Modeling Physical Interconnects

(Part 2)

Dr. José Ernesto Rayas Sánchez

Outline

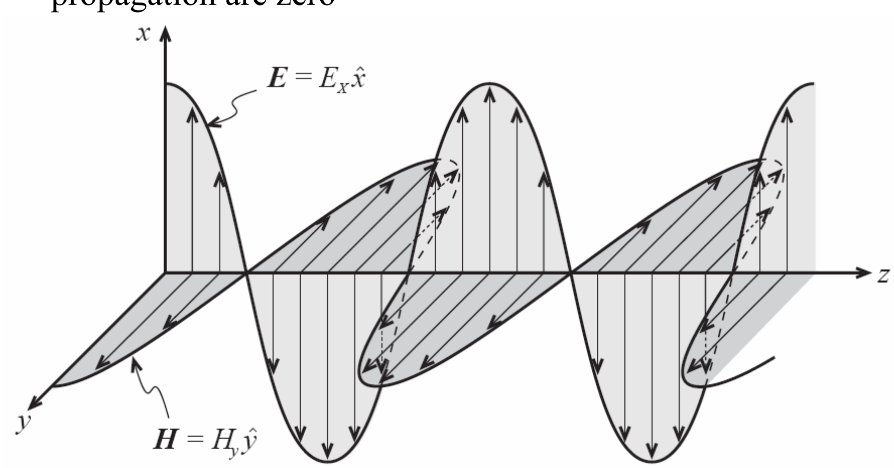
- Stripline
- Stripline geometry and field distribution
- Characterizing striplines
- Fabrication of PCBs (stackup)
- Microstrip line
- Microstrip geometry and field distribution
- Characterizing microstrip lines
- Embedded microstrips
- Losses in striplines and microstrip lines

Striplines

- A stripline trace is immersed in a dielectric and sandwiched between two metallic planes
- The electric and magnetic fields are confined to the dielectric (TEM propagation if losses are small)

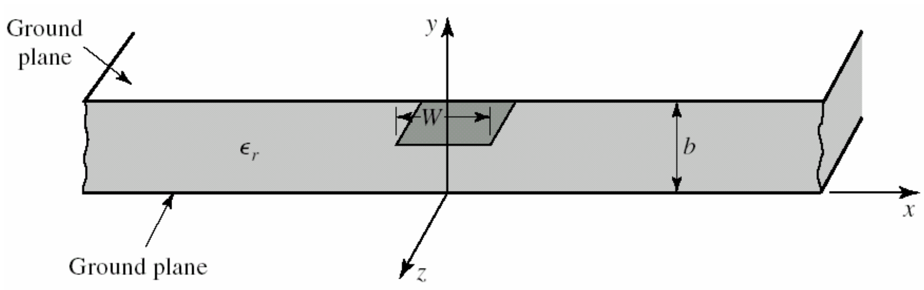
TEM Propagation

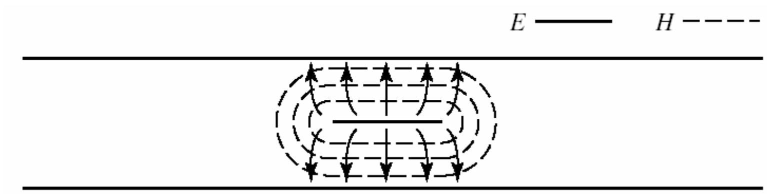
The electric and magnetic fields in the direction of propagation are zero



(R. Ludwig and P. Bretchko, RF Circuit Design, Prentice Hall, 2000)

Stripline Geometry and Field Distribution

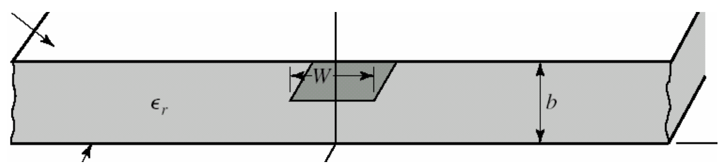




$$v_p = \frac{c}{\sqrt{\varepsilon_e}} \qquad \varepsilon_e = \varepsilon_r \qquad c = 300\text{Mm/s}$$

 (D. M. Pozar, Microwave Engineering, Wiley, 2005)

Characterizing Striplines (Zero Thickness)



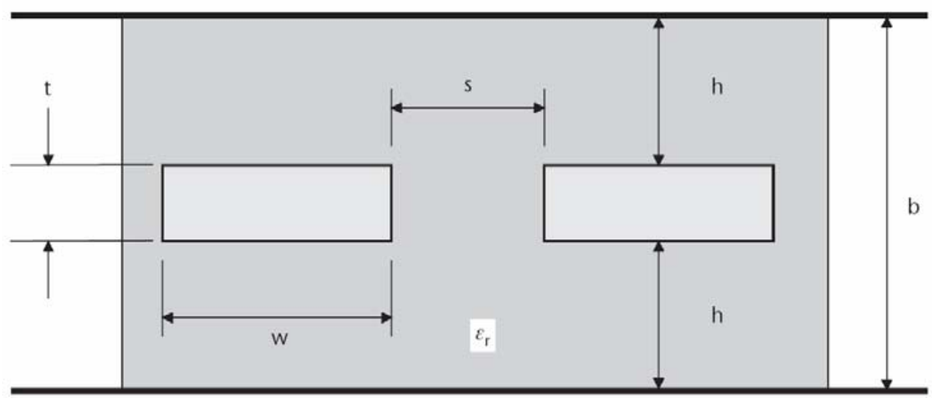
$$Z_o = \frac{30\pi}{\sqrt{\varepsilon_r}} \frac{b}{(W_e + 0.44b)}$$

where W_e is the effective width given by

$$\frac{W_e}{b} = \frac{W}{b} - \begin{cases} 0 & \text{for } \frac{W}{b} \geq 0.35 \\ (0.35 - \frac{W}{b})^2 & \text{for } \frac{W}{b} \leq 0.35 \end{cases}$$

 (D. M. Pozar, Microwave Engineering, Wiley, 2005)

Characterizing Striplines (Non Zero Thickness)



 (S. C. Thierauf, High-Speed Circuit Board Signal Integrity, Artech, 2004)

Characterizing Striplines (Non Zero Thickness)

$$Z_o = \frac{94.15}{\sqrt{\varepsilon_r}\left(\frac{w}{b}k + \frac{C_f}{8.854\varepsilon_r}\right)} \quad \text{for} \quad \frac{w}{b-t} \geq 0.35$$

where

$$k \equiv \frac{1}{1-\frac{t}{b}}$$

and C_f is the fringing capacitance given by

$$C_f = \frac{8.854\varepsilon_r}{\pi}\left[2k\ln(k+1) - (k-1)\ln(k^2-1)\right] \text{ (pF/m)}$$

 (S. C. Thierauf, High-Speed Circuit Board Signal Integrity, Artech, 2004)

Dr. J. E. Rayas Sánchez
http://iteso.mx/~erayas   erayas@iteso.mx

Characterizing Striplines (Non Zero Thickness)

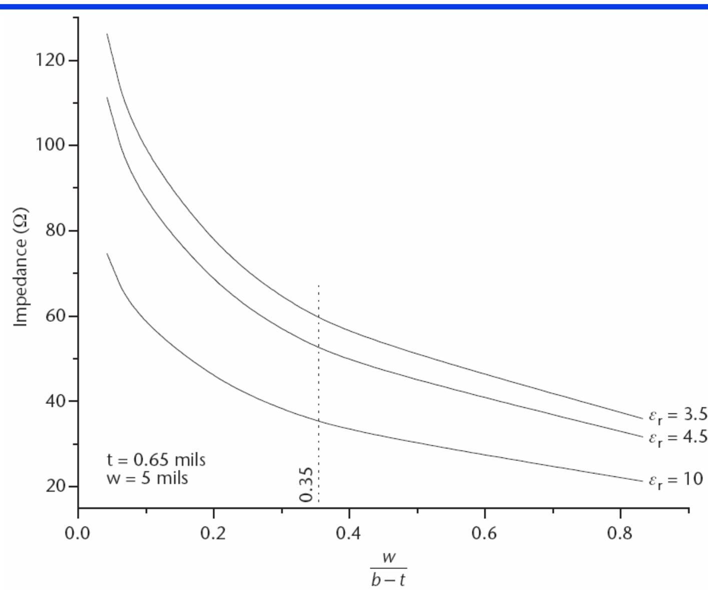
$$Z_o = \frac{60}{\sqrt{\varepsilon_r}} \ln\left(\frac{4b}{\pi d}\right) \quad \text{for} \quad \frac{w}{b-t} < 0.35$$

where

$$d = \frac{w}{2}\left\{1 + \frac{t}{\pi w}\left[1 + \ln\left(\frac{4\pi w}{t}\right) + 0.51\pi\left(\frac{t}{w}\right)^2\right]\right\}$$

 (S. C. Thierauf, High-Speed Circuit Board Signal Integrity, Artech, 2004)

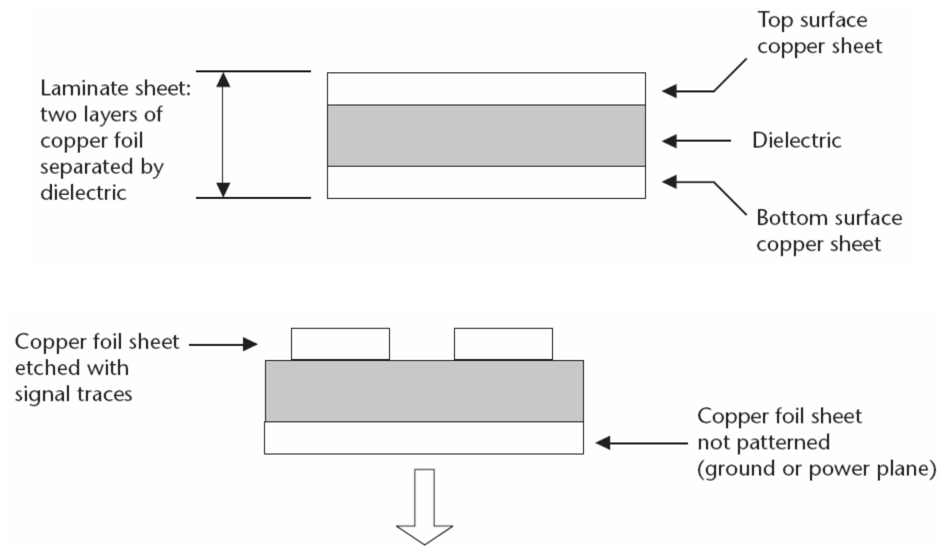
Characterizing Striplines (Non Zero Thickness)



 (S. C. Thierauf, High-Speed Circuit Board Signal Integrity, Artech, 2004)

Dr. J. E. Rayas Sánchez
http://iteso.mx/~erayas erayas@iteso.mx

Fabrication of PCB Stackup



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Fabrication of PCB Stackup (cont)

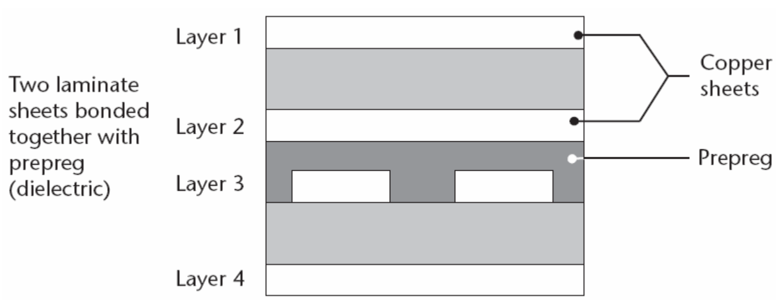

Table 9.1 Differences in Hi-TG FR4 Laminate and Prepreg ε_r

Case	*Prepreg Thickness (mils)/ε_r*	*Core Thickness (mils)/ε_r*	*Change ε_r*
1	4.8/4.36	5.2/4.60	5.5%
2	4.8/4.36	22/4.65	6.7%
3	4.7/3.65	3.8/4.19	14.7%

- 😐 PCB manufacturers usually select the laminate and prepeg thickness of each layer
- ☹ Identical routing patterns can have different times of flight on the same PCB

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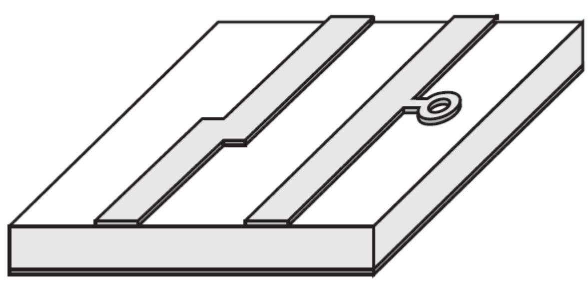
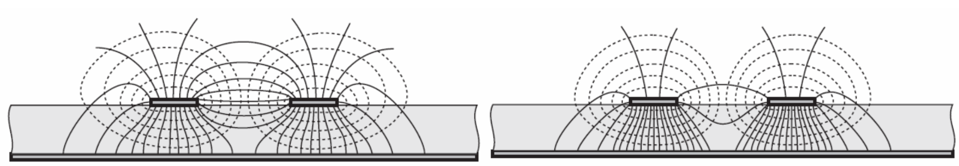
Microstrips

- A microstrip trace is sandwiched between two very different dielectrics
- Due to this non-homogeneous media, microstrips propagate in non TEM mode
- Using the effective dielectric constant approach, microstrips can be modeled as if they had an homogeneous media (quasi TEM propagation if the losses are small)

Microstrip Geometry and Field Distribution





(a) Teflon epoxy ($\varepsilon_r = 2.55$) (b) Alumina ($\varepsilon_r = 10.0$)

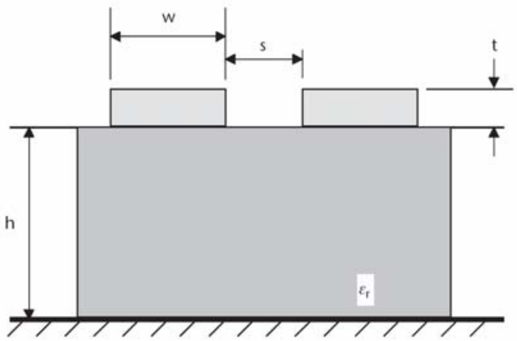
Substrates with higher ε_r reduce field leakage and cross coupling
Substrates with smaller ε_r reduce dielectric losses

(R. Ludwig and P. Bretchko, RF Circuit Design, Prentice Hall, 2000)

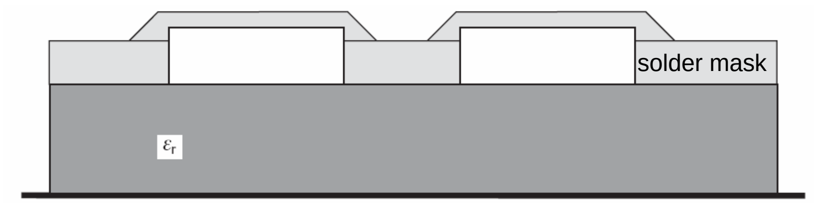
Dr. J. E. Rayas Sánchez
http://iteso.mx/~erayas erayas@iteso.mx

Microstrip Geometry (cont)

Exposed microstrip:



Embedded microstrip:



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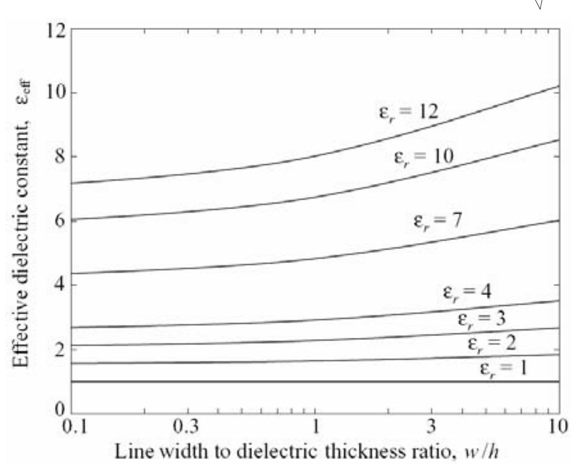
Characterizing Exposed Microstrip Lines

$$v_p = \frac{c}{\sqrt{\varepsilon_e}} \qquad c = 300\text{Mm/s} \qquad \varepsilon_e = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2\sqrt{1 + (10h/w)}}$$



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Characterizing Exposed Microstrip Lines (cont)

Z_o neglecting thickness ($t = 0$)

Model 1: Walker's formulae

$$\text{if } \frac{w}{h} \le 1, \quad Z_o = \frac{60}{\sqrt{\varepsilon_e}} \ln\left(\frac{8h}{w} + \frac{w}{4h}\right) \ \Omega$$

$$\text{if } \frac{w}{h} > 1, \quad Z_o = \frac{120\pi}{\sqrt{\varepsilon_e}} \frac{1}{\left(\frac{w}{h}\right) + 2.42 - 0.44\left(\frac{h}{w}\right) + \left(1 - \frac{h}{w}\right)^6} \ \Omega$$

 (C.S. Walker, Capacitance, Inductance and Crosstalk Analysis; Artech, 1990)

Characterizing Exposed Microstrip Lines (cont)

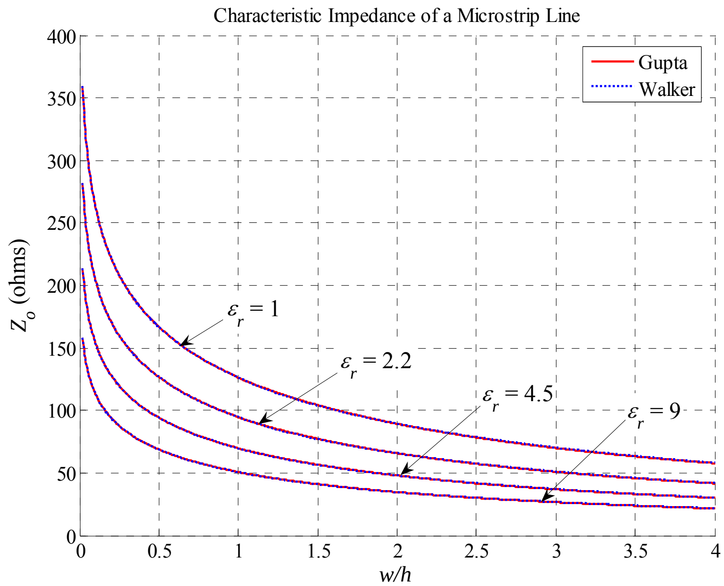
Model 2: Gupta's formulae

$$\text{if } \frac{w}{h} \le 1, \quad Z_o = \frac{60}{\sqrt{\varepsilon_e}} \ln\left(\frac{8h}{w} + \frac{w}{4h}\right) \ \Omega$$

$$\text{if } \frac{w}{h} > 1, \quad Z_o = \frac{120\pi}{\sqrt{\varepsilon_e}} \frac{1}{\left(\frac{w}{h}\right) + 1.393 + 0.667 \ln\left(\frac{w}{h} + 1.444\right)} \ \Omega$$

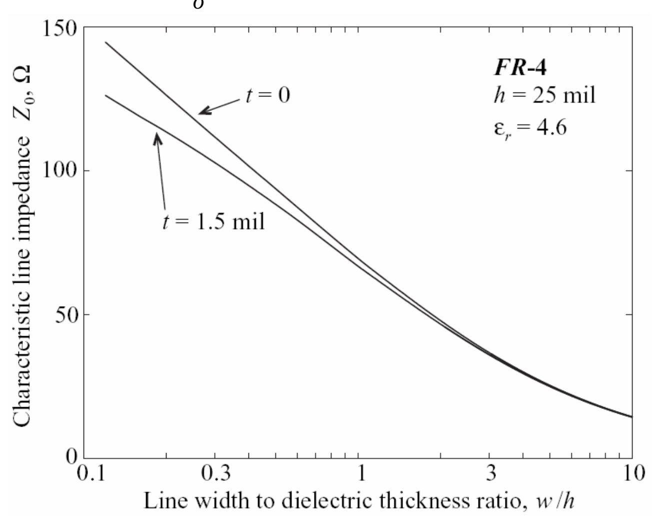
 (*K.C. Gupta* et. al, *Computer-Aided Design of Microwave Circuits; Artech, 1981*)

Characterizing Exposed Microstrip Lines (cont)



Characterizing Exposed Microstrip Lines (cont)

Effects of $t \neq 0$ on Z_o



(R. Ludwig and P. Bretchko, RF Circuit Design, Prentice Hall, 2000)

Characterizing Exposed Microstrip Lines (cont)

Z_o considering thickness ($t \neq 0$)

$$\text{if } \frac{w}{h} \leq 2, \quad Z_o = \frac{60}{\sqrt{\varepsilon_e}} \ln\left(\frac{5.98h}{0.8w + t}\right) \quad \Omega$$

$$\text{if } \frac{w}{h} > 2, \quad Z_o = \frac{120\pi}{\sqrt{\varepsilon_e}} \frac{1}{\left(\frac{w}{h}\right) + 1.393 + 0.667\ln\left(\frac{w}{h} + 1.444\right)} \quad \Omega$$

(S. C. Thierauf, High-Speed Circuit Board Signal Integrity, Artech, 2004)

Embedded Microstrips

- Usually PCBs are covered in solder mask, creating embedded microstrip lines in the extreme layers
- The solder mask properties vary among manufacturers
- Typical parameter values for the solder mask are:
  - Thickness: 0.6-0.8 mil
  - Dielectric constant: 3.1-3.3
  - Loss tangent: ~ 0.02
- Analytical models for embedded microstrip lines become very complicated

Dr. J. E. Rayas Sánchez
http://iteso.mx/~erayas erayas@iteso.mx

Effects of the Solder Mask

- Reduce the characteristic impedance, Z_o
- Increase the flight time, t_d
- Increase losses

☺ Vendors offer PCBs with "controlled impedance"

b: bare laminate
s: with solder mask

Table 9.2 Effects of Solder Mask on Microstrip Z_o, t_d, α_t

w (mils)	w/h	$Z_{\_b}$ (Ω)	$Z_{\_s}$ (Ω)	t_{d_b} (pS/in)	t_{d_s} (pS/in)	$\alpha t_{\_b}$ (dB/in)	$at_{\_s}$ (dB/in)
3	2	49	44	151	166	0.30	0.34
3	0.5	89	83	147	158	0.18	0.20
8	2	47	45	155	163	0.19	0.21
8	0.5	92	89	148	154	0.13	0.14

(S. C. Thierauf, High-Speed Circuit Board Signal Integrity, Artech, 2004)

Lossy *vs* Lossless Transmission Lines

$$V(z) = V_o^+[e^{-\gamma z} + \Gamma e^{+\gamma z}]$$

$$I(z) = \frac{V_o^+}{Z_o}[e^{-\gamma z} - \Gamma e^{+\gamma z}]$$

$$\gamma = \sqrt{(R + j\omega L)(G + j\omega C)}$$

$$\gamma \equiv \alpha + j\beta$$

$$Z_o = \sqrt{\frac{R + j\omega L}{G + j\omega C}}$$

$$\Gamma_z(z) = \Gamma e^{+2\gamma z}$$

$$V(z) = V_o^+[e^{-j\beta z} + \Gamma e^{+j\beta z}]$$

$$I(z) = \frac{V_o^+}{Z_o}[e^{-j\beta z} - \Gamma e^{+j\beta z}]$$

$$\beta = \omega\sqrt{LC} \qquad Z_o = \sqrt{\frac{L}{C}}$$

$$\Gamma_z(z) = \Gamma e^{+2j\beta z}$$

$$v(z,t) = |V_o^+|\cos(\omega t - \beta z + \phi^+)e^{-\alpha z} + |V_o^-|\cos(\omega t + \beta z + \phi^-)e^{+\alpha z}$$

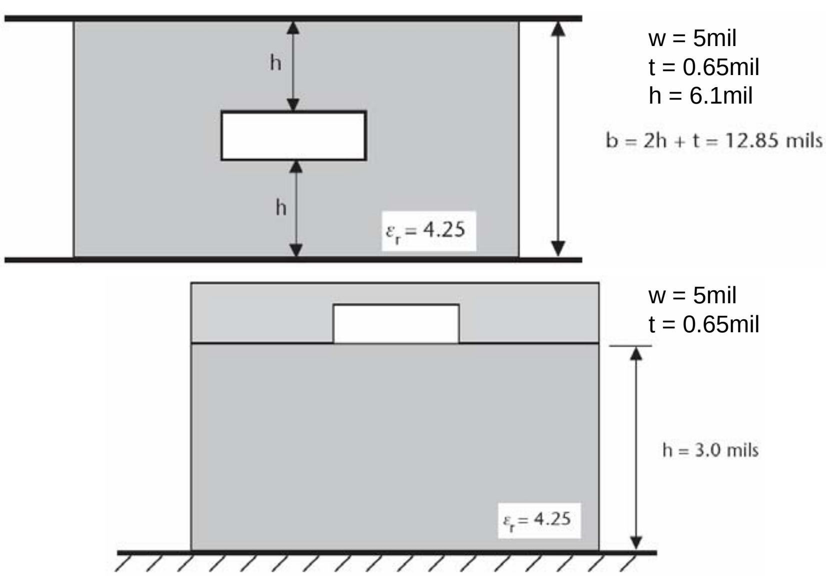
Losses in Transmission Lines

- The total loss α_t is the sum of the conductor and dielectric losses

$$\alpha \equiv \alpha_t = \alpha_c + \alpha_d$$

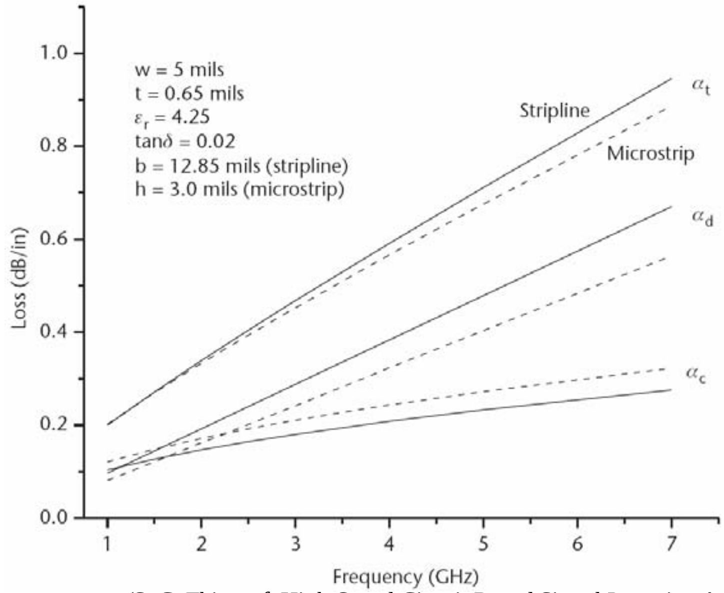
- Conductor losses α_c are due to the resistive losses in the signal trace and the return path (produced by a conductive current)
- Dielectric losses α_d are due to the energy lost in the dielectric layers (produced by a displacement current)

50-Ω Stripline and 50-Ω Embedded Microstrip



(S. C. Thierauf, High-Speed Circuit Board Signal Integrity, Artech, 2004)

50-Ω Stripline and 50-Ω Embedded Microstrip



 (S. C. Thierauf, High-Speed Circuit Board Signal Integrity, Artech, 2004)

Estimating Dielectric Losses

Dielectric losses α_d can be estimated for striplines and microstrip lines using

$$\alpha_d = 2.318 f \sqrt{\varepsilon_e} \tan\delta \quad \text{(dB/inch)}$$

with f in GHz.

 (S. C. Thierauf, High-Speed Circuit Board Signal Integrity, Artech, 2004)

Estimating Conductive Losses in Striplines

Conductive losses α_c can be estimated for striplines using

$$\alpha_c = \frac{2.02\times 10^{-3}\varepsilon_r Z_o k\sqrt{f}}{b}\left[1+\frac{2wk}{b}+\frac{k}{\pi}\left(1+\frac{t}{b}\right)\ln\left(\frac{k+1}{k-1}\right)\right] \text{ (dB/inch)}$$

where $$k \equiv \frac{1}{1-\dfrac{t}{b}}$$

with b, w and t in mils, and f in GHz.

(S. C. Thierauf, High-Speed Circuit Board Signal Integrity, Artech, 2004)

Estimating Conductive Losses in Microstrips

Conductive losses α_c can be estimated for striplines using

$$\alpha_c = \frac{11.411\sqrt{f}}{hZ_o}\left\{\left[1-\left(\frac{w_p}{4h}\right)^2\right]\left[1+\frac{h}{w_p}+\frac{h}{\pi w_p}\left(\ln\left(\frac{2h}{t}\right)-\frac{t}{h}\right)\right]\right\} \text{ (dB/inch)}$$

with b, w and t in mils, and f in GHz.

(S. C. Thierauf, High-Speed Circuit Board Signal Integrity, Artech, 2004)

Dr. J. E. Rayas Sánchez
http://iteso.mx/~erayas   erayas@iteso.mx

The Low-Loss Transmission Line

- It is a line where $R << \omega L$ and $G << \omega C$

$$\gamma \approx j\omega\sqrt{LC}\left[1 - \frac{j}{2}\left(\frac{R}{\omega L} + \frac{G}{\omega C}\right)\right]$$

$$\gamma \equiv \alpha + j\beta$$

$\beta \approx \omega\sqrt{LC}$ β is almost a linear function of ω (no dispersion)

$$\alpha \approx \frac{1}{2}\left(R\sqrt{\frac{C}{L}} + G\sqrt{\frac{L}{C}}\right) \qquad Z_o = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \approx \sqrt{\frac{L}{C}}$$

$$\alpha \approx \frac{1}{2}\left(\frac{R}{Z_o} + GZ_o\right)$$

The Lossy Distorsionless Transmission Line

- It is a line where $R/L = G/C$

Since $\gamma = j\omega\sqrt{LC}\sqrt{1 - j\left(\frac{R}{\omega L} + \frac{G}{\omega C}\right) - \frac{RG}{\omega^2 LC}}$

$$\gamma = j\omega\sqrt{LC}\sqrt{1 - 2j\frac{R}{\omega L} - \frac{R^2}{\omega^2 L^2}}$$

$$\gamma = j\omega\sqrt{LC}\left(1 - j\frac{R}{\omega L}\right)$$

$$\gamma \equiv \alpha + j\beta$$

$$\beta = \omega\sqrt{LC} \qquad \alpha = R\sqrt{\frac{C}{L}}$$

β is a linear function of ω (non dispersive TL)