Basic Interconnects at High Frequencies

(Part 1)

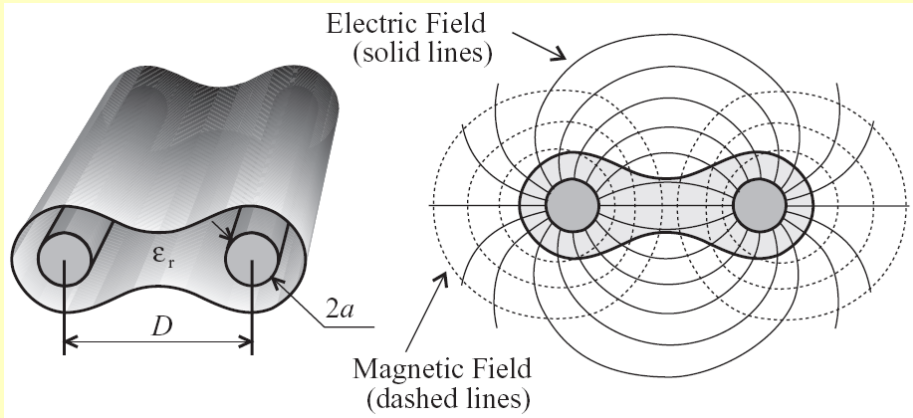
Dr. José Ernesto Rayas-Sánchez

Outline

- Two-wire cables and coaxial cables
- Stripline
- Stripline geometry and field distribution
- Characterizing striplines
- Microstrip line
- Microstrip geometry and field distribution
- Characterizing microstrip lines
- Embedded microstrips
- Losses in striplines and microstrip lines

Two-Wire Lines

- Unsuitable for high-frequency applications
- They have high radiation losses (large EMI)



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2-Wire Line – Transmission Line Parameters

$$L = \frac{\mu}{\pi}\cosh^{-1}\left(\frac{D}{2a}\right) \quad \text{(H/m)}$$

$$C = \frac{\pi\varepsilon'}{\cosh^{-1}(D/2a)} \quad \text{(F/m)}$$

$$R = \frac{R_s}{a\pi} \quad (\Omega\text{/m})$$

$$G = \frac{\pi\omega\varepsilon''}{\cosh^{-1}(D/2a)} \quad \text{(S/m)}$$

where

$$R_s = \frac{1}{\sigma\delta_s} \quad \text{surface resistivity}$$

$$\delta_s = \frac{1}{\sqrt{\pi f\sigma\mu}} \quad \text{skin depth}$$

$$\varepsilon = \varepsilon' - j\varepsilon'' = \varepsilon'(1 - j\tan\delta)$$

$$\varepsilon' = \varepsilon_o\varepsilon_r \qquad \mu = \mu_o\mu_r$$

$$\varepsilon_0 = 8.854\times10^{-12} \quad \text{(F/m)}$$

$$\mu_0 = 4\pi\times10^{-7} \quad \text{(H/m)}$$

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Two-Wire Line – Z_0 (Neglecting Losses)

$$L = \frac{\mu}{\pi}\cosh^{-1}\left(\frac{D}{2a}\right) \quad \text{(H/m)}$$

$$C = \frac{\pi\varepsilon'}{\cosh^{-1}(D/2a)} \quad \text{(F/m)}$$

$$Z_0 = \frac{1}{\pi}\cosh^{-1}\left(\frac{D}{2a}\right)\sqrt{\frac{\mu}{\varepsilon'}} \quad (\Omega)$$

$$Z_0 = \frac{376.73}{\pi\sqrt{\varepsilon_r}}\cosh^{-1}\left(\frac{D}{2a}\right) \quad (\Omega)$$

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Two-Wire Line – Transmission Line Parameters

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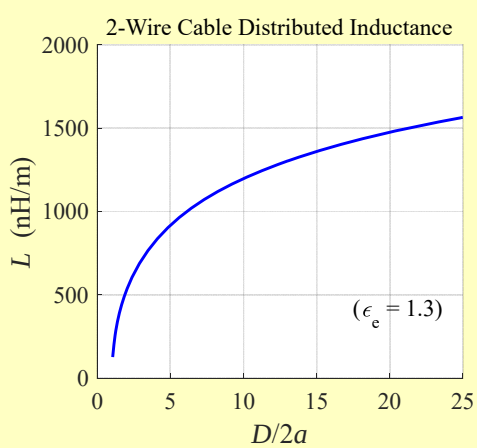

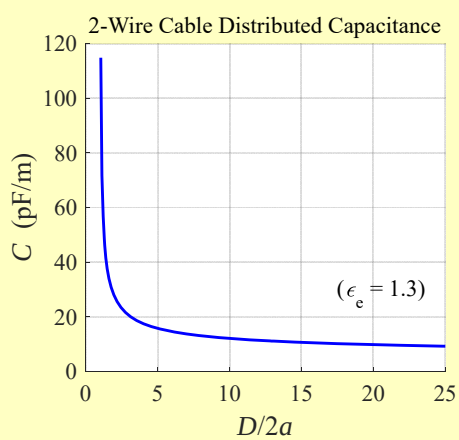

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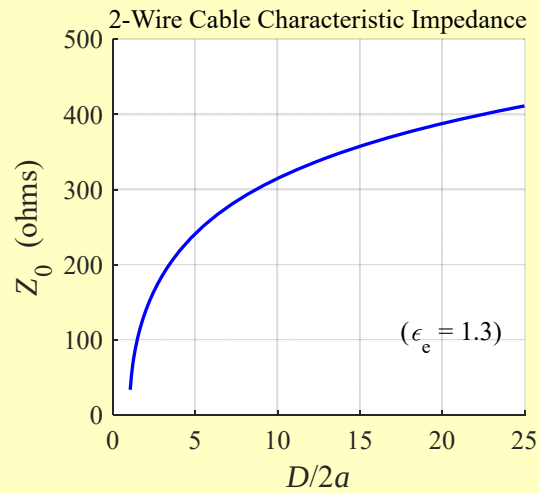
Two-Wire Line – Z_0 (Neglecting Losses)

$$Z_0 = \frac{1}{\pi}\cosh^{-1}\left(\frac{D}{2a}\right)\sqrt{\frac{\mu}{\varepsilon'}} \quad (\Omega)$$



Two-Wire Line – Practical Issues

- The most common 2-wire TL is the "twin-lead" line
- Typical Z_o for twin-lead lines: 75Ω, 300Ω, and 400Ω
- They use copper for the wires, separated by a plastic (typically polyethylene) ribbon

300-Ω twin-line

400-Ω ladder twin-line

300Ω to 75Ω balun

(K. L. Kaiser, Transmission Line Matching and Crosstalk, CRC, 2005)

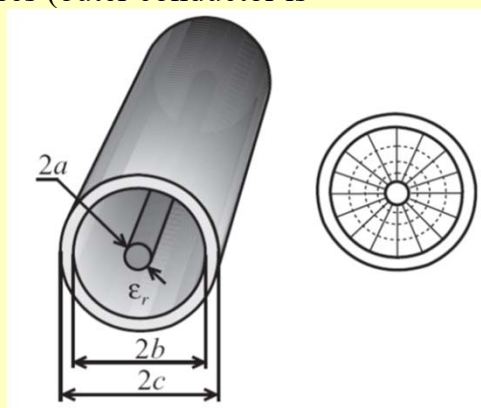
Coaxial Cables

- Typical coaxial cables are used up to 10 GHz (high-end coaxial lines can be used up to 80 GHz)
- They have no radiation losses (outer conductor is grounded)

Typical dielectrics:

- Polystyrene ($\varepsilon_r = 2.5$, $\tan\delta = 0.0003^*$)
- Polyethylene ($\varepsilon_r = 2.3$, $\tan\delta = 0.0004^*$)
- Teflon ($\varepsilon_r = 2.1$, $\tan\delta = 0.0004^*$)

* at 10 GHz



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

Coaxial Cables – Transmission Line Parameters

$$L = \frac{\mu}{2\pi}\ln\frac{b}{a} \quad \text{(H/m)}$$

$$C = \frac{2\pi\varepsilon'}{\ln(b/a)} \quad \text{(F/m)}$$

$$R = \frac{R_s}{2\pi}\left(\frac{1}{a}+\frac{1}{b}\right) \quad (\Omega\text{/m})$$

$$G = \frac{2\pi\omega\varepsilon''}{\ln(b/a)} \quad \text{(S/m)}$$

where

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

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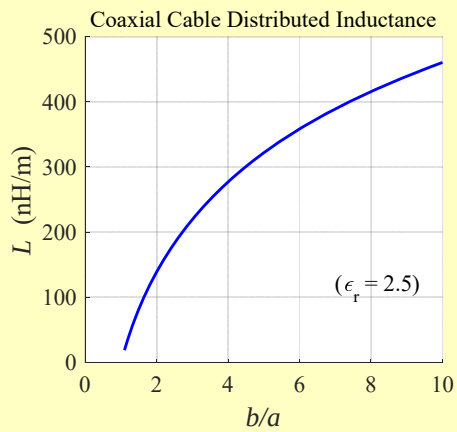

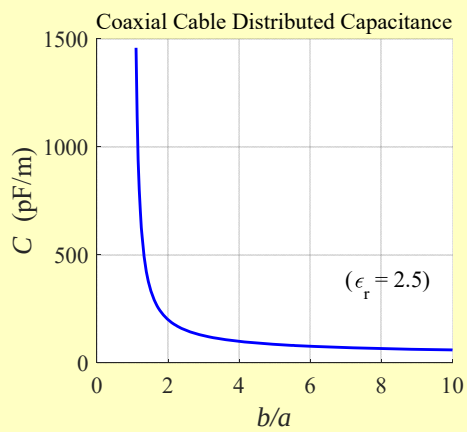

Coaxial Cables – Z_0 (Neglecting Losses)

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$$Z_0 = \frac{1}{2\pi}\ln\left(\frac{b}{a}\right)\sqrt{\frac{\mu}{\varepsilon'}} \quad (\Omega)$$

$$Z_0 = \frac{376.73}{2\pi\sqrt{\varepsilon_r}}\ln\left(\frac{b}{a}\right) \quad (\Omega)$$

Coaxial Cables – Z_0 (Neglecting Losses)

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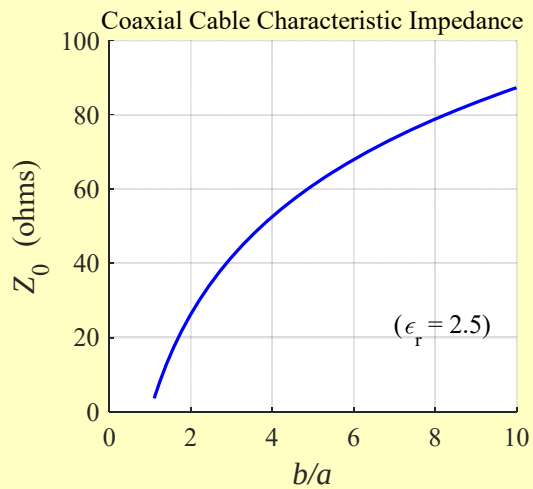
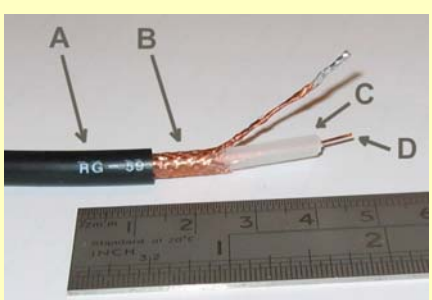


Coaxial Line – Practical Issues

- Typical Z_o for coaxial lines: 50Ω, 75Ω and 93Ω
- The most common type is the RG-6 cable (TV, 75Ω)
- Detailed technical data-sheets are available for each type



RG-59

Connectors

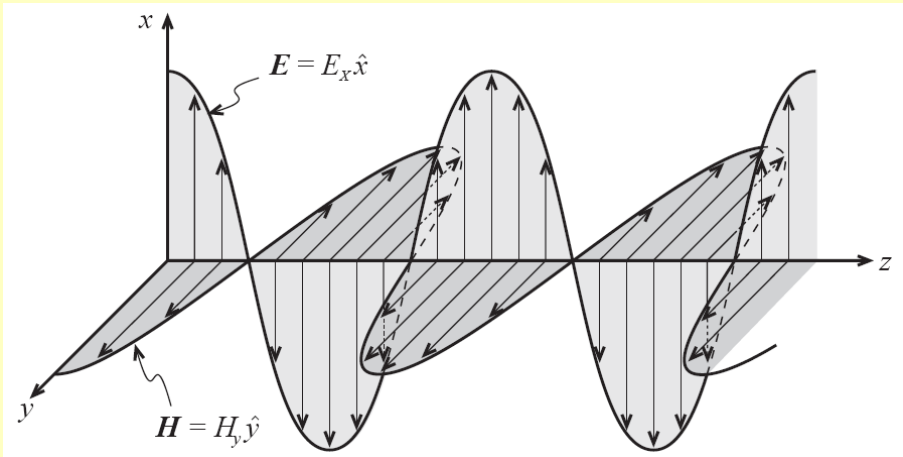
(http://en.wikipedia.org/wiki/Coaxial_cable#References, 2009)

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)

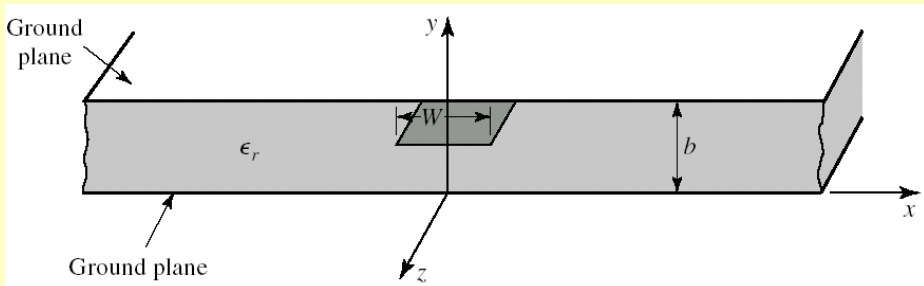
TEM Propagation

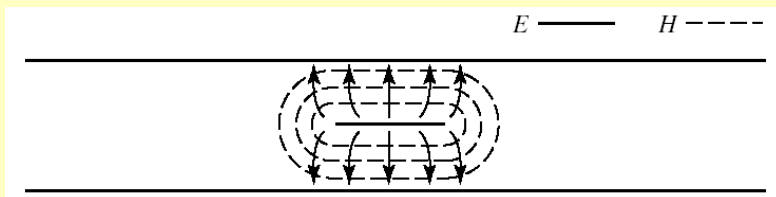
The electric and magnetic fields in the direction of propagation are zero



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

Stripline Geometry and Field Distribution

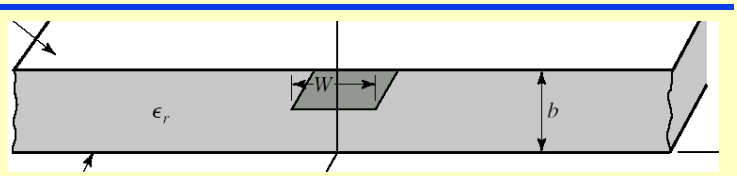




$$v_p = \frac{c}{\sqrt{\varepsilon_e}} \qquad \varepsilon_e = \varepsilon_r \qquad c = 300\text{Mm/s}$$

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

Characterizing Striplines (Zero Thickness)



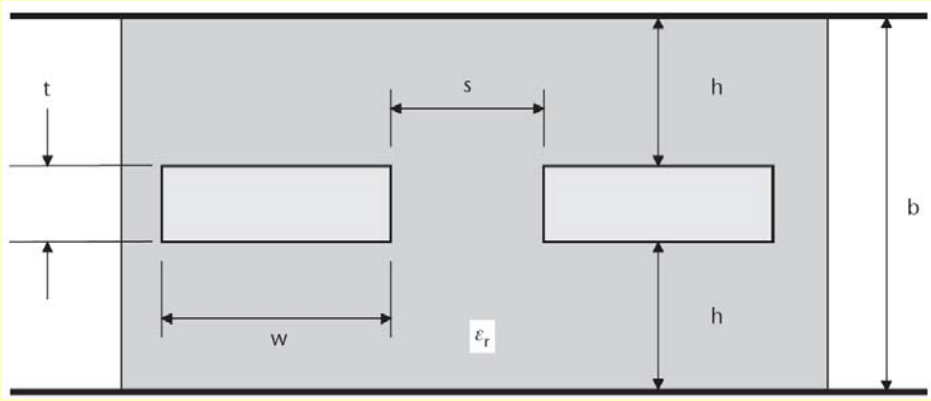
$$Z_o = \frac{30\pi}{\sqrt{\varepsilon_r}} \frac{b}{(W_e + 0.44b)}$$

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)



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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

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

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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

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

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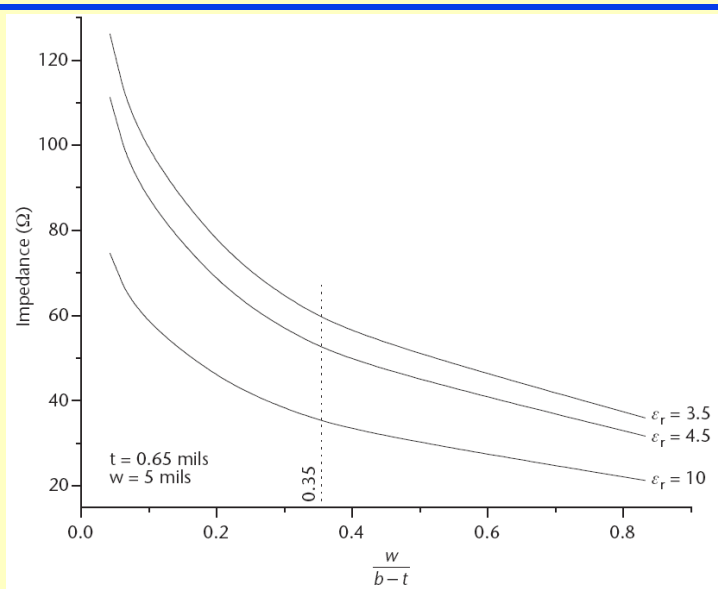
Characterizing Striplines (Non Zero Thickness)



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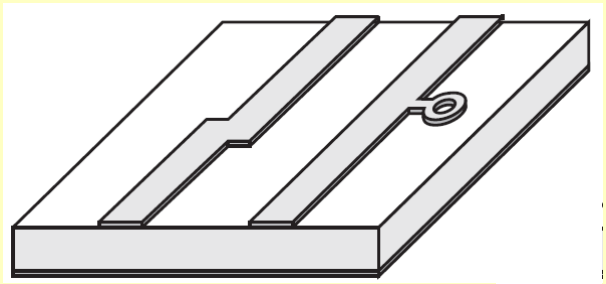
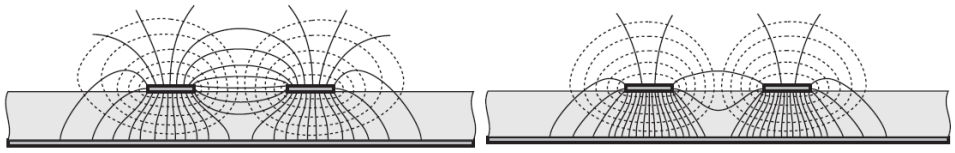
Microstrips

- 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





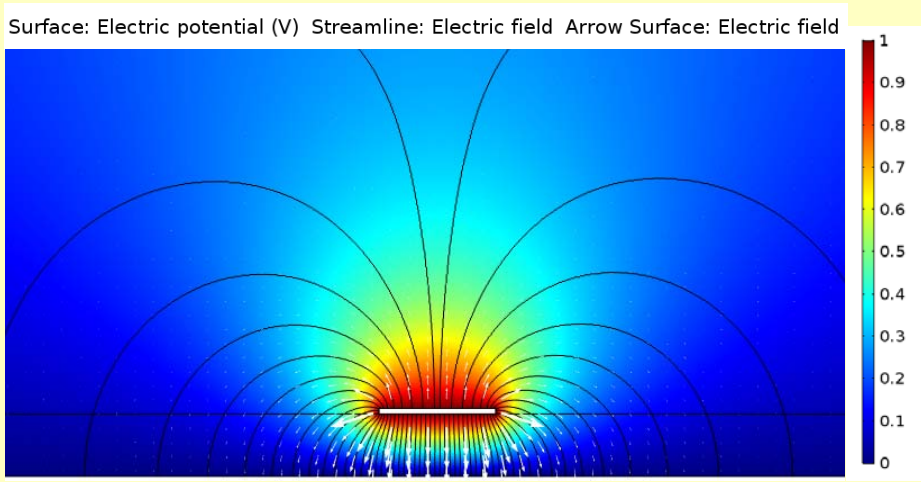
(a) Teflon epoxy ($\varepsilon_r = 2.55$) (b) Alumina ($\varepsilon_r = 10.0$)

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)

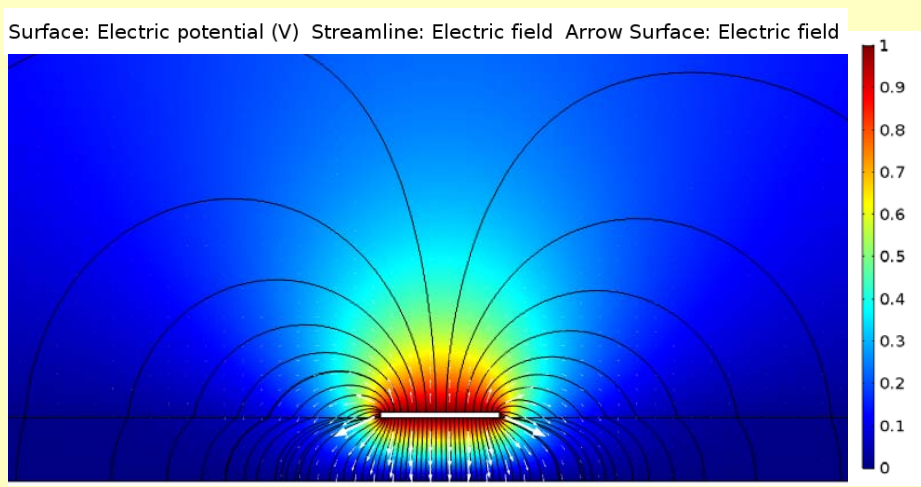
Potential and E Field Distributions (Open Box)

Substrate: Air ($\varepsilon_r = 1$)



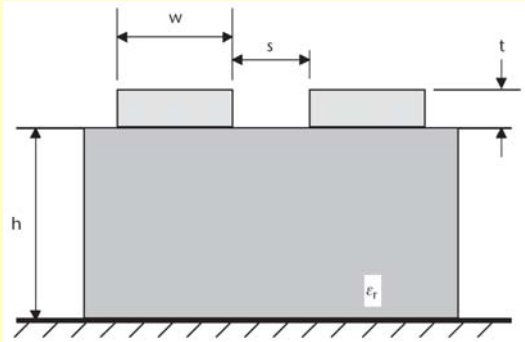
Potential and E Field Distributions (Open Box)

Substrate: FR4 ($\varepsilon_r = 4.5$)

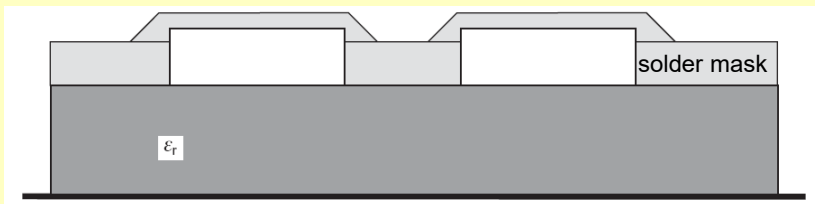


Microstrip Geometry (cont.)

Exposed microstrip:



Embedded microstrip:



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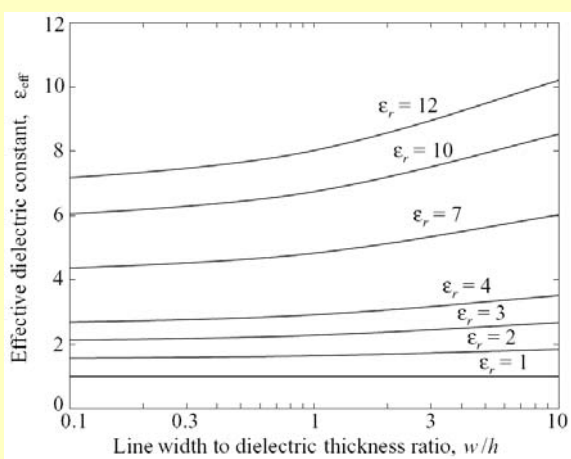
Characterizing Exposed Microstrip Lines

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



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Characterizing Exposed Microstrip Lines (cont.)

Z_o neglecting thickness ($t = 0$)

Model 1: Walker's formulae

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

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

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

Characterizing Exposed Microstrip Lines (cont.)

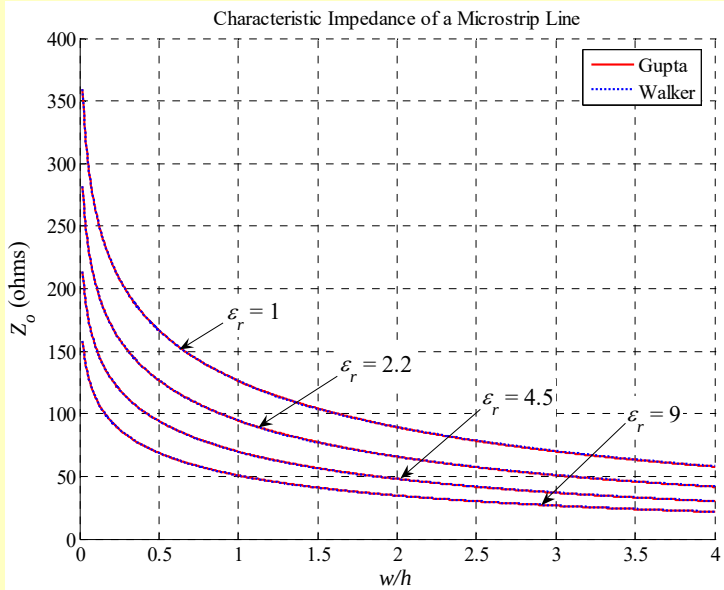
Model 2: Gupta's formulae

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

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

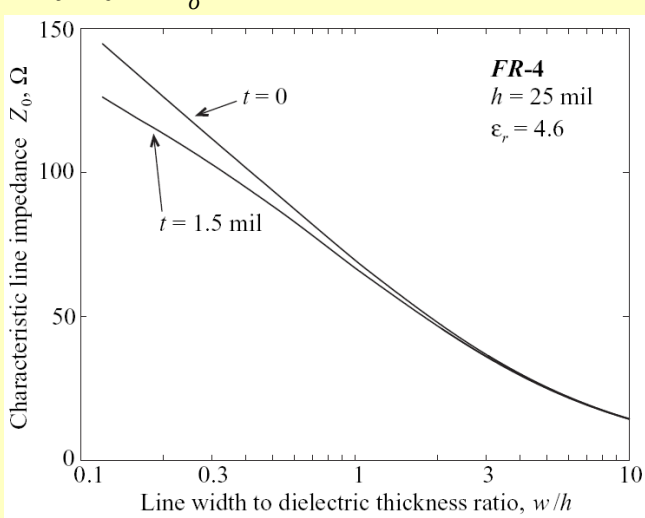
 (K.C. Gupta et. al, *Computer-Aided Design of Microwave Circuits; Artech, 1981)*

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 ($t \neq 0$)

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

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

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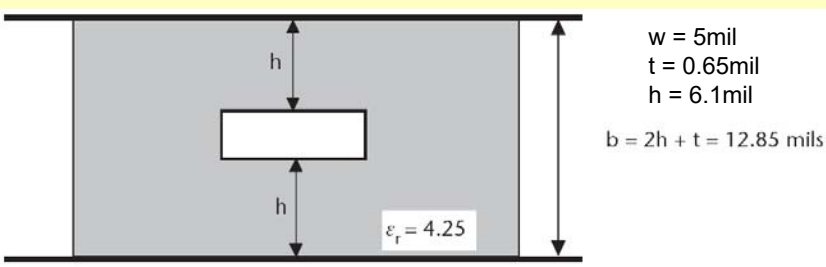
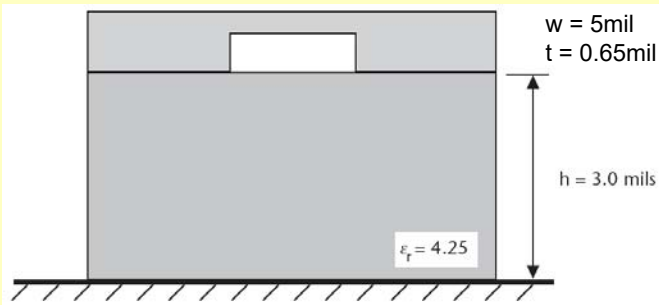
50-Ω Stripline and 50-Ω Embedded Microstrip





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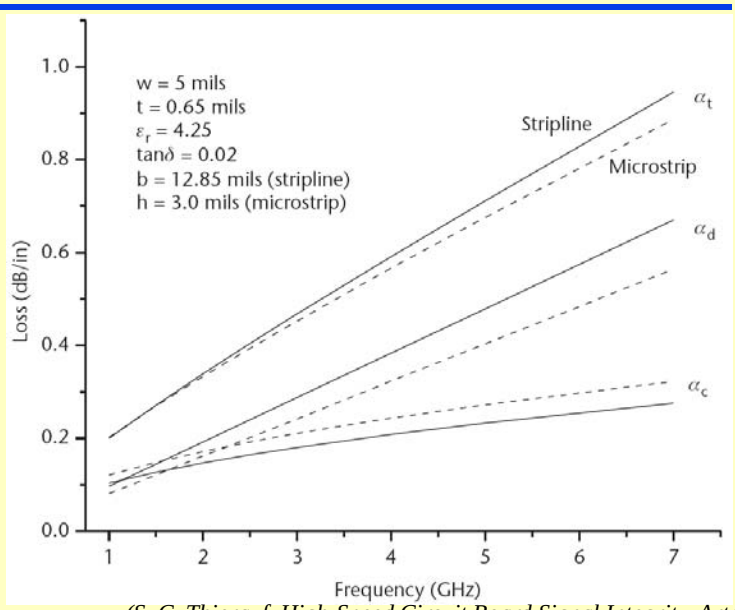
Losses in Transmission Lines

- 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)