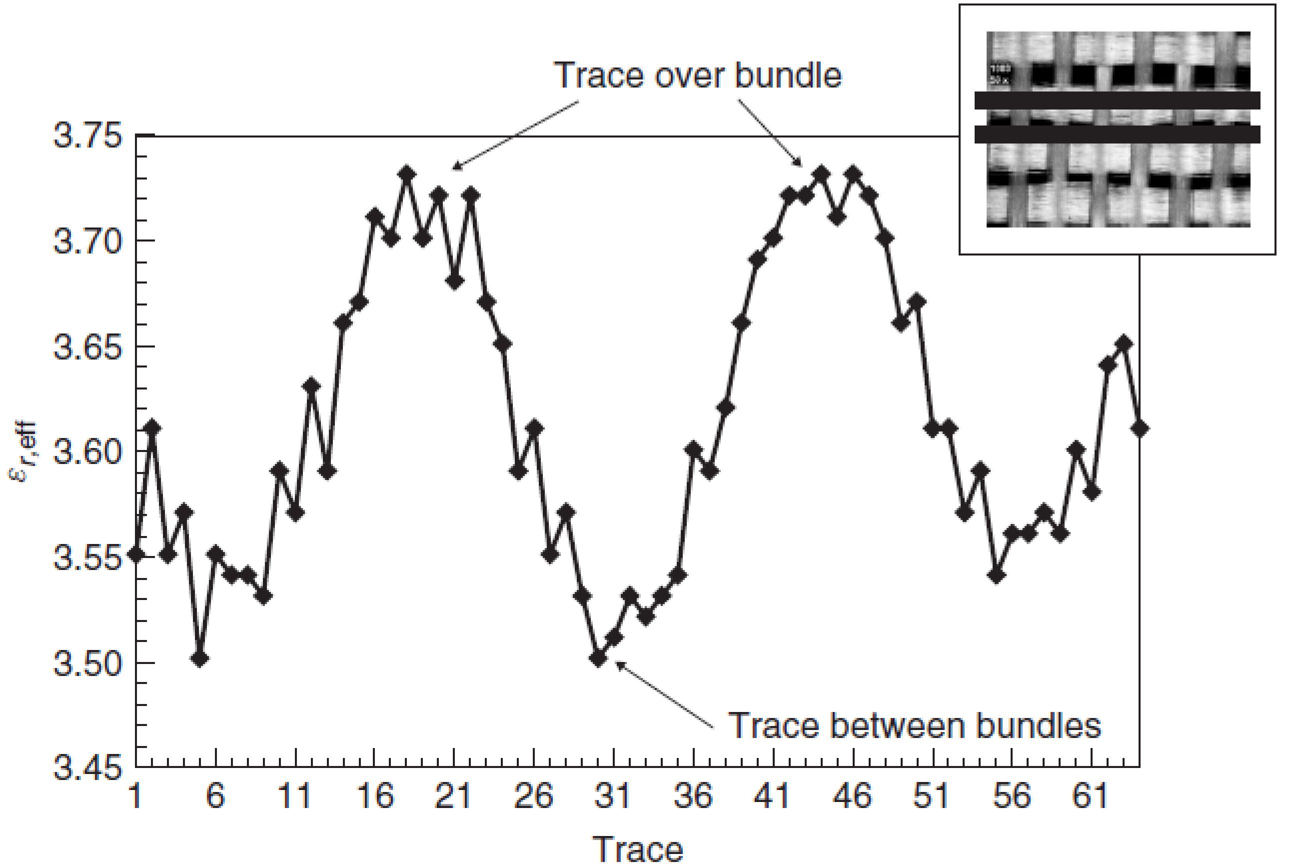




Source: S. McMorrow, C. Heard, "The Impact of PCB Laminate Weave on the Electrical Performance of Differential Signaling at Multi-Gigabit Data Rates", DesignCon 2005.

Fiber Weave Effect

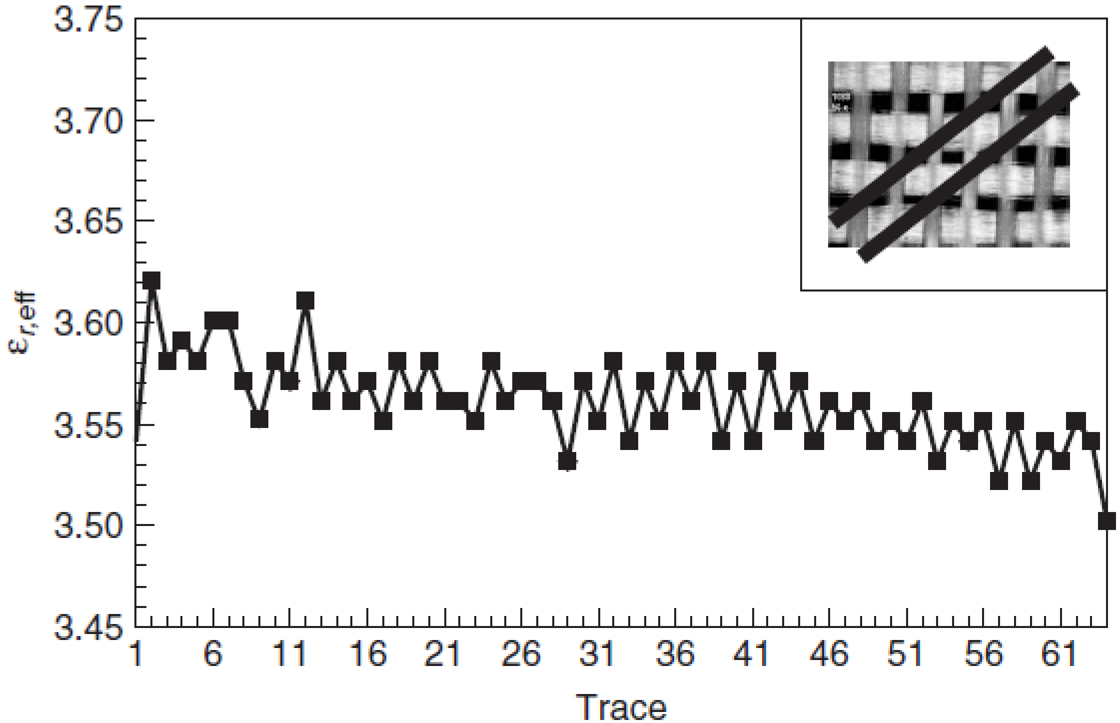
Straight traces



Source: S. Hall and H. Heck , Advanced Signal Integrity for High-Speed Digital Designs, J. Wiley, IEEE , 2009.

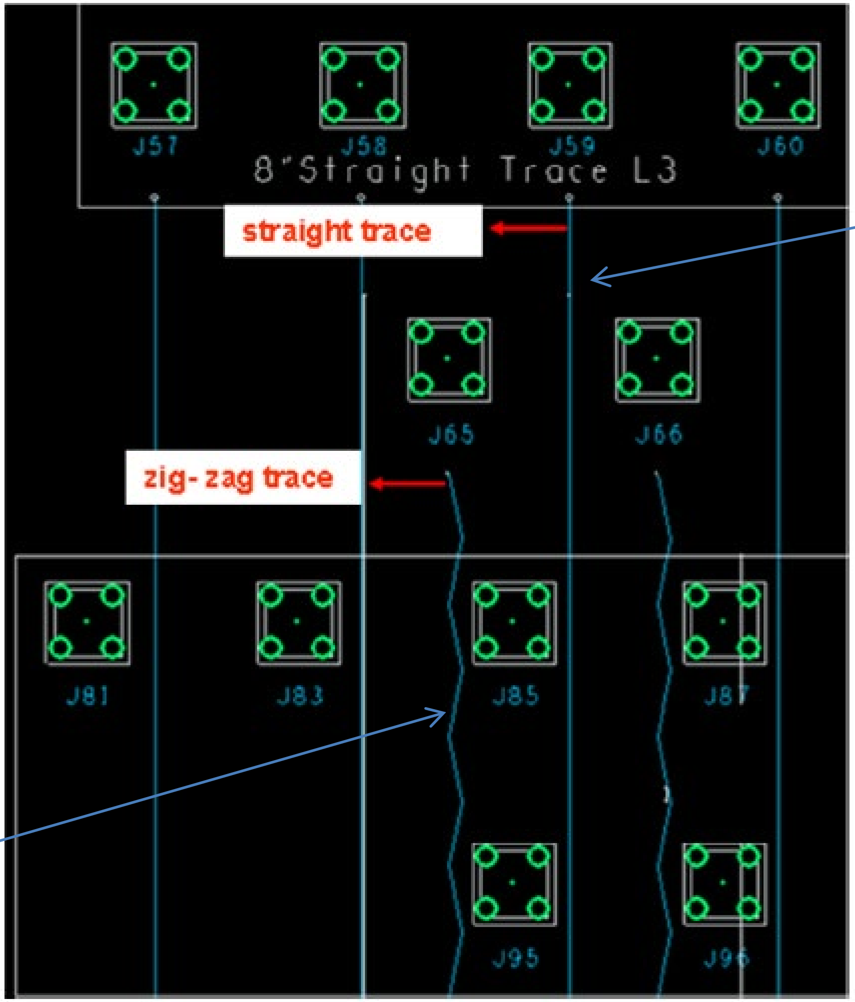
Fiber Weave Effect

45º traces



Source: S. Hall and H. Heck , Advanced Signal Integrity for High-Speed Digital Designs, J. Wiley, IEEE , 2009.

Fiber Weave Effect



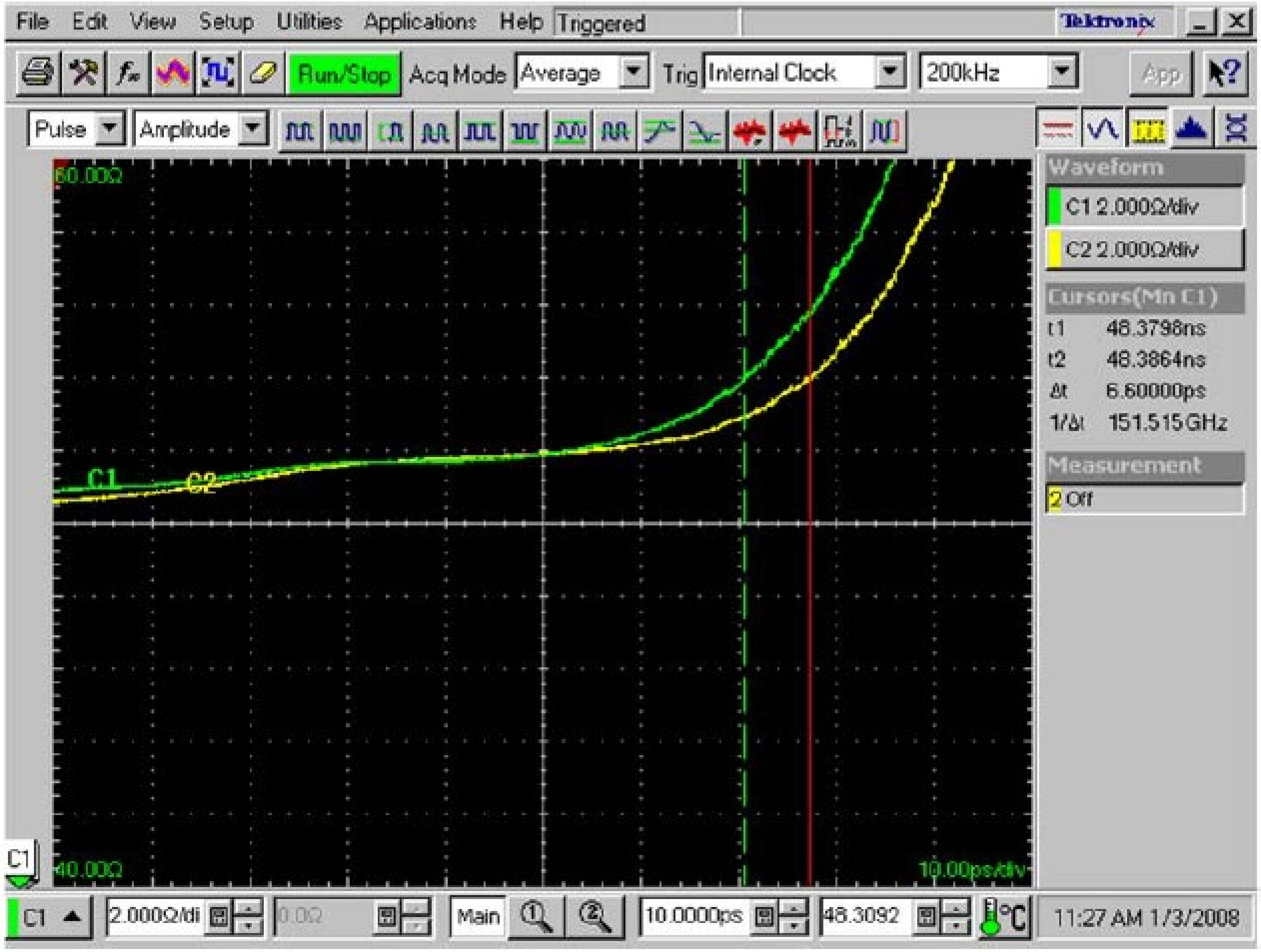
straight traces

zig-zag traces

Source: PCB Dielectric Material Selection and Fiber Weave Effect on High-Speed Channel Routing, Altera Application Note AN-528-1.1, January 2011.

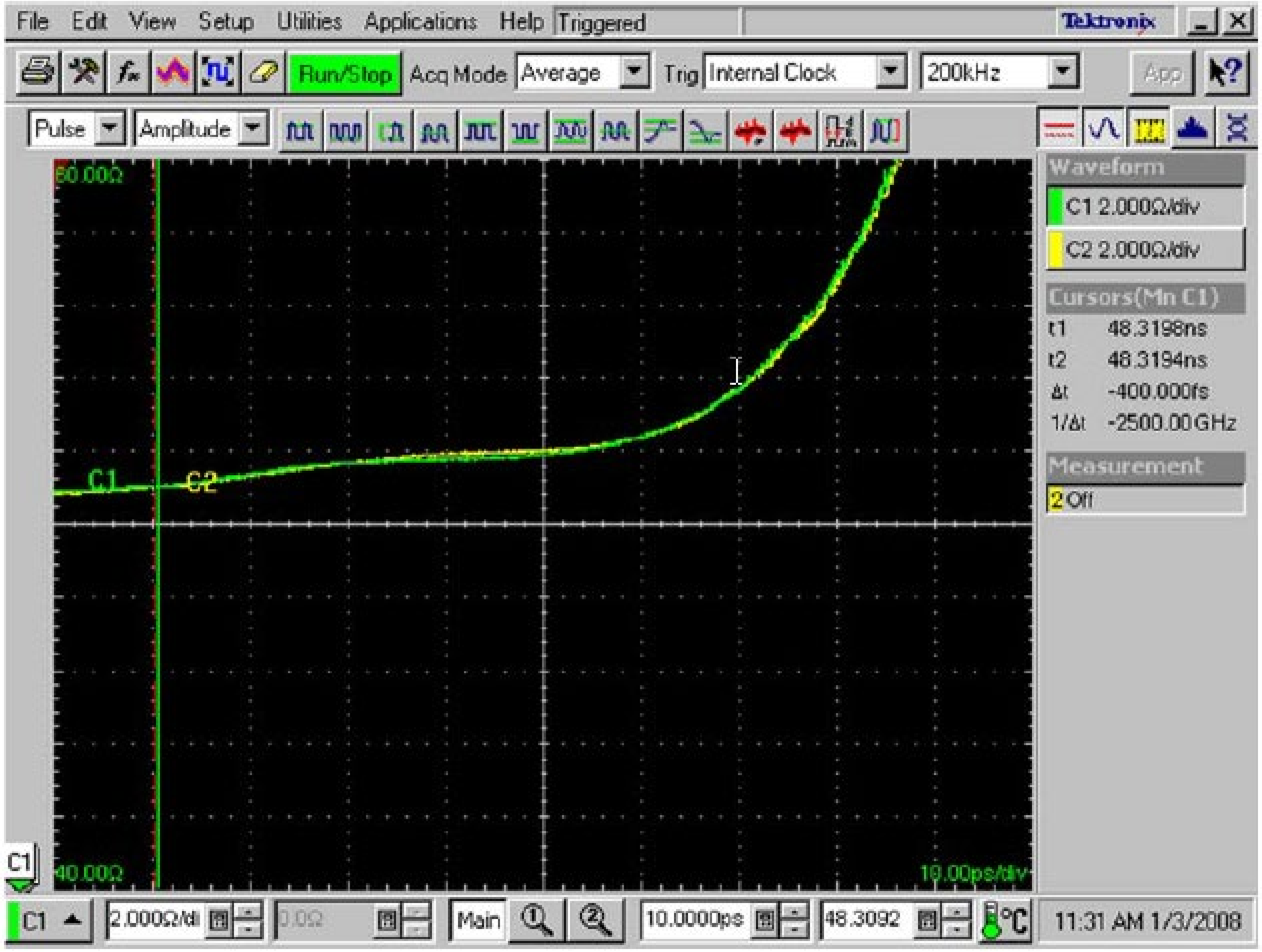
Fiber Weave Effect

Skew on straight traces



Source: PCB Dielectric Material Selection and Fiber Weave Effect on High-Speed Channel Routing, Altera Application Note AN-528-1.1, January 2011.

Fiber Weave Effect



Skew on zig-zag traces

Source: PCB Dielectric Material Selection and Fiber Weave Effect on High-Speed Channel Routing, Altera Application Note AN-528-1.1, January 2011.

Fiber Weave Effect

- **Mitigation Techniques**
  - Use wider widths to achieve impedance targets.
  - Specify a denser weave (2116, 2113, 7268, 1652) compared to a sparse weave (106, 1080).
  - Move to a better substrate such as Nelco 4000-13
  - Perform floor planning such that routing is at an angle rather than orthogonal.
  - Make use of zig-zag routing