Chapter 8

Radiated Emissions and Susceptibility

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Outline

- Simple Emission Models for Wires and PCB Lands
  - Differential-Mode versus Common-Mode Currents
  - Differential-Mode Current Emission Model
  - Common-Mode Current Emission Model
  - Current Probes
  - Experimental Results
- Simple Susceptibility Models for Wires and PCB Lands
  - Experimental Results
  - Shield Cables and Surface Transfer Impedance

Preview

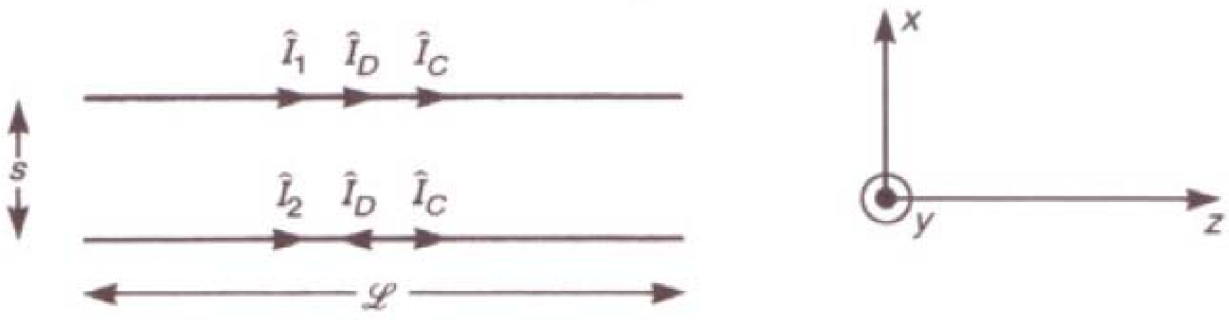
- Assumptions
  - Form simplicity, we will assume that the measurement antenna is in the far field of the emission (product), although this is not necessarily the case over the entire frequency range of the regulatory limit.
  - In the far field, the inverse-distance rules applies, which is used to translate an emission measured at one distance to another distance.

Simple Emission Models for Wires and PCB Lands

- Differential-Mode versus Common-Mode Currents
  - Decomposition of Currents
    - The currents could be decomposed into differential-mode and common-mode components by writing

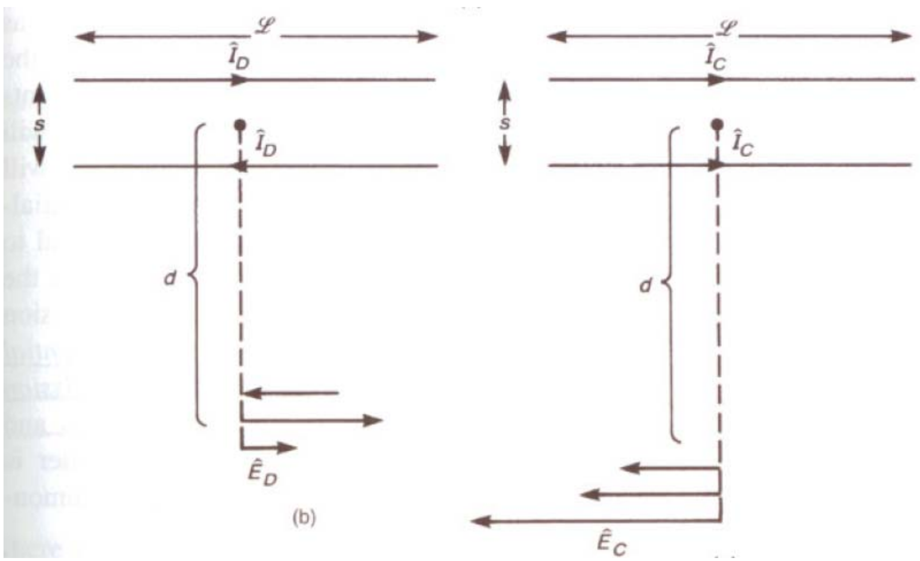
$$\hat{I}_1 = \hat{I}_C + \hat{I}_D$$
$$\hat{I}_2 = \hat{I}_C - \hat{I}_D$$

$$\hat{I}_D = \frac{\hat{I}_1 - \hat{I}_2}{2}$$
$$\hat{I}_C = \frac{\hat{I}_1 + \hat{I}_2}{2}$$



Simple Emission Models for Wires and PCB Lands

- Differential-Mode versus Common-Mode Currents
  - Radiation Emissions of Different Currents
    - Common-mode currents are not inconsequential in typical products, and, moreover, they often produce larger radiated emissions than do the differential-mode currents.



Simple Emission Models for Wires and PCB Lands

- Differential-Mode versus Common-Mode Currents
  - Far Fields of Wire Currents
    - The total radiated electric field will be the sum of each radiated electric field, which is

$$\hat{E}_\theta = \hat{E}_{\theta,1} + \hat{E}_{\theta,2}$$

    - where the far fields of each antenna are of the form

$$\hat{E}_{\theta,i} = \hat{M}\hat{I}_i \frac{e^{-j\beta_0 r_i}}{r_i} F(\theta)$$

    - and

$$\left.\begin{aligned} \hat{M} &= j\frac{\eta_0\beta_0}{4\pi}\mathscr{L} = j2\pi \times 10^{-7} f\,\mathscr{L} \\ F(\theta) &= \sin\theta \end{aligned}\right\} \quad \text{(Hertzian dipoles)}$$

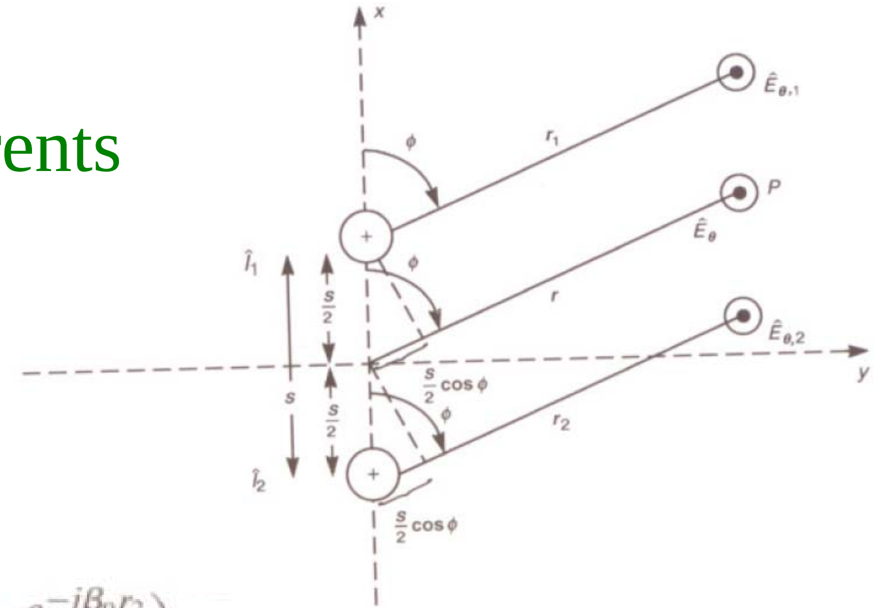
$$\left.\begin{aligned} \hat{M} &= j\frac{\eta_0}{2\pi} = j60 \\ F(\theta) &= \frac{\cos\left(\frac{1}{2}\pi\cos\theta\right)}{\sin\theta} \end{aligned}\right\} \quad \text{(half-wave dipoles, } \mathscr{L} = \tfrac{1}{2}\lambda_0)$$

Simple Emission Models for Wires and PCB Lands

- Differential-Mode versus Common-Mode Currents
  - Far Fields of Wire Currents
    - Since

$$r_1 = r - \frac{s}{2}\cos\phi$$

$$r_2 = r + \frac{s}{2}\cos\phi$$



    - The total field becomes

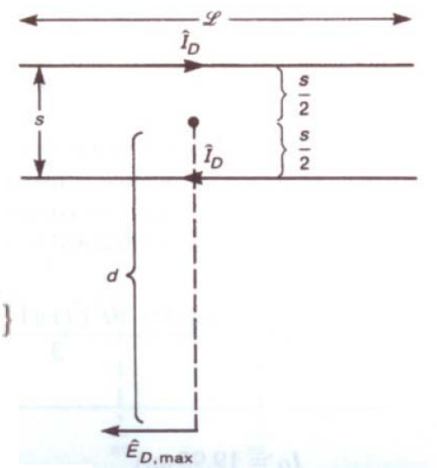
$$\hat{E}_\theta = \hat{M}\left(\hat{I}_1 \frac{e^{-j\beta_0 r_1}}{r_1} + \hat{I}_2 \frac{e^{-j\beta_0 r_2}}{r_2}\right) F(\theta)$$

$$\longrightarrow \quad \hat{E}_\theta = \hat{M}\frac{e^{-j\beta_0 r}}{r}\left(\hat{I}_1 e^{+j\beta_0 s/2\cos\phi} + \hat{I}_2 e^{-j\beta_0 s/2\cos\phi}\right) F(\theta) \qquad \text{(a)}$$

Simple Emission Models for Wires and PCB Lands

- Differential-Mode Current Emission Model
  - Far Fields
    - In order to simplify the resulting model, a Hertzian dipole is used.
    - For I_1=-I_2, the maximum will occur in the plane of the wires and on a line perpendicular to the wires.
    - Since $\hat{I}_1 = \hat{I}_D$

      $\hat{I}_2 = -\hat{I}_D$



    - The radiated field becomes

φ =0

(a) $$\hat{E}_{D,\max} = j2\pi \times 10^{-7} \frac{f\hat{I}_D\mathscr{L}}{d} e^{-j\beta_0 d}\{e^{j\beta_0 s/2} - e^{-j\beta_0 s/2}\}$$

$$= -4\pi \times 10^{-7} \frac{f\hat{I}_D\mathscr{L}}{d} e^{-j\beta_0 d} \sin(\tfrac{1}{2}\beta_0 s)$$

$$|\hat{E}_{D,\max}| = 1.316 \times 10^{-14} \frac{|\hat{I}_D| f^2 \mathscr{L} s}{d}$$

Simple Emission Models for Wires and PCB Lands

- Differential-Mode Current Emission Model
  - Example 8.1
    - Considering a ribbon cable of s=50mil and L=1m, operating at f=30MHz, the current I_D required to satisfy the FCC Class B limit (100 μ V/m at 30MHz) is

$$100\,\mu\text{V/m} = 1.316 \times 10^{-14} \frac{|\hat{I}_D|(3 \times 10^7)^2(1)(1.27 \times 10^{-3})}{3}$$

$$\longrightarrow I_D = 19.95\text{ mA}$$

which is large

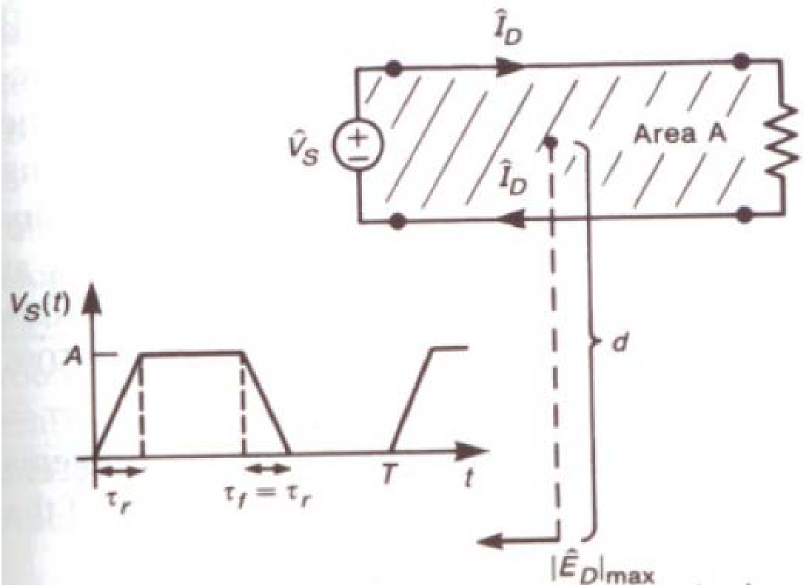
- Generally, the formula for the maximum emission given is sufficient for estimation purposes.

Simple Emission Models for Wires and PCB Lands

- Differential-Mode Current Emission Model
  - Example 8.1
    - Consider a current *I* of a trapezoidal waveform
    - The transfer function relating the maximum received electric field to the current is

$$\left|\frac{\hat{E}_{D,\max}}{\hat{I}_D}\right| = Kf^2A$$

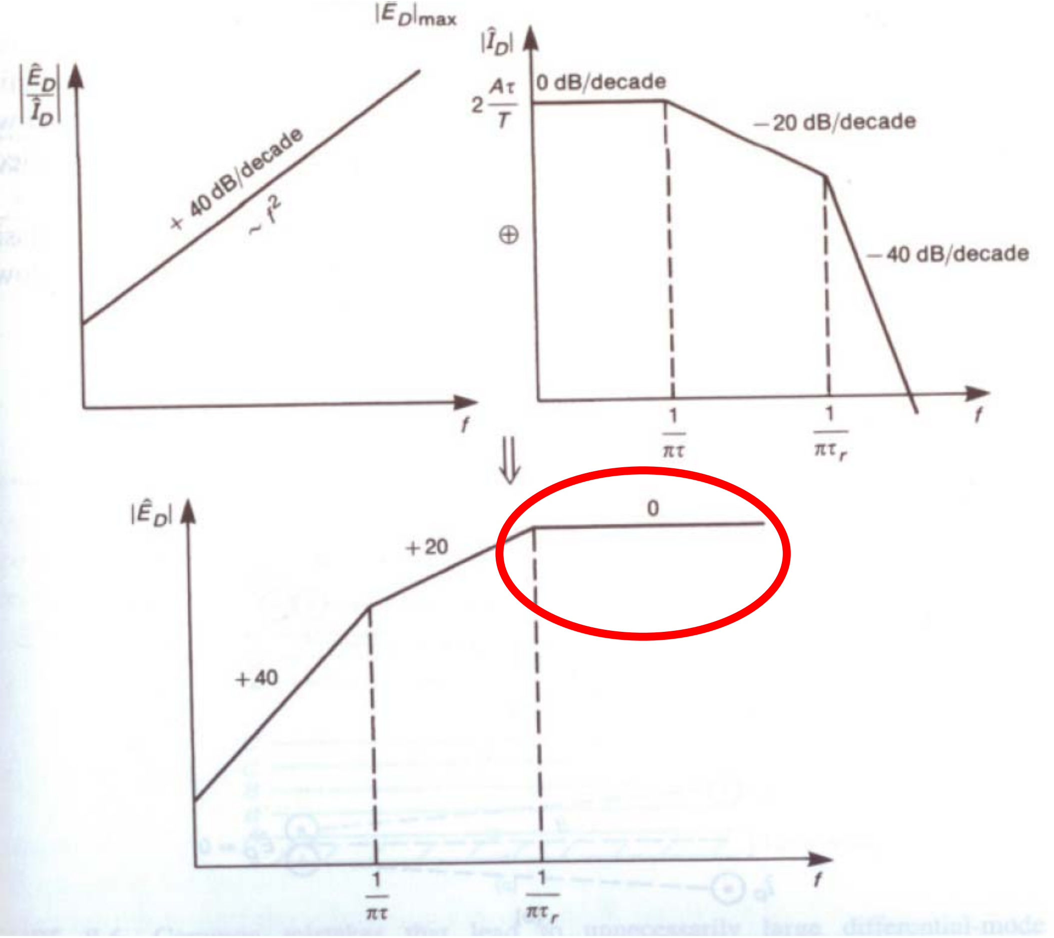
The frequency response is shown in the next page



Simple Emission Models for Wires and PCB Lands

- Differential-Mode Current Emission Model
  - Example 8.1

If the regulatory limit of the red circle is satisfied, the all other portions are satisfied.

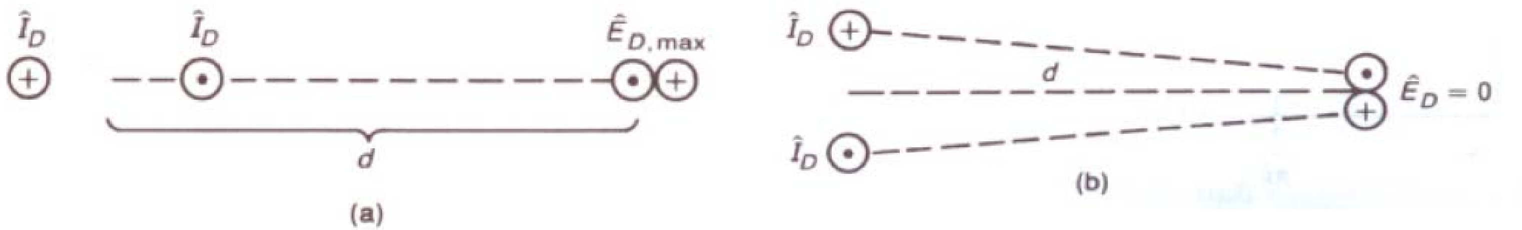


Simple Emission Models for Wires and PCB Lands

- Differential-Mode Current Emission Model
  - How to Reduce the Emission Level
    - The radiated emission is proportional to (1) the square of the frequency, (2) the loop area $A=Ls$, (3) the current level I_D.

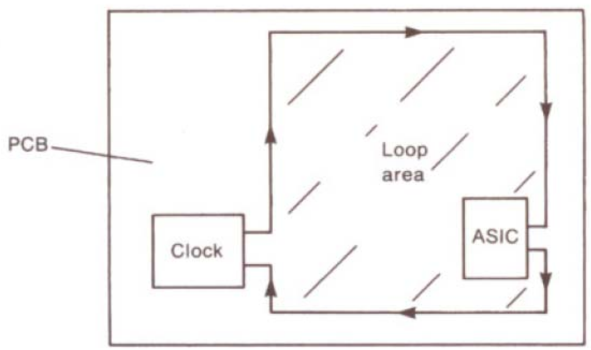
$$|\hat{E}_{D,\max}| = 1.316 \times 10^{-14} \frac{|\hat{I}_D| f^2 \mathscr{L} s}{d}$$

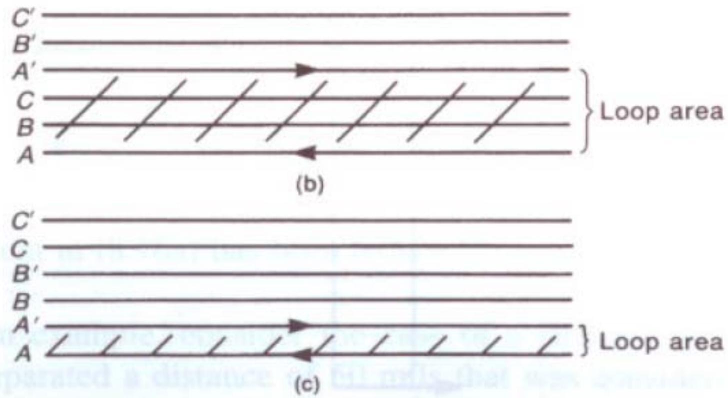
    - Thus, ways to reduce the radiated emission are (1) increase the values of τ_r and/or τ, (2) reduce the loop area, and (3) reduce the current level.



Simple Emission Models for Wires and PCB Lands

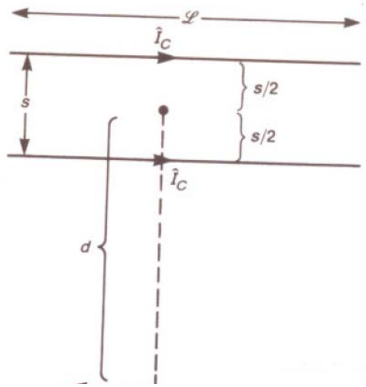
- Differential-Mode Current Emission Model
  - For Example
    - Place the clock as close as possible to the ASIC to lessen the loop area.
    - Place the differential pair as close as possible to lessen the loop area.





Simple Emission Models for Wires and PCB Lands

- Common-Mode Current Emission Model
  - Far Fields



- Since $\hat{I}_1 = \hat{I}_C$

  $\hat{I}_2 = \hat{I}_C$

- The far field as the figure shown is

φ =0

(a) $$\hat{E}_{C,\max} = j2\pi \times 10^{-7} \frac{f\hat{I}_C \mathscr{L}}{d} e^{-j\beta_0 d}\{e^{j\beta_0 s/2} + e^{-j\beta_0 s/2}\}$$

$$= j4\pi \times 10^{-7} \frac{f\hat{I}_C \mathscr{L}}{d} e^{-j\beta_0 d} \cos\left(\tfrac{1}{2}\beta_0 s\right)$$

$$|\hat{E}_{C,\max}| = 1.257 \times 10^{-6} \frac{|\hat{I}_C| f \mathscr{L}}{d}$$ (b)

- Although this is not the maximum field point, this approximately is.
- Since s is electrical small, the field is omnidirectional in φ.

Simple Emission Models for Wires and PCB Lands

- Common-Mode Current Emission Model
  - Far Fields
    - For common-mode currents and electrically small wire separations, the "pattern" is virtually omnidirectional around the wires.
    - Also, we may replace the two wires, each carrying current I_C, with one wire carrying current $2I_C$ without substantially changing the radiated fields at any point around it.
    - If the total current is $I_{probe}=2I_C$, we have

(b) $\longrightarrow$ $$|\hat{E}_{C,\max}| = 6.283 \times 10^{-7} \frac{|\hat{I}_{\text{probe}}| f \mathscr{L}}{d}$$

Simple Emission Models for Wires and PCB Lands

- Common-Mode Current Emission Model
  - Example 8.2
    - Considering a ribbon cable of s=50mil and L=1m, operating at f=30MHz, the current I_C required to satisfy the FCC Class B limit (100 μ V/m at 30MHz) is

$$100\mu\text{V/m} = 1.257 \times 10^{-6} \frac{|\hat{I}_C|(3 \times 10^7)(1)}{3}$$

$$\longrightarrow I_C = 7.96\ \mu\text{A}$$

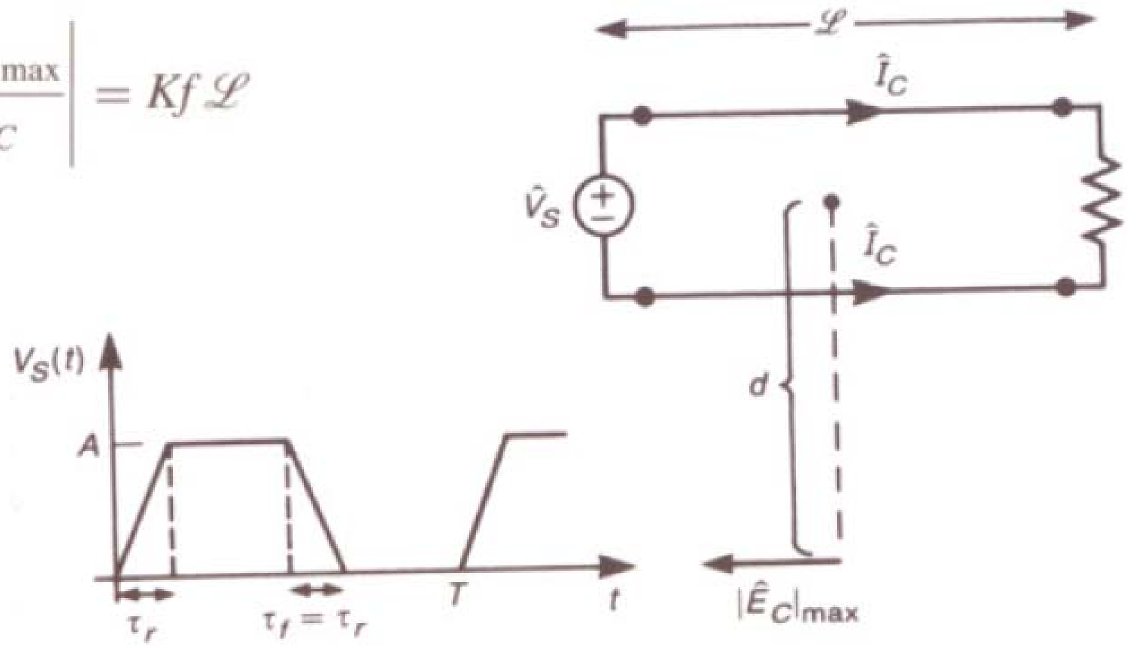
which is small

    - Generally, the formula for the maximum emission given is sufficient for estimation purposes.

Simple Emission Models for Wires and PCB Lands

- Common-Mode Current Emission Model
  - Example 8.2
    - Consider a current *I* of a trapezoidal waveform
    - The transfer function relating the maximum received electric field to the current is

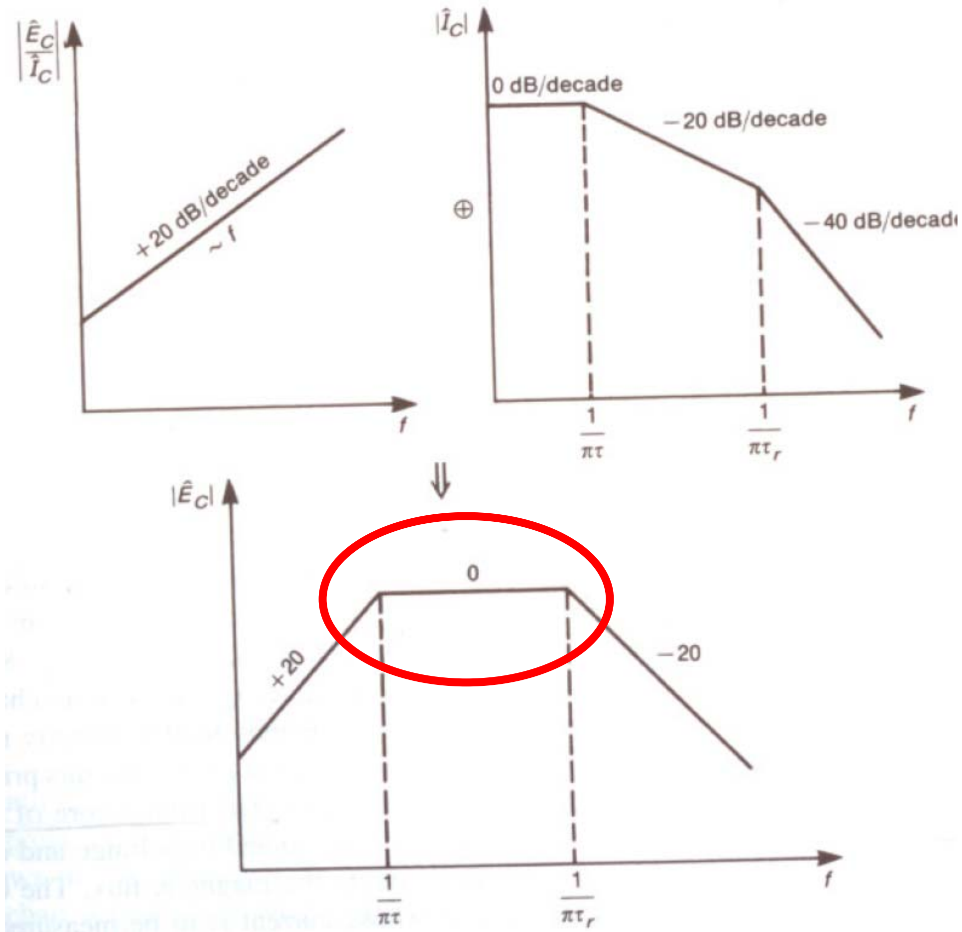
$$\left|\frac{\hat{E}_{C,\max}}{I_C}\right| = Kf\mathscr{L}$$



Simple Emission Models for Wires and PCB Lands

- Common-Mode Current Emission Model
  - Example 8.2

If the regulatory limit of the red circle is satisfied, the all other portions are satisfied.



Simple Emission Models for Wires and PCB Lands

- Common-Mode Current Emission Model
  - How to Reduce the Emission Level
    - The radiated emission is proportional to (1) the frequency, (2) the line length L, and (3) the current level I_C.

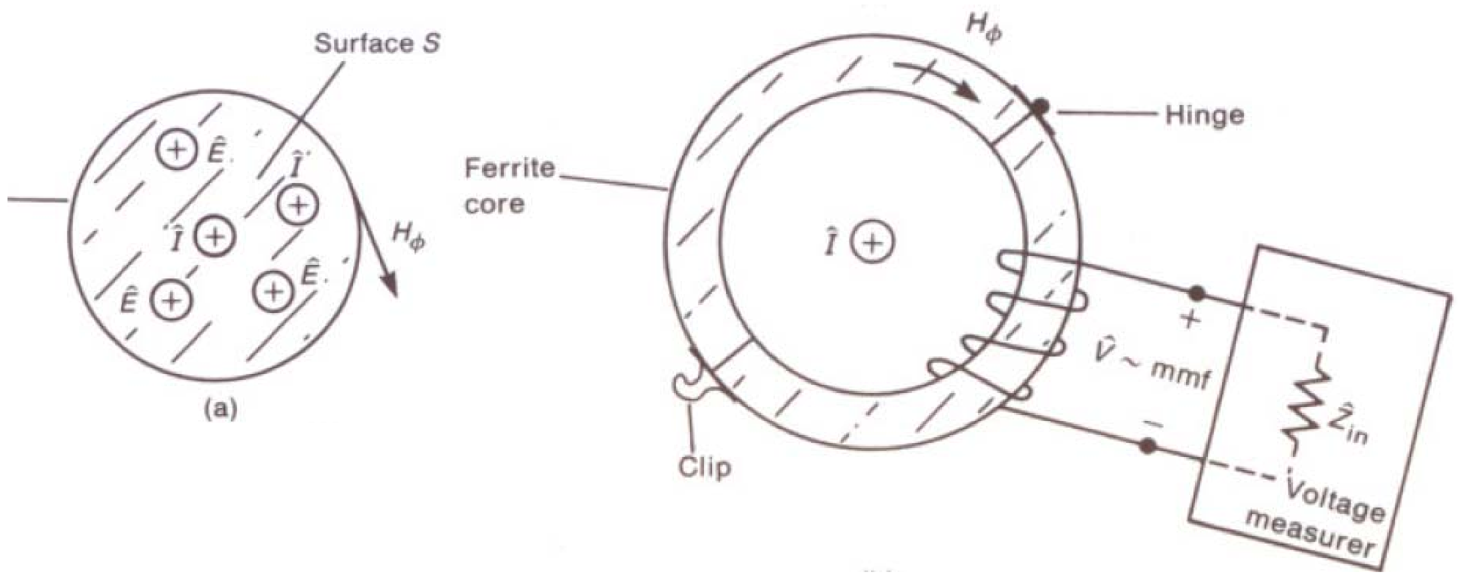
$$|\hat{E}_{C,\max}| = 1.257 \times 10^{-6} \frac{|\hat{I}_C| f \mathscr{L}}{d}$$

    - Thus, ways to reduce the radiated emission are (1) increase the values of τ_r and/or τ, (2) reduce the line length, and (3) reduce the current level.

Simple Emission Models for Wires and PCB Lands

- Current Probes
  - Principle
    - Current probes make use of Ampere's law

$$\oint_C \vec{H} \cdot \vec{dl} = \int_S \vec{J} \cdot \vec{ds} + \frac{d}{dt} \epsilon \int_S \vec{E} \cdot \vec{ds}$$



Simple Emission Models for Wires and PCB Lands

- Current Probes
  - Principle
    - Simply pass a current of know magnitude and frequency through the probe and measure the resulting voltage produced at the terminals, we can obtain the transfer impedance as

$$\hat{Z}_T = \frac{\hat{V}}{\hat{I}} \longrightarrow |\hat{Z}_T|_{\mathrm{dB}\Omega} = |\hat{V}|_{\mathrm{dB}\mu\mathrm{V}} - |\hat{I}|_{\mathrm{dB}\mu\mathrm{A}}$$

    - The calibration curve of the current probe is valid only when the probe is terminated in the same impedance as was used in the course of its calibration (usually 50 Ω)

Simple Emission Models for Wires and PCB Lands

- Current Probes
  - Principle
    - The current probe will not measure differential-mode current unless it is placed around each individual wire.
    - The radiated emission due to the total current $I_{C,\,net}$ could be obtained by dividing the $I_{C,\,net}$ in two equal currents $I_C = I_{C,\,net}/2$ and using the radiated field equation of the common-mode currents, which is

$$|\hat{E}_C|_{\max} = 6.28 \times 10^{-7} \frac{|\hat{I}_{C,\,\mathrm{net}}| f \mathscr{L}}{d}$$

$$\hat{Z}_T = \frac{\hat{V}}{\hat{I}} \longrightarrow |\hat{E}_C|_{\max} = 6.28 \times 10^{-7} \frac{|\hat{V}_{SA}| f \mathscr{L}}{|\hat{Z}_T| d}$$

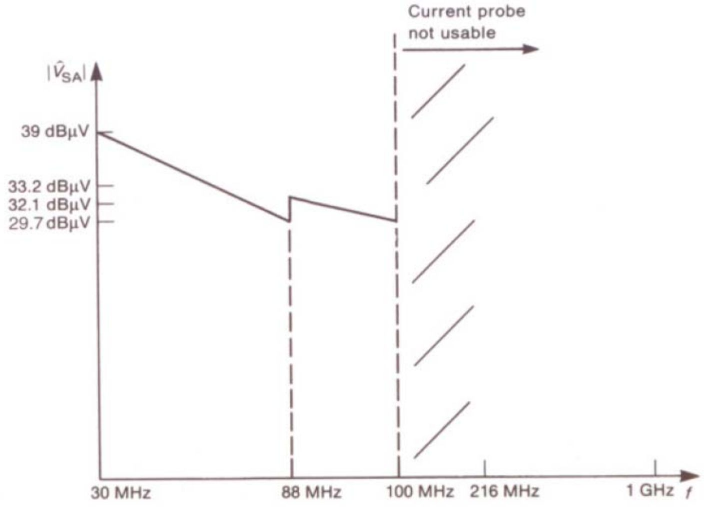
Simple Emission Models for Wires and PCB Lands

- Current Probes
  - Principle
    - In dB form, we obtain

$$|\hat{V}_{SA}|_{\mathrm{dB\mu V}} = |\hat{E}|_{\mathrm{limit,\,dB\mu V/m}} + |\hat{Z}_T|_{\mathrm{dB\Omega}} + 20\log_{10} d$$
$$- 20\log_{10} f_{\mathrm{MHz}} - 20\log_{10}\mathscr{L} + 4.041$$

    - This could be used to transform the regulatory electric field limits into regulatory voltage limits.

By simply measuring the voltage or current, we could determine if the product meets the regulatory limits with using the complex and expensive semianechoic chamber.

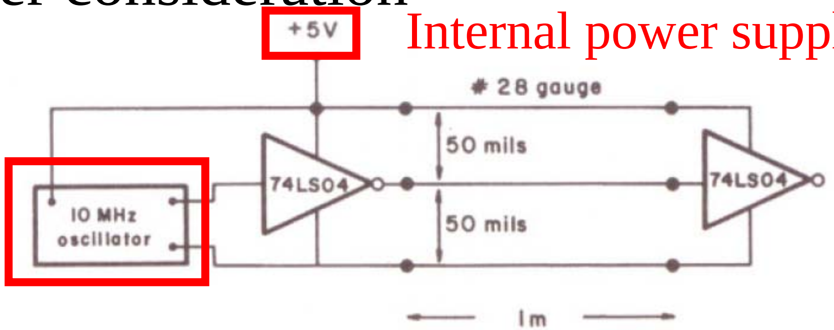


Experimental Results

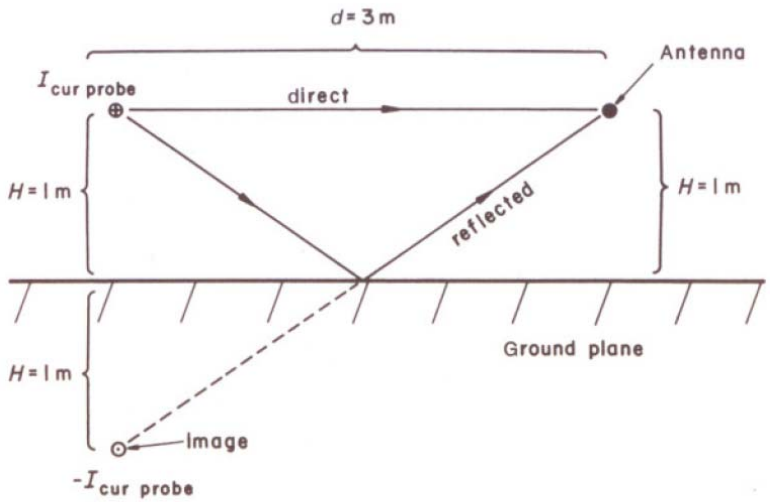
- Cable Emissions
  - Circuit and Measurement Setup
    - Circuit under consideration

Internal power supply

DIP-packaged oscillator



    - Measurement site



Experimental Results

- Cable Emissions
  - Prediction and Measurement Results
    - The predicted emission is described as follows

$$|\hat{E}_C|_{\max} = 6.28 \times 10^{-7} \frac{|\hat{I}_{\text{probe}}| f \mathscr{L}}{d} \hat{F}_{\text{GP}}$$

    - Since the measured probe current is

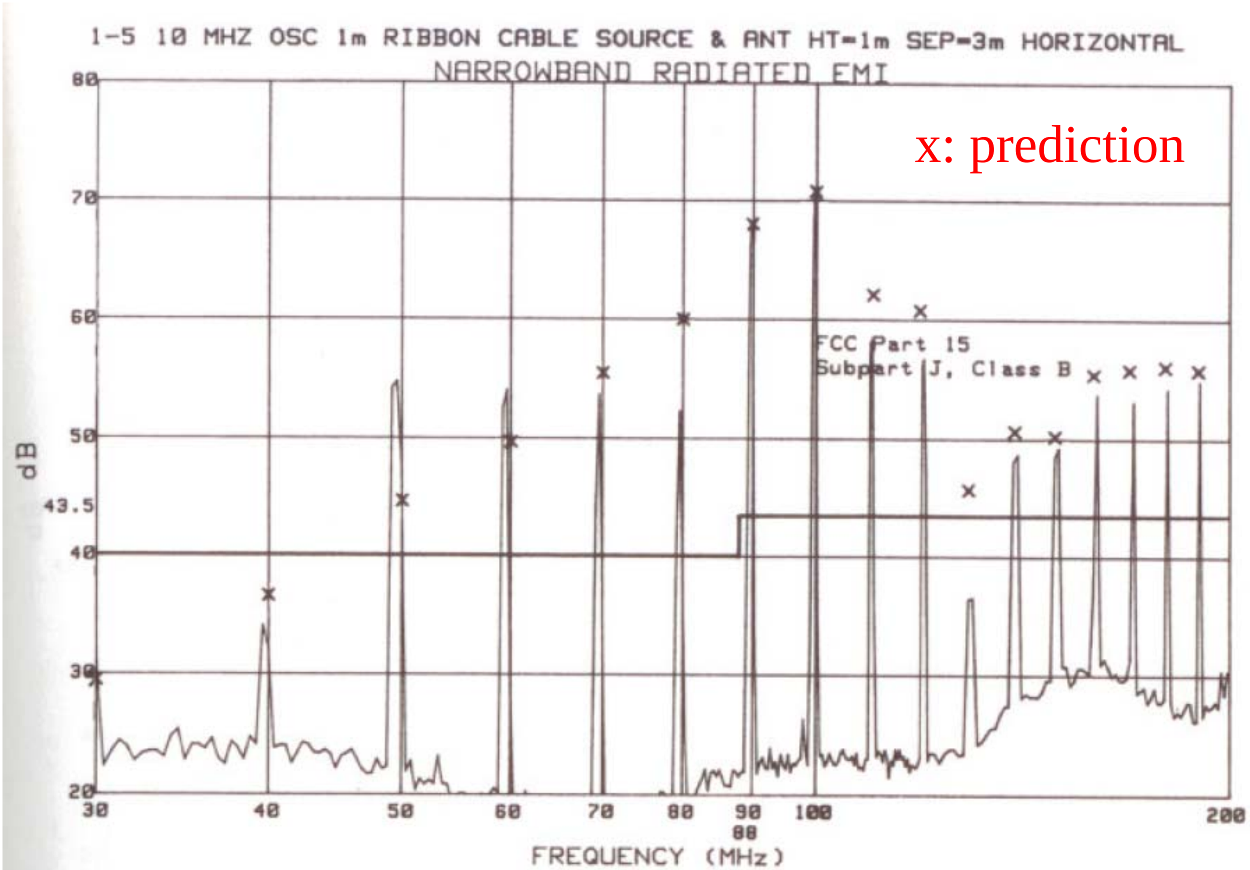
$$\begin{aligned} |\hat{I}_{\text{probe}}|_{\text{dB}\mu A} &= |\hat{V}_{SA}|_{\text{dB}\mu\text{V}} + \text{cable loss}_{\text{dB}} - |\hat{Z}_T|_{\text{dB}\Omega} \\ &= |\hat{V}_{SA}|_{\text{dB}\mu\text{V}} + \text{cable loss}_{\text{dB}} - 15 \end{aligned}$$

    - Combing the above two equations and translating into dB form, we have

$$\begin{aligned} |\hat{E}_C|_{\text{dB}\mu\text{V/m}} = |\hat{V}_{SA}|_{\text{dB}\mu V} + \text{cable loss}_{\text{dB}} - |\hat{Z}_T|_{\text{dB}\Omega} + 20\log_{10} f_{\text{MHz}} \\ + |\hat{F}_{GP}|_{\text{dB}} - 13.58 \end{aligned}$$

Experimental Results

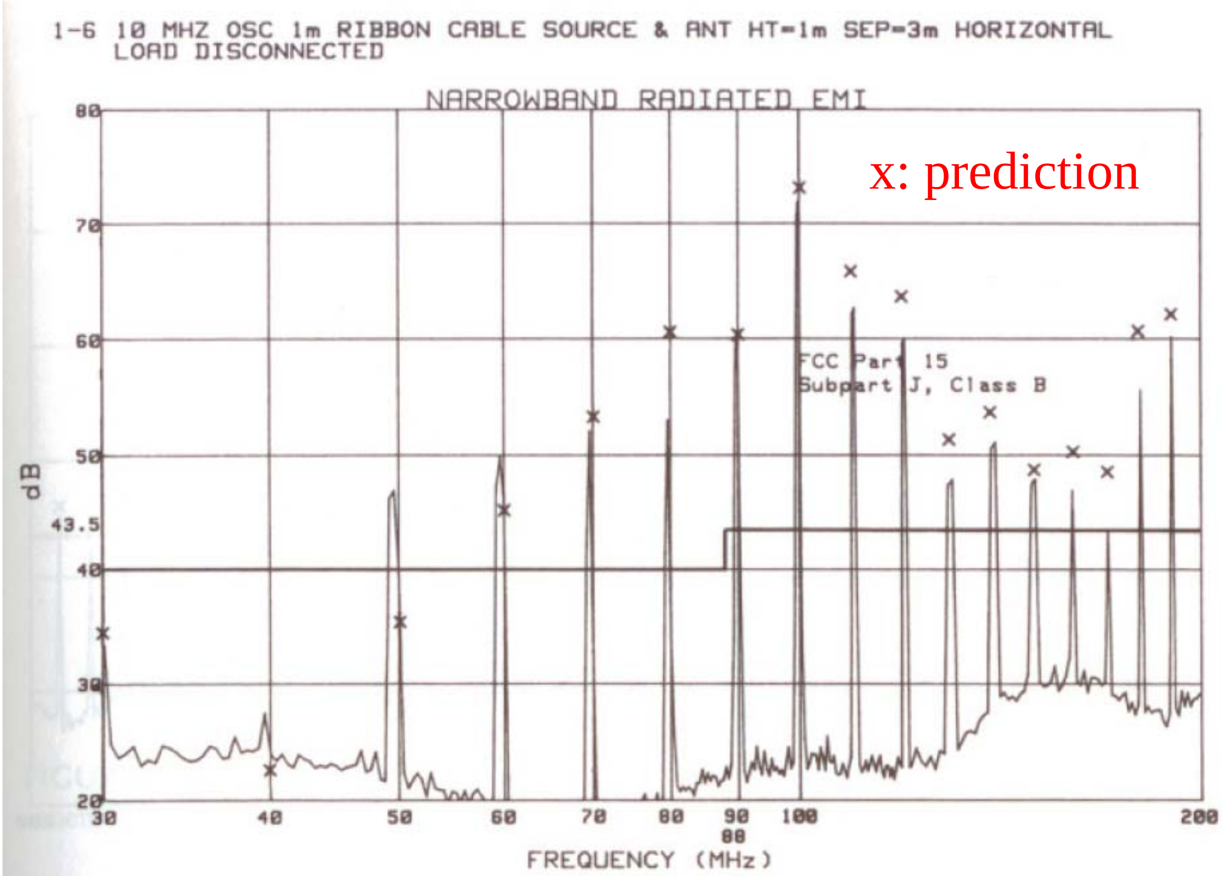
- Cable Emissions
  – Prediction and Measurement Results – with Load



Experimental Results

- Cable Emissions
  - Prediction and Measurement Results – without Load

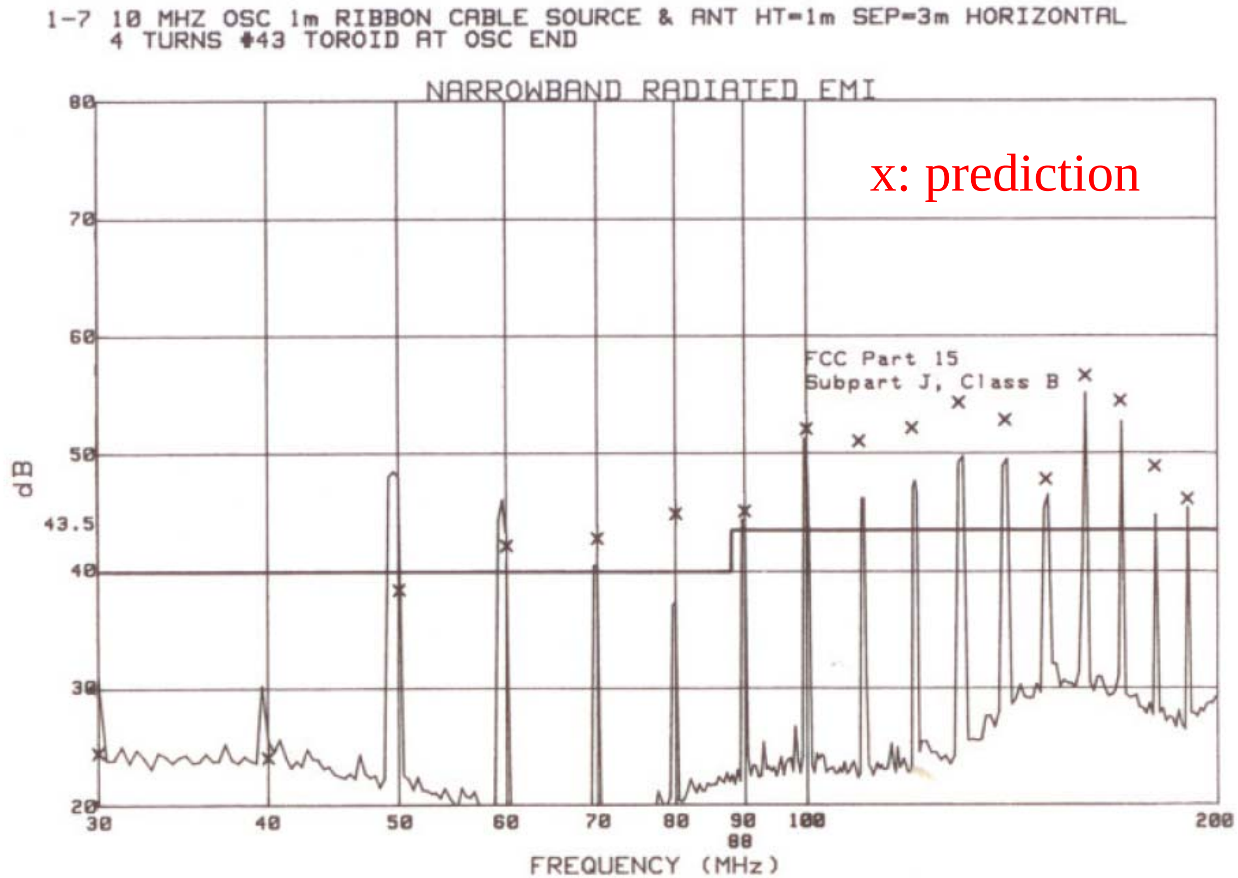
Only common-mode current is excited.



Experimental Results

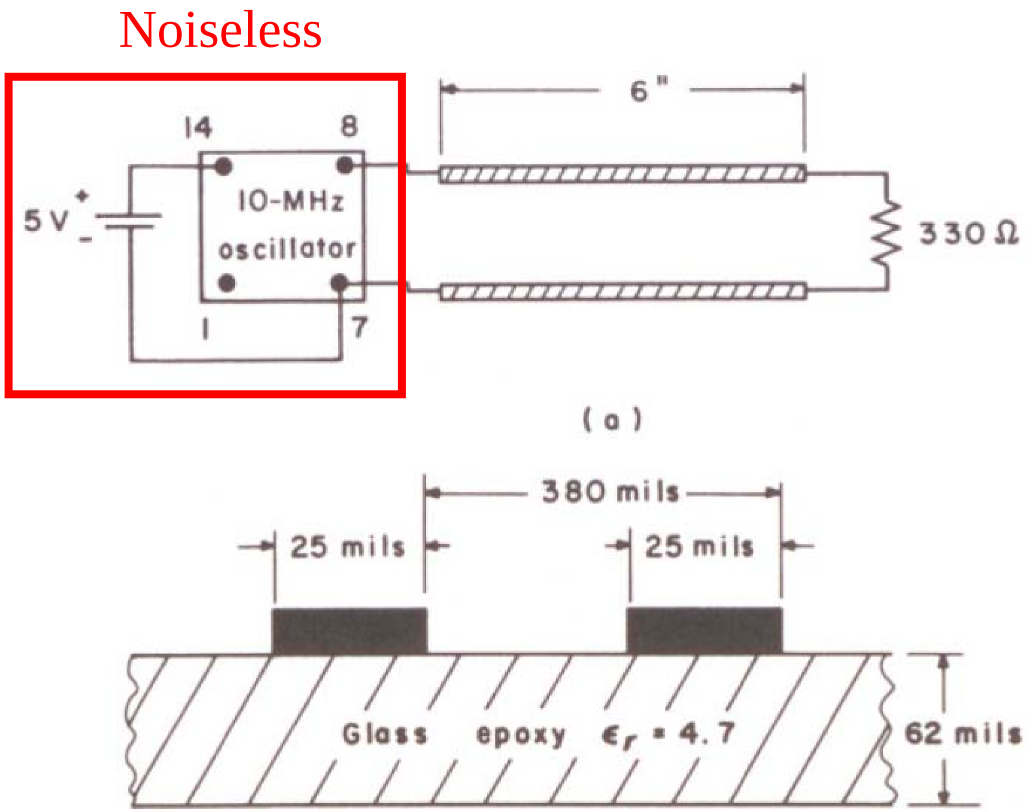
- Cable Emissions
  - Prediction and Measurement Results – with Load and Ferrite Toroid

common-mode emission is reduced.



Experimental Results

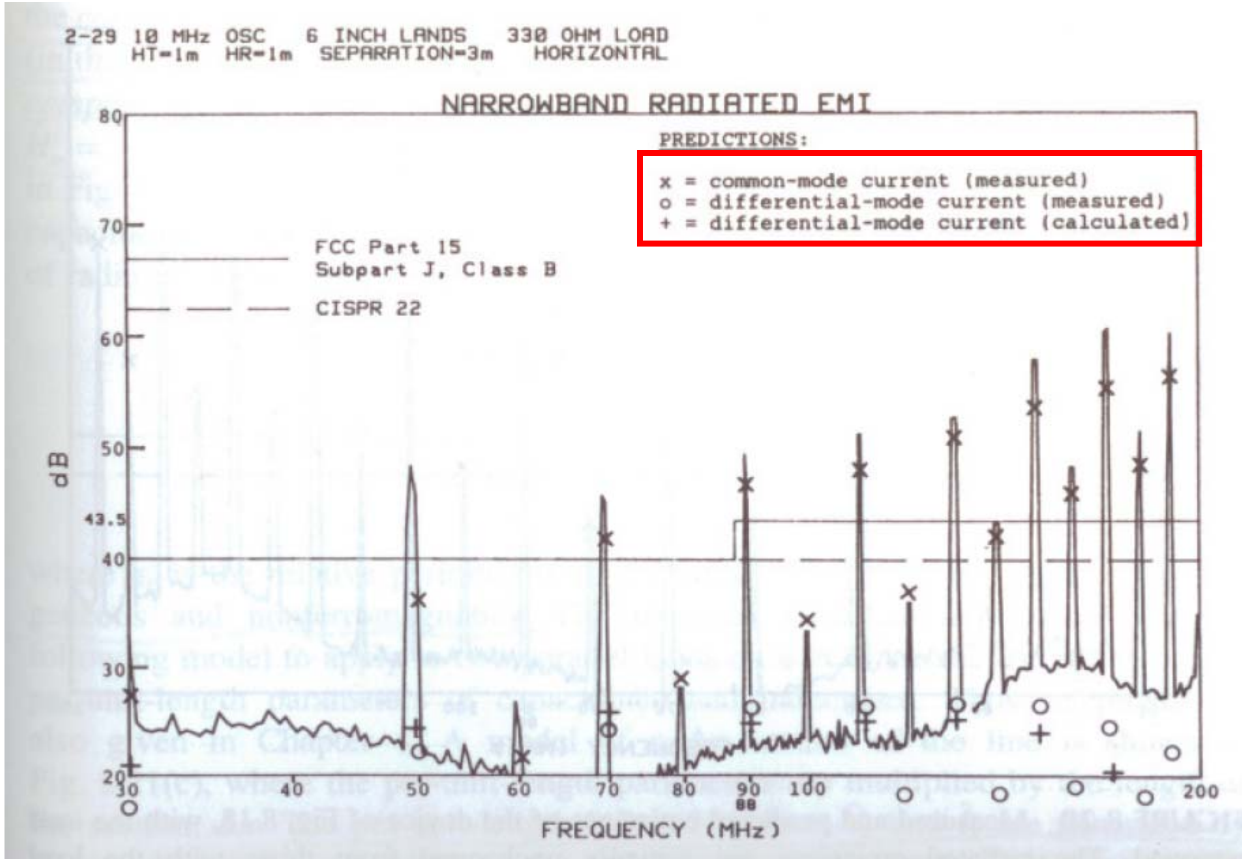
- PCB Lands Emissions
  - Circuit



Experimental Results

- PCB Lands Emissions
  - Prediction and Measurement Results – with Load

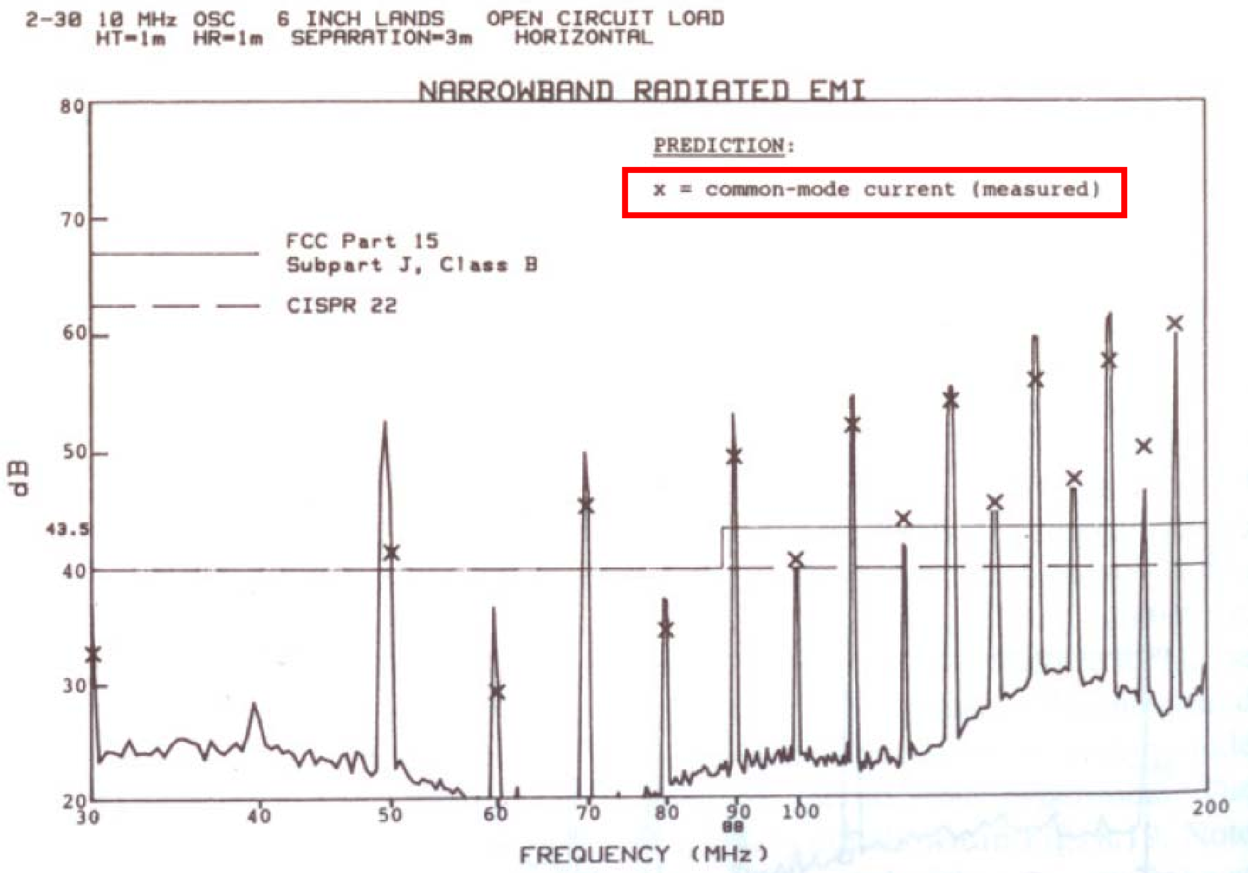
Common-mode emission dominates



Experimental Results

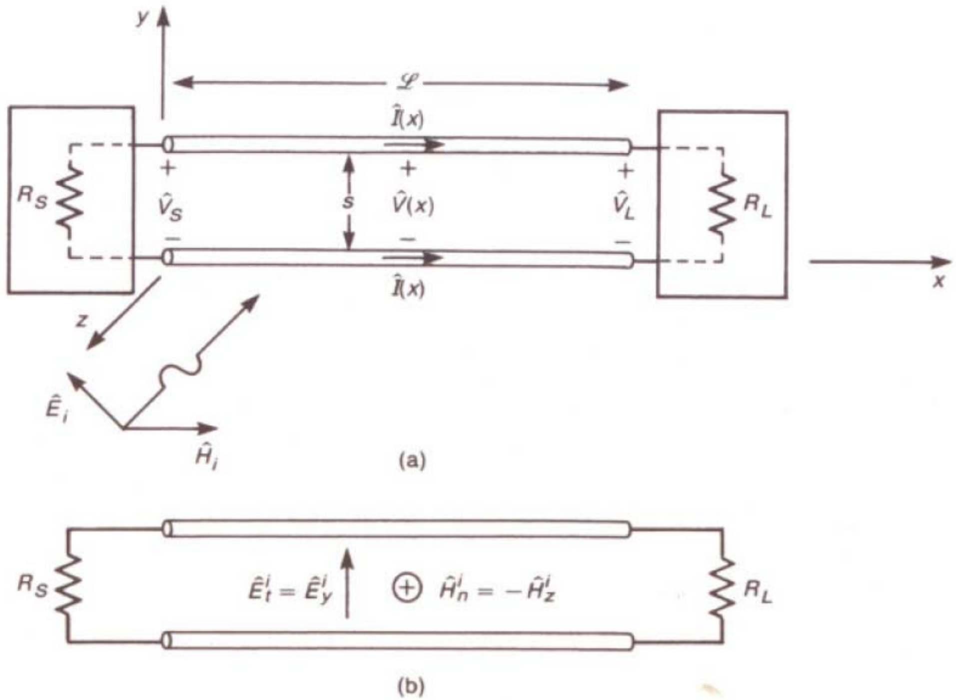
- PCB Lands Emissions
  - Prediction and Measurement Results – without Load

Only common-mode current is excited.



Simple Susceptibility Models for Wires and PCB Lands

- Two-Conductor Line
  - General Susceptibility Model
    - The two effective components of the incident wave are (1) transverse electric field E_y (2) perpendicular magnetic field $-H_z$



Simple Susceptibility Models for Wires and PCB Lands

- Two-Conductor Line
  - General Susceptibility Model
    - The per-unit-length inductance and capacitance are

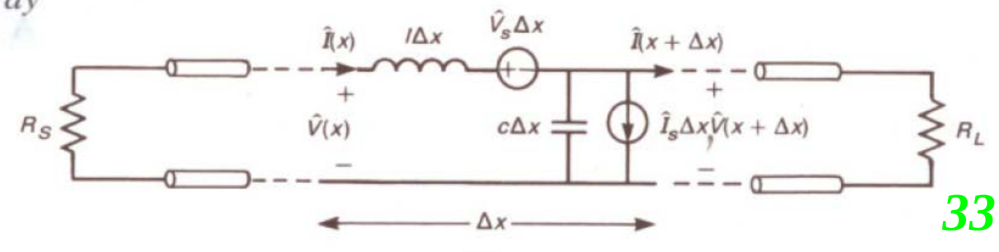
$$l = \frac{\mu_0}{\pi} \ln\left(\frac{s}{r_w}\right) \quad \text{(in H/m)}$$

$$c = \pi \epsilon_0 \epsilon_r / \ln\left(\frac{s}{r_w}\right) \quad \text{(in F/m)}$$

    - According to Faraday's law, the induced emf is

$$\begin{aligned} \text{emf} &= j\omega \int_S \hat{B}_n^i \, ds \\ &= j\omega\mu_0 \int_S \hat{H}_n^i \, ds \\ &= j\omega\mu_0 \, \Delta x \int_{y=0}^{s} \hat{H}_n^i \, dy \end{aligned} \longrightarrow \hat{V}_s(x) = j\omega\mu_0 \int_{y=0}^{s} \hat{H}_n^i dy$$

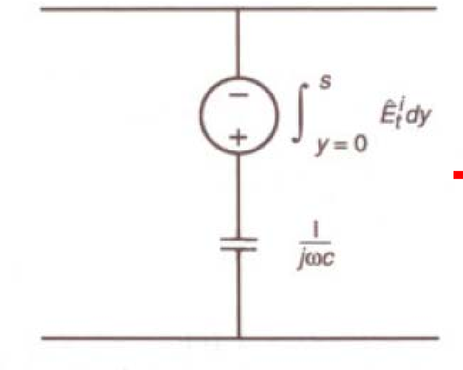
The per-unit-length induced voltage source



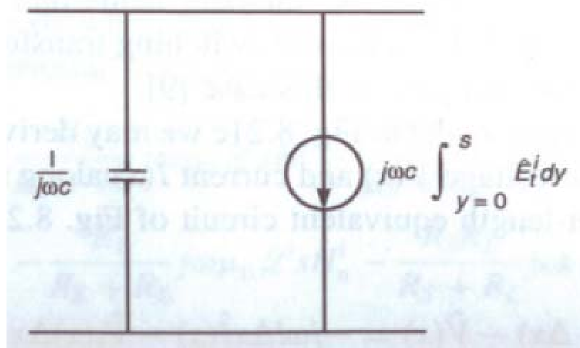
Simple Susceptibility Models for Wires and PCB Lands

- Two-Conductor Line
  - General Susceptibility Model
    - The per-unit-length induced current source is

$$\hat{I}_s(x) = j\omega c \int_{y=0}^{s} \hat{E}_t^i \, dy$$



Thevenin to Norton transformation



- The incident electric field is

$$|\hat{E}^i| = \frac{\sqrt{60 P_T G}}{d} \longrightarrow |\hat{H}^i| = \frac{|\hat{E}^i|}{n_0}$$ the incident magnetic field

Simple Susceptibility Models for Wires and PCB Lands

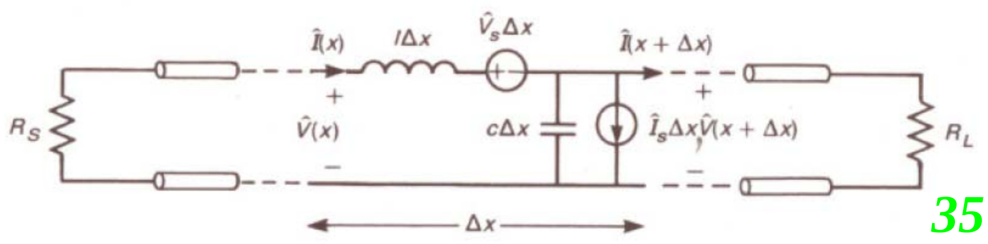
- Two-Conductor Line
  - General Susceptibility Model - TX Line Equations
    - Using KCL and KVL, we have

$$\hat{V}(x+\Delta x) - \hat{V}(x) = -j\omega l \Delta x \hat{I}(x) - \hat{V}_s(x)\Delta x$$

$$\hat{I}(x+\Delta x) - \hat{I}(x) = -j\omega c \Delta x \hat{V}(x+\Delta x) - \hat{I}_s(x)\Delta x$$

$$\frac{d\hat{V}(x)}{dx} + j\omega l \hat{I}(x) = -\hat{V}_s(x) = -j\omega\mu_0 \int_{y=0}^{s} \hat{H}_n^i dy$$

$$\frac{d\hat{I}(x)}{dx} + j\omega c \hat{V}(x) = -\hat{I}_s(x) = -j\omega c \int_{y=0}^{s} \hat{E}_t^i dy$$



Simple Susceptibility Models for Wires and PCB Lands

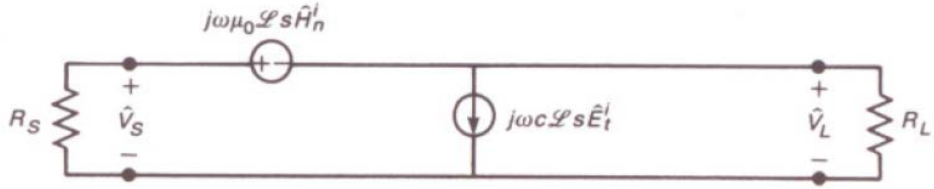
- Two-Conductor Line
  - General Susceptibility Model - TX Line Equations
    - When the line is electrically short, $L << \lambda_0$ and the line inductance and capacitance are neglected, we have the simplified model

If loads not approaching open or short circuit.

$$\hat{V}_s \mathscr{L} \cong j\omega\mu_0 \hat{H}_n^i A$$

$$\hat{I}_s \mathscr{L} \cong j\omega c \hat{E}_t^i A$$

$$A = s\mathscr{L}$$



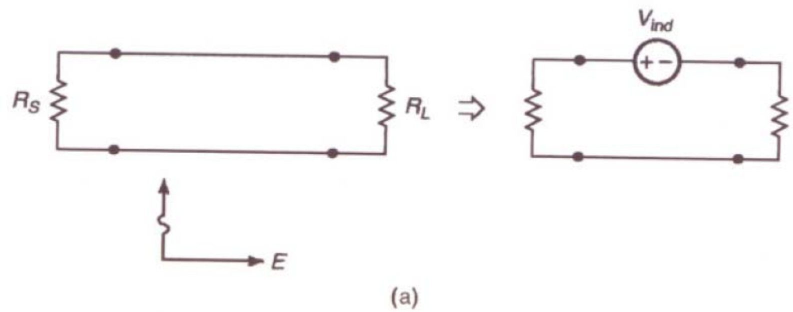
- The induced terminal voltages are (superposition)

$$\hat{V}_S = \frac{R_S}{R_S + R_L} j\omega\mu_0 \mathscr{L} s \hat{H}_n^i - \frac{R_S R_L}{R_S + R_L} j\omega c \mathscr{L} s \hat{E}_t^i$$

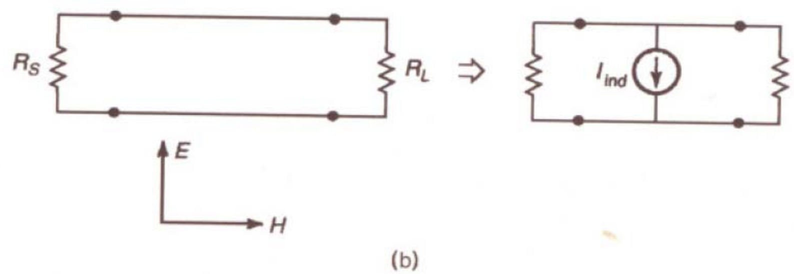
$$\hat{V}_L = -\frac{R_L}{R_S + R_L} j\omega\mu_0 \mathscr{L} s \hat{H}_n^i - \frac{R_S R_L}{R_S + R_L} j\omega c \mathscr{L} s \hat{E}_t^i$$

Simple Susceptibility Models for Wires and PCB Lands

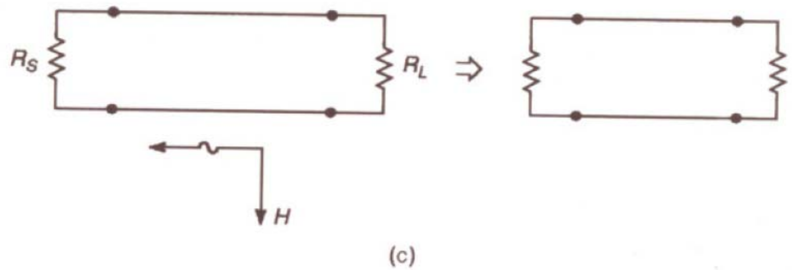
- Effect of Polarization of Incident Wave
  - Various Incident Waves



Perpendicular magnetic field



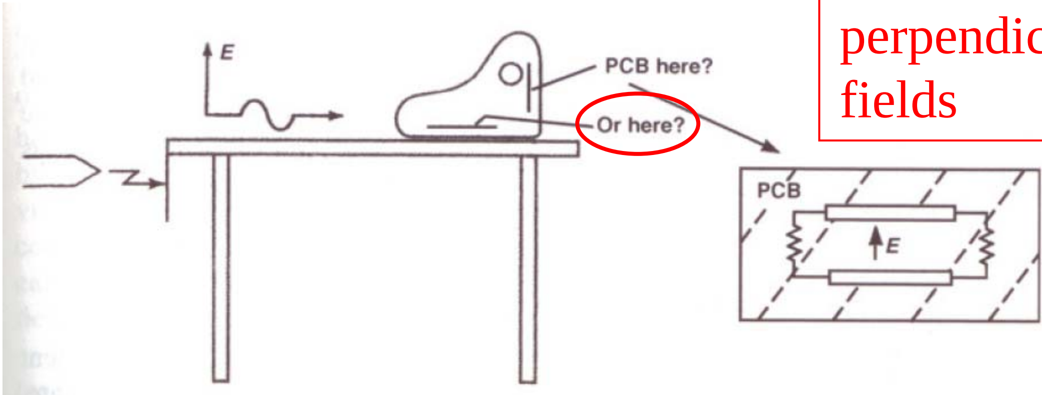
Transverse electric field



No transverse electric and perpendicular magnetic fields

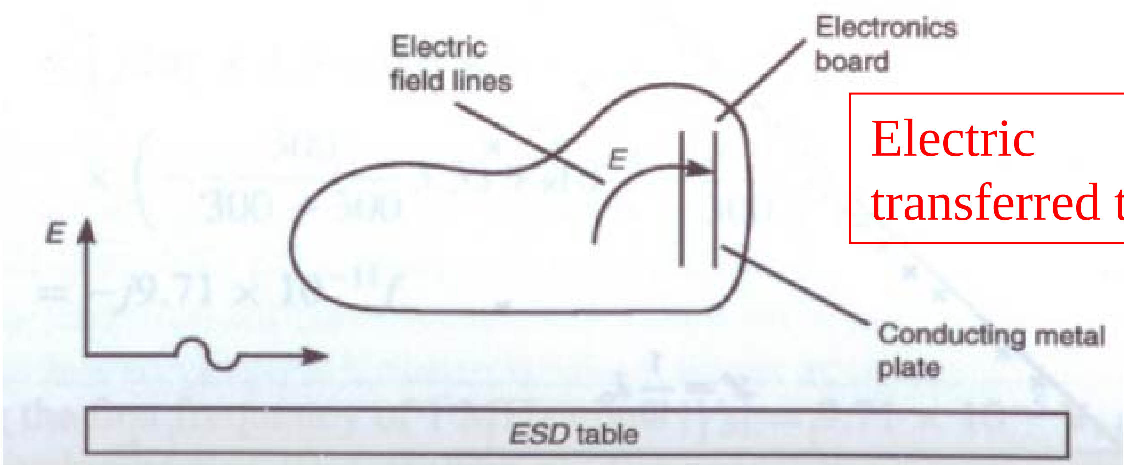
Simple Susceptibility Models for Wires and PCB Lands

- Two Ways to Preventing from ESD
  - PCB Placed Horizontal



No transverse electric and perpendicular magnetic fields

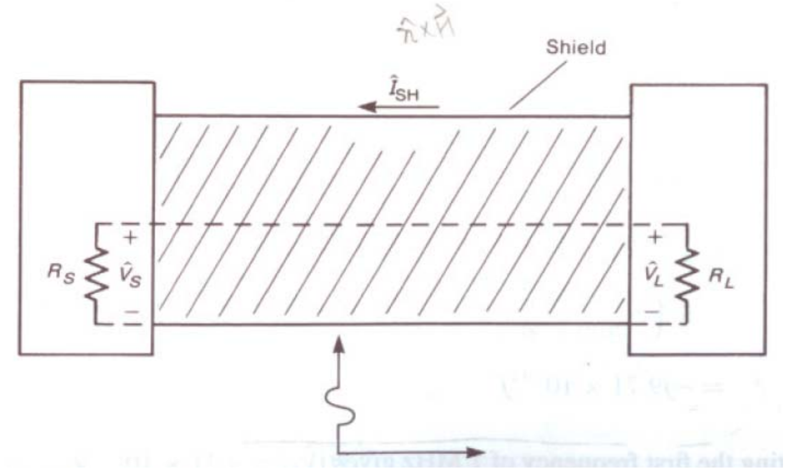
  - Placing Another PEC at the Back of PCB



Electric field be transferred to normal.

Simple Susceptibility Models for Wires and PCB Lands

- Shielded Cables and Surface Transfer Impedance
  - Incident Field Pickup for a Shielded Cable



- The shield current diffuses through the shield wall to give a voltage drop on the interior surface of the shield of

$$d\hat{V} = \hat{Z}_T \hat{I}_{SH}\, dx$$

Simple Susceptibility Models for Wires and PCB Lands

- Shielded Cables and Surface Transfer Impedance
  - Incident Field Pickup for a Shielded Cable
    - where the surface transfer impedance of the shield is given by

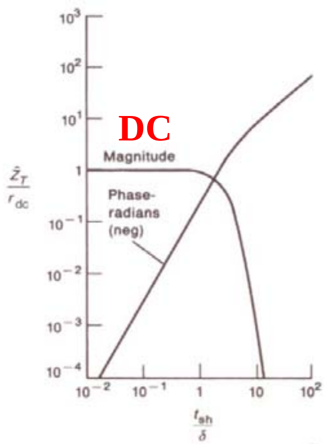
$$\hat{Z}_T = \underbrace{\boxed{\frac{1}{\sigma 2\pi r_{\mathrm{sh}} t_{\mathrm{sh}}}}}_{r_{\mathrm{dc}}} \frac{\gamma t_{\mathrm{sh}}}{\sinh \gamma t_{\mathrm{sh}}} \quad (\text{in } \Omega/\mathrm{m})$$

$$\gamma = \frac{1 + j1}{\delta}$$

$$\delta = 1/\sqrt{\pi f \mu_0 \sigma}$$

    - and the per-unit-length dc resistance of the shield is

$$r_{\mathrm{dc}} = \frac{1}{\sigma 2\pi r_{\mathrm{sh}} t_{\mathrm{sh}}} \quad (\text{in } \Omega/\mathrm{m}) \quad \text{for} \quad t_{\mathrm{sh}} \ll \delta$$



    - The shield inner radius is denoted by r_{sh} and the shield thickness is by t_{sh}.

Simple Susceptibility Models for Wires and PCB Lands

- Shielded Cables and Surface Transfer Impedance
  - Incident Field Pickup for a Shielded Cable
    - For braided shields, this becomes

$$\hat{Z}_T = \underbrace{\boxed{\frac{1}{\sigma\pi r_{bw}^2 BW \cos\theta_w}}}_{r_{dc}} \frac{\gamma 2 r_{bw}}{\sinh(\gamma 2 r_{bw})} \quad (\text{in } \Omega/\text{m})$$

    - and the per-unit-length dc resistance of the shield is

$$r_{dc} = \frac{r_b}{BW\cos\theta_w} \quad (\text{in } \Omega/\text{m})$$

    - and the per-unit-length dc resistance of the braid wires is

$$r_b = \frac{1}{\sigma\pi r_{bw}^2} \quad (\text{in } \Omega/\text{m}) \quad \text{for } r_{bw} \ll \delta$$

r_{bw}: radius of the wire

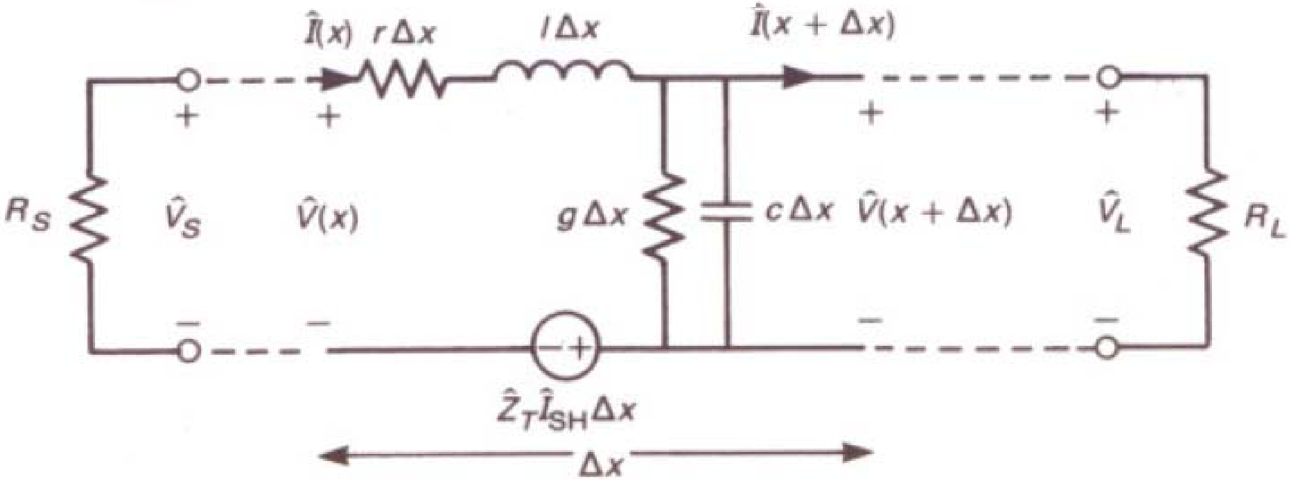
    - where B is the number of belts in the shield braid, W is the number of the braid wires per belt, θ_w is the weave angle of these belts.

Simple Susceptibility Models for Wires and PCB Lands

- Shielded Cables and Surface Transfer Impedance
  - Equivalent Circuit
    - The transmission lines equations are

$$\frac{d\hat{V}(x)}{dx} + (r + j\omega l)\hat{I}(x) = -\hat{Z}_T\hat{I}_{SH}$$

$$\frac{d\hat{I}(x)}{dx} + (g + j\omega c)\hat{V}(x) = 0$$

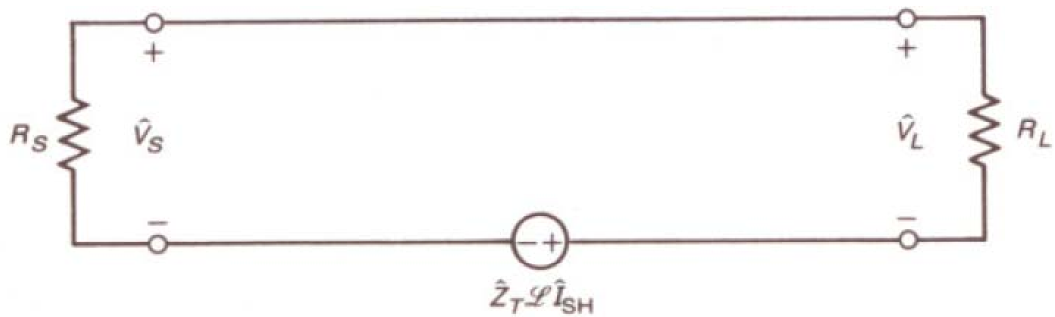


Simple Susceptibility Models for Wires and PCB Lands

- Shielded Cables and Surface Transfer Impedance
  - Equivalent Circuit
    - Assuming the line is electrically short and neglecting the inductance and capacitance, the equivalent circuit simplifies to

$$\hat{V}_S = \frac{R_S}{R_S + R_L}\hat{Z}_T \hat{I}_{SH}\mathscr{L}$$

$$\hat{V}_L = -\frac{R_L}{R_S + R_L}\hat{Z}_T \hat{I}_{SH}\mathscr{L}$$



Simple Susceptibility Models for Wires and PCB Lands

- Shielded Cables and Surface Transfer Impedance
  - Equivalent Circuit – Braided Shield
    - For magnetic field penetrating the holes in the braided shields, the surface transfer impedance becomes

$$\hat{Z}_T = \frac{1}{\sigma \pi r_{bw}^2 BW \cos\theta_w} \frac{\gamma 2 r_{bw}}{\sinh(\gamma 2 r_{bw})} + j\omega m_{12} \quad (\text{in } \Omega/\text{m})$$

    - For electric field penetrating the holes in the braided shields, a current source $Y_T V_{SG}$ must be added in parallel in the equivalent circuit.

$$\hat{Y}_T = \frac{1}{\hat{V}_{SG}} \frac{d\hat{I}}{dx}$$

V_{SG}: voltage between the shield and the ground plane