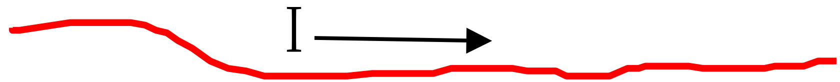
網路分析儀

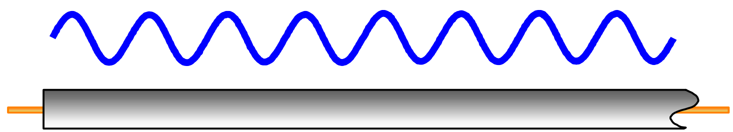
CONTENTS

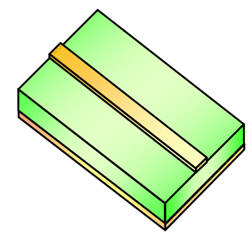
Transmission Line Theory



Low frequencies

- Wavelength >> wire length
- Current (I) travels down wires easily for efficient power transmission
- Voltage and current not dependent on position

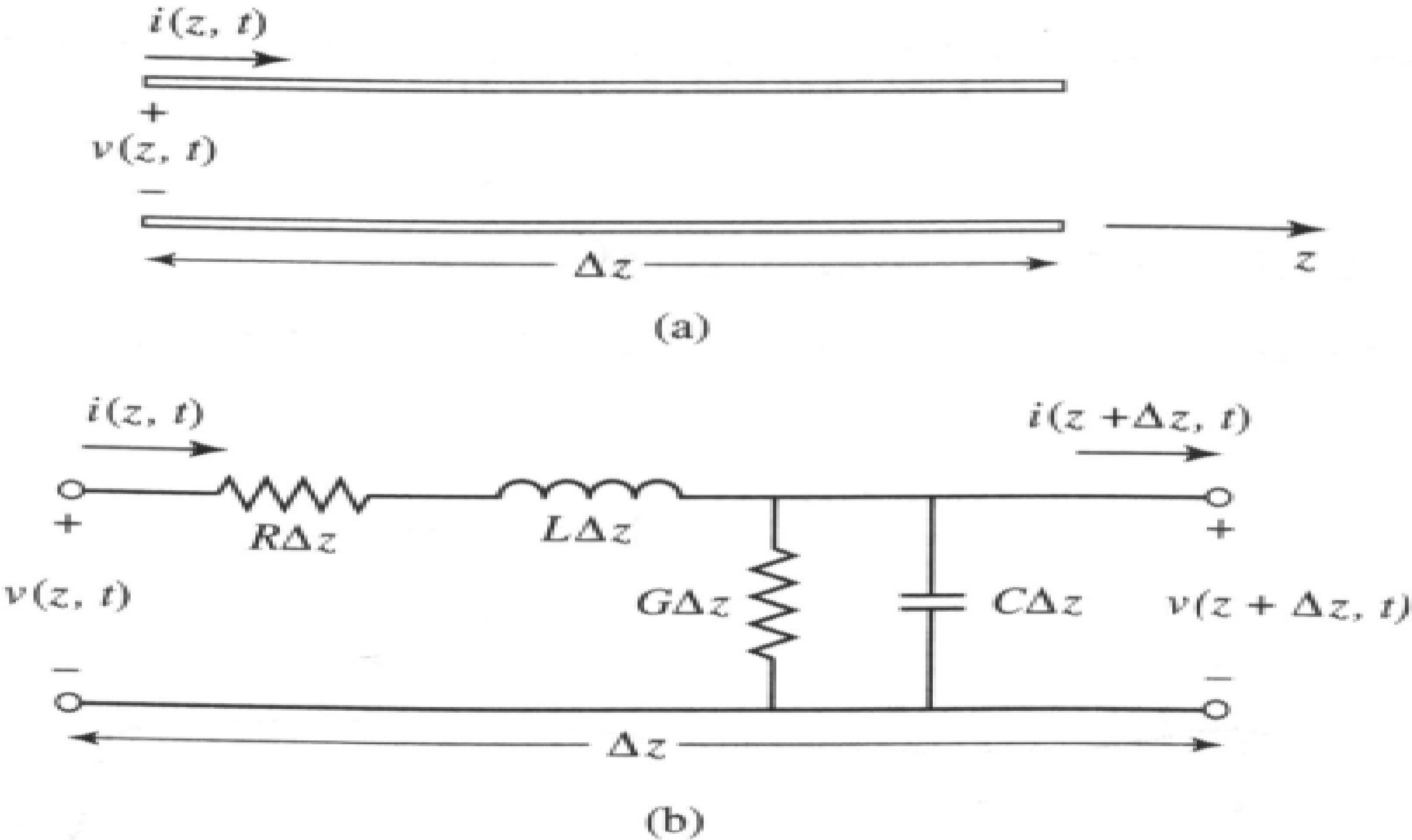




High frequencies

- Wavelength ≈ or << wire (transmission line) length
- Need transmission-line structures for efficient power transmission
- Matching to characteristic impedance (Z0) is very important for low reflection
- Voltage dependent on position along line

Transmission Line Theory



Transmission Line Theory

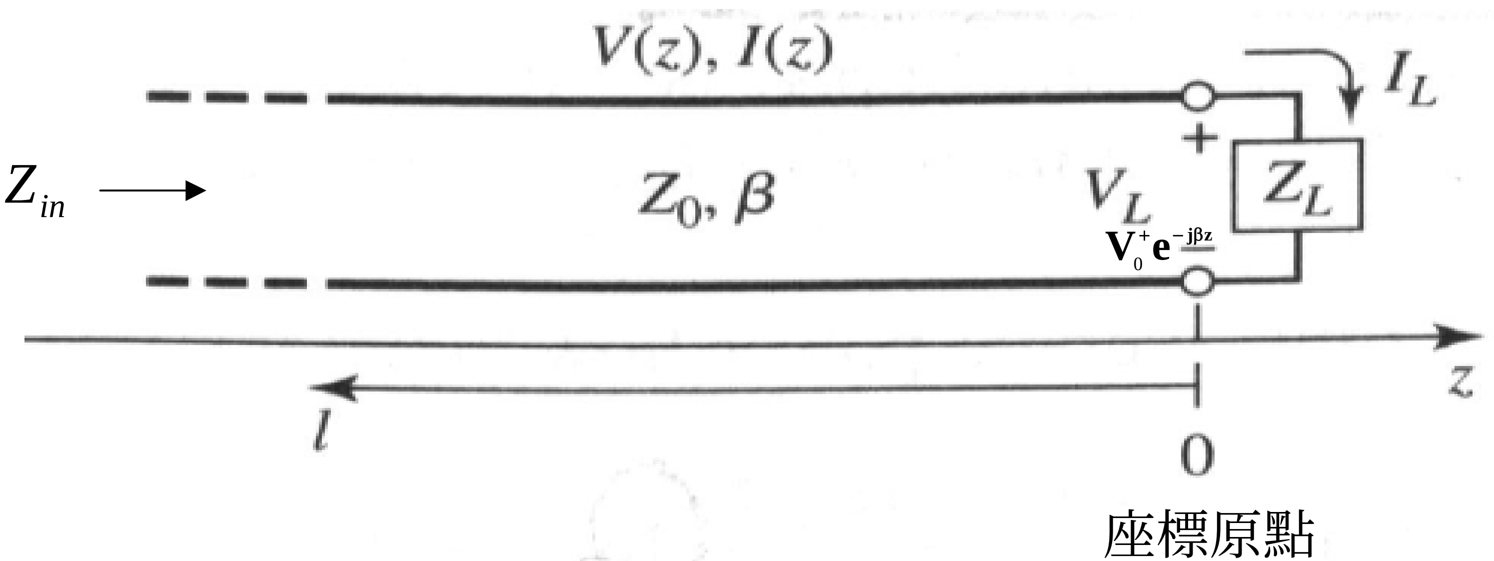
- R: series resistance per unit length
- L: series inductance per unit length
- G: shunt conductance per unit length
- C: shunt capacitance per unit length

R & G 代表loss項

G → dielectric loss

R → finite conductivity

Transmission Line Theory



$$\mathbf{Z}_0 = \frac{\mathbf{V}_0^+}{\mathbf{I}_0^+}$$

$$Z_0 = \sqrt{\frac{R + jwL}{G + jwC}} \qquad \gamma = \sqrt{(R + jwL)(G + jwC)}$$

R=G=0(無損耗傳輸線)

$$Z_0 = \sqrt{\frac{L}{C}} \qquad \gamma = jw\sqrt{LC} = j\beta$$

Transmission Line Theory

當 $Z_L \neq Z_0$時，不可能只有 ***traveling wave***

$$\Rightarrow \quad \begin{aligned} \mathbf{V(z)} &= \mathbf{V_0^+ e^{-j\beta z} + V_0^- e^{j\beta z}} \\ \mathbf{I(z)} &= \mathbf{\frac{V_0^+}{Z_0} e^{-j\beta z} - \frac{V_0^-}{Z_0} e^{j\beta z}} \end{aligned}$$

當 $z = 0$ 時 (此z代表距離)

$$\mathbf{Z_L = \frac{V(0)}{I(0)} = \frac{V_0^+ + V_0^-}{V_0^+ - V_0^-} Z_0}$$

$$\mathbf{V_0^- = \frac{Z_L - Z_0}{Z_L + Z_0} V_0^+} \quad ; \quad \Gamma = \frac{V_0^-}{V_0^+} = \frac{Z_L - Z_0}{Z_L + Z_0}$$

Return loss (RL) in dB ; $\mathbf{RL} = -20\,\mathbf{log}|\Gamma|$

Transmission Line Theory

Special cases :

1. short circuit

$Z_{\mathrm{L}} = 0$; $\Gamma = \dfrac{Z_L - Z_0}{Z_L + Z_0} = -1$

2. open circuit

$Z_L = \infty$; $\Gamma = \dfrac{Z_L - Z_0}{Z_L + Z_0} = 1$

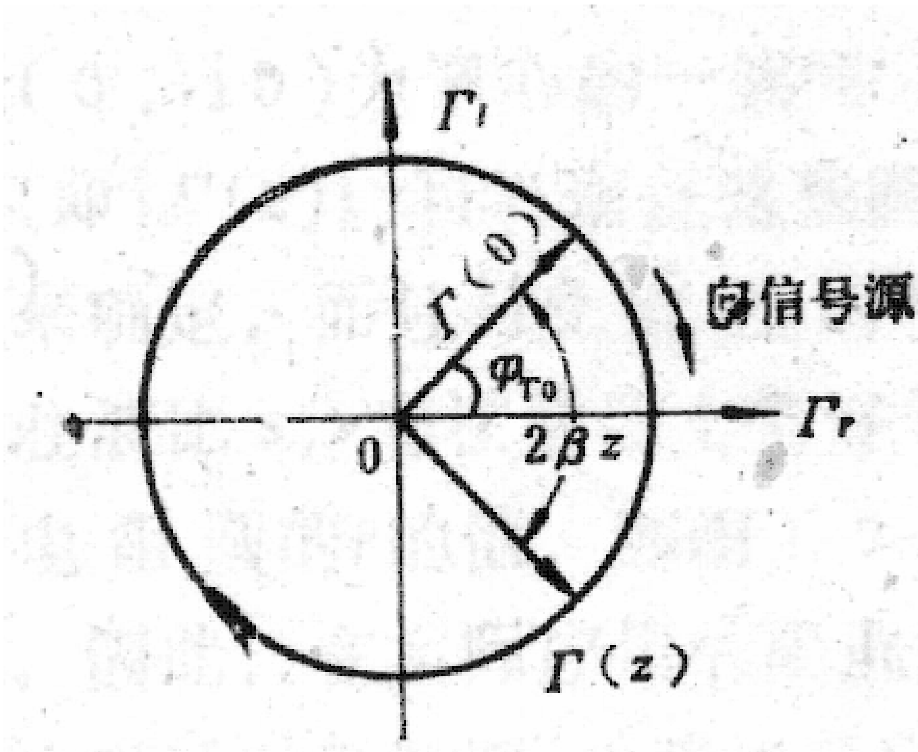
3. Load

$\mathrm{Z_L} = \mathrm{Z_0}(\text{in general}) = 50\Omega$; $\Gamma = 0$

The Smith Chart

It is essentially a polar plot of the voltage reflection coefficient , Γ .

反射係數圖



$$\Gamma(z) = \Gamma(0)e^{2j\beta z}$$

(往負載方向z增加)

(往source方向z減少)

The Smith Chart

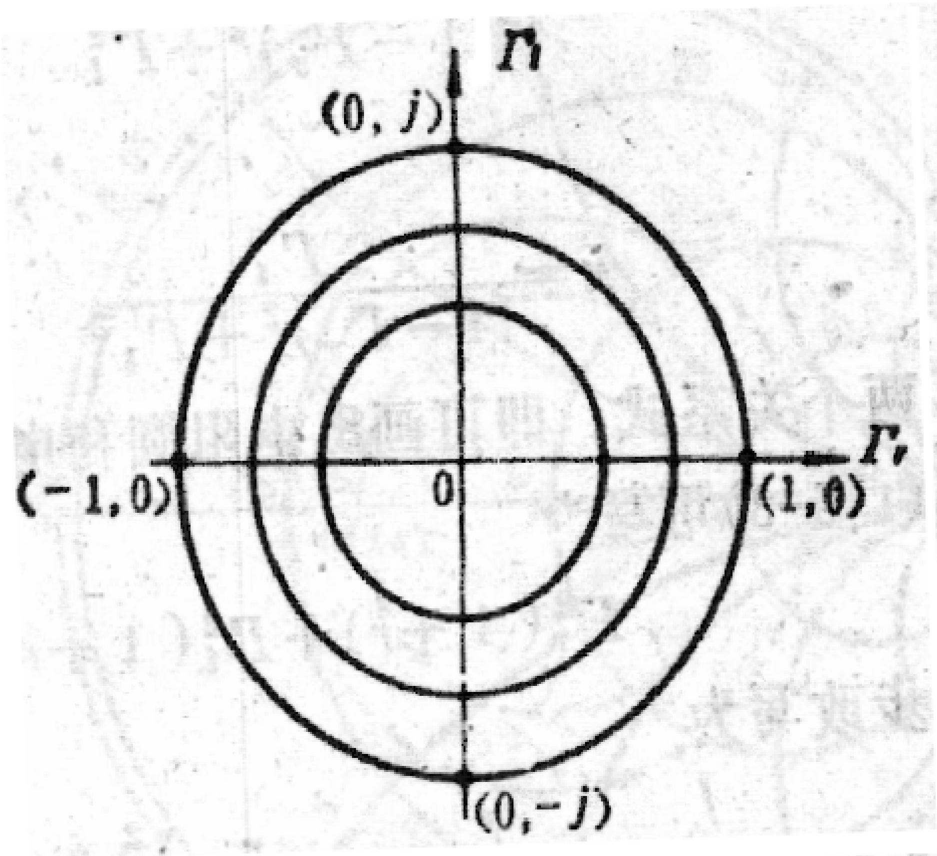
- 觀察點朝信號源方向移動時, $\Gamma(z)$ 沿順時針方向旋轉。
- 觀察點朝負載方向移動時, $\Gamma(z)$ 沿逆時針方向旋轉。
- $\Gamma(z)$ 旋轉 360^0, 相當於z變化了半個波長。

$$\Gamma(0) = \frac{Z_L - Z_0}{Z_L + Z_0}$$

$\Rightarrow$ 不同之負載阻抗

$\Rightarrow$ $\Gamma(0)$ 有不同之半徑

The Smith Chart



$$0 \le |\Gamma(z)| \le 1$$

- 在無損的傳輸線上移動，相當於在同半徑的圓上移動。

The Smith Chart

電阻圖與電抗圖(resistance circle & reactance circle)

根據 $\mathbf{Z_{in}(z)}$ 與 $\Gamma(\mathbf{z})$ 的關係式可以繪出電阻圖與電抗圖。

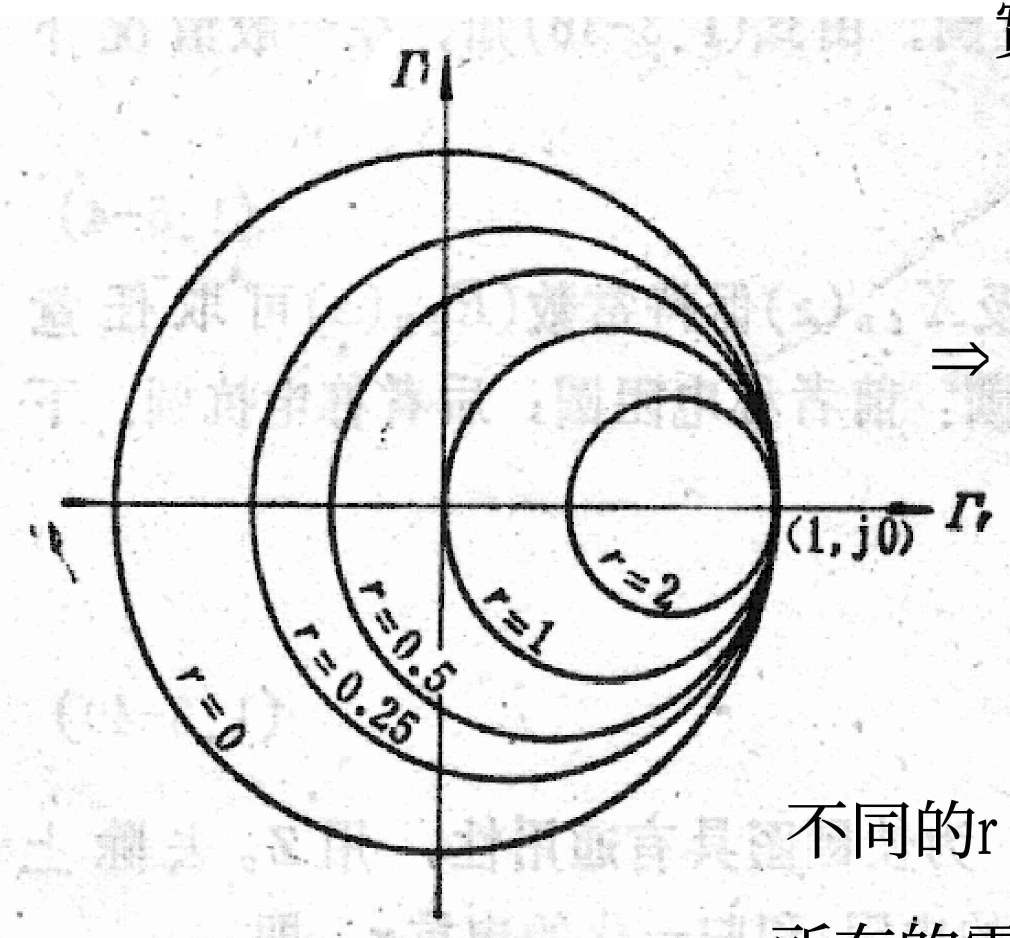
Normalized impedance

$$\mathbf{z} = \frac{\mathbf{Z}}{\mathbf{Z}_0} = \frac{\mathbf{R}}{\mathbf{Z}_0} + \mathbf{j}\frac{\mathbf{X}}{\mathbf{Z}_0} = \mathbf{r} + \mathbf{jx} \quad ; \quad \Gamma = \frac{\mathbf{Z} - \mathbf{Z}_0}{\mathbf{Z} + \mathbf{Z}_0} = \frac{\mathbf{z} - 1}{\mathbf{z} + 1}$$

$$\mathbf{z} = \frac{1 + \Gamma}{1 - \Gamma} \quad ; \quad \Gamma = \Gamma_{\mathbf{r}} + \mathbf{j}\Gamma_{\mathbf{i}}$$

$$\Rightarrow \quad \mathbf{r} + \mathbf{jx} = \frac{1 + \Gamma_{\mathbf{r}} + \mathbf{j}\Gamma_{\mathbf{i}}}{1 - \Gamma_{\mathbf{r}} - \mathbf{j}\Gamma_{\mathbf{i}}}$$

The Smith Chart



實數部分:

$$\mathbf{r}=\frac{1-\Gamma_r^2-\Gamma_i^2}{(1-\Gamma_r)^2+\Gamma_i^2}$$

$$\Rightarrow (\Gamma_r-\frac{\mathbf{r}}{1+\mathbf{r}})^2+\Gamma_i^2=(\frac{1}{1+\mathbf{r}})^2$$

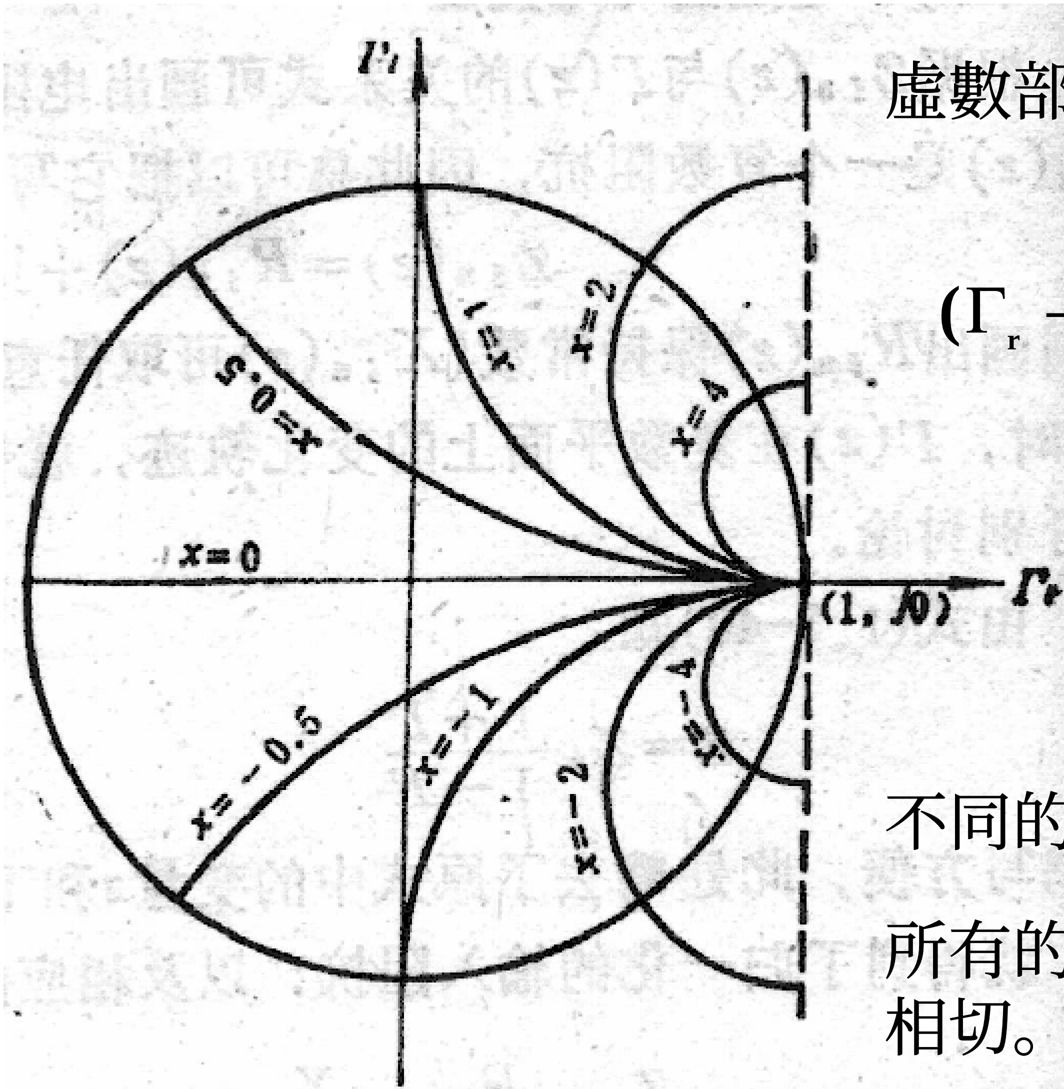
圓心座標: $(\frac{\mathbf{r}}{1+\mathbf{r}},0)$

半徑: $\frac{1}{1+\mathbf{r}}$

不同的r 有不同的圓:電阻圖

所有的電阻圖都在(1,0)點相切

The Smith Chart



虛數部分: $\mathbf{x} = \dfrac{2\Gamma_i}{(1-\Gamma_r)^2 + \Gamma_i^2}$

$$(\Gamma_r - 1)^2 + (\Gamma_i - \frac{1}{\mathbf{x}})^2 = (\frac{1}{\mathbf{x}})^2$$

圓心: $(1\,,\ \dfrac{1}{\mathbf{x}})$

半徑: $\dfrac{1}{|x|}$

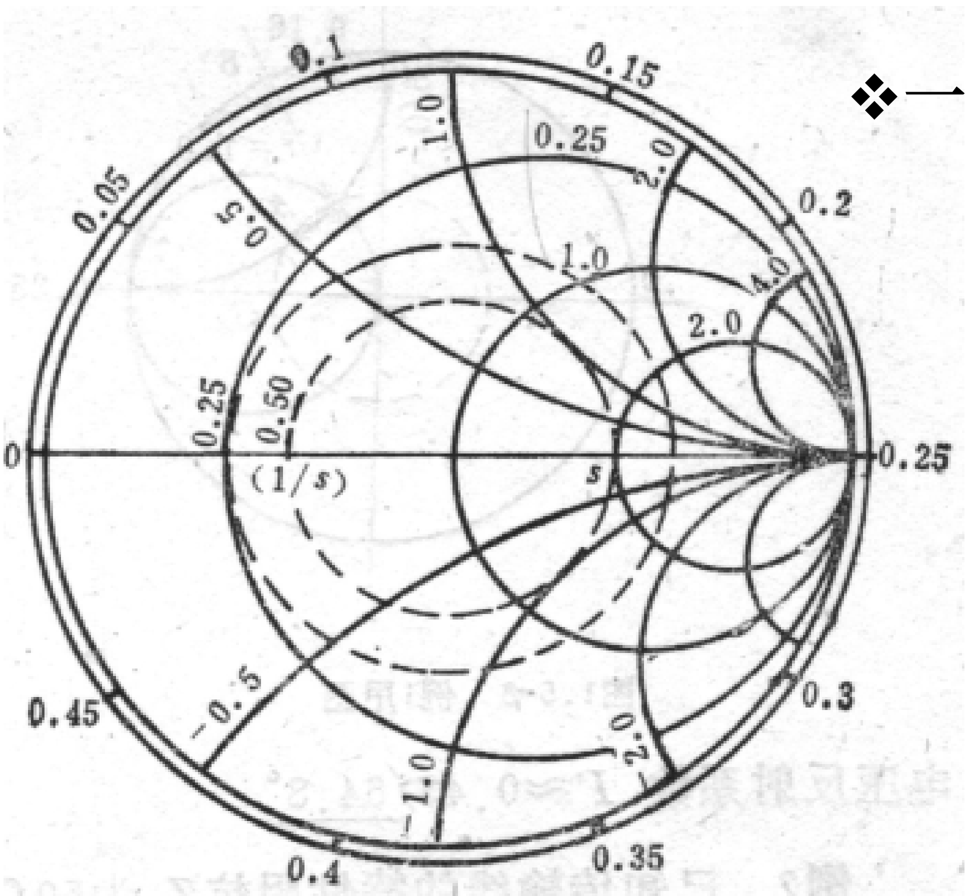
不同的x有不同的圓:電抗圖

所有的圓都在(1,0)處與實軸相切。

The Smith Chart

阻抗圓圖(impedance smith chart)

結合反射係數圖，電阻圖及電抗圖:阻抗圓圖



❖一般只繪出電阻圖及電抗圖

Γ_i 與 x 同號

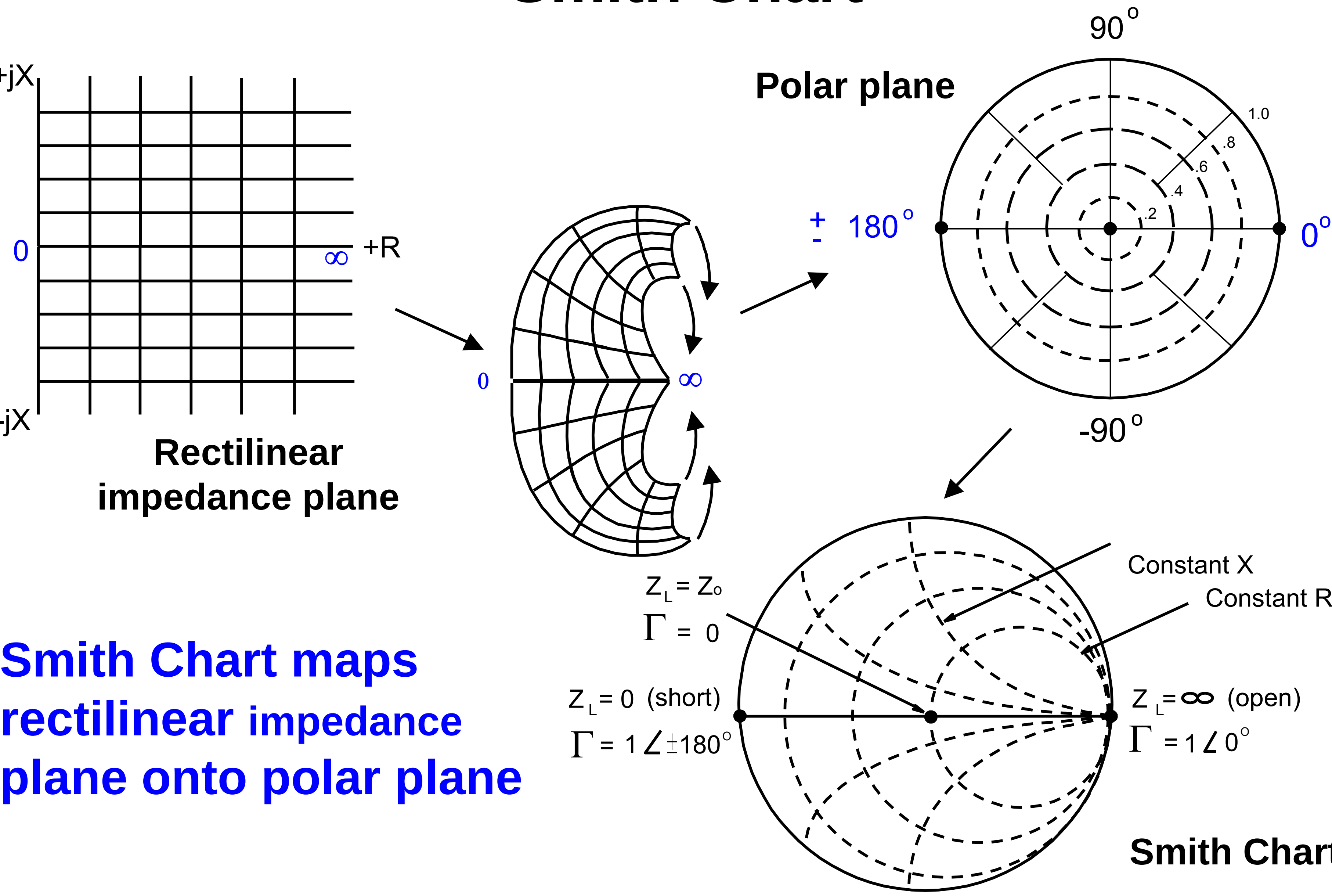
⇒ 上半圓: 電感性 ωL

⇒ 下半圓: 電容性 $1/\omega c$

The Smith Chart

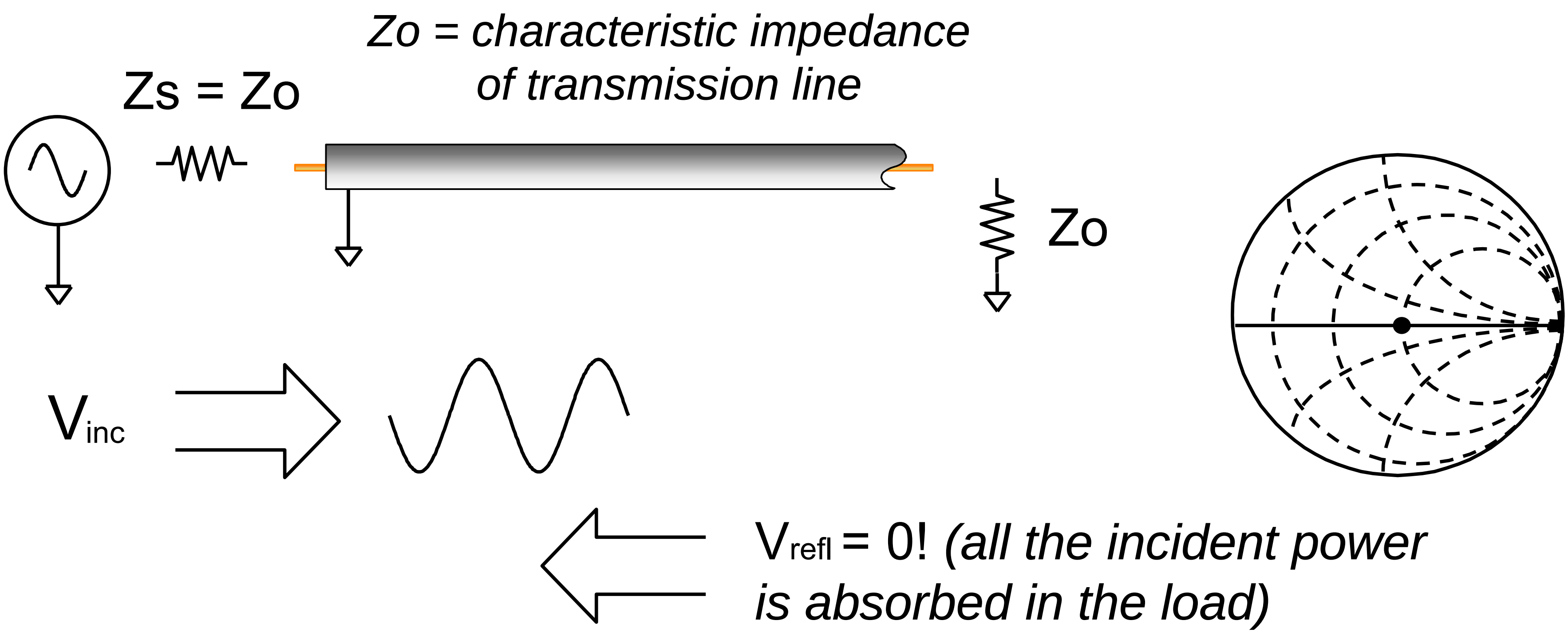
- 反射係數圖是以(0,0)為圓心的同心圓，半徑大小由圓與實軸的交點來決定 $\Rightarrow \ |\Gamma| = \frac{\mathbf{r}-1}{\mathbf{r}+1}$
- 駐波比(SWR)與交點處的r值相同。
- 實軸的右端點(1,0)為開路點。
- 實軸的左端點(-1,0)為短路點。
- 座標原點為匹配點。
- 實軸上所有的點(兩端點除外): 純電阻
- $\Gamma(z)=1$ 的圓為純電抗。

Smith Chart



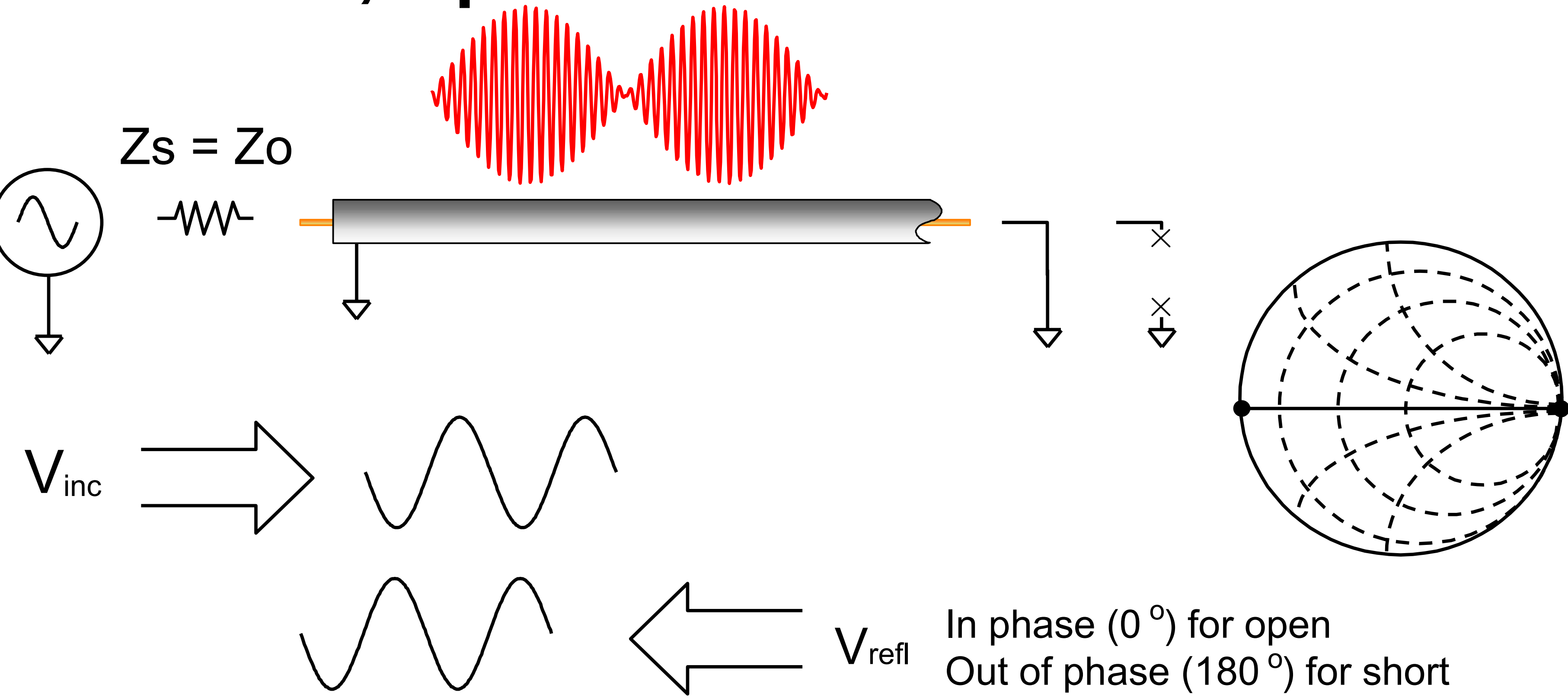
Smith Chart maps rectilinear impedance plane onto polar plane

Transmission Line Terminated with Zo



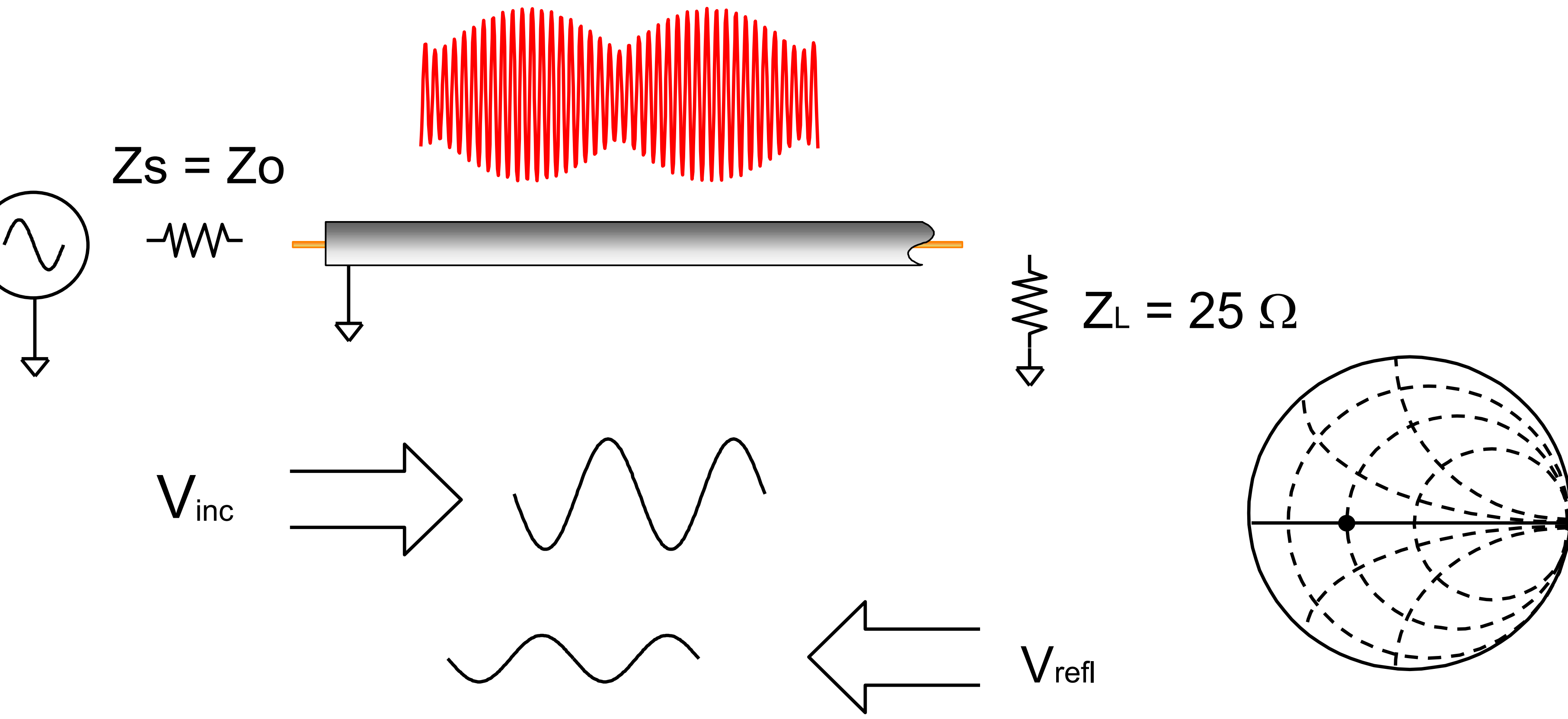
For reflection, a transmission line terminated in Zo behaves like an infinitely long transmission line

Transmission Line Terminated with Short, Open



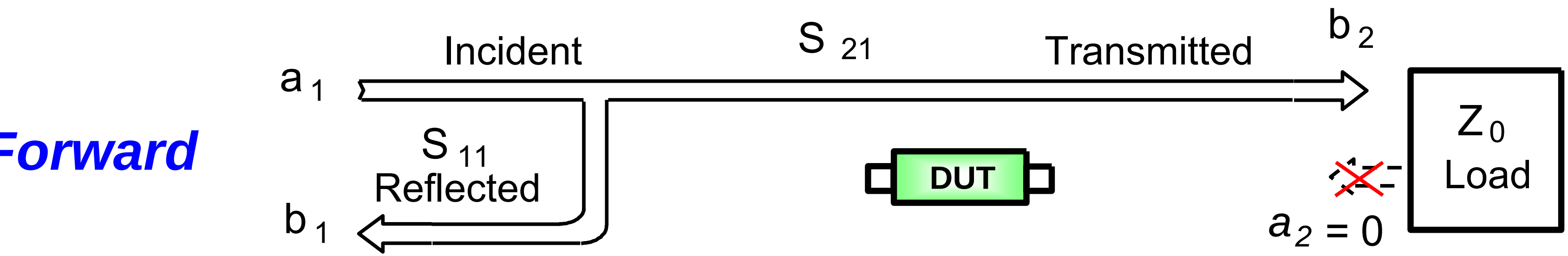
For reflection, a transmission line terminated in a short or open reflects all power back to source

Transmission Line Terminated with 25 Ω



Standing wave pattern does not go to zero as with short or open

Measuring S-Parameters

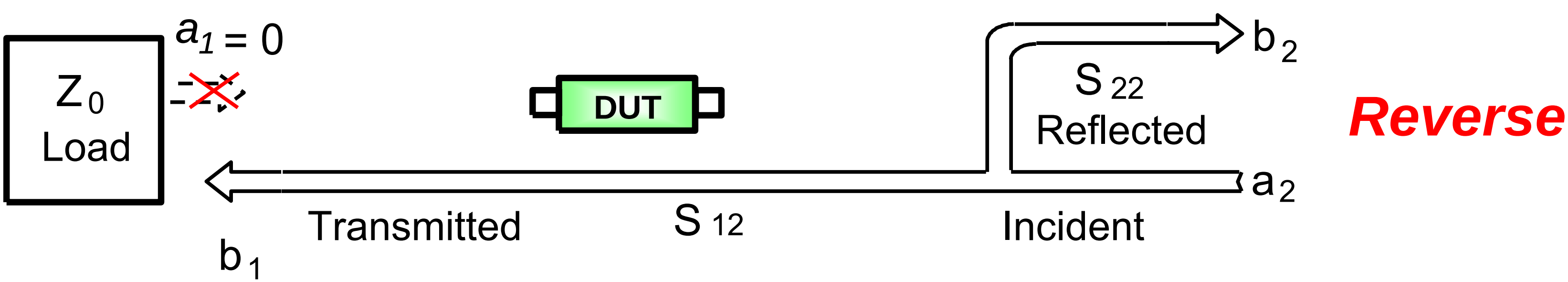


$$S_{11} = \frac{\text{Reflected}}{\text{Incident}} = \left.\frac{b_1}{a_1}\right|_{a_2 = 0}$$

$$S_{21} = \frac{\text{Transmitted}}{\text{Incident}} = \left.\frac{b_2}{a_1}\right|_{a_2 = 0}$$

$$S_{22} = \frac{\text{Reflected}}{\text{Incident}} = \left.\frac{b_2}{a_2}\right|_{a_1 = 0}$$

$$S_{12} = \frac{\text{Transmitted}}{\text{Incident}} = \left.\frac{b_1}{a_2}\right|_{a_1 = 0}$$

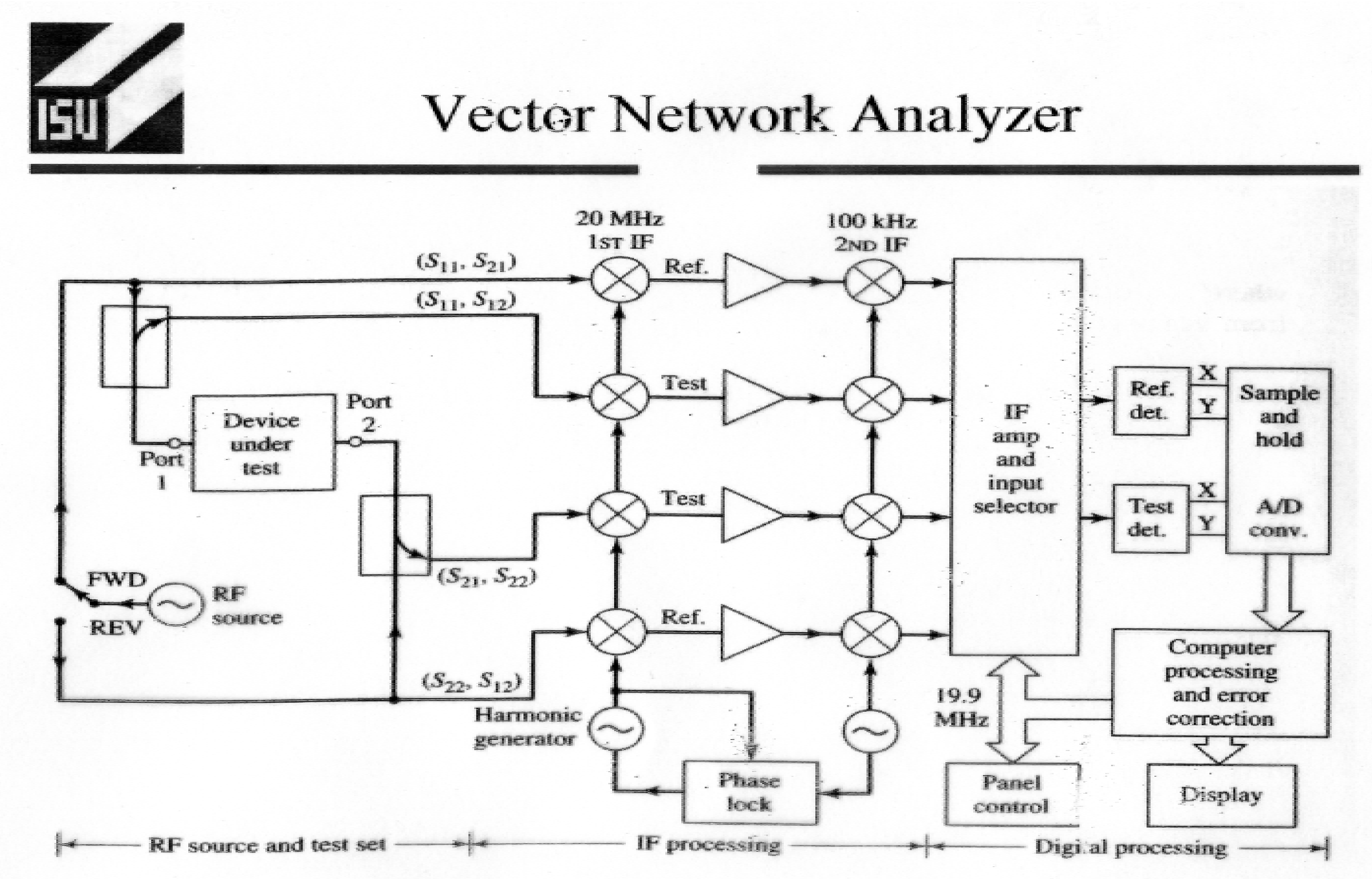


S-Parameters

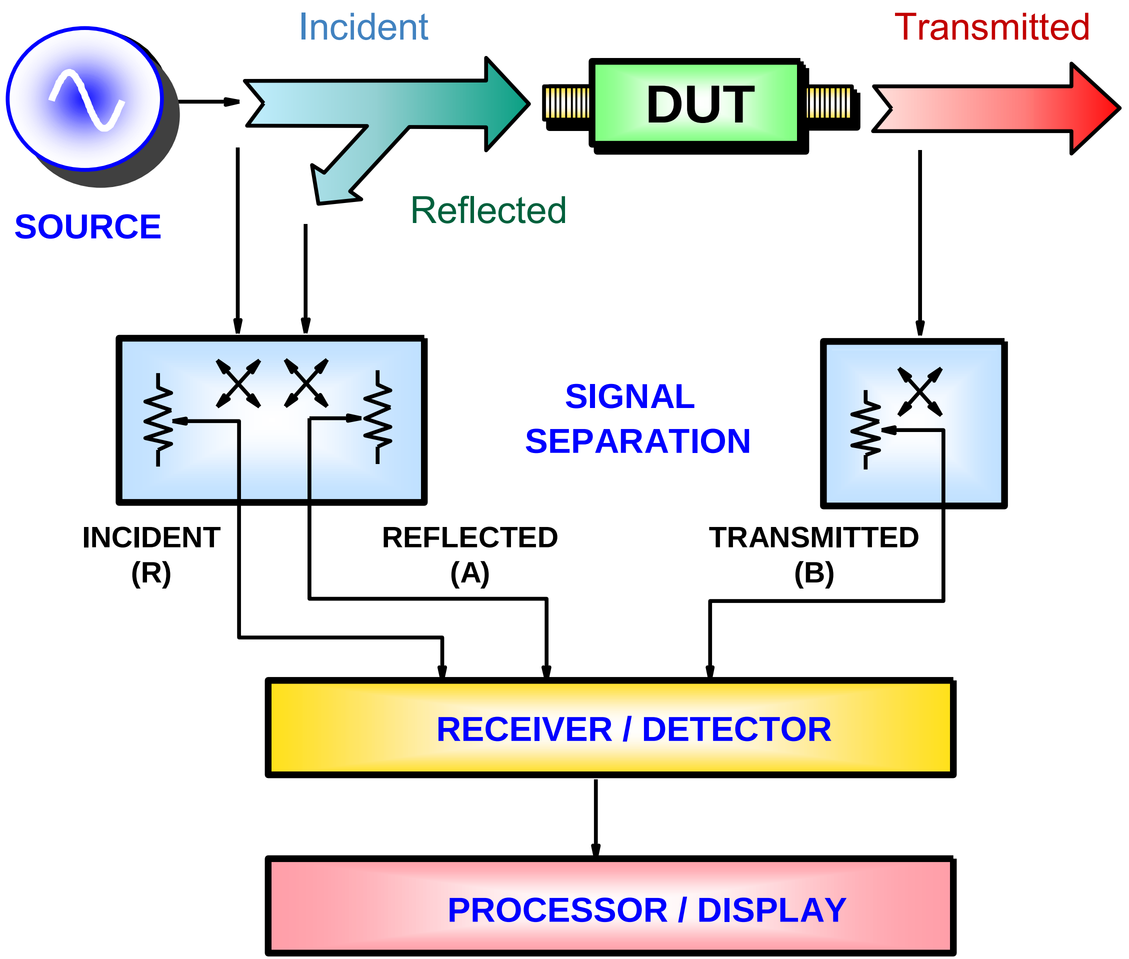
S_{11} = forward reflection coefficient ***(input match)***
S_{22} = reverse reflection coefficient ***(output match)***
S_{21} = forward transmission coefficient ***(gain or loss)***
S_{12} = reverse transmission coefficient ***(isolation)***

Remember, S-parameters are inherently linear quantities -- however, we often express them in a log-magnitude format

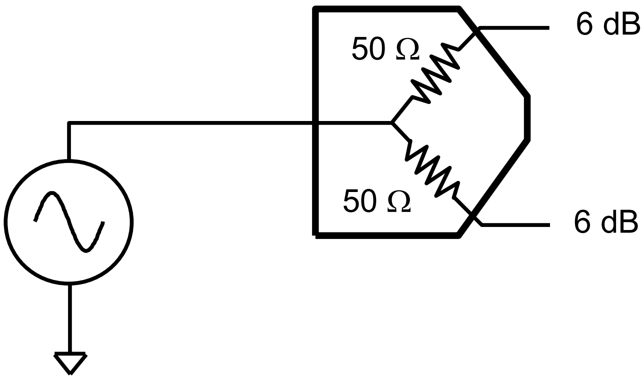
Network Analyzer Block Diagram



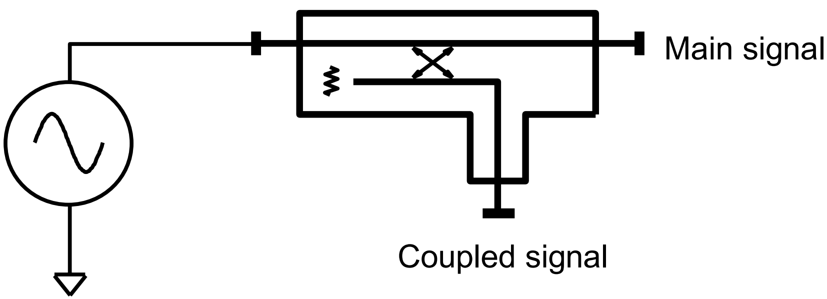
Generalized Network Analyzer Block Diagram



Signal Separation



- ***Splitter***
  - ➔usually resistive
  - ➔non-directional
  - ➔broadband



- ***Coupler***
  - ➔directional
  - ➔low loss
  - ➔good isolation, directivity
  - ➔hard to get low freq performance

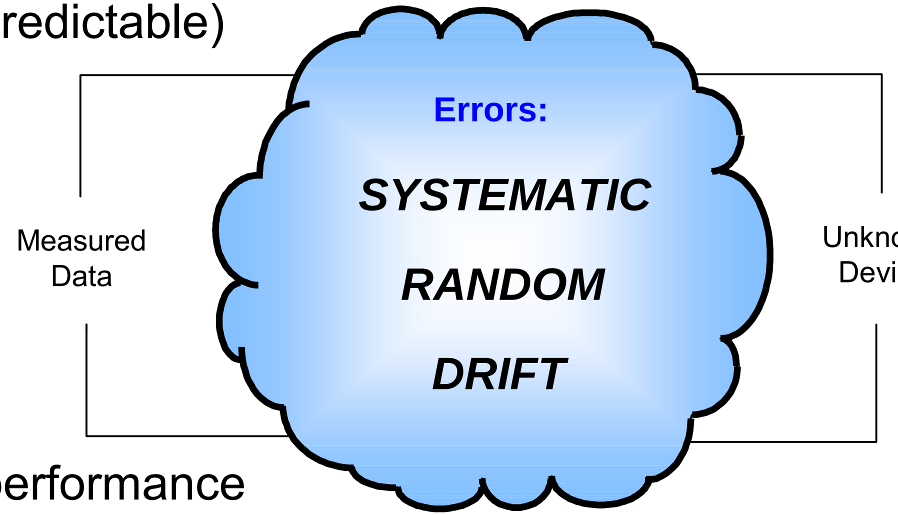
Measurement Error Modeling

Systematic errors

- due to **imperfections** in the analyzer and test setup
- are assumed to be **time invariant** (predictable)
- can be characterized (during calibration process) and **mathematically removed** during measurements

Random errors

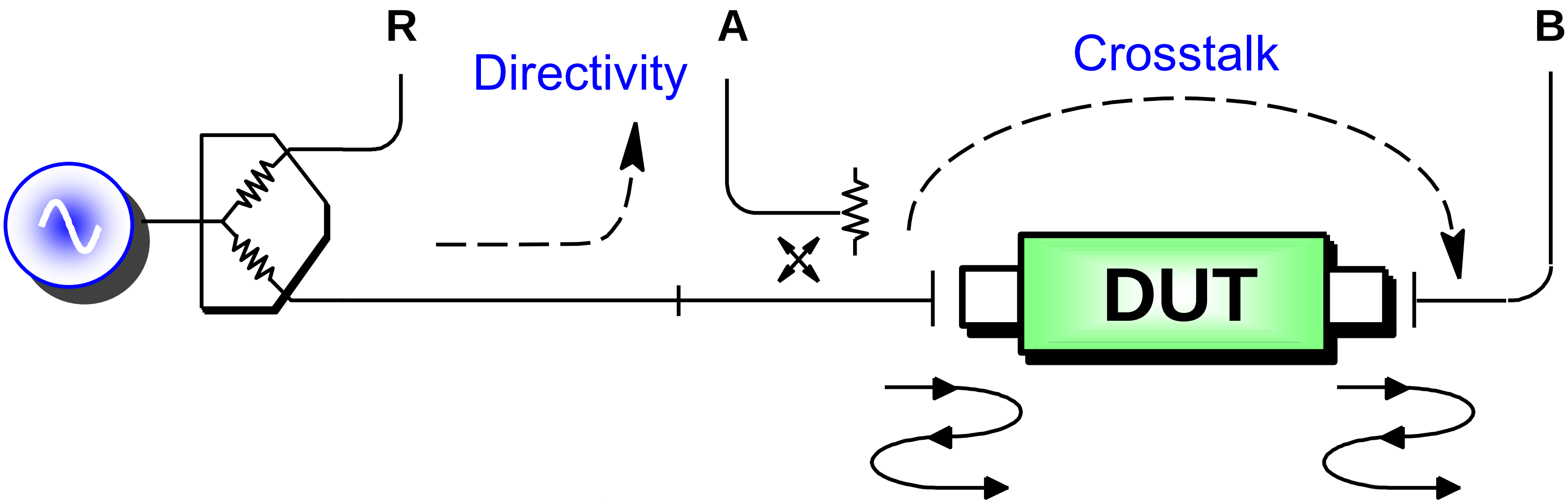
- **vary** with time in random fashion (unpredictable)
- **cannot be removed** by calibration
- main contributors:
  - →**instrument noise** (source phase noise, IF noise floor, etc.)
  - →**switch** repeatability
  - →**connector** repeatability



Drift errors

- are due to instrument or test-system performance changing ***after*** a calibration has been done
- are primarily caused by **temperature variation**
- can be removed by further calibration(s)

Systematic Measurement Errors



Frequency response

- reflection tracking (A/R)
- transmission tracking (B/R)

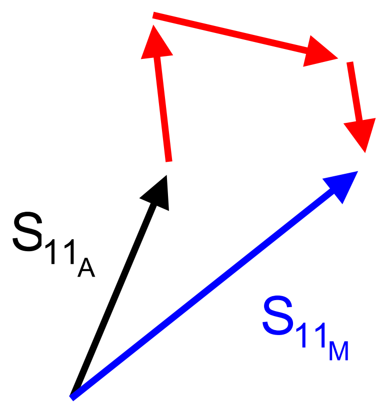
Six forward and six reverse error terms yields 12 error terms for two-port devices

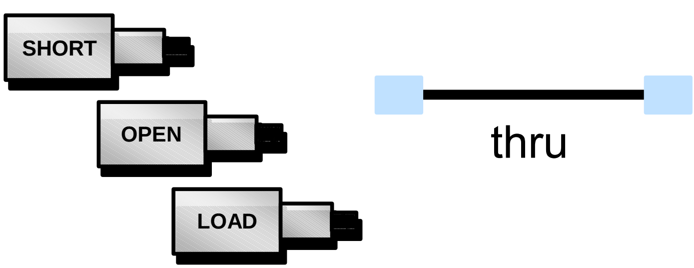
Types of Error Correction

Two main types of error correction:

- **response (normalization)**
  - simple to perform
  - only corrects for tracking errors
  - stores reference trace in memory, then does data divided by memory

- **vector**
  - requires more standards
  - requires an analyzer that can measure phase
  - accounts for all major sources of systematic error

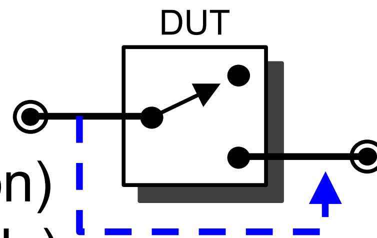




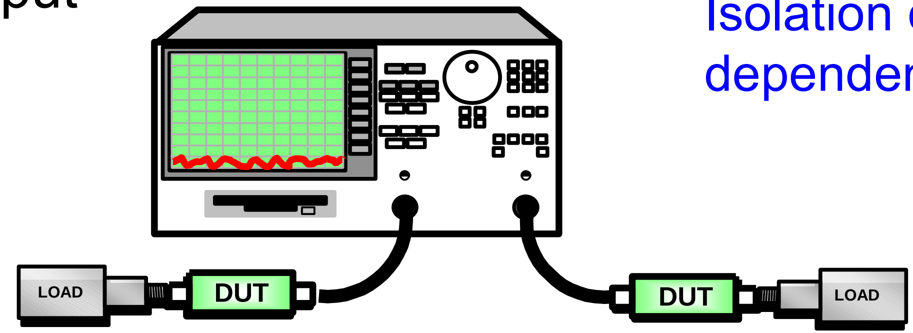
What is Vector-Error Correction?

- Process of characterizing systematic error terms
  - → measure **known standards**
  - → remove effects from subsequent measurements.
- **1-port calibration** *(reflection measurements)*
  - → only 3 systematic error terms measured
  - → directivity, source match, and reflection tracking
- **Full 2-port calibration**
  (reflection and transmission measurements)
  - → 12 systematic error terms measured
  - → usually requires 12 measurements on four known standards (SOLT)
- Some standards can be measured **multiple** times
  (e.g., THRU is usually measured four times)
- Standards defined in **cal kit definition** file
  - → network analyzer contains standard cal kit definitions
  - → **CAL KIT DEFINITION MUST MATCH ACTUAL CAL KIT USED!**

Crosstalk (Isolation)



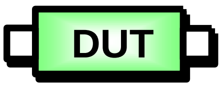
- Crosstalk definition: signal **leakage** between ports
- Can be a problem with:
  - High-isolation devices (e.g., switch in open position)
  - High-dynamic range devices (some filter stopbands)
- Isolation calibration
  - Adds noise to error model (measuring noise floor of system)
  - Only perform if really needed (use averaging)
  - if crosstalk is **independent** of DUT match, use two terminations
  - if **dependent** on DUT match, use DUT with termination on output



Isolation cal when crosstalk is dependent on match of DUT

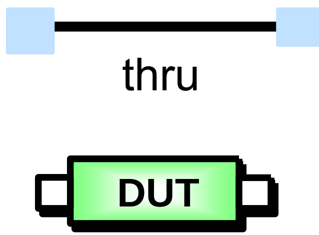
Errors and Calibration Standards

UNCORRECTED



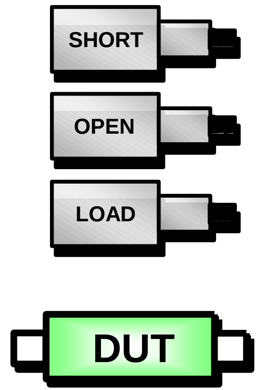
- Convenient
- Generally not accurate
- No errors removed

RESPONSE



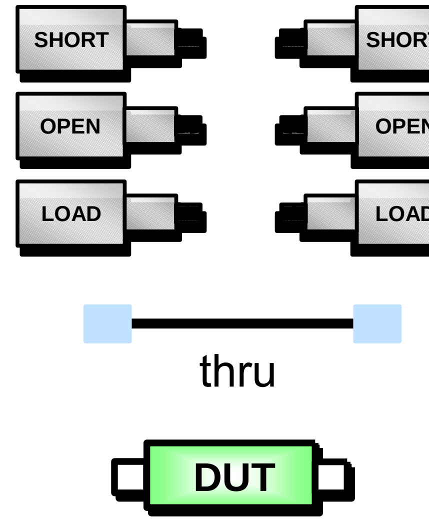
- Easy to perform
- Use when highest accuracy is not required
- Removes frequency response error

1-PORT



- For reflection measurements
- Need good termination for high accuracy with two-port devices
- Removes these errors:
  - Directivity
  - Source match
  - Reflection tracking

FULL 2-PORT



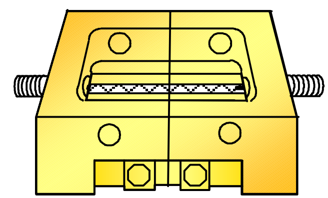
- Highest accuracy
- Removes these errors:
  - Directivity
  - Source, load match
  - Reflection tracking
  - Transmission tracking
  - Crosstalk

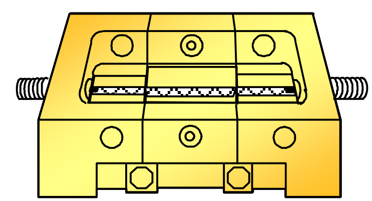
Other errors:
Random (Noise, Repeatability)
Drift

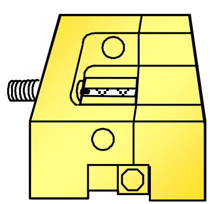
Thru-Reflect-Line (TRL) Calibration

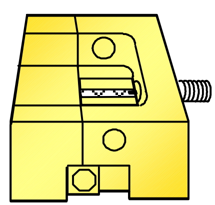
We know about Short-Open-Load-Thru (SOLT) calibration...
What is TRL?

- A two-port calibration technique
- Good for noncoaxial environments (waveguide, fixtures, wafer probing)
- Uses the same 12-term error model as the more common SOLT cal
- Uses practical calibration standards that are easily fabricated and characterized
- Two variations: TRL (requires 4 samplers) and TRL* (only three samplers needed)
- Other variations: Line-Reflect-Match (LRM), Thru-Reflect-Match (TRM), plus many others









網路分析儀校準步驟

- 設定工作頻率: Start ⟶ 輸入起始頻率 ⟶ Stop ⟶ 輸入截止頻率，網路分析儀工作頻率範圍300KHz~3GHz。
- 設定取樣點: Menu ⟶ Number of point ⟶ 有201 、401、801三種點數可選。
- 校準過程: (1) Cal ⟶ Cal Kit ⟶ 3.5mm ⟶ Return。
  (2) Calibrate Menu ⟶ Full 2-Port
  (3) REFECTION
  REFECTION中有(S11)和(S22)兩個部分，(S11) ⟶ 將PORT1分別接上校準元件OPEN、SHORT、LORD(每接上一端須按下右邊的鍵，出現橫線時即可換端)，(S22) ⟶ 將校準元件接到PORT2，步驟與(S11)相同 ⟶ REFECTION DONE

網路分析儀校準步驟

(4) TRANSMISSION

將PORT1和PORT2接上 → 分別按下FWD.TRANS THRU、FWD.MATCH THRU、REV.TRANS THRU、REV.MATCH THRU → TRANS DONE

(5) ISOLATION → OMIT ISOLATION → ISOLATION DONE

(6) DONE 2-PORT CAL

- 元件量測:將元件接上 → MEAS → 選擇S11、S21、S12、S22
- 選擇顯示型式: FORMAT → 如:Log MAG、Smith Chart、Phase

實驗項目

- 濾波器
  - **低通濾波器(Low-pass filter)**
    - 利用網路分析儀量出S參數及Group delay
  - **帶通濾波器(Band-pass filter)**
    - 利用網路分析儀量出S參數及Group delay
    - 找出20dB頻寬及3dB頻寬，可求得Shape factor
    - Shape factor= 20dB頻寬/ 3dB頻寬

實驗項目

全集總枝幹耦和器(L-C Branch line coupler)

量測耦合器之S參數(量測時其餘兩埠請接上50Ω負載)

觀察之間的相位

威爾金森功率分配器(Wilkinson power splitter)

量測功率分配器之S參數(量測時第三埠請接上50Ω負載)

觀察相位及Group Delay