

Lossy T-lines; Practical Considerations

In many practical situations, the losses along a transmission line are small.

For most frequency ranges of interest in high-speed digital applications, a low loss approximation for loss is entirely adequate. In fact, the lossless model is acceptable well into the 100's of megahertz.

For frequencies above about 1GHz, however, the dielectric losses exceed the conductor loss for 8 mil traces, 50Ω + FR4.

The greatest signal integrity issue for signals above ≈ 1GHz and lengths approaching 10 inches is loss. Examples include high speed serial busses & Gigabit Ethernet.

First, let's look at a low loss approximation, where:

$$R \ll j\omega L \quad \underline{\text{AND}} \quad G \ll j\omega C$$

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If $R \ll jWL + G \ll jWC$... \Leftarrow The Low Loss Approximation

$$\alpha + j\beta = \sqrt{(R+jWL)(G+jWC)}$$

$$= \sqrt{jWRd + jWLG + jWLjWC + RG}$$

$$= \sqrt{jWLjWC \left(\frac{R}{jWL} + \frac{G}{jWC} + 1 + \frac{RG}{jWLjWC} \right)}$$

$$= \sqrt{jWLjWC \left(\frac{1}{j} \left(\frac{R}{WL} + \frac{G}{WC} + j + \frac{jRG}{jWLjWC} \right) \right)}$$

$$= \sqrt{jWLjWC \left[-j \left(\frac{R}{WL} + \frac{G}{WC} + j + \frac{jRG}{jWLjWC} \right) \right]}$$

$$= \sqrt{jWLjWC \left[1 - j \left(\frac{R}{WL} + \frac{G}{WC} + \frac{jRG}{jWLjWC} \right) \right]}$$

$$= \sqrt{jWLjWC \left[1 - j \left(\frac{R}{WL} + \frac{G}{WC} \right) - \frac{RG}{jWLjWC} \right]}$$

$$= \sqrt{jWLjWC \left[1 - j \left(\frac{R}{WL} + \frac{G}{WC} \right) - \frac{RG}{W^2LC} \right]} \xrightarrow{\circ} \begin{array}{l} \text{IF } R \ll WL \text{ & } G \ll WC \text{ then} \\ RG \ll W^2LC \end{array}$$

$$\approx jWL \sqrt{LC} \sqrt{1 - j \left(\frac{R}{WL} + \frac{G}{WC} \right)}$$

Taylor Approximation: $\sqrt{1 \pm x} \approx 1 \pm \frac{x}{2}$ ($x \ll 1$)

$$\alpha + j\beta \approx jWL \sqrt{LC} \left[1 - \frac{j}{2} \left(\frac{R}{WL} + \frac{G}{WC} \right) \right]$$

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

$$\alpha = \text{Re}\{\gamma\} \text{ so, } \dots \Rightarrow \beta = \text{Im}\{\gamma\} \text{ so,}$$

$$\alpha = \frac{\omega}{2} \sqrt{LC} \left(\frac{R}{\omega L} + \frac{G}{\omega C} \right)$$

$$\beta \approx \underline{\omega \sqrt{LC}}$$

(no loss, same)
(neglecting dispersion)

$$= \frac{1}{2} \left(\frac{\sqrt{LC} R}{L} + \frac{\sqrt{LC} G}{C} \right)$$

$$= \frac{1}{2} \left(R \sqrt{\frac{C}{L}} + G \sqrt{\frac{L}{C}} \right)$$

$$\alpha = \frac{1}{2} \left(\underbrace{\frac{R}{Z_0}}_{\alpha_r} + \underbrace{G Z_0}_{\alpha_g} \right)$$

} holds for low loss lines

higher Z_0 increases dielectric loss, reduces conduction loss

α_r { Resistive loss - proportional to cross-sectional area & resistance of the conductors

skin effect loss - proportional to frequency - current redistributes its self to minimize inductance (loop) and self inductance. $\delta = 66 \sqrt{\frac{1}{f}} \left(\frac{\text{skin depth}}{\text{in nm}} \right) (\text{f in GHz})$

α_g { dielectric loss - caused by leakage current created by ionic movement or reorientation of electric dipoles in the dielectric.

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Low Loss Approximation:

$$Z_0 = \sqrt{\frac{R + j\omega C}{G + j\omega L}} \approx \sqrt{\frac{L}{C}}$$

$$\alpha = \frac{1}{2} \left(\underbrace{\frac{R}{Z_0}}_{\alpha_r} + G Z_0 \right) \text{ refers/length}$$

$$\beta = \omega \sqrt{LC}, \quad \eta_p = \left(\frac{\omega}{\beta} \right) \text{ (Dispersion is neglected)}$$

Lossy T-Lines - Low Frequency Approximation

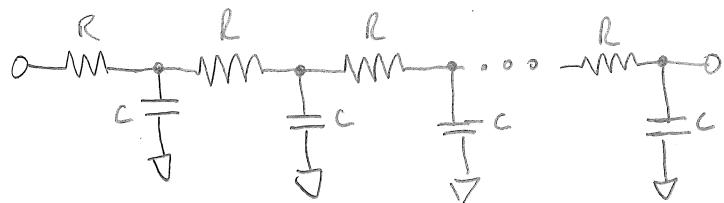
Low frequencies: $R \gg \omega L$ AND $G \ll \omega C$ (An RG transmission line)

The resistance of the line begins to dominate the characteristic impedance.

$$Z_0 = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \Rightarrow Z_0 = \sqrt{\frac{R}{\omega C}}$$

lossy

$$\gamma = \sqrt{(R + j\omega L)(G + j\omega C)} \Rightarrow \alpha \approx \sqrt{Rj\omega C} = \underbrace{\sqrt{\frac{\omega RC}{2}}}_{\alpha} + j\underbrace{\sqrt{\frac{\omega RC}{2}}}_{\beta}$$

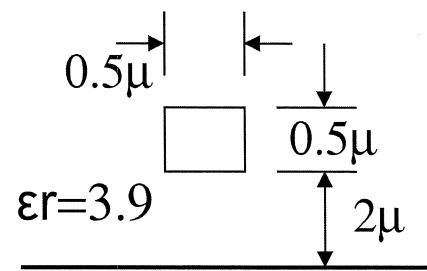


The low frequency region extends from DC to $\omega_{lc} = \frac{R_{dc}}{L} \text{ rad/m}$

Lossy T-Lines - Low Frequency Approximation (RC Region)

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- Typical on-chip interconnect

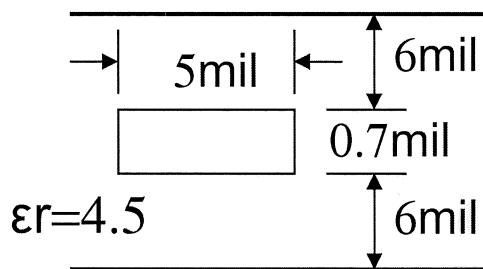


$$\begin{aligned}L &= 0.6 \text{nH/mm} \\C &= 73 \text{ fF/mm} \\R_{dc} &= 120 \text{ Ω/mm}\end{aligned}$$

$$\omega = \frac{R_{dc}}{L} ; f = \frac{R_{dc}}{2\pi L} = 32 \text{ GHz}$$

[On chip interconnect is operating in the RC region under about 32 GHz.
(Steady state AC excitation)]

- Typical PCB interconnect



$$\begin{aligned}L &= 0.35 \text{nH/mm} \\C &= 140 \text{ fF/mm} \\R_{dc} &= 8 \text{ mΩ/mm}\end{aligned}$$

$$\omega = \frac{R_{dc}}{L} ; f = \frac{R_{dc}}{2\pi L} = 3.6 \text{ MHz}$$

PCB interconnect operates in RC region for frequencies below 3.6 MHz.
(Steady state AC excitation)

Lossy T-Lines: Practical Considerations (Performance Regions)

Loss on a transmission line increases with frequency monotonically.

As the frequency increases, different mechanisms dominate the loss equation.

WL is insignificant in comparison to DC resistance

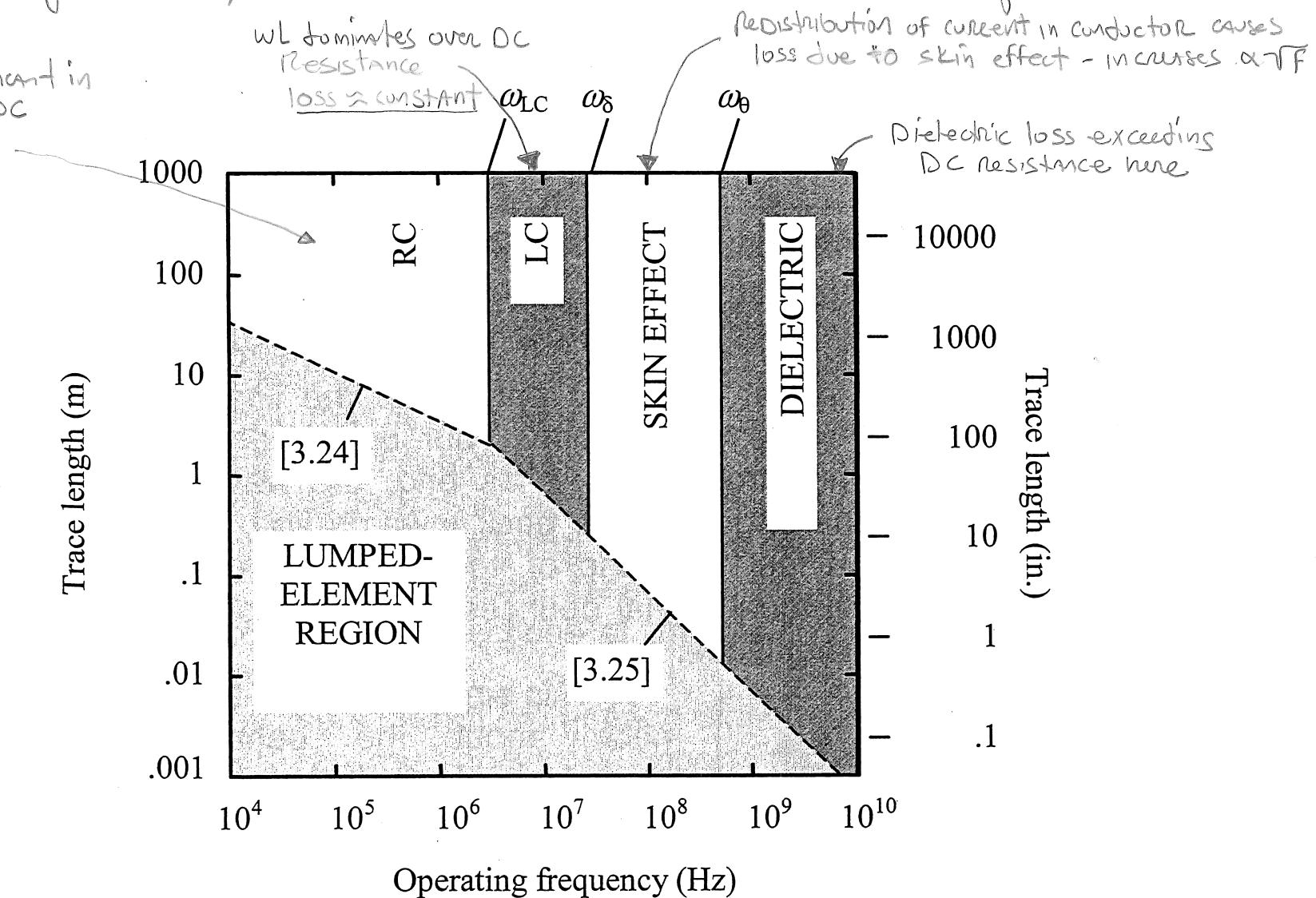


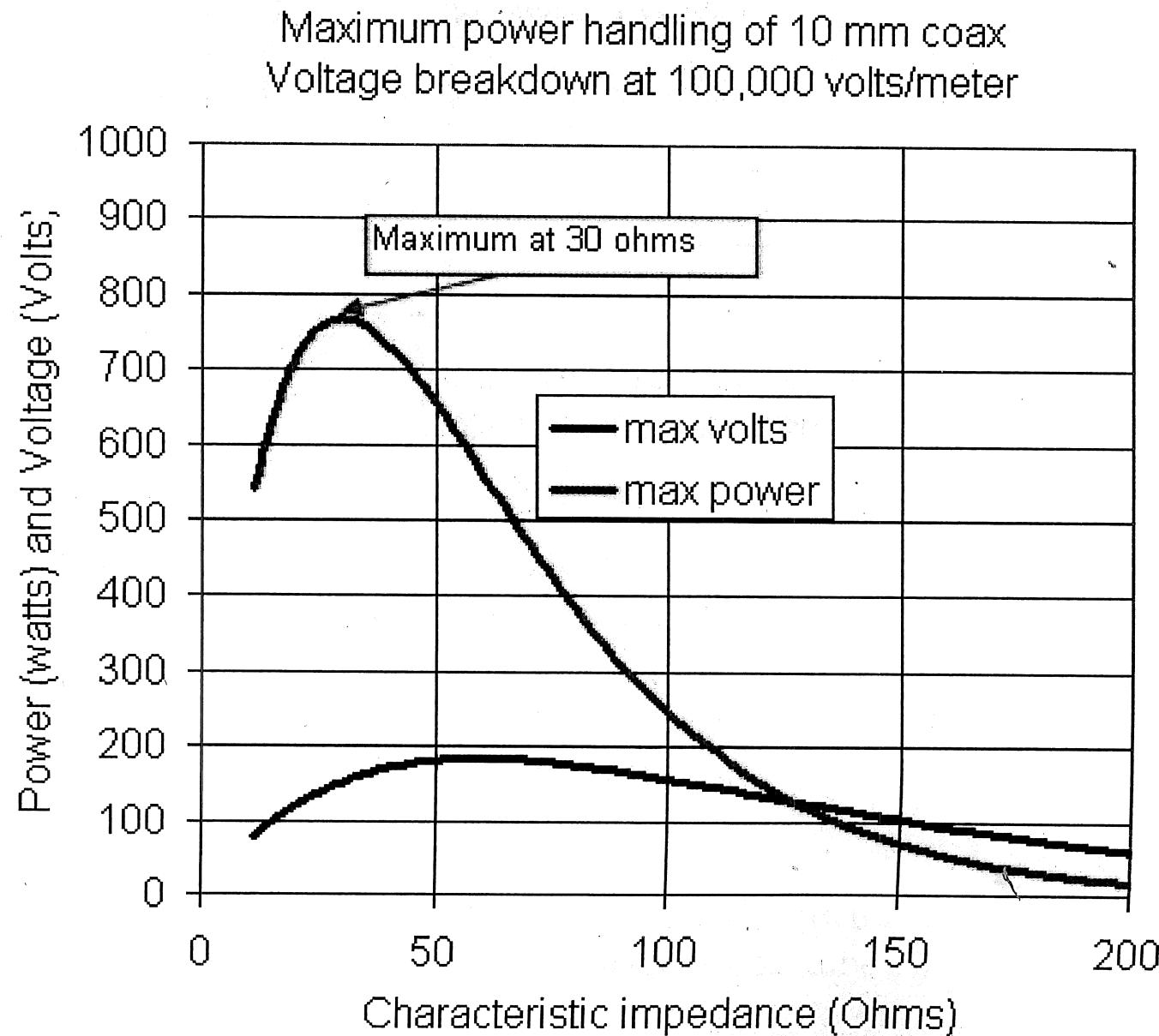
Figure 3.2—Performance regions for a 150- μm (6-mil), 50- Ω , FR-4 stripline.

From: High Speed Signal Propagation - ADVANCED BLACK MAGIC, Howard Johnson & Martin Graham

Lossy T-Lines Practical Considerations

Why 50Ω?

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Lossy T-Lines: Practical Considerations

Why 50Ω ?

