Electromagnetic Compatibility (*EMC*)

Basic knowledge used in EMC

Agenda

- *Circuit Analysis*
  - Use of Network Theory
  - Capacitor Coupling
  - Inductor Coupling
  - Discrimination
- Practical Model of Component and Frequency Response
- Common mode and Differential mode
- Near Field and Far Field
- Antenna Effect
- Transmission Line Analysis

Use of Network Theory

- Circuit analysis assumes the following
  - All *electric fields* are confined to the interiors of *capacitors*.
  - All *magnetic fields* are confined to the interiors of *inductors*.
  - Dimensions of the circuits are very small compared to the wavelength under consideration.

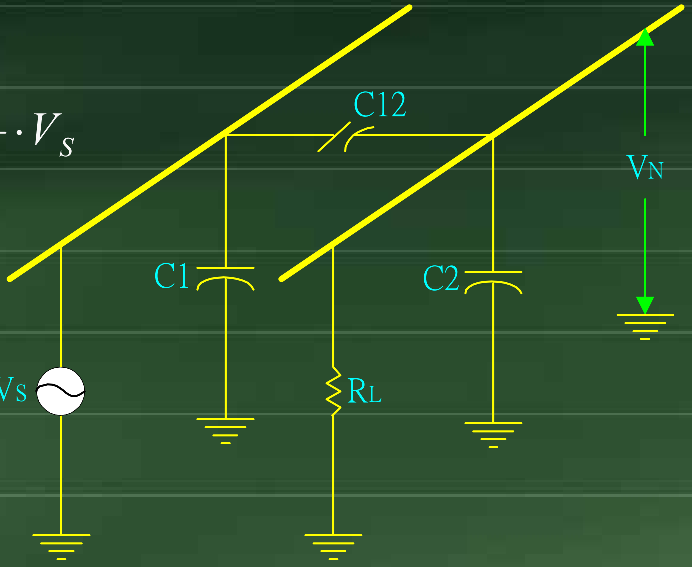
Capacitor Coupling

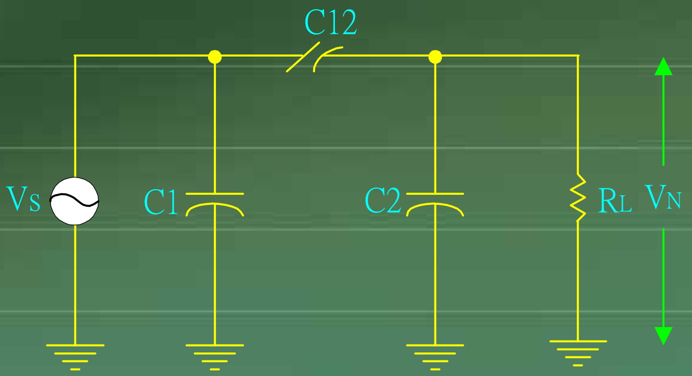
- Noise voltage： $V_N = \dfrac{j\omega[C_{12}/(C_{12}+C_2)]}{j\omega + 1/R_{\mathrm{L}}(C_{12}+C_2)} \cdot V_S$

  for $R_L \ll \dfrac{1}{j\omega(C_{12}+C_2)}$

  $$V_N = jwR_L C_{12} V_S$$

- Assuming the voltage and frequency of the noise source cannot be changed
  - *Decreasing capacitance C12*
  - Let receiver circuit operate at a lower resistance level R_L



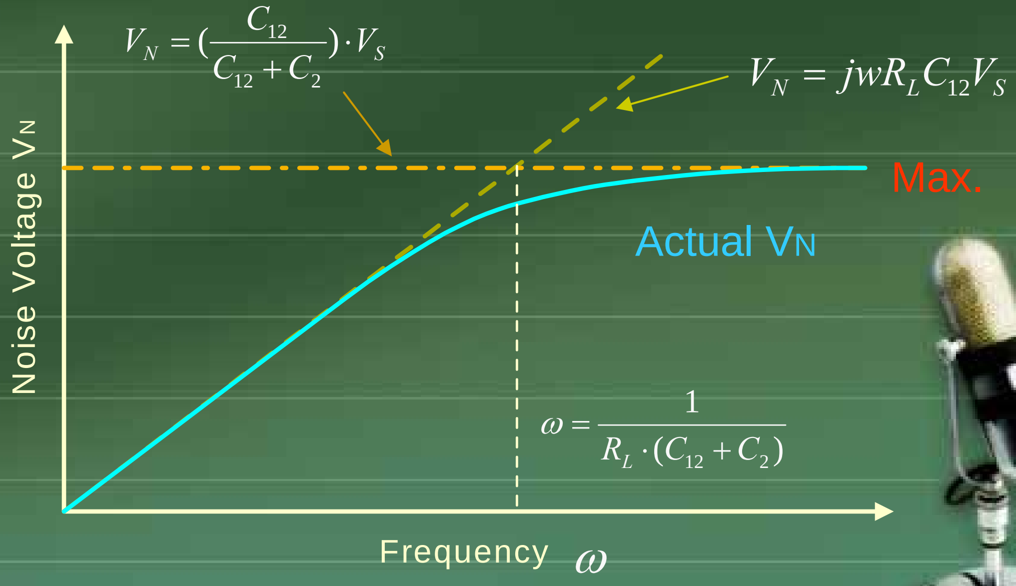


Capacitor Coupling

- Noise voltage : $V_N = \frac{j\omega[C_{12} /(C_{12}+C_2)]}{j\omega + 1/R(C_{12}+C_2)} \cdot V_S$

for $R_L >> \frac{1}{j\omega(C_1+C_2)}$

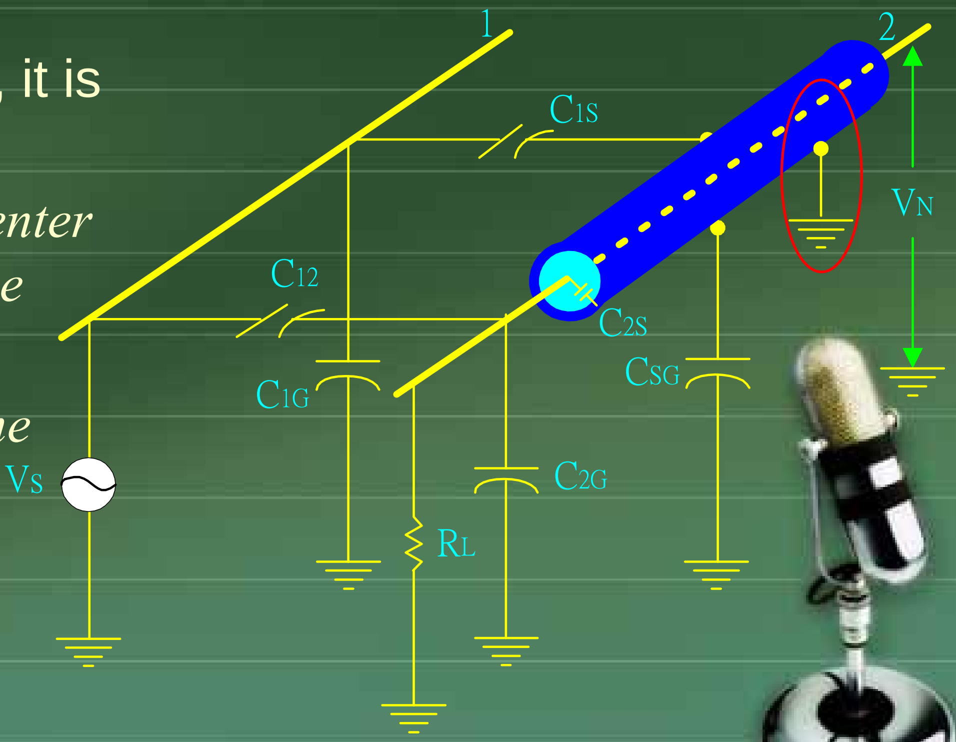
$$V_N = V_{N(\max)} = (\frac{C_{12}}{C_{12}+C_2}) \cdot V_S$$



Capacitor Coupling

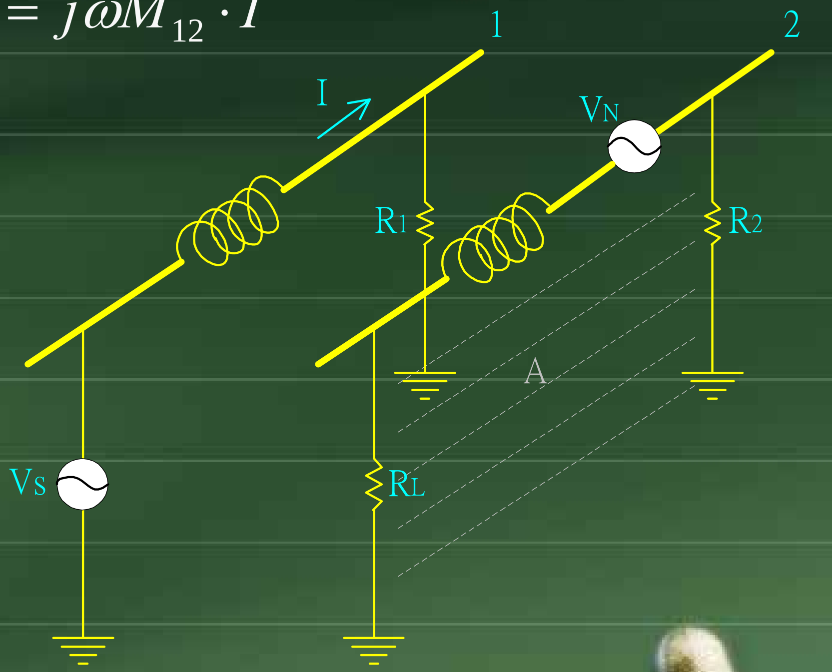
With Shielding

- Noise voltage： $V_N = \left(\frac{C_{12}}{C_{12}+C_{2G}+C_{2S}}\right)\cdot V_S$
  - C_{12} depends on the length of conductor 2 that extends beyond the shield.
- For good electric field shielding, it is therefore necessary
  - *to minimize the length of the center conductor extending beyond the shield.*
  - *to provide a good ground on the shield.*



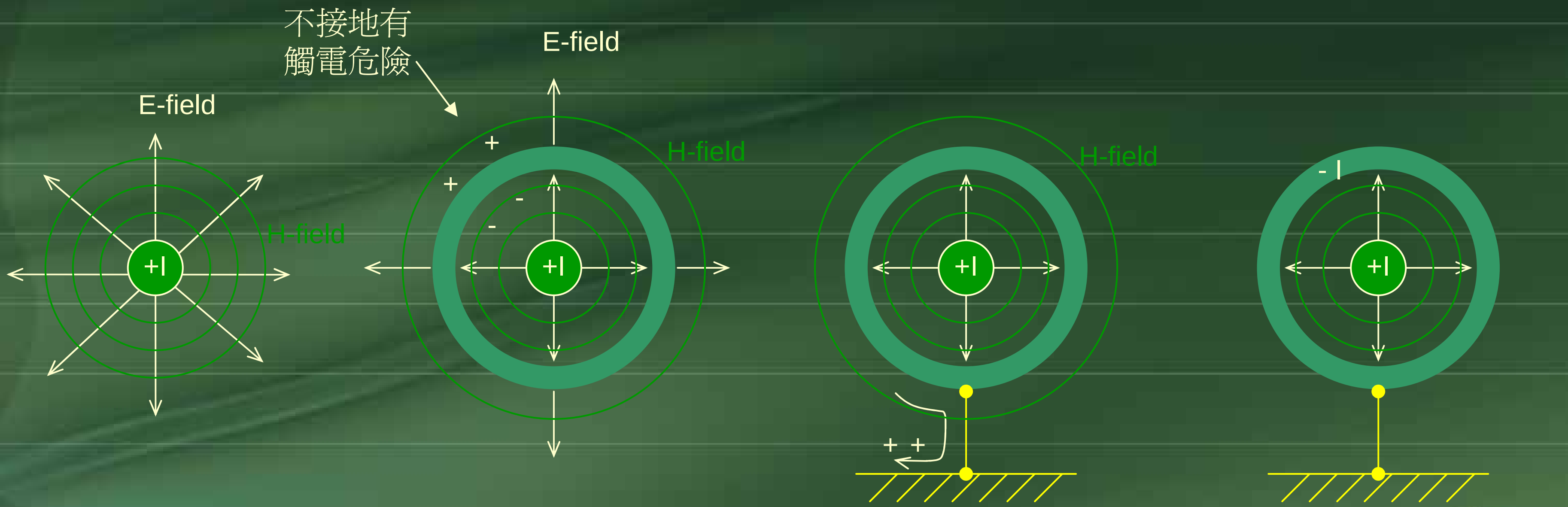
Inductor Coupling

- Noise voltage： $V_N = j\omega BA\cos\theta = j\omega M_{12}\cdot I$
  - $\vec{B}$ is the rms value of the sinusoidally varying flex density produced by current I in circuit 1.
  - $\vec{A}$ is the area of closed loop in circuit 2.
  - M_{12} is the mutual inductance between conductor 1 and 2.



- Strategies
  - Decreasing loop area $\vec{A}$
    - Twisted line, proper grounding,shielding …
  - Decreasing flux density $\vec{B}$ or mutual inductance M_{12}
    - Physical separation of the circuits, current flowing in the twisted pair…

Cable Shield Grounding



Connecting wire
without shield

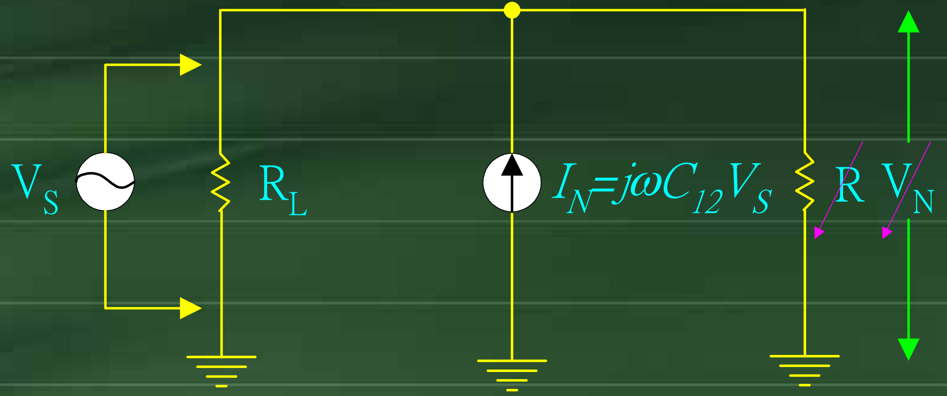
Cable shield
without grounding

Cable shield grounded

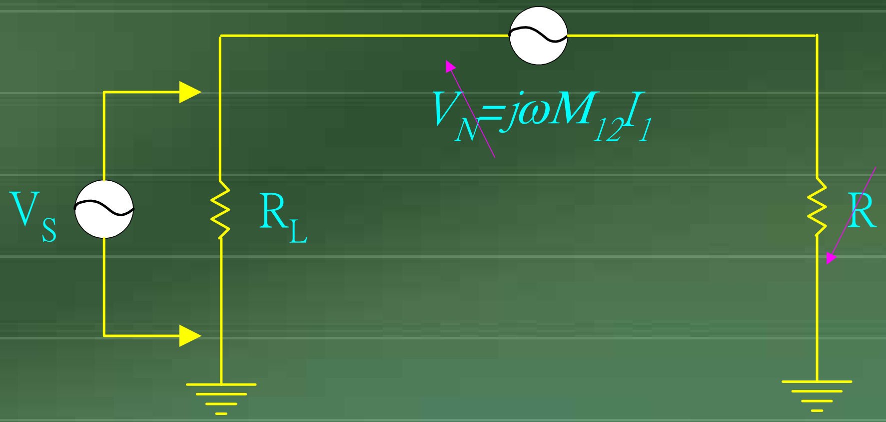
Cable shield grounded
and current in shield

Discrimination

- Electric coupling



- Magnetic coupling



Agenda

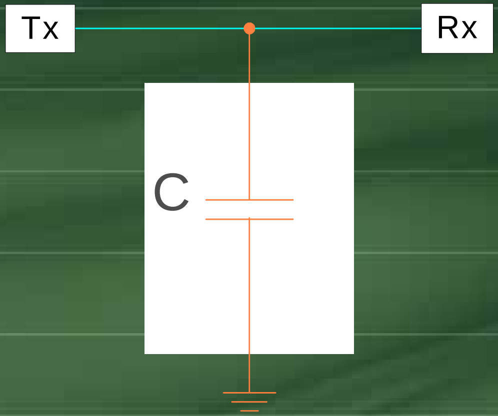
- Circuit Analysis
- *Practical Model of Component and Frequency Response*
  - Capacitor
  - Inductor
- Common mode and Differential mode
- Near Field and Far Field
- Antenna Effect
- Transmission Line Analysis

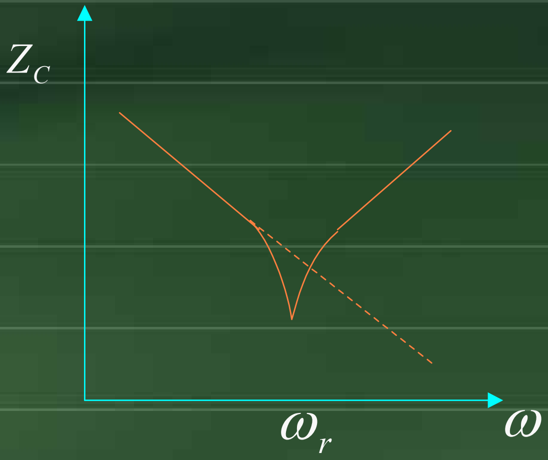
Practical Model of Component

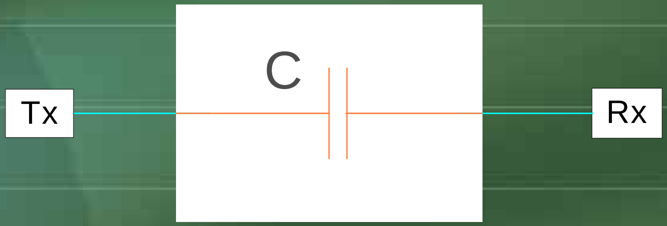
Capacitor

- Measurement setup

Practical Capacitor







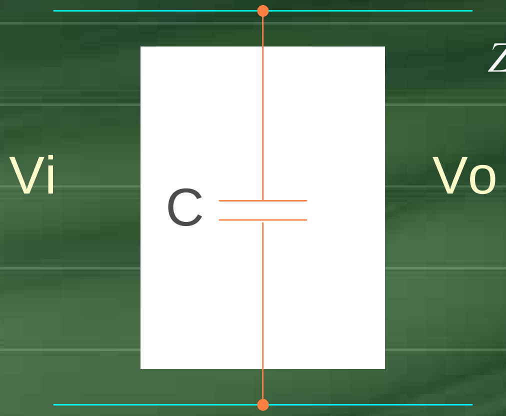
Practical Model of Component

Capacitor

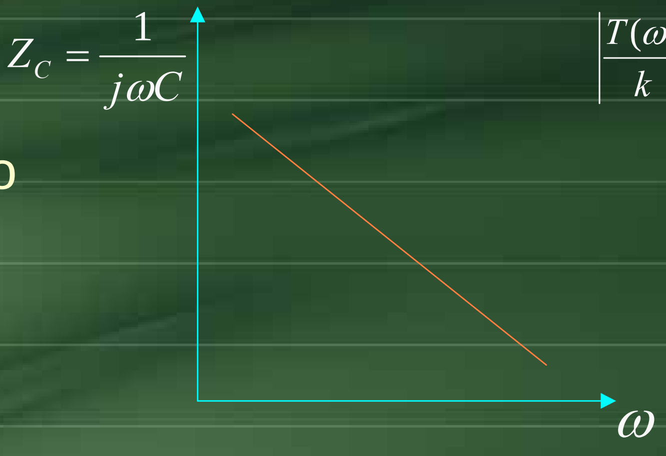
- Ideal Capacitor

Impedance

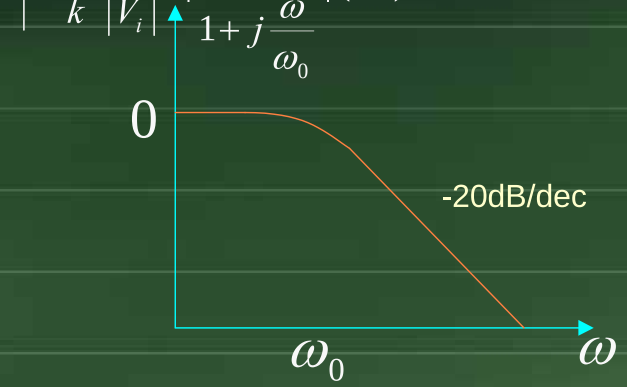
Transfer Function



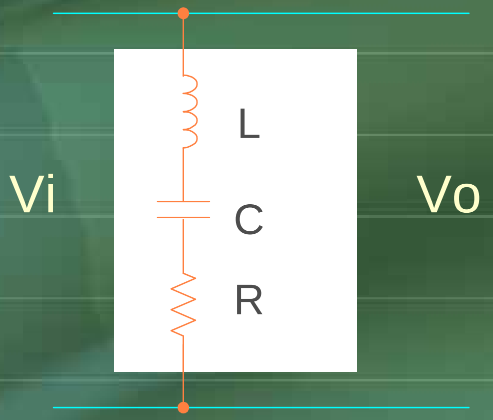
$$Z_C = \frac{1}{j\omega C}$$

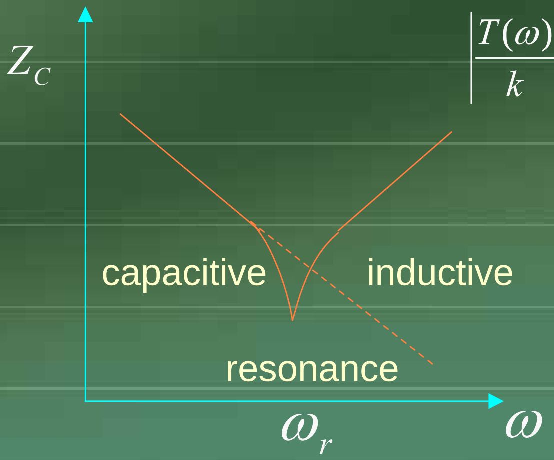


$$\left|\frac{T(\omega)}{k}\right| = \frac{1}{k}\cdot\left|\frac{V_o}{V_i}\right| = \left|\frac{1}{1+j\dfrac{\omega}{\omega_0}}\right|(dB)$$

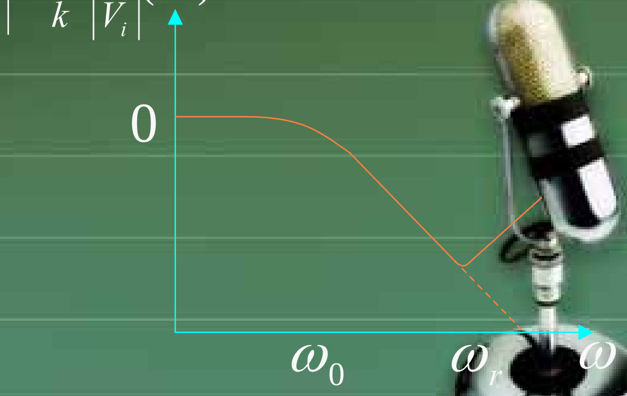


- Practical Capacitor



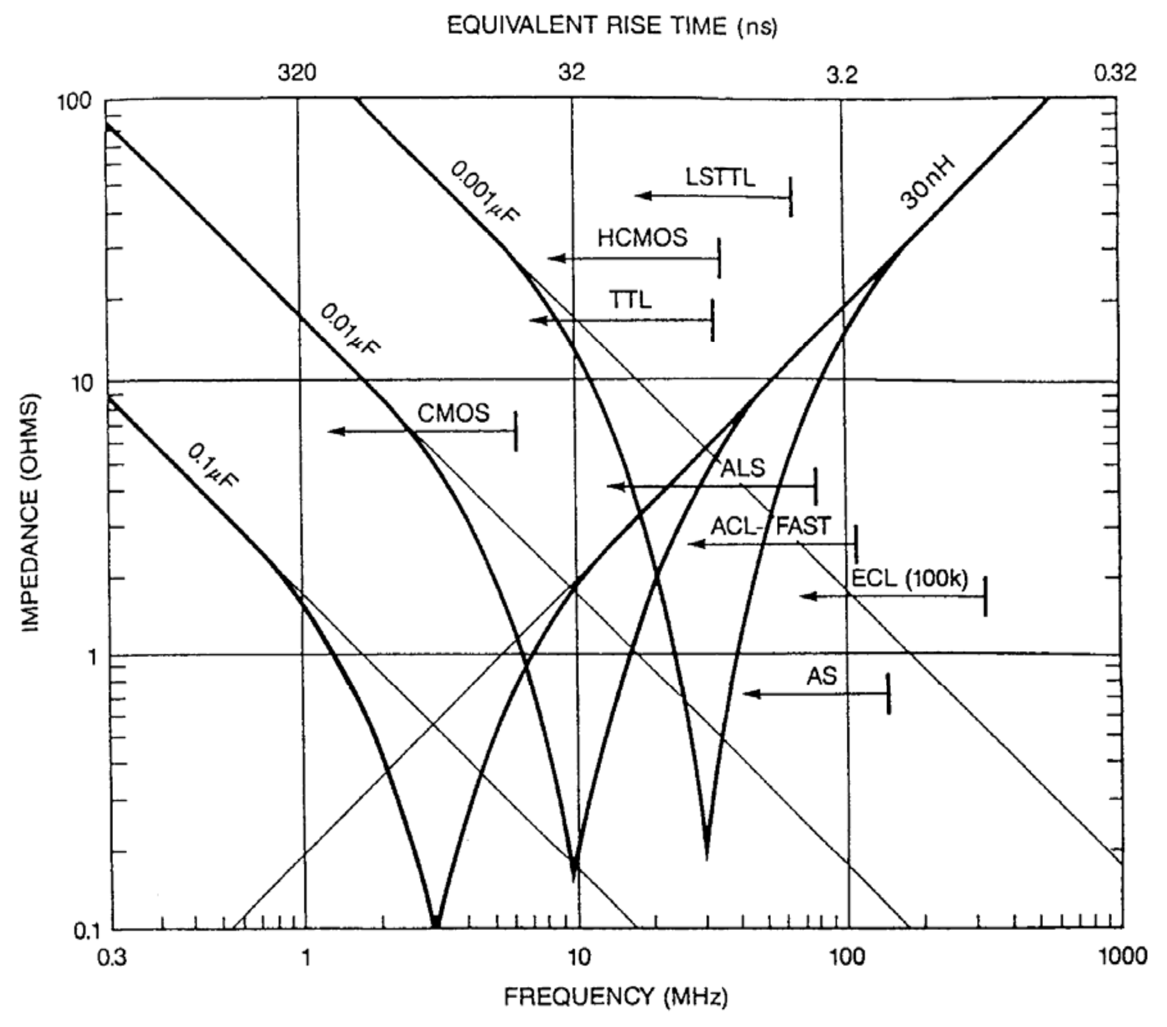


$$\left|\frac{T(\omega)}{k}\right| = \frac{1}{k}\cdot\left|\frac{V_o}{V_i}\right|(dB)$$



Practical Model of Component

Capacitor



Impedance of various value decoupling capacitors in series with 30nH of inductance

Practical Model of Component

Capacitor

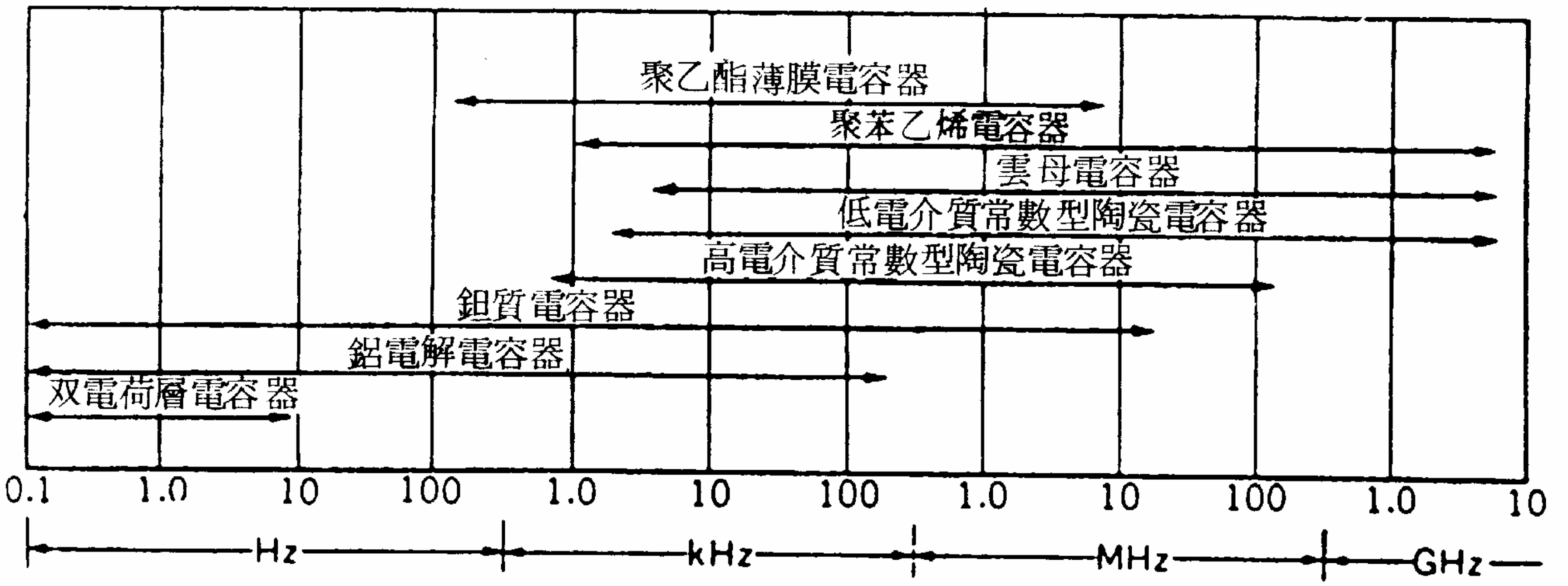


圖 3-5　主要電容器的頻率特性

Practical Model of Component

Capacitor

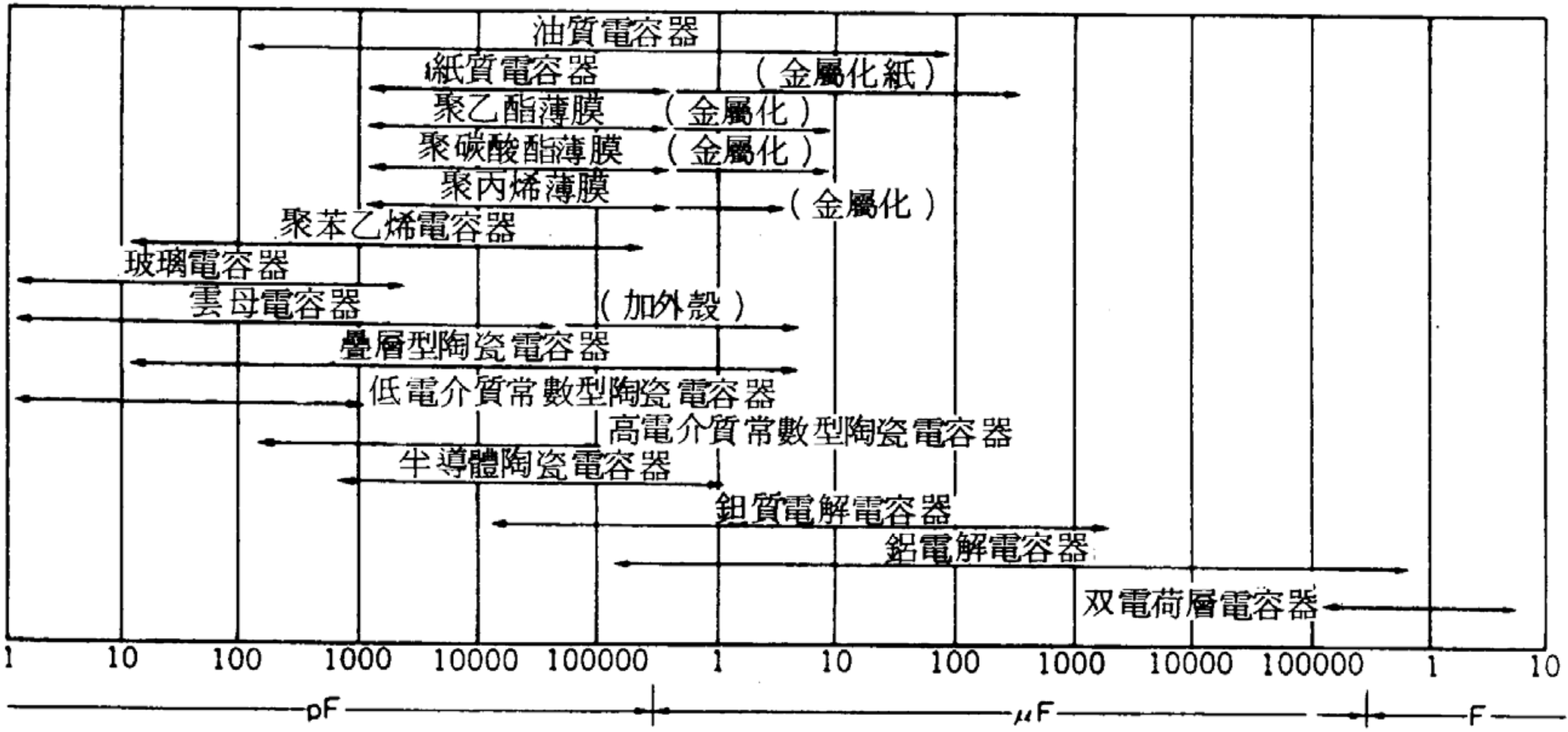


圖 3-6　各種電容器的靜電容量

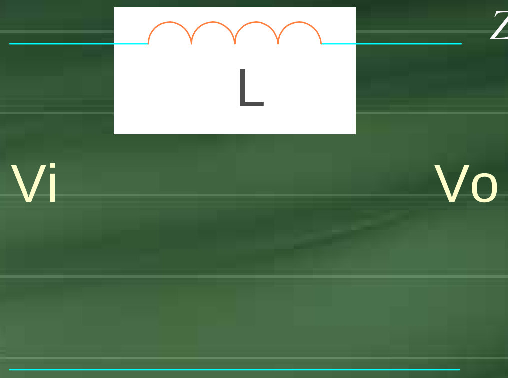
Practical Model of Component

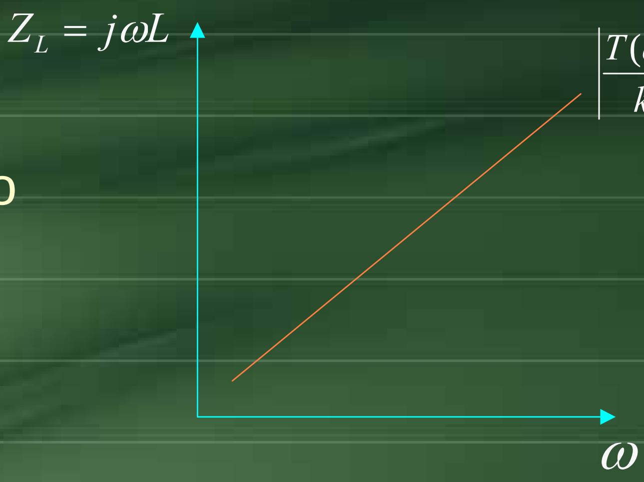
Inductor

- Ideal Inductor

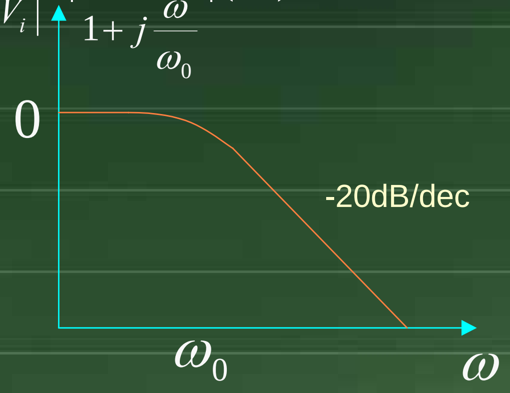
Impedance

Transfer Function

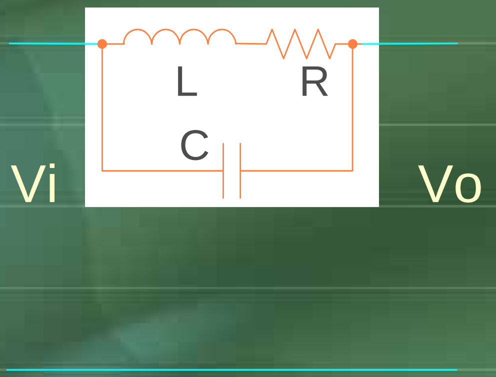


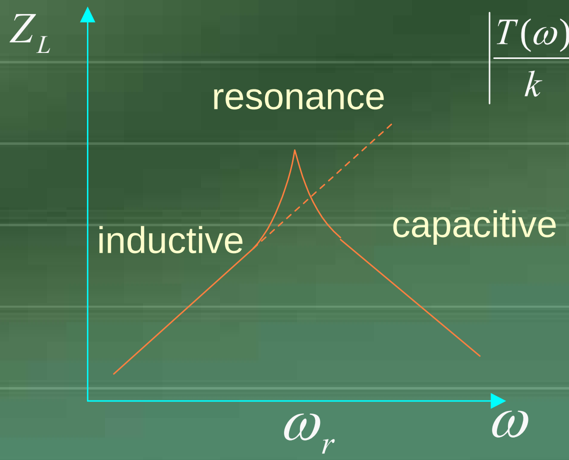


$$\left|\frac{T(\omega)}{k}\right| = \frac{1}{k}\cdot\left|\frac{V_o}{V_i}\right| = \left|\frac{1}{1+j\frac{\omega}{\omega_0}}\right|(dB)$$

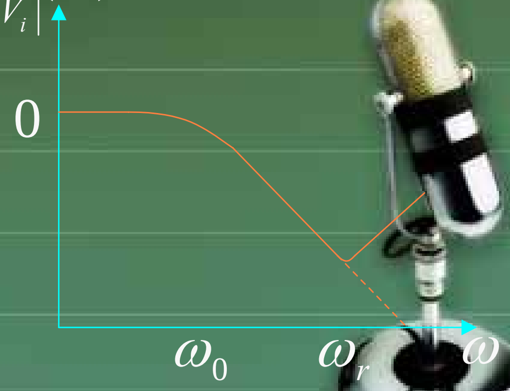


- Practical Inductor





$$\left|\frac{T(\omega)}{k}\right| = \frac{1}{k}\cdot\left|\frac{V_o}{V_i}\right|(dB)$$



Agenda

- Circuit Analysis
- Practical Model of Component and Frequency Response
  - Capacitor
  - Inductor
- *Common mode and Differential mode*
- Near Field and Far Field
- Antenna Effect
- Transmission Line Analysis

Common Mode and Differential Mode

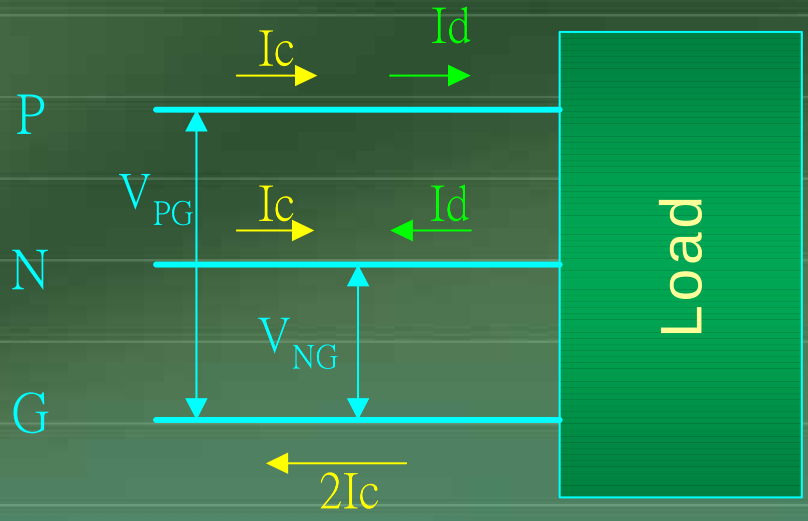
- Common-Mode(CM) – Balance Circuit
  - Cause of ground impedance in design or measurement system
- Differential-Mode(DM) – Unbalance Circuit
  - Cause of internal circuit operation or unbalance

V_{PG} : Voltage between phase and ground

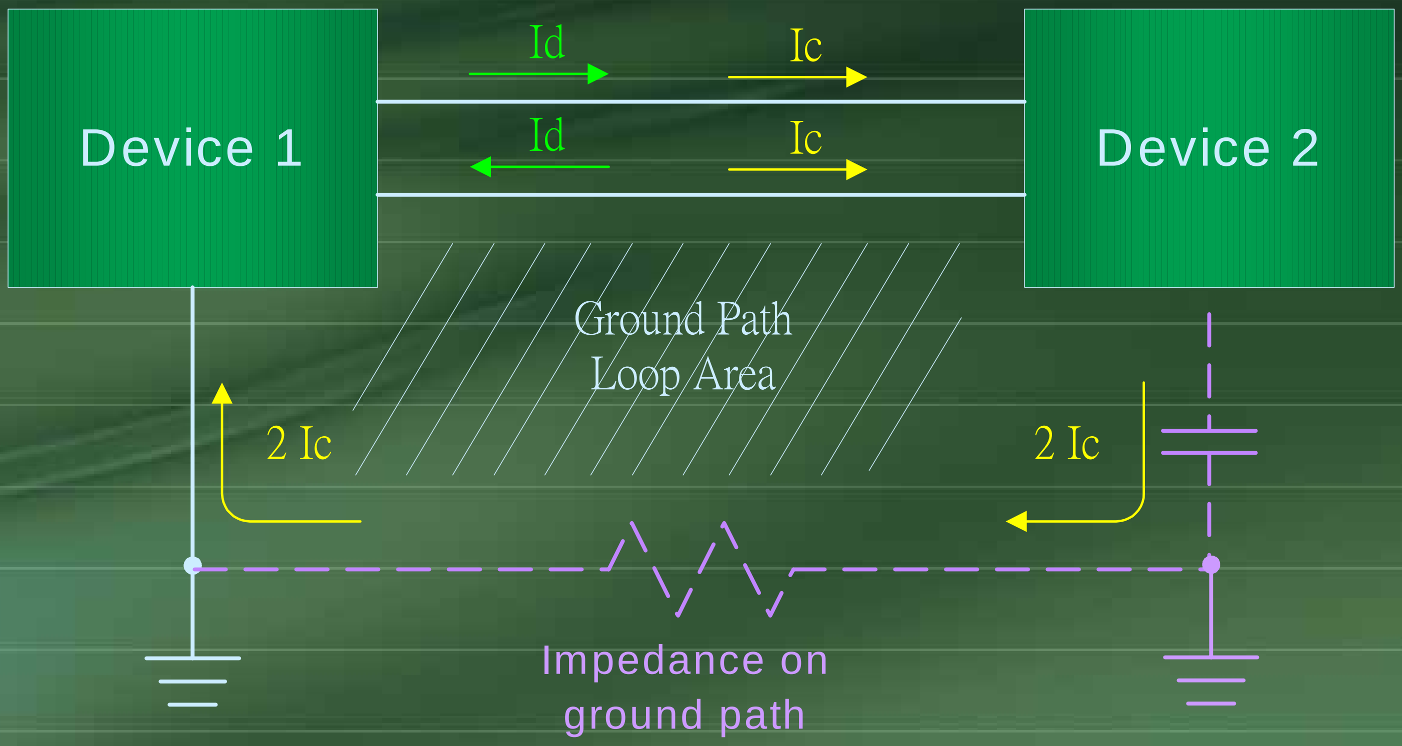
V_{NG} : Voltage between neutral and ground

CM : $V_C=(V_{PG}+V_{NG})/2$

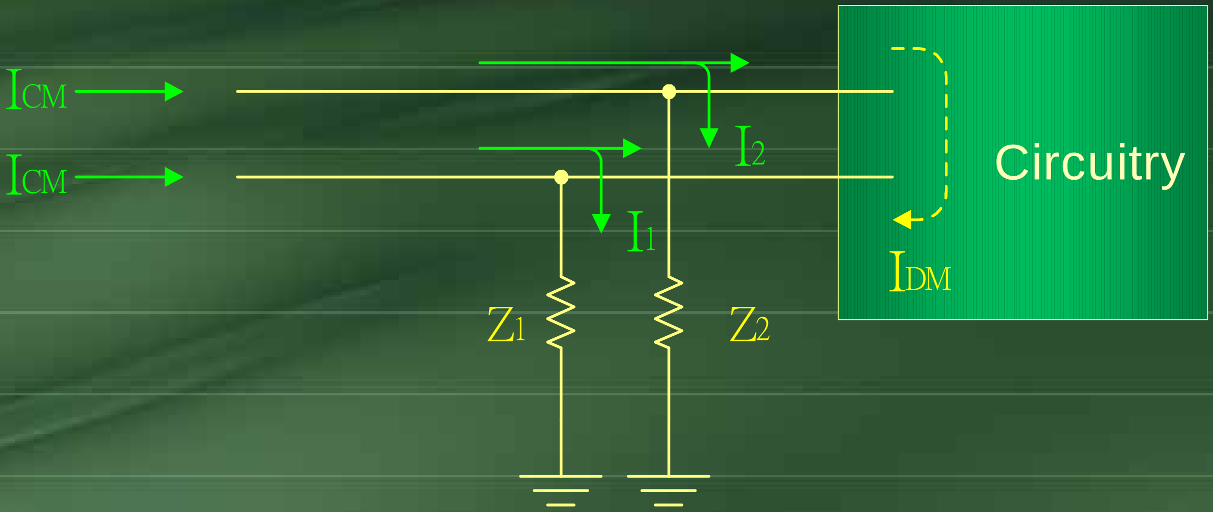
DM : $V_D=(V_{PG}-V_{NG})/2$



Common Mode and Differential Mode

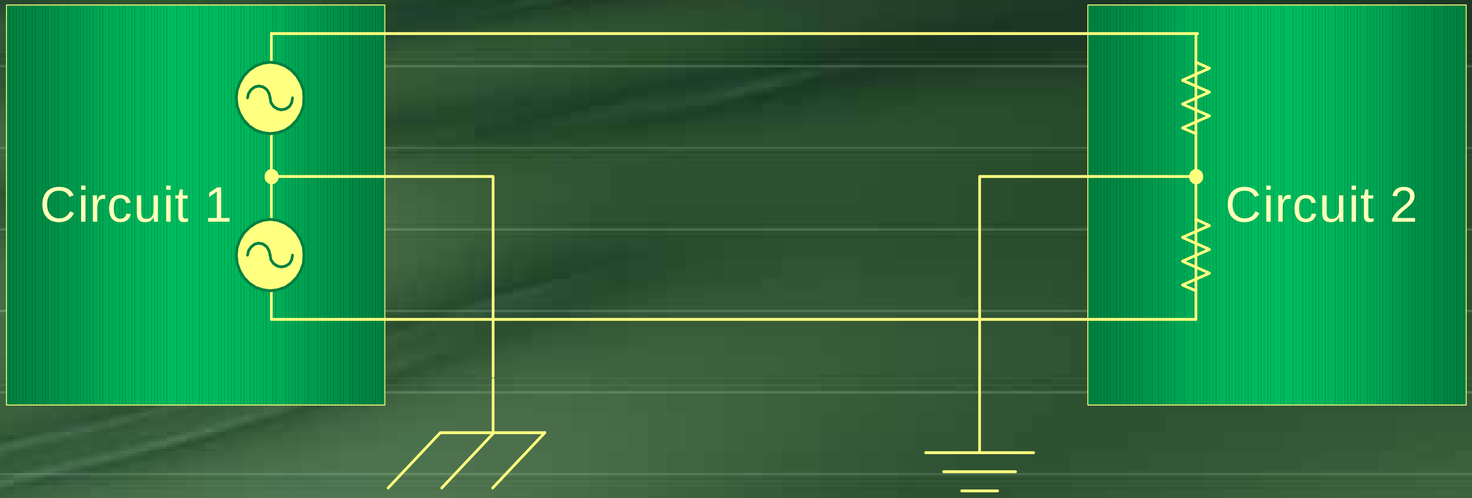


Balanced Circuitry



- If $Z_1=Z_2$ then $I_1=I_2$ and $I_{DM}=0$.
  - No DM current flows into the circuitry.
- If $Z_1 \neq Z_2$ then $I_1 \neq I_2$ and $I_{DM} \neq 0$.
  - There is DM current flows into the circuitry, which is transferred from CM.

Balanced Circuitry



- The balanced receiver responds only to the difference between the two inputs.
- *The better the balance is, the larger the CM rejection is.*

Balanced Circuitry

Example -- Differential Amplifiers

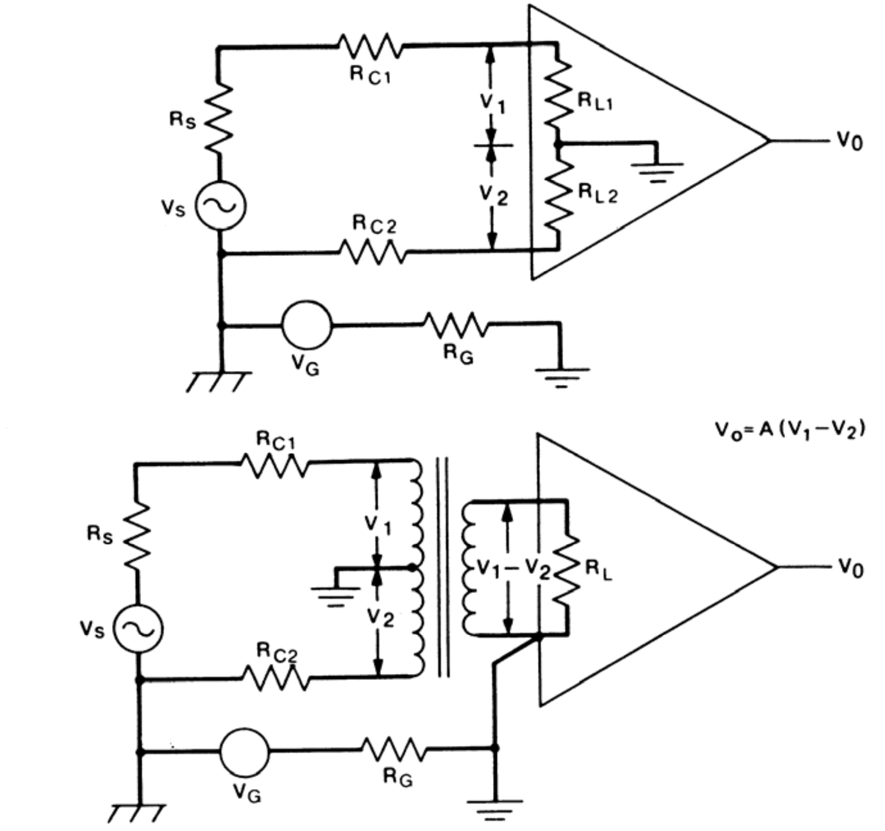
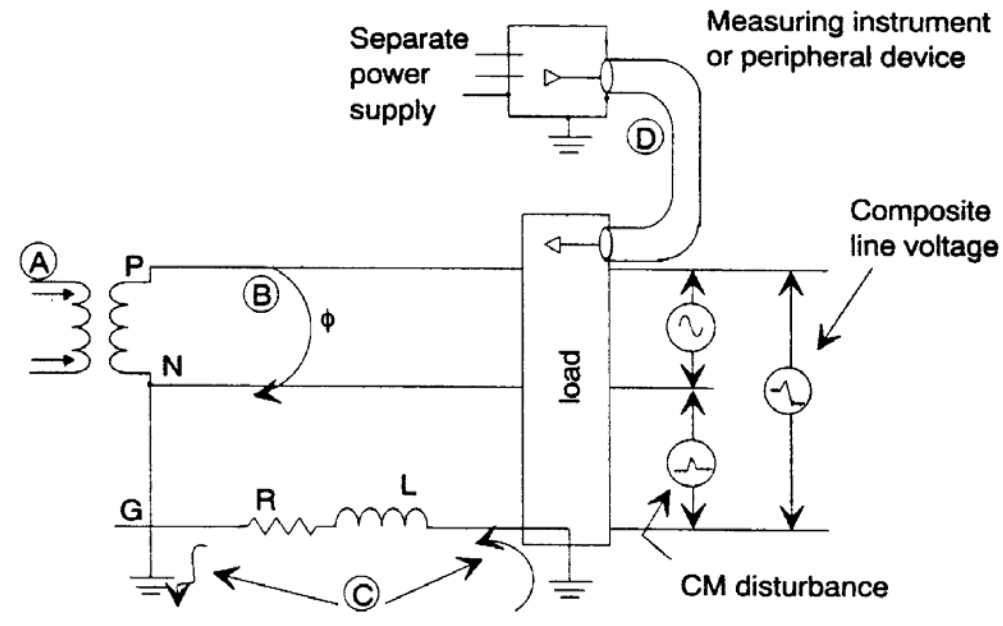
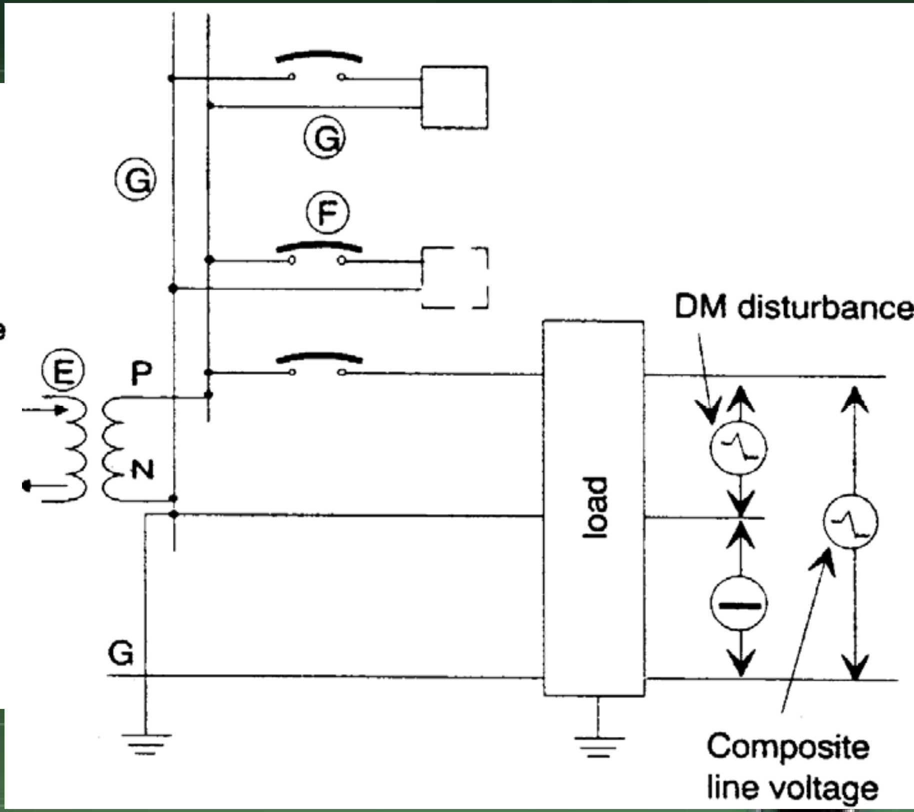


Figure 3-35. *A differential amplifier—or a single-ended amplifier with transformer—can be used to reduce the effects of a common-mode noise voltage.*

- A single-ended (or unbalanced) amplifier with transformer can be used to simulate the performance of a balanced amplifier.
  - Using a transformer

CM / DM Example



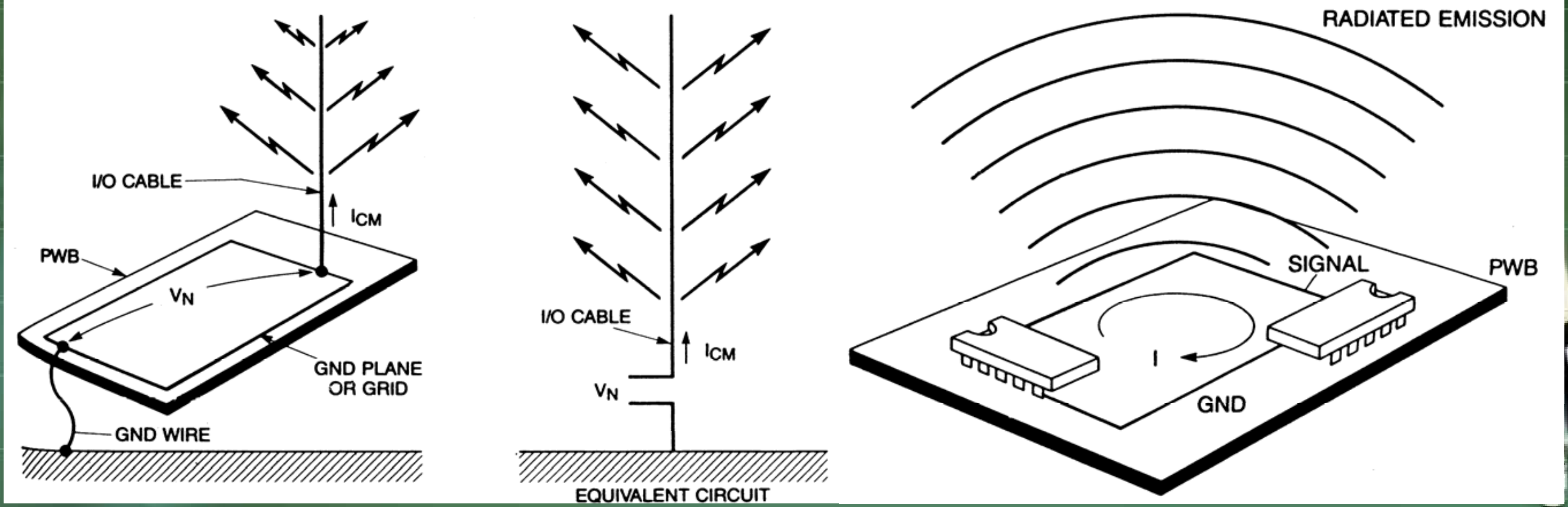


CM

DM

CM / DM Radiation

- CM radiation
  - A low current and high voltage source, like a rod or straight antenna.
  - 用電場探棒量
- DM radiation
  - A high current and low voltage source, like a loop antenna.
  - 用磁場探棒量



Agenda

- Circuit Analysis
- Practical Model of Component and Frequency Response
  - Capacitor
  - Inductor
- Common mode and Differential mode
- *Near Field and Far Field*
- Antenna Effect
- Transmission Line Analysis

Near Fields and Far Fields

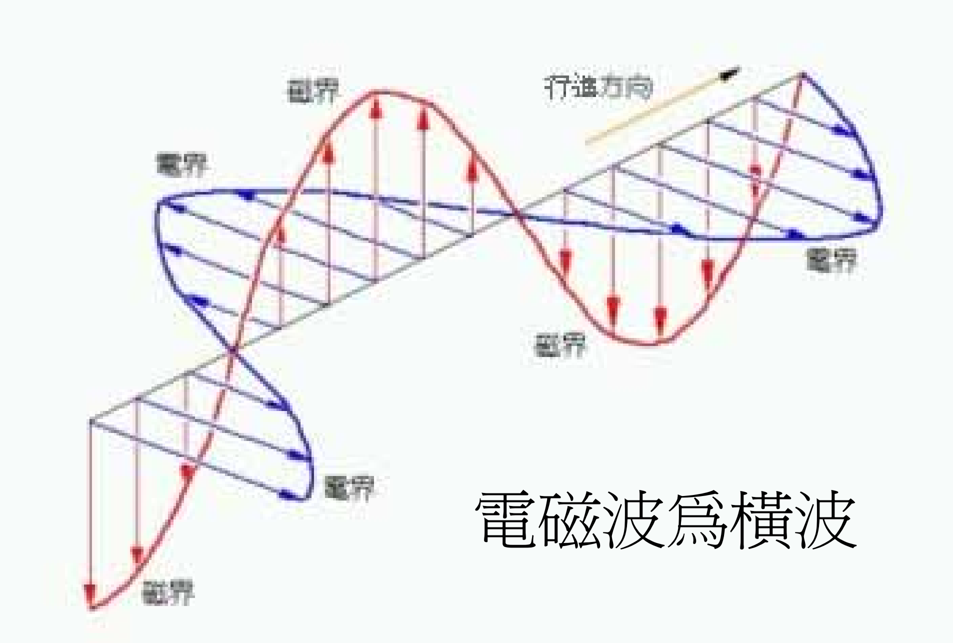
- *Wave Impedance*： $Z_w = \frac{|\vec{E}_t|}{|\vec{H}_t|} \Leftrightarrow R = \frac{V}{I}$

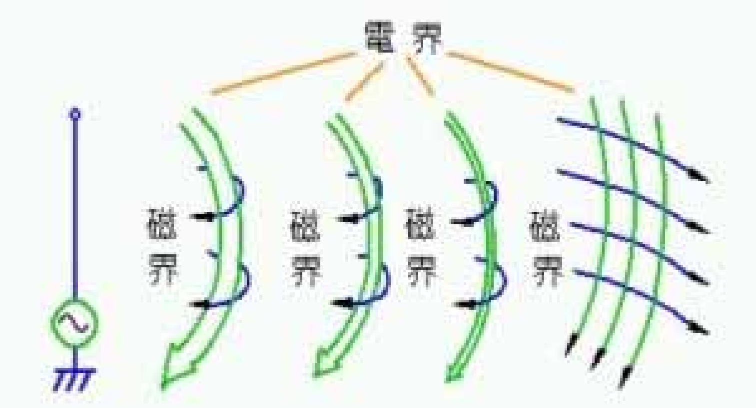
E-field SE(dB)=20 $\log_{10}(E_1/E_2)$
H-field SE(dB)=20 $\log_{10}(H_1/H_2)$

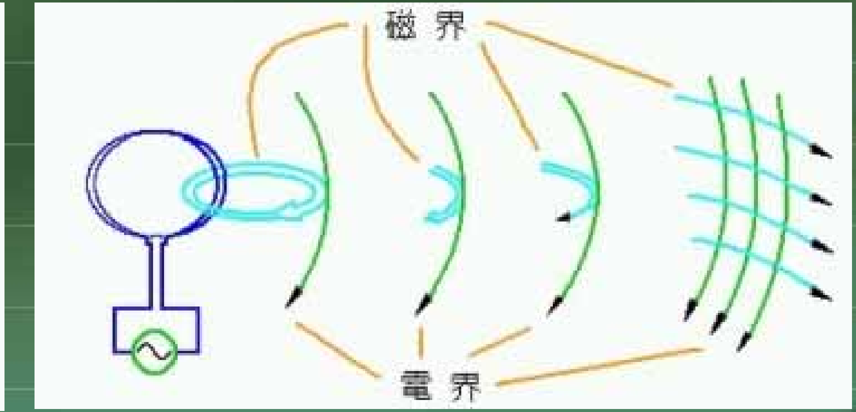
Near Fields and Far Fields

- Field characteristics are determined by the source, the media surrounding the source, and the distance between the source and the point observed.
- *Near (Induction) field*
  - *For a high current and low voltage source (like a loop antenna), the near field is predominantly magnetic.*
  - *For a low current and high voltage source (like a rod or straight antenna), the near field is predominantly electric.*
- *Far (Radiation) field*
  - *The wave impedance equals the characteristic impedance of the medium (e.g. 377Ω for air)*
  - Magnetic and electric effects don't need to concern separately.

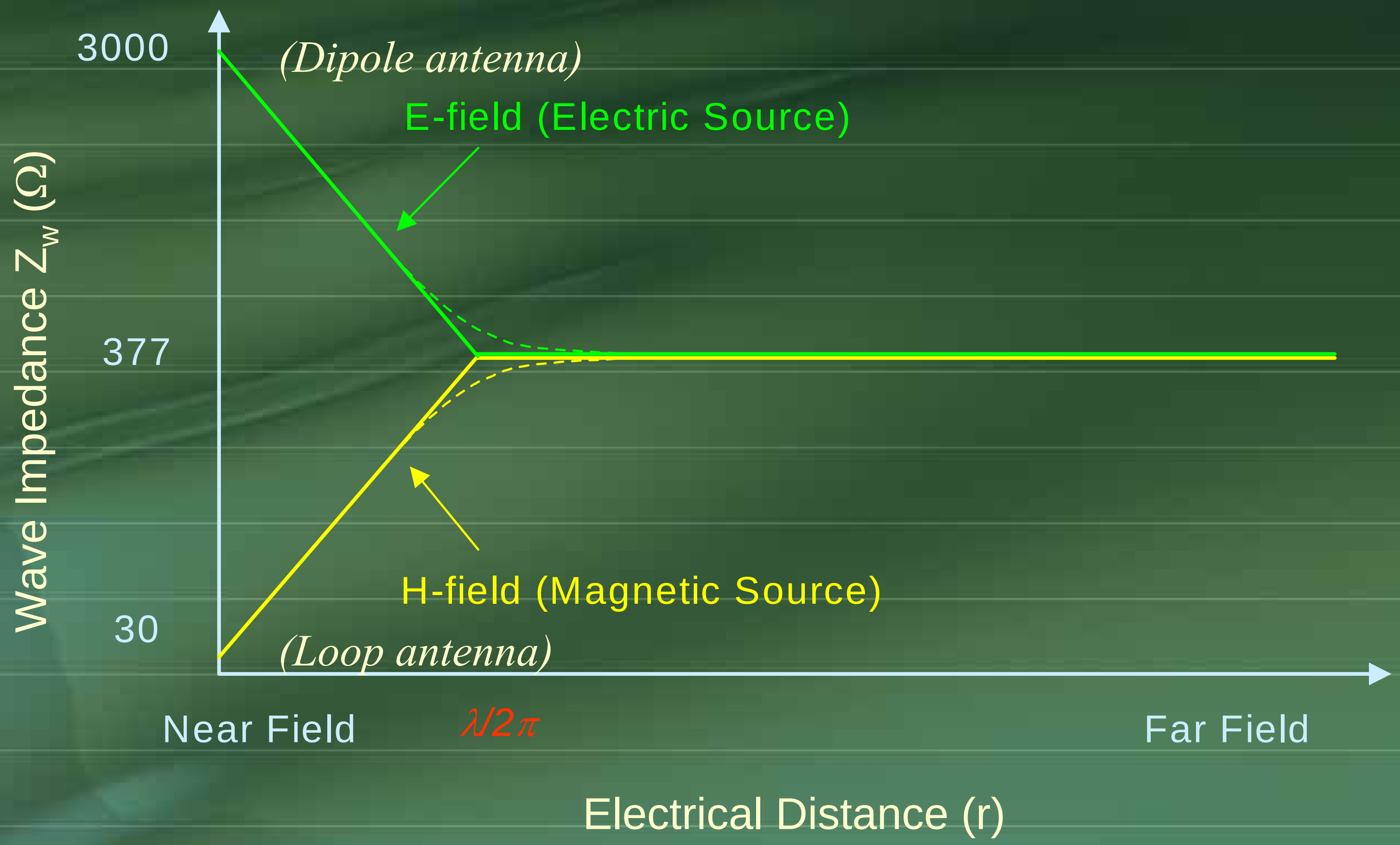
Near Fields and Far Fields







Near Fields and Far Fields



Agenda

- Circuit Analysis
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- Common mode and Differential mode
- Near Field and Far Field
- *Antenna Effect*
- Transmission Line Analysis

Antenna Effect

- If the length of a cable is longer than $\lambda/4$ it can be seen as a good polar antenna.
  - As cables approach a quarter-wavelength in length, some of the current in the cable is out of phase. When the cable is a half-wavelength long the out-of-phase currents will cause the external coupling to be zero due to ***cancellation*** of effects.

Antenna Effect

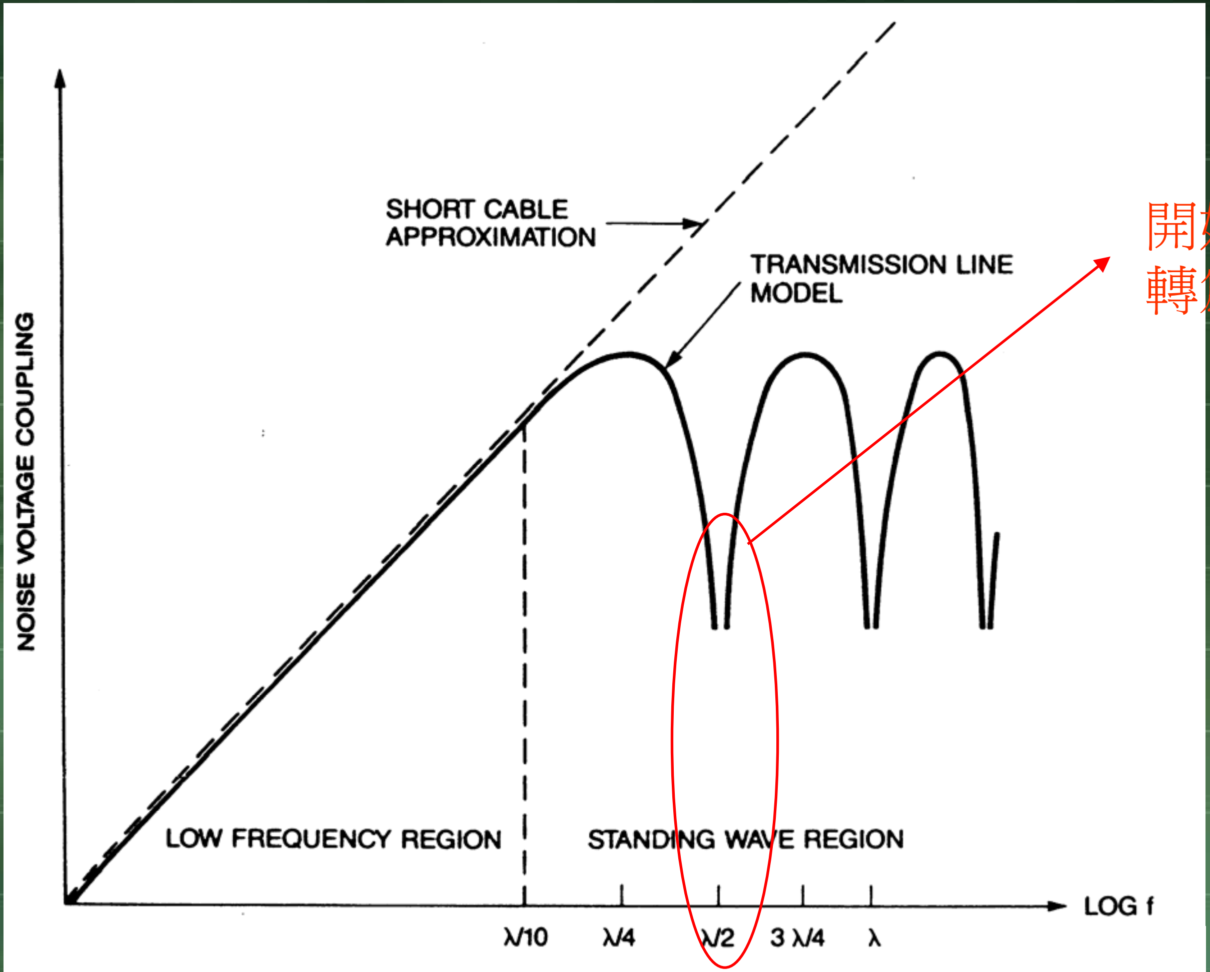


Figure 2-39. *Electric field coupling between cables using the short cable approximations and the transmission line model.*

Coupling factor

開始從近場耦合
轉爲輻射發射

Agenda

- Circuit Analysis
- Practical Model of Component and Frequency Response
- Common mode and Differential mode
- Near Field and Far Field
- Antenna Effect
- *Transmission Line Analysis*
  - Transmission Line Model
  - Transfer Impedance
  - Characteristic Impedance
  - Reflection

Transmission Line Model

- If $L \leq \frac{1}{6} \cdot t_r$, *lumped model* is used ([4], p8)
- If $L > \frac{1}{6} \cdot t_r$, *distributed model* is used

L：*Electrical line length*；it is the time that a electron spends on running through a lead (pico-sec)

tr：Rising time of the signal transmitting on the lead

Furthermore,

$$L = \frac{t_r \cdot V_p}{8}, \qquad V_p = \frac{C}{\sqrt{\varepsilon_r}}$$

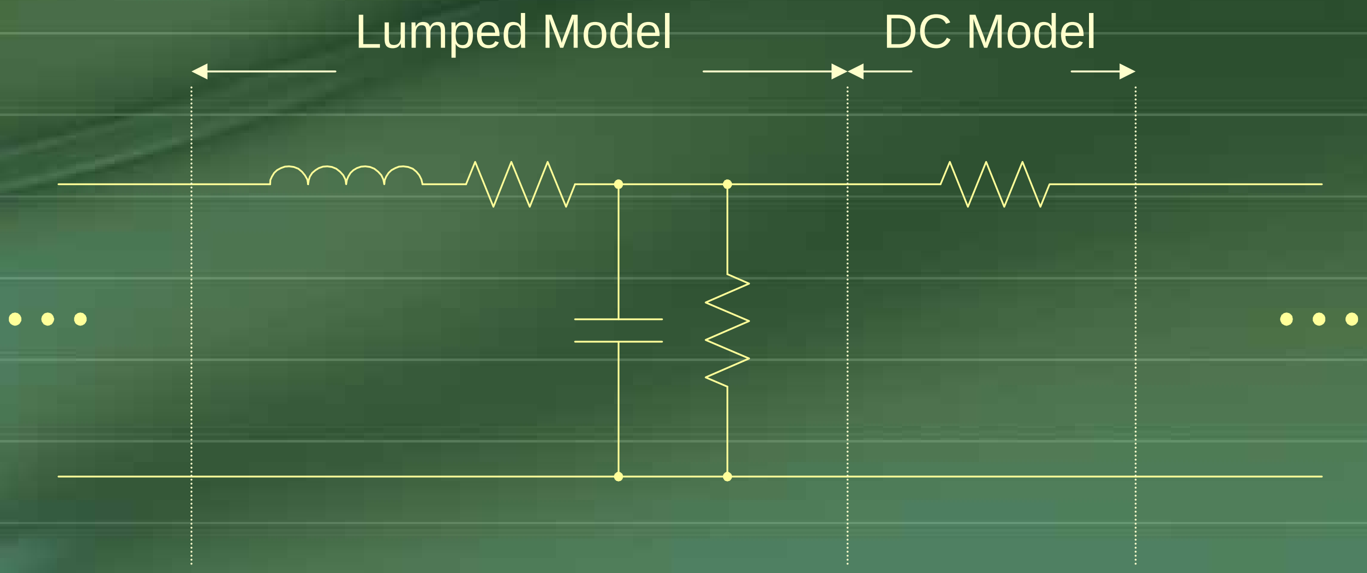
V_P：Propagation velocity

C ：3×10^8 m/s, ε_r：dielectric constant= $\varepsilon / \varepsilon_o$

Transmission Line Model

Lumped Model

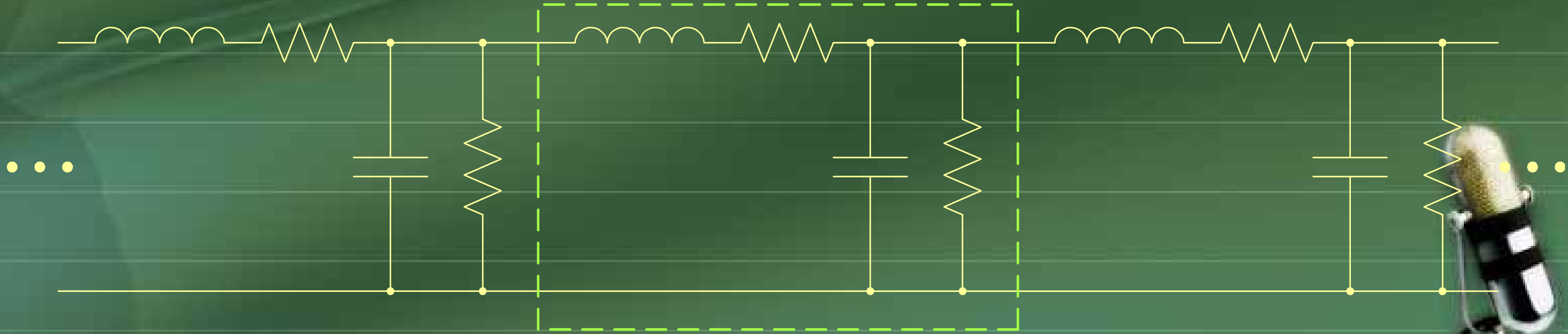
- Delay for entire line << Signal transition time
- Every point on the transmission line can be seen *with the same voltage potential*.



Transmission Line Model

Distributed Model

- Delay per section << Signal transition time
- Every point on the transmission line should be seen as a point *with different voltage potential*.
- *Ringing, overshoot, reflection, and crosstalk will be more serious in the condition.*



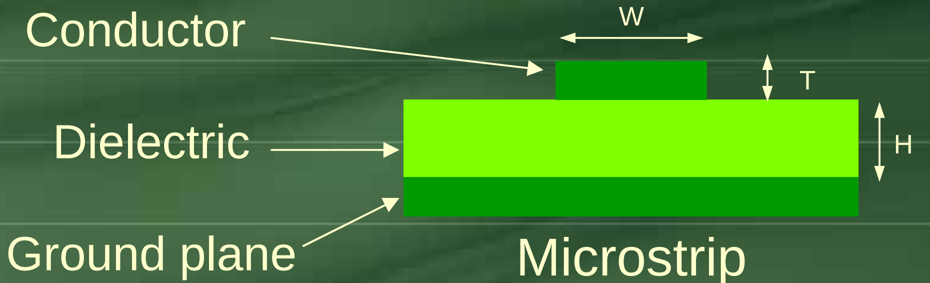
Transmission Line Model

- *Keeping design within the DC-modeled or lump-modeled region as far as possible* is the key point.
  - Traces (wires) of critical signals, such as clock sources, should be as short as possible
  - Rising time and falling time of the fastest frequency signal in a circuitry should be as slow as possible.
  - The lead running high frequency should have small propagation delay (ε_r is small).
  - Circuitry and components should be scale down.

Transmission Line Model

Cross sections of popular transmission line geometries

- *Transmission line – two conductors* ([4], p.140,187)
- $Z_0=f(\varepsilon_r,W,H,T,\text{topology})$

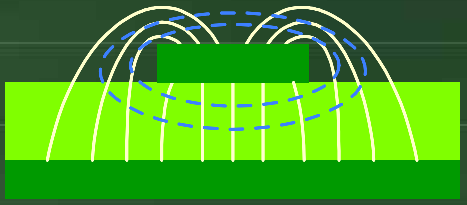

Conductor

Dielectric

Ground plane

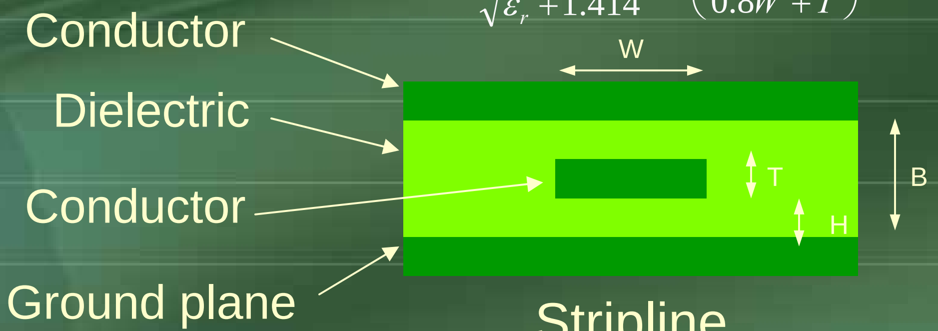
Microstrip

$$Z_0=\frac{87}{\sqrt{\varepsilon_r+1.414}}\cdot\ln\left(\frac{5.98H}{0.8W+T}\right)$$



Dielectric constant=2.8~4.5

→ fast


Conductor

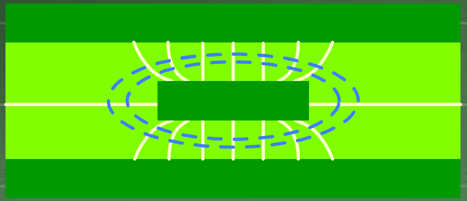
Dielectric

Conductor

Ground plane

Stripline

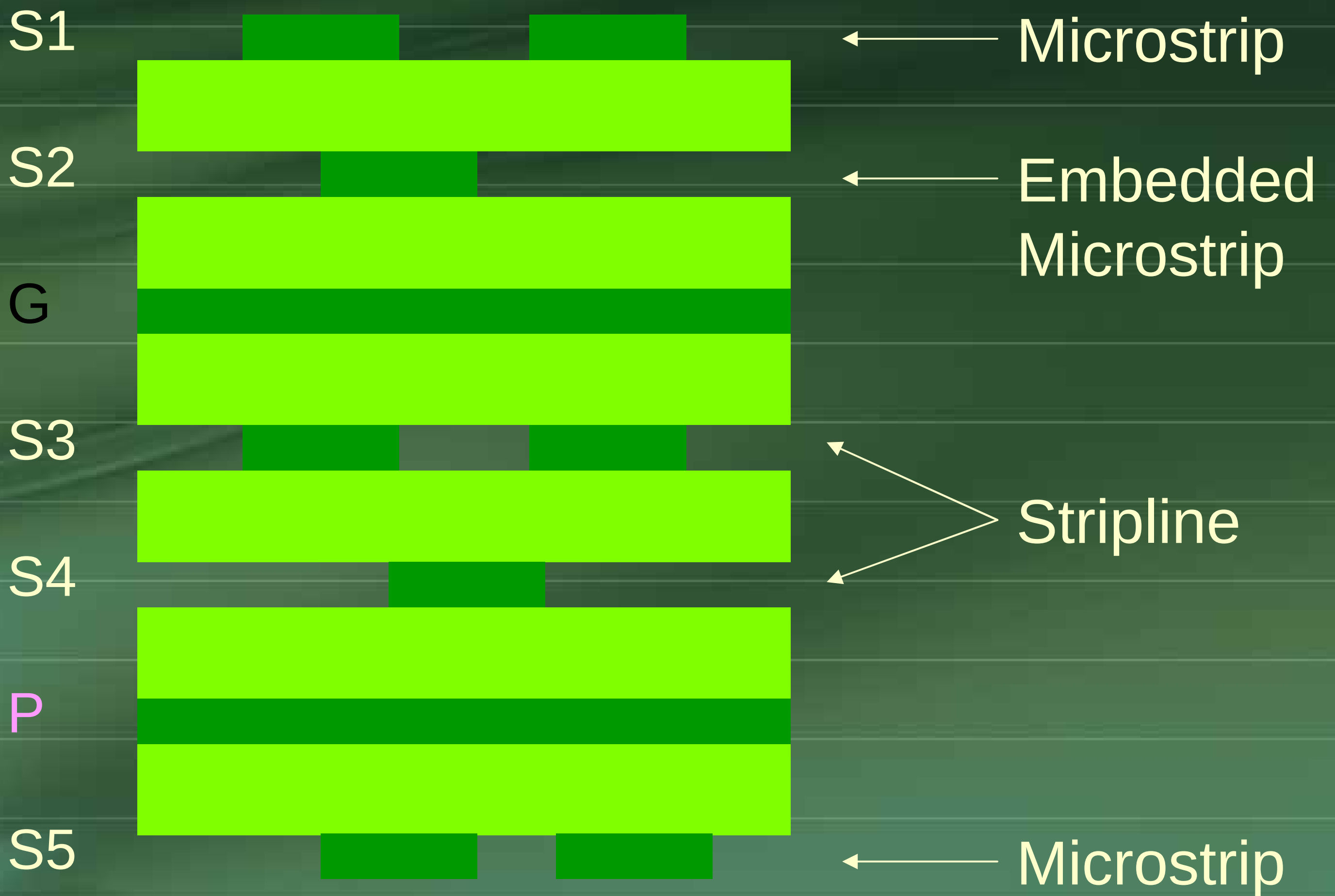
$$Z_0=\frac{60}{\sqrt{\varepsilon_r}}\cdot\ln\left[\frac{4H}{0.67\pi W(0.8+\frac{T}{W})}\right]$$



Dielectric constant=4.5

→ slow, but good for noise

Transmission Line Model



Transmission Line Model

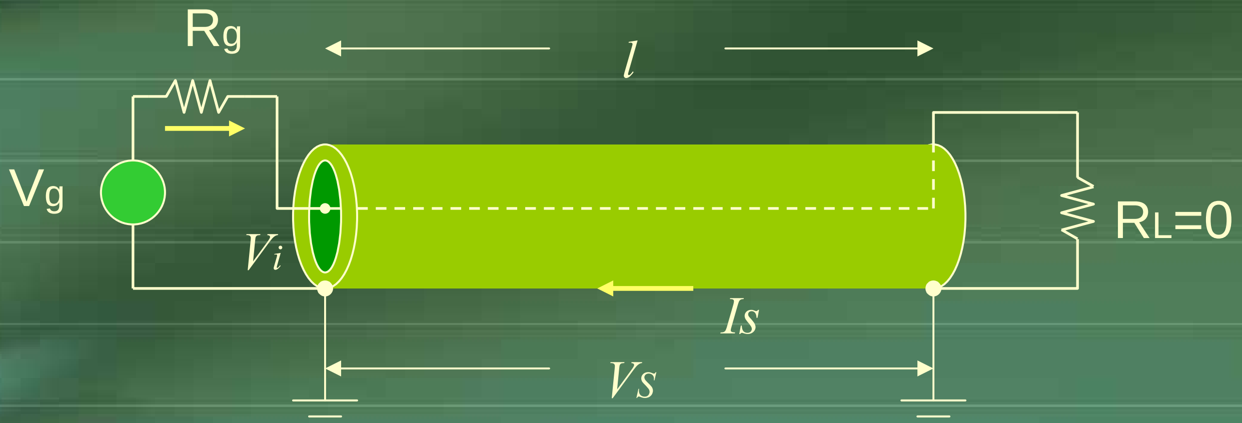
Dielectric material	Propagation delay(ps/in.)	Dielectric constant ε_r
Air	85	1.0
Coaxial cable(75%)	113	1.8
Coaxial cable(66%)	129	2.3
FR-4 PCB, outer conductor	140 ~ 180	2.8 ~ 4.5
FR-4 PCB, inner conductor	180	4.5
Al PCB, inner conductor	240 ~270	8 ~ 10

Transfer Impedance

- The transfer impedance of a cable shield：

$$Z_t = \frac{V_S}{I_S} = \frac{1}{I_S}\left(\frac{dV_i}{dl}\right) \qquad (\Omega / m)$$

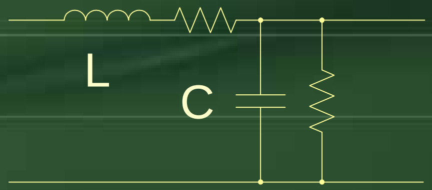
- The shielding effectiveness of a cable can be expressed in terms of the shield transfer impedance.*Lower* Z_t *results from a better shielding.*



Characteristic Impedance

- The characteristic impedance of an *ideal* transmission line： $Z_0 = \sqrt{\frac{L}{C}}$

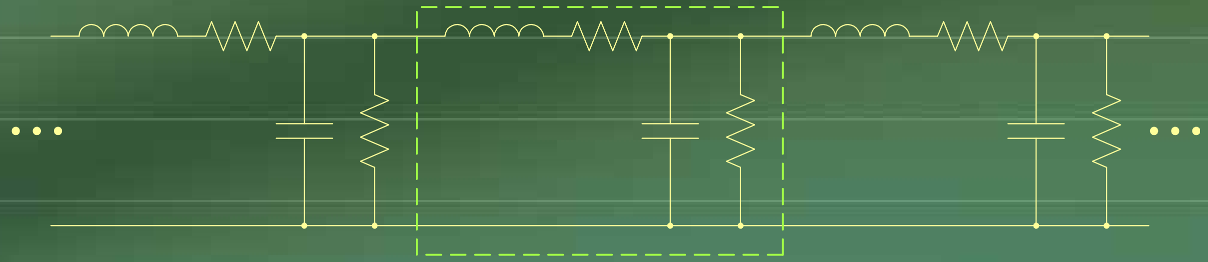
  It is a constant.



- The characteristic impedance of an *practical* transmission line：

  it is a function with frequency.

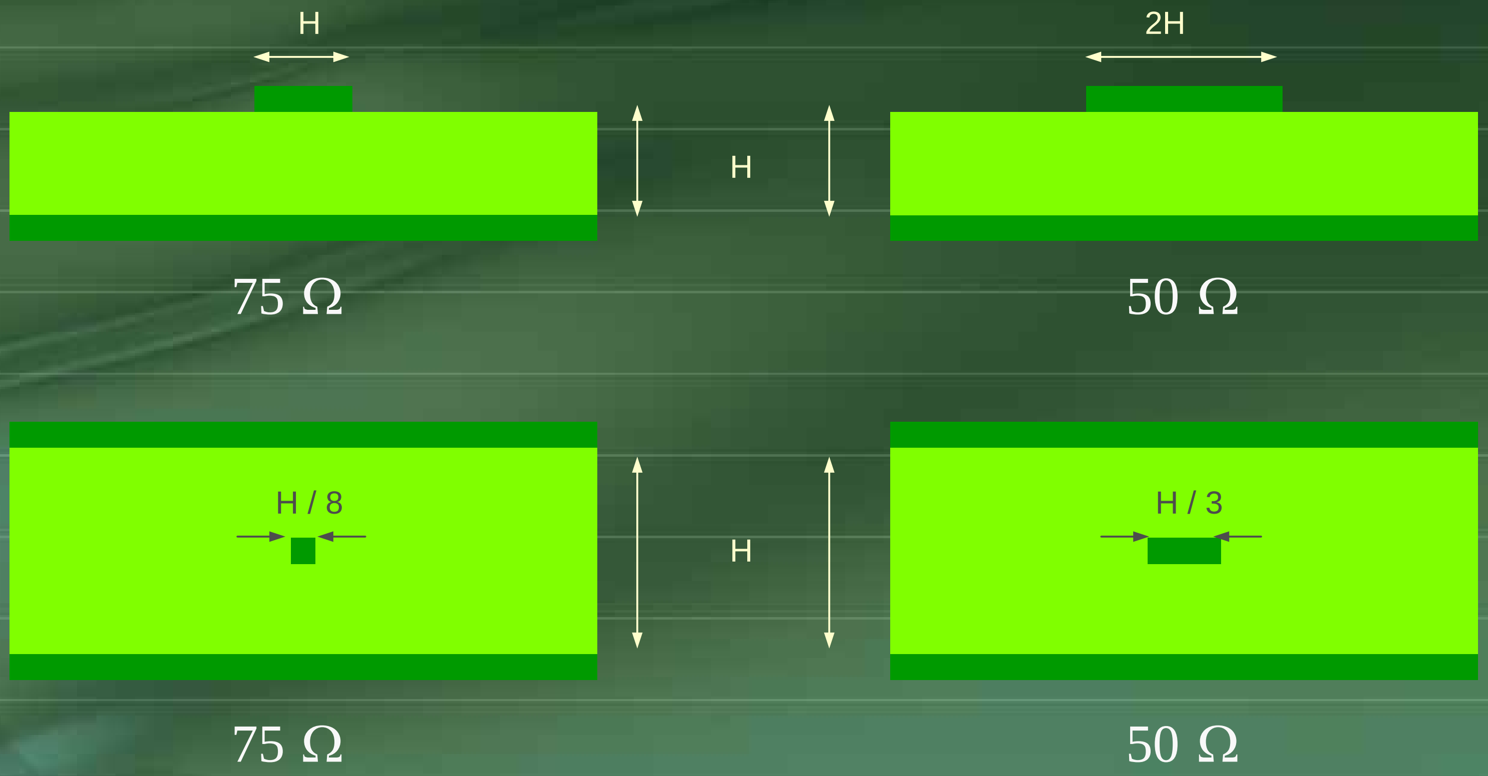
  - *Z_0 can be defined as the ratio of voltage to current while a high-frequency current is flowing on the transmission line.*



Characteristic Impedance

Example

- All substrate FR-4；ε_r=4.5，Z_0 accuracy ±30%



Reflection

- Reflection coefficient：

$$\Gamma_R = \frac{Z_r - Z_0}{Z_r + Z_0}$$

Z_r ：characteristic impedance of termination

Z_0 ：characteristic impedance of transmission line

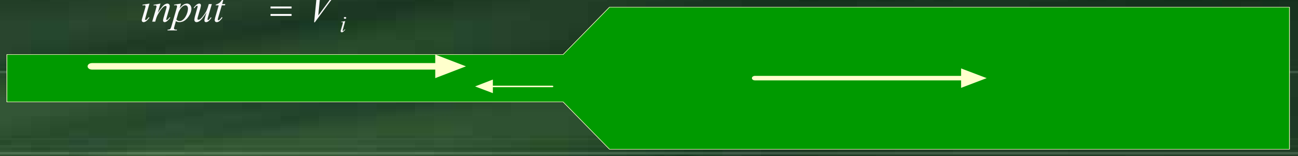
- Reflected signal = input signal x Γ_R

Reflection

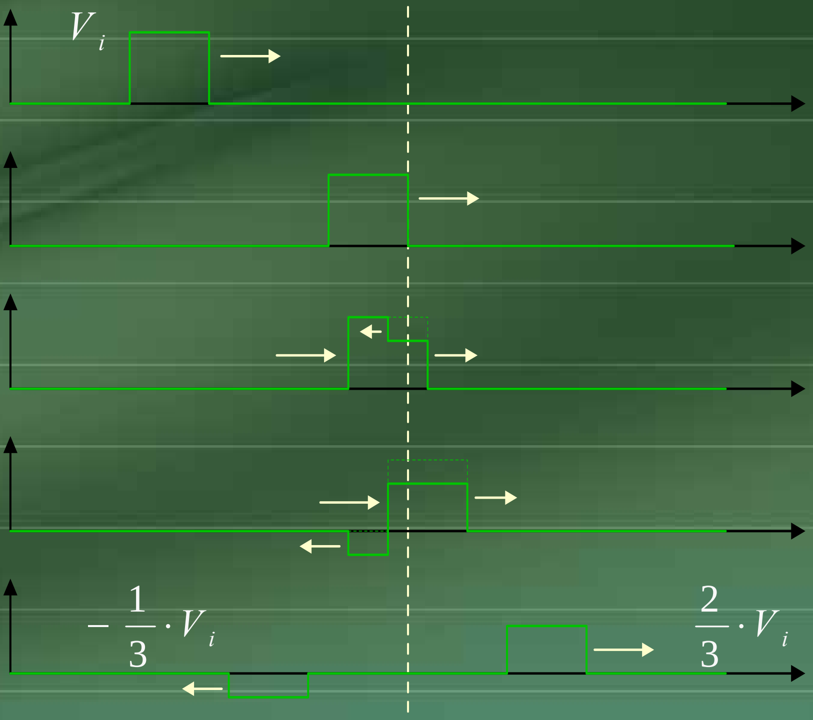
Example

$$Z_0 > \left(Z_0' = \frac{1}{2}\cdot Z_0\right) \qquad 0 > \left(\Gamma_R = -\frac{1}{3}\right) > -1$$

$$input = V_i$$



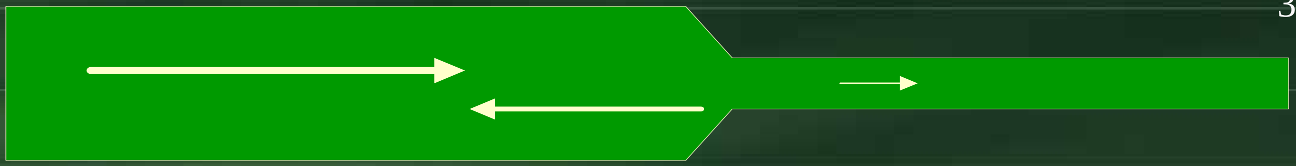
$$reflection = -\frac{1}{3}\cdot V_i \qquad transmission = \frac{2}{3}\cdot V_i$$



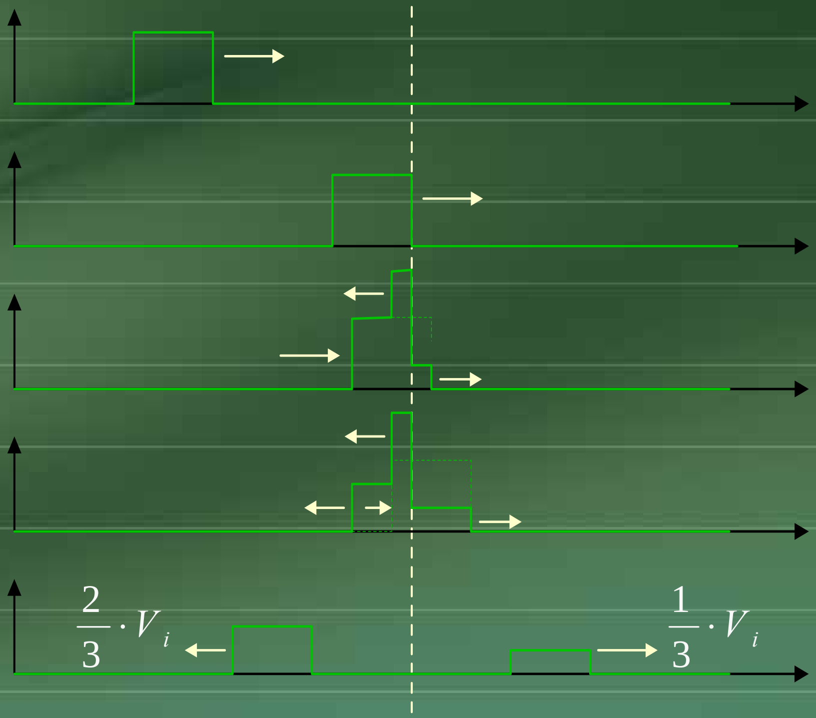
Reflection

Example

$input = V_i \qquad Z_0 < (Z_0' = 2 \cdot Z_0) \qquad 1 > (\Gamma_R = \frac{1}{3}) > 0$

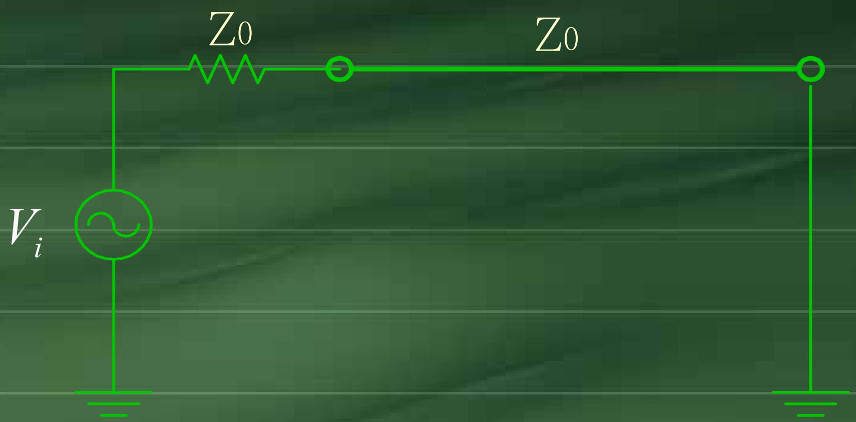


$reflection = \frac{2}{3} \cdot V_i \qquad transmission = \frac{1}{3} \cdot V_i$



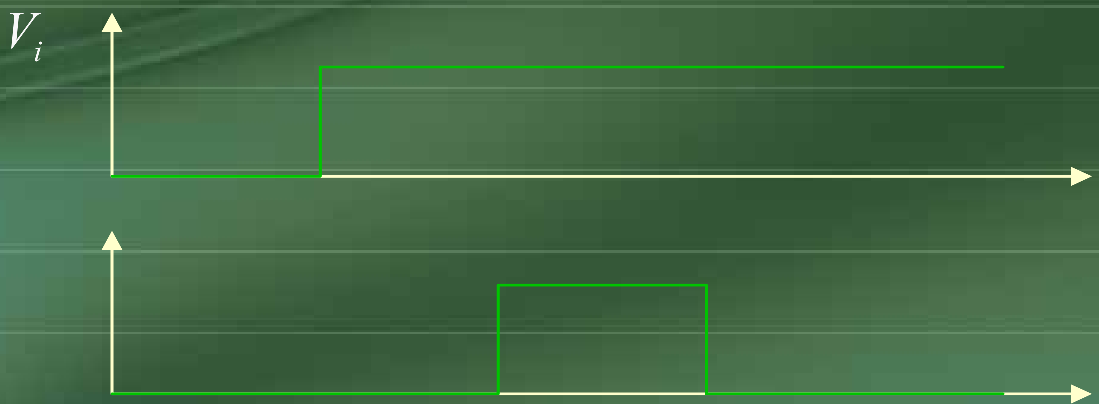
Reflection

Example



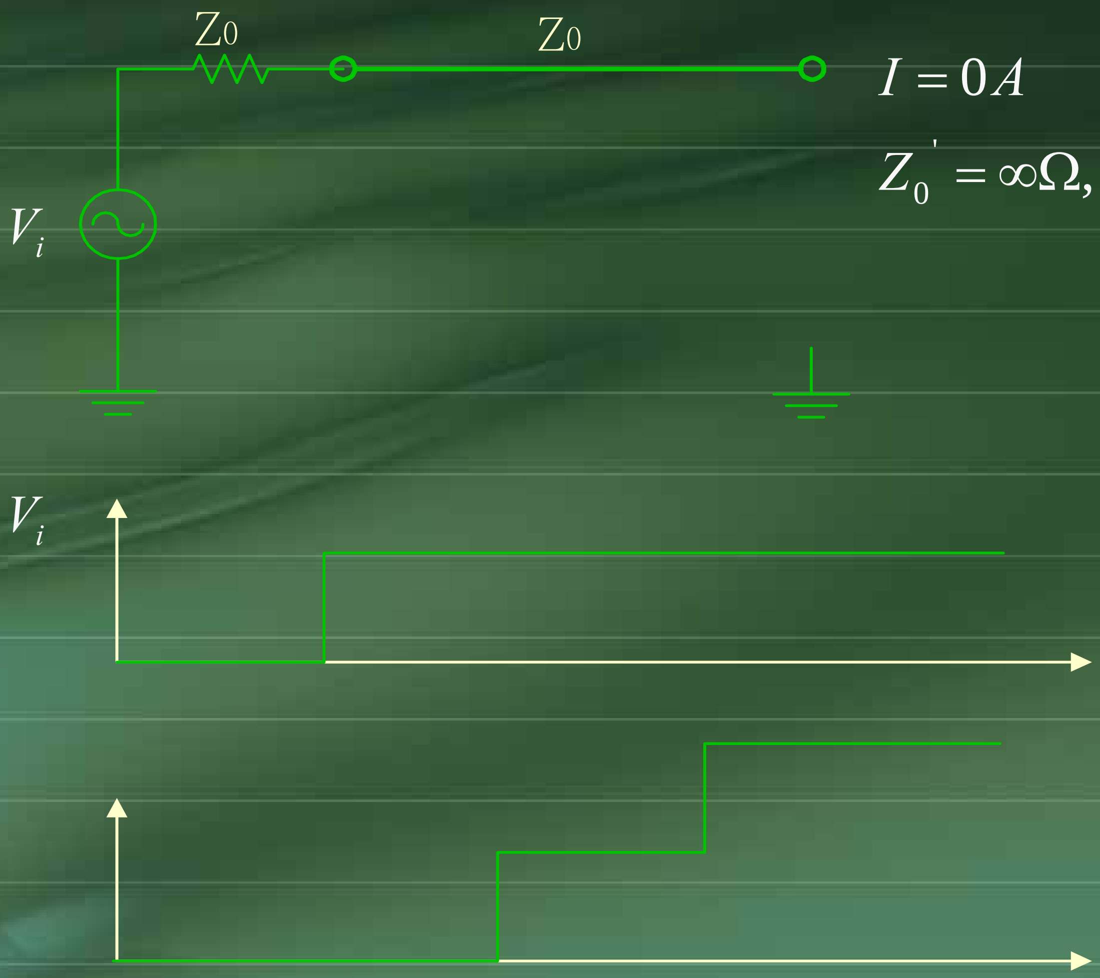
$$V = 0V$$

$$Z_0' = 0\Omega, \qquad \Gamma_R = -1$$



Reflection

Example

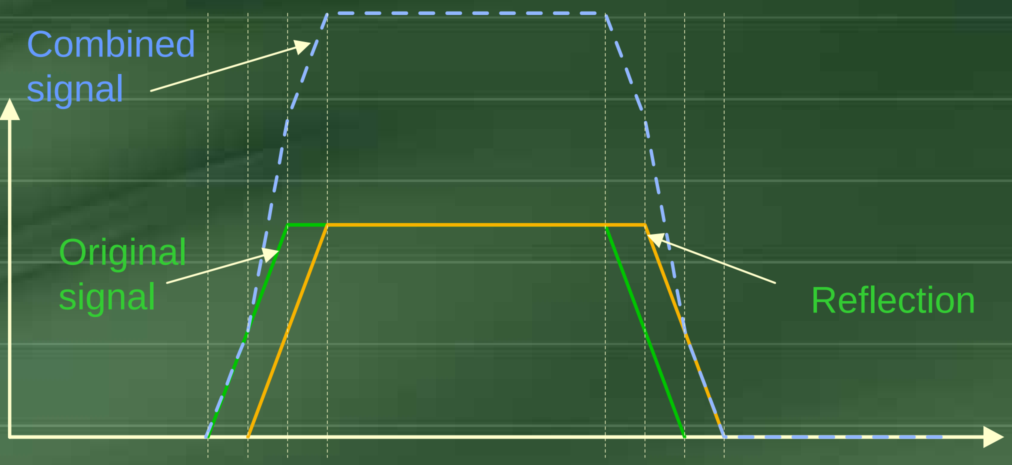


$I = 0A$

$Z_0' = \infty\Omega,\quad \Gamma_R = 1$

Reflection

- Low-speed circuit：$2 \cdot T_{pd} < t_r, t_f$
  - Reflections are masked by rising/falling edges -- insignificant



- High-speed circuit：$2 \cdot T_{pd} > t_r, t_f$
  - Reflections cause ringing – overshoot / undershoot