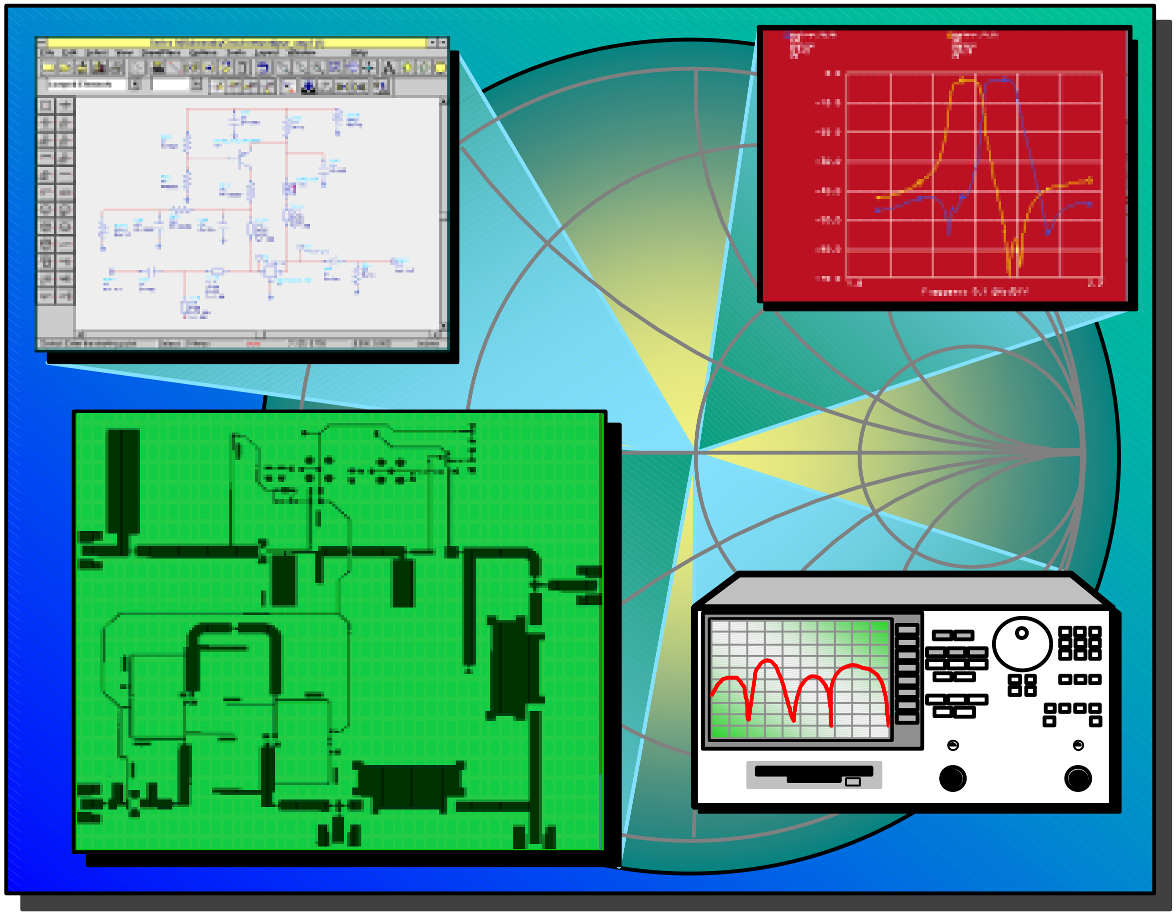
Appendix



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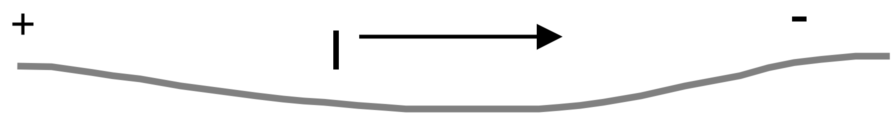
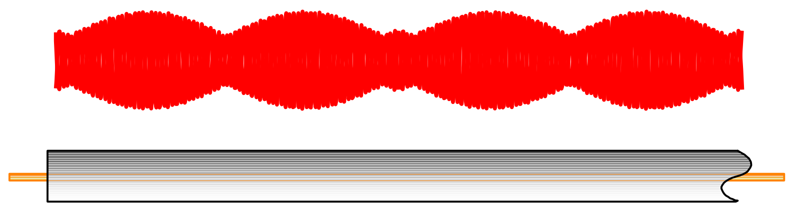
Power Transfer Basics



Low frequencies

- wavelengths >> wire length
- current (I) travels down wires easily for efficient power transmission
- measured voltage and current not dependent on position along wire

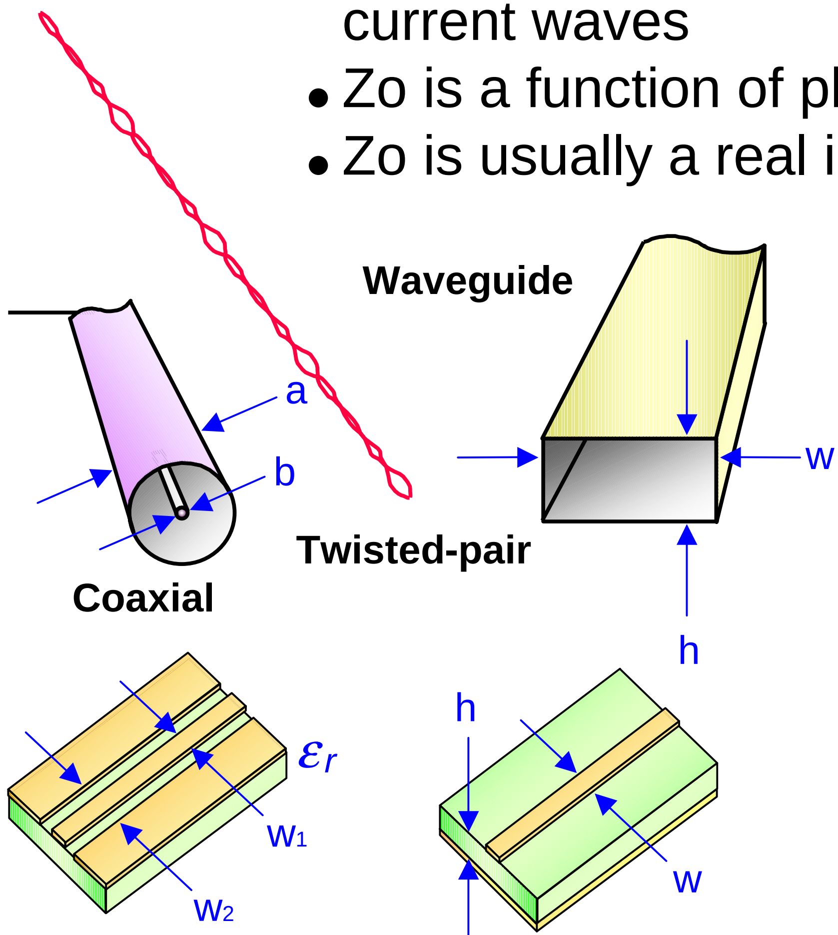


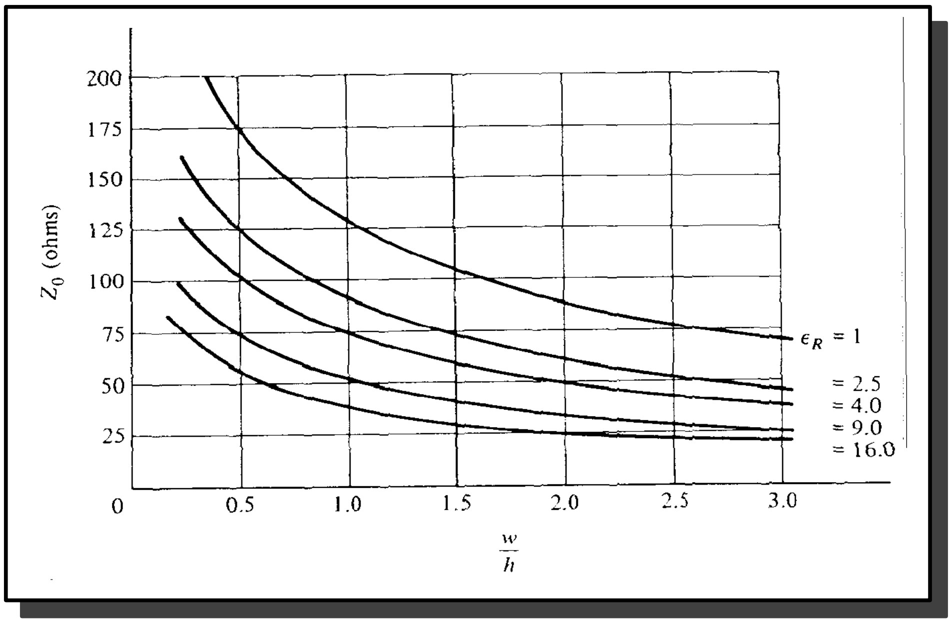
High frequencies

- wavelength ≈ or << length of transmission medium
- need transmission lines for efficient power transmission
- matching to characteristic impedance (Z_0) is very important for low reflection and maximum power transfer
- measured envelope voltage dependent on position along line

Transmission Line Basics

- Zo determines relationship between voltage and current waves
- Zo is a function of physical dimensions and ε_r
- Zo is usually a real impedance (e.g. 50 or 75 ohms)





Characteristic impedance for microstrip transmission lines

(assumes nonmagnetic dielectric)

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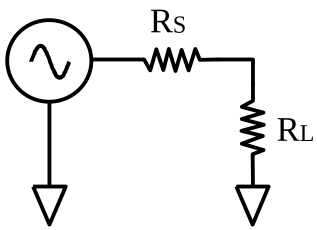
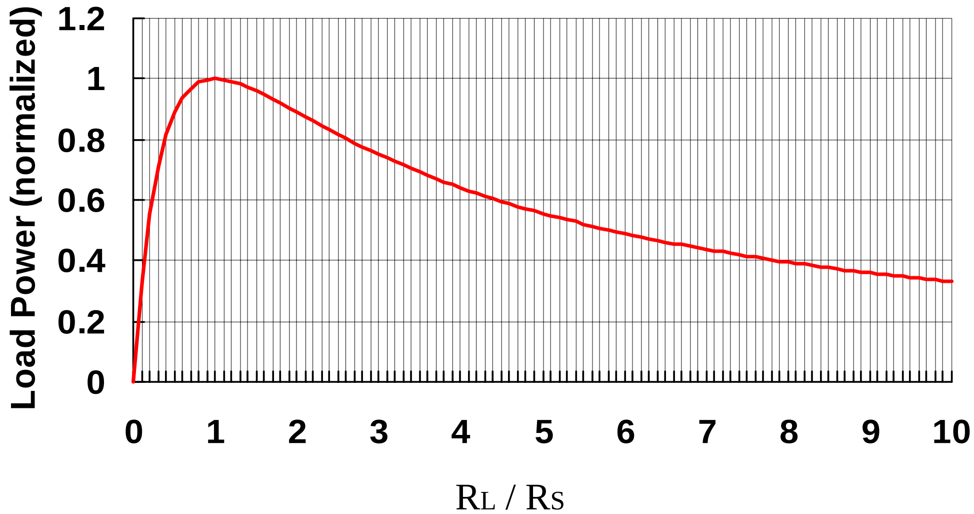
Power Transfer Efficiency





Maximum power is transferred when $R_L = R_S$

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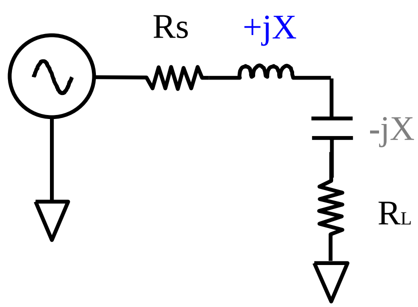
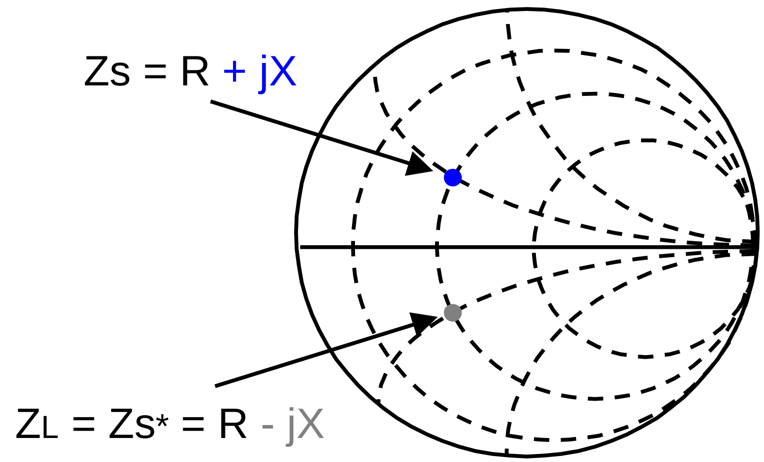
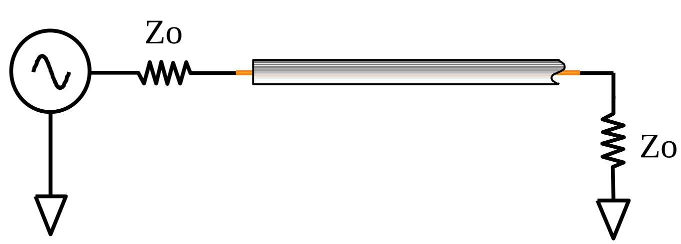
Power Transfer Efficiency

For complex impedances, maximum power transfer occurs when $Z_L = Z_S^*$ (conjugate match)





At high frequencies, maximum power transfer occurs when $R_S = R_L = Z_o$



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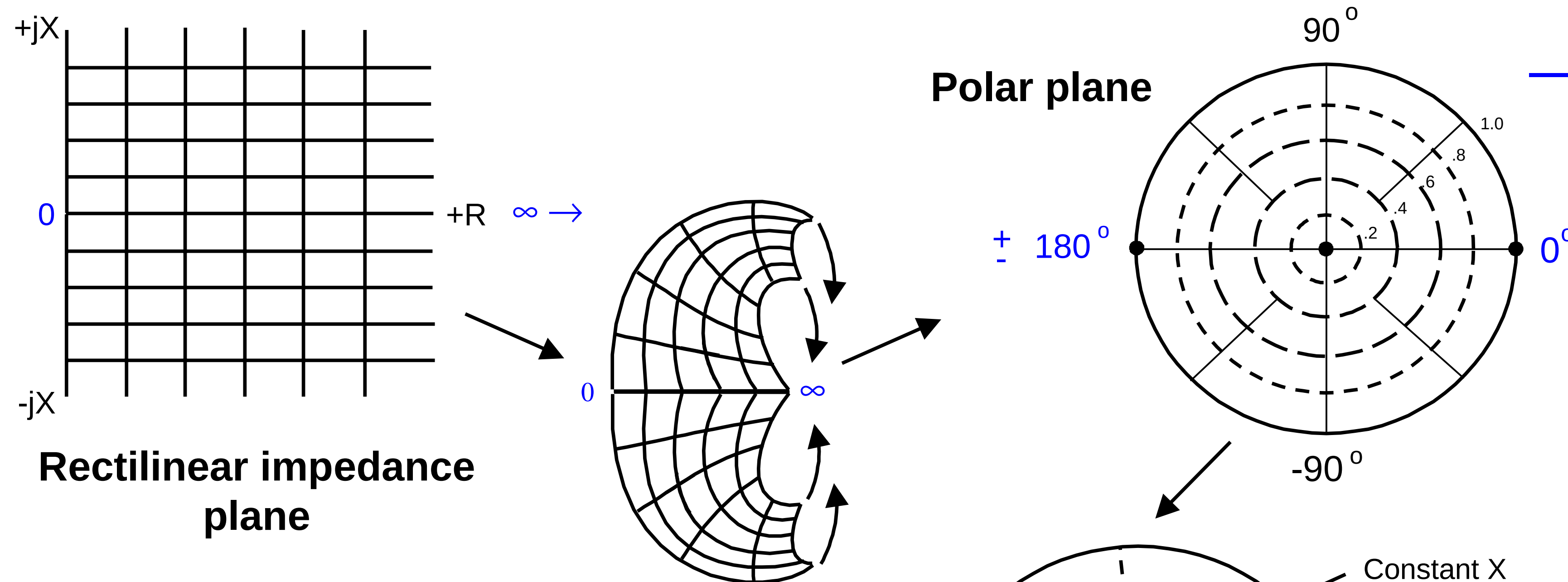
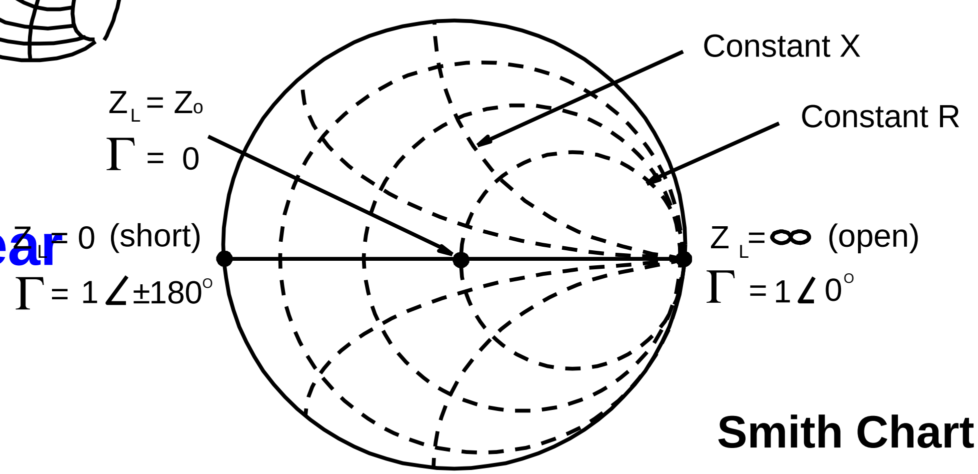
Smith Chart Review





Smith Chart maps rectilinear impedance plane onto polar plane

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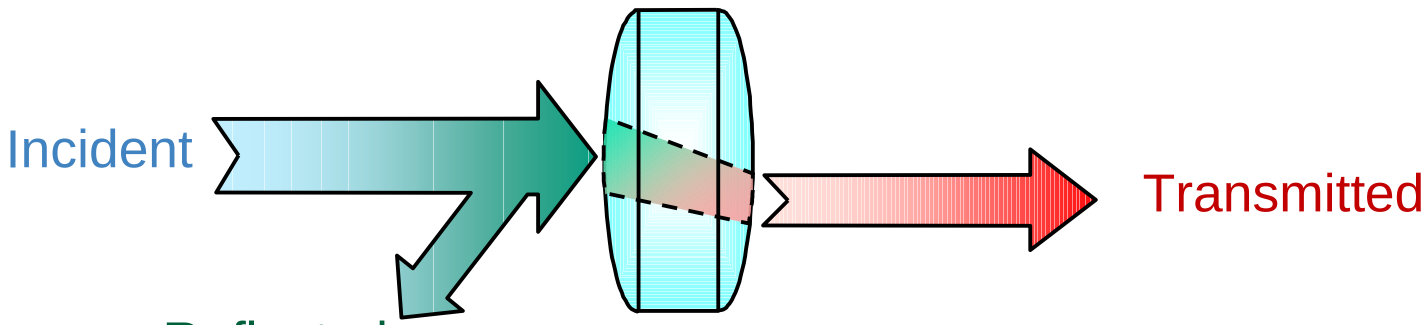
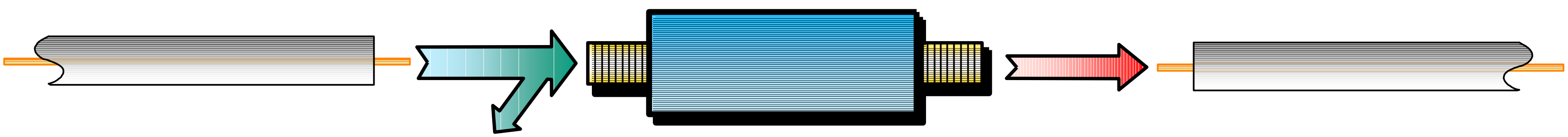
Lightwave Analogy to RF Energy



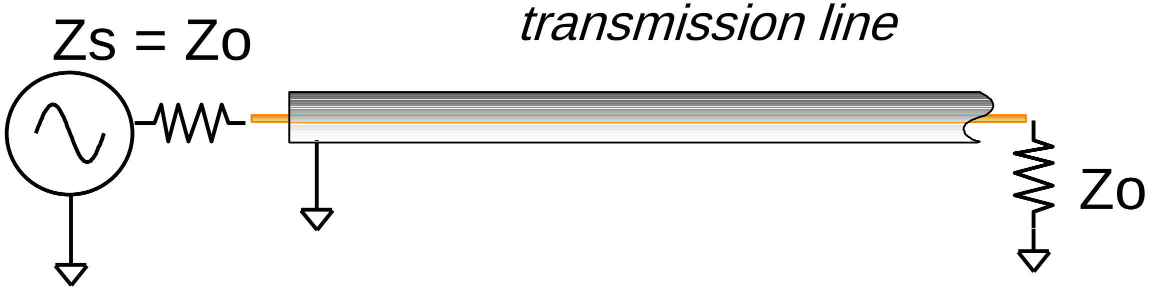
Lightwave

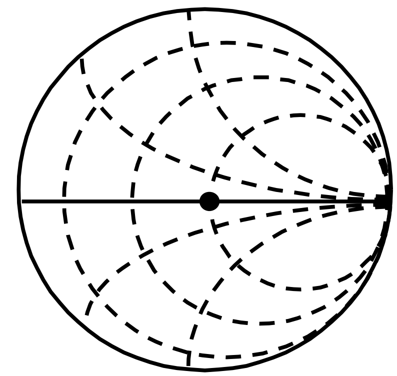


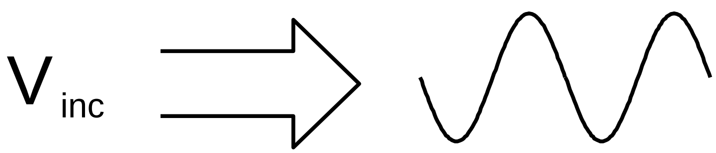
RF

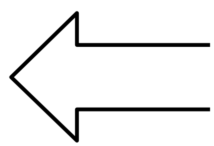
Transmission Line Terminated with Zo

Zo = characteristic impedance of transmission line





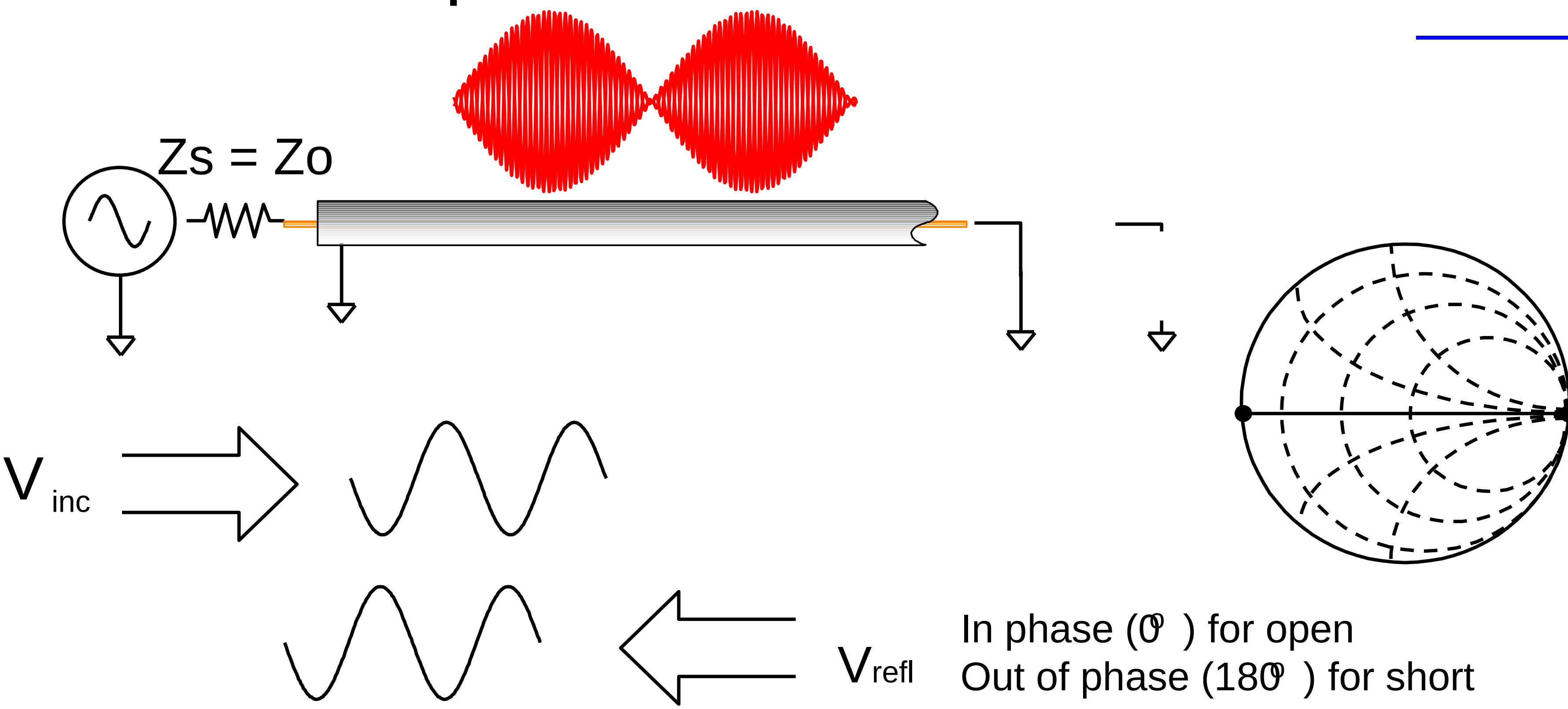




V_{refl} = 0! *(all the incident power is absorbed in the load)*

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

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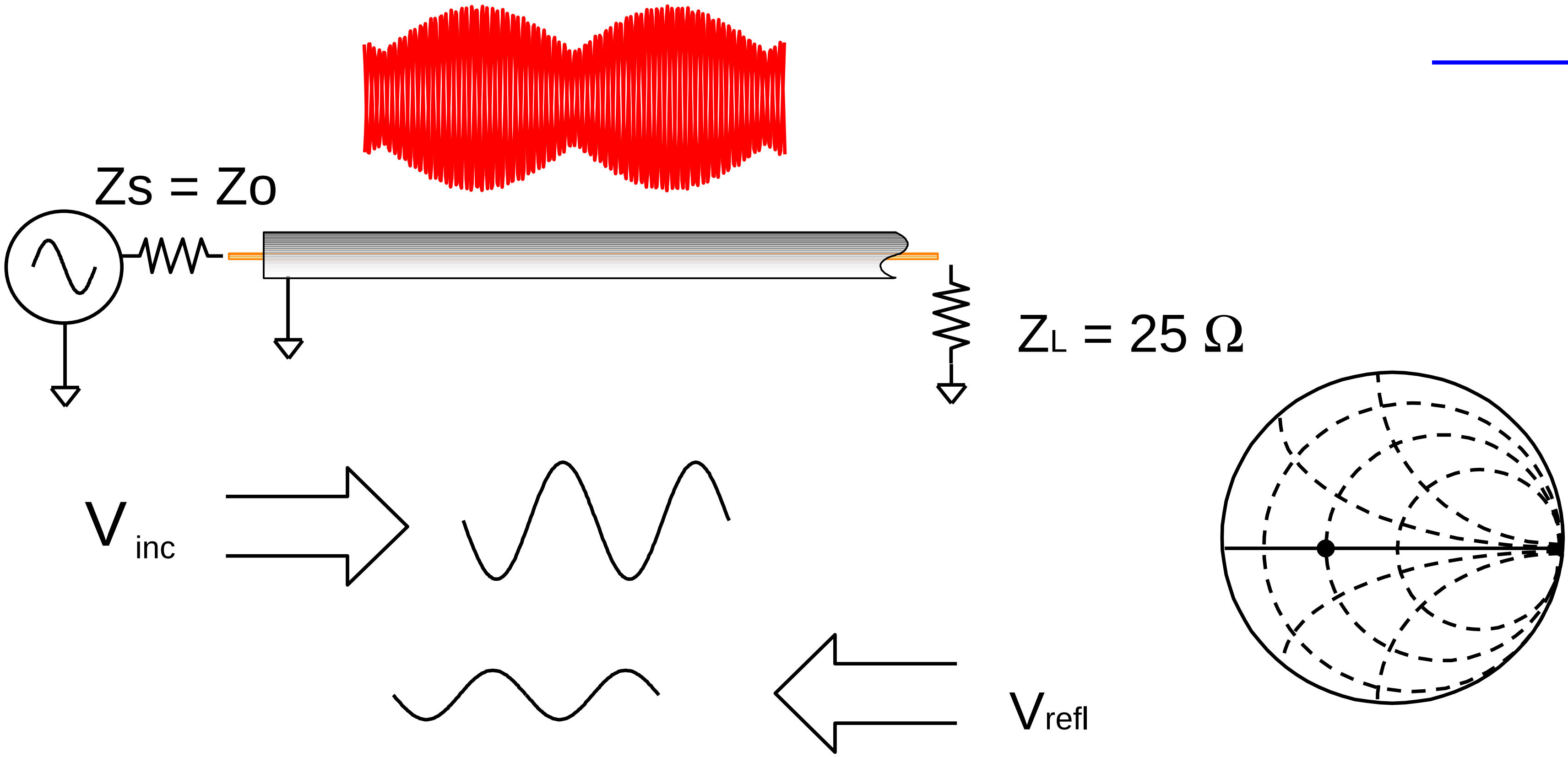
Transmission Line Terminated with 25 Ω

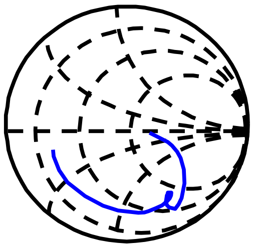


Standing wave pattern does not go to zero as with short or open

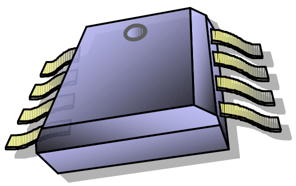
Device Characteristics

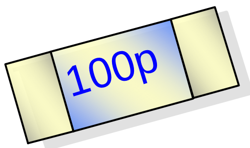
Devices have many distinctive characteristics such as:

- ***electrical behavior***
  - DC power consumption
  - linear (e.g. S-parameters, noise figure)
  - nonlinear (e.g. distortion, compression)

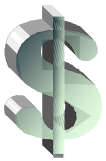


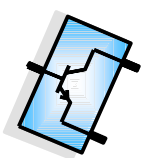
- ***physical specifications***
  - package type
  - package size
  - thermal resistance

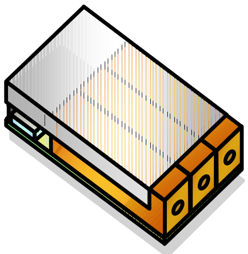




- ***other things...***
  - cost
  - availability



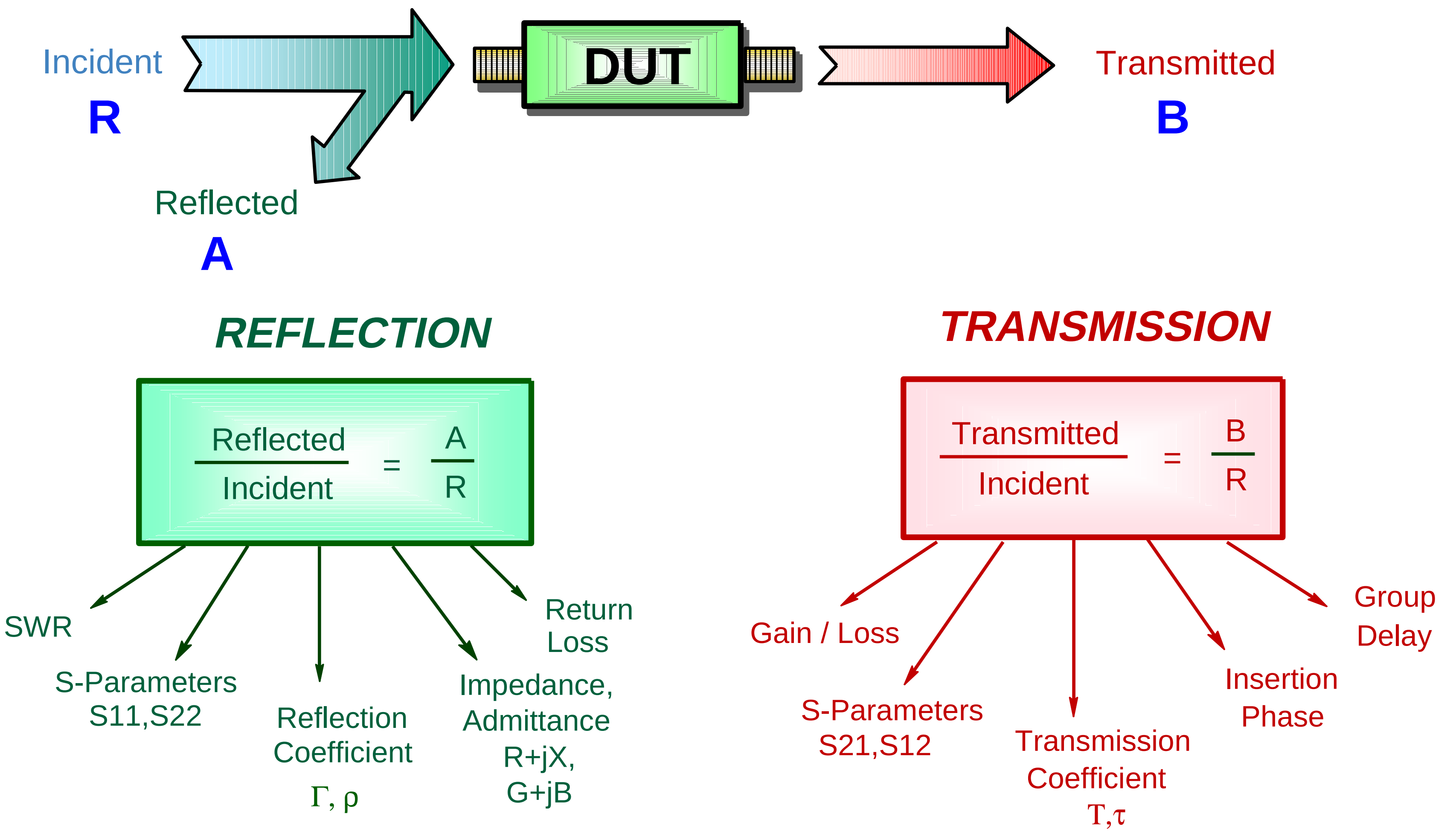




When selecting parts for design, characteristics are traded-off

Let's look at important electrical characteristics for RF design ...

High-Frequency Device Characterization



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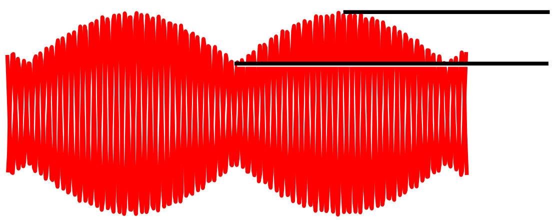
Reflection Parameters

Reflection Coefficient

$$\Gamma = \frac{V_{reflected}}{V_{incident}} = \rho \angle \Phi = \frac{Z_L - Z_O}{Z_L + Z_O}$$

Return loss = -20 log(ρ), $\rho = |\Gamma|$



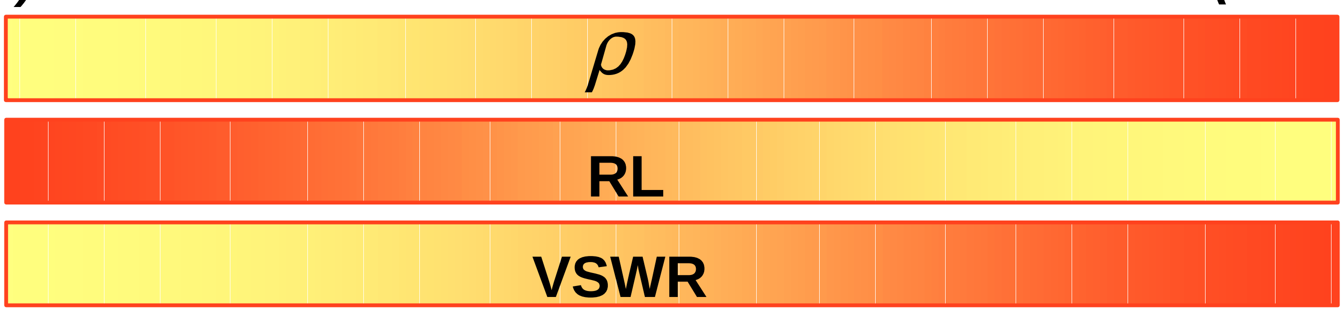
Voltage Standing Wave Ratio

$$\mathbf{VSWR} = \frac{E_{max}}{E_{min}} = \frac{1+\rho}{1-\rho}$$

No reflection
(Z_L = Zo)

Full reflection
(Z_L = open, short)

0	ρ	1
∞ dB	RL	0 dB
1	VSWR	∞



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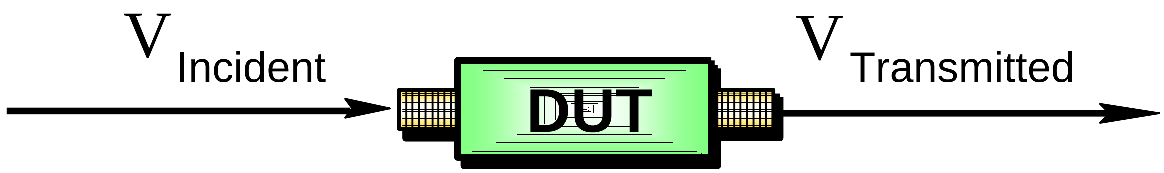
Transmission Parameters



Transmission Coefficient = $T = \dfrac{V_{\text{Transmitted}}}{V_{\text{Incident}}} = \tau\angle\phi$

Insertion Loss (dB) = *- 20 Log* $\left|\dfrac{V_{\text{Trans}}}{V_{\text{Inc}}}\right| = -20 \log \tau$

Gain (dB) = *20 Log* $\left|\dfrac{V_{\text{Trans}}}{V_{\text{Inc}}}\right| = 20 \log \tau$

Insertion Phase (deg) = $\angle \dfrac{V_{\text{Trans}}}{V_{\text{Inc}}} = \phi$

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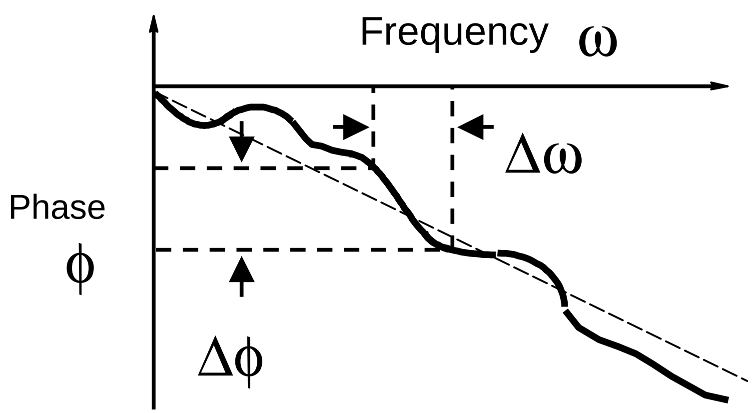
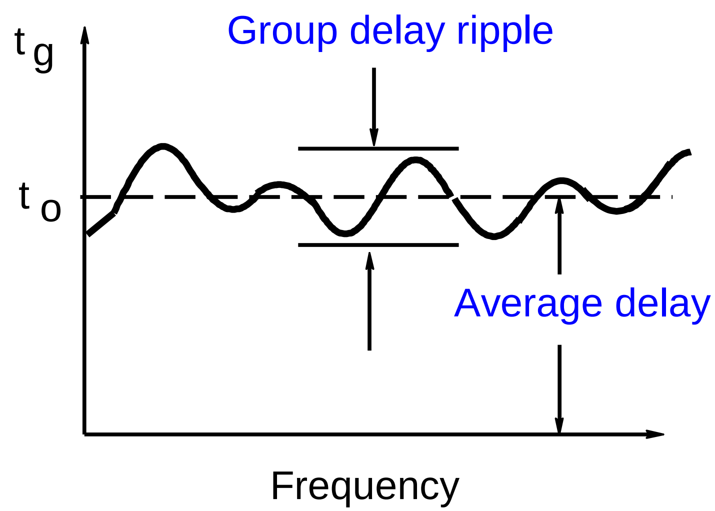
Group Delay (GD)





Group Delay (t_g) =

$$\frac{-d\,\phi}{d\,\omega} = \frac{-1}{360^{o}} * \frac{d\,\phi}{d\,f}$$

ϕ in radians

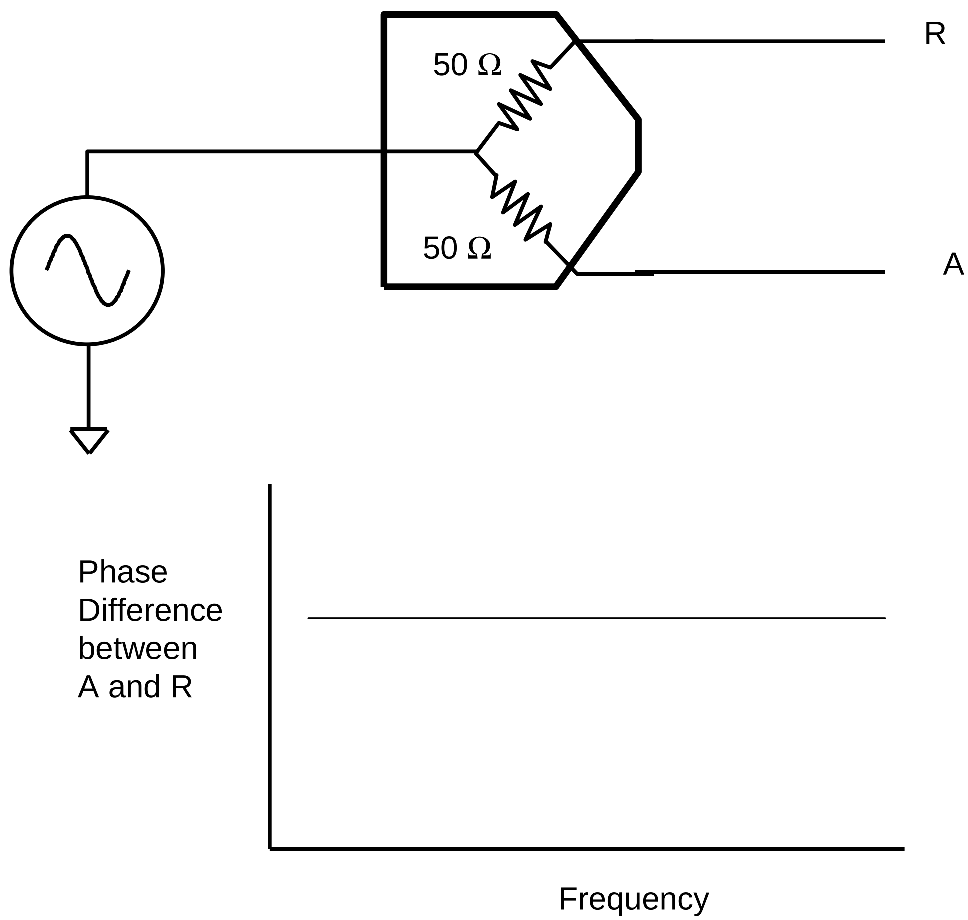
ω in radians/sec

ϕ in degrees

f in Hertz ($\omega = 2\,\pi\,f$)

- average delay indicates electrical length
- GD ripple indicates distortion
- aperture of measurement is very important
  - aperture is frequency-delta used to calculate GD
  - wider aperture: lower noise / less resolution
  - narrower aperture: more resolution / higher noise

Phase versus Frequency



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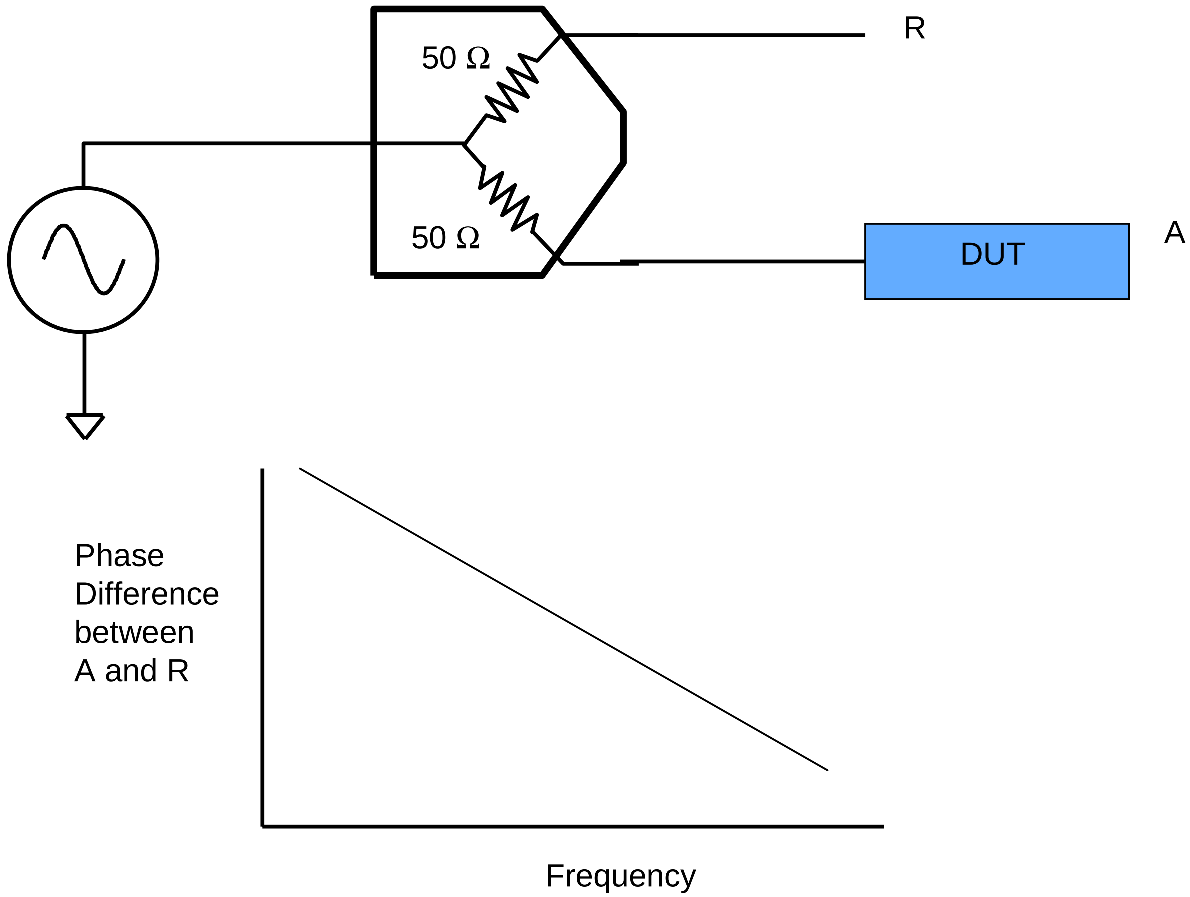
Phase versus Frequency



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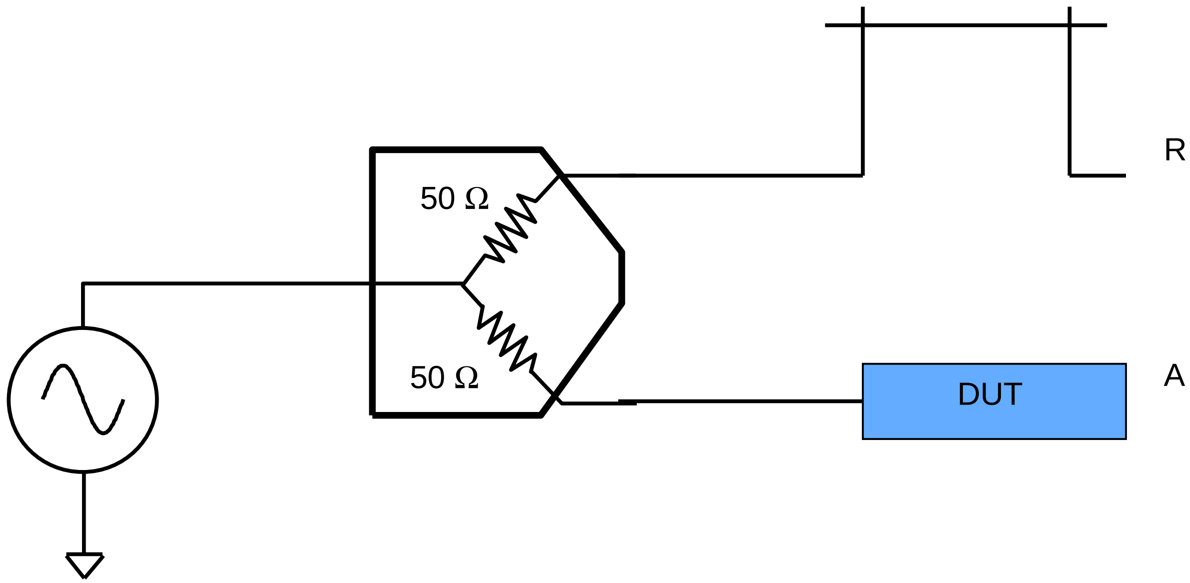
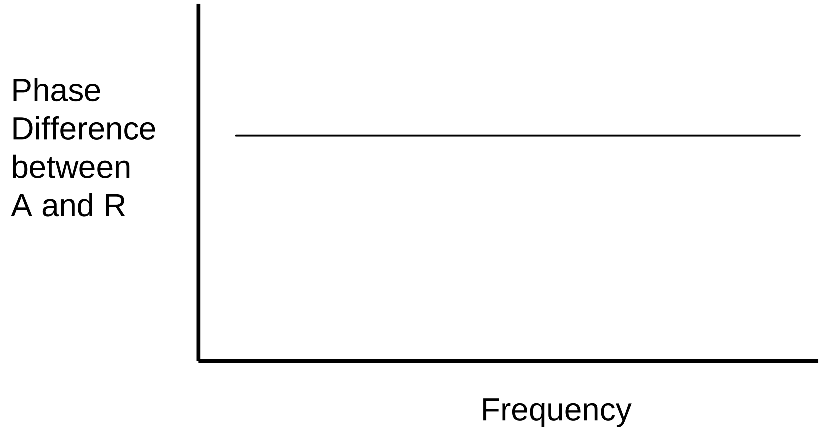
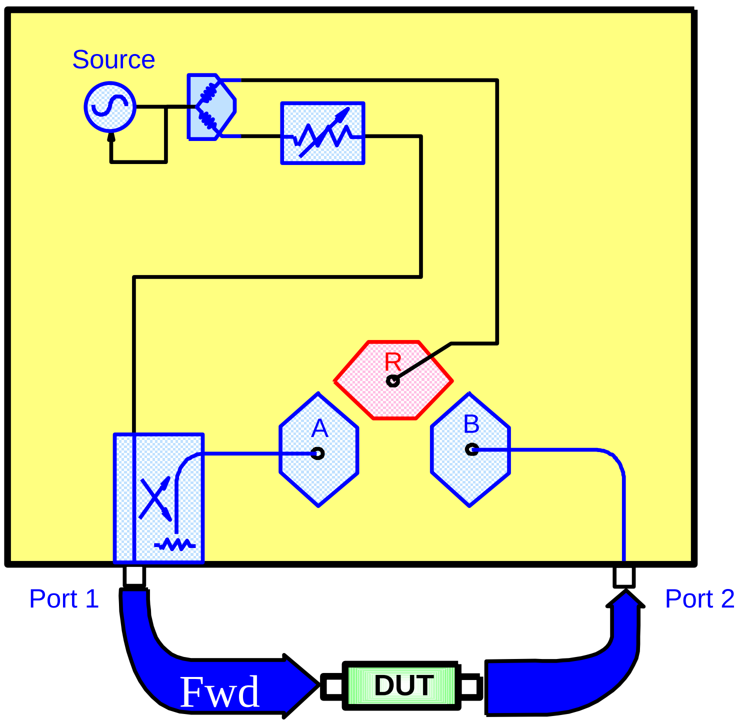
Phase versus Frequency



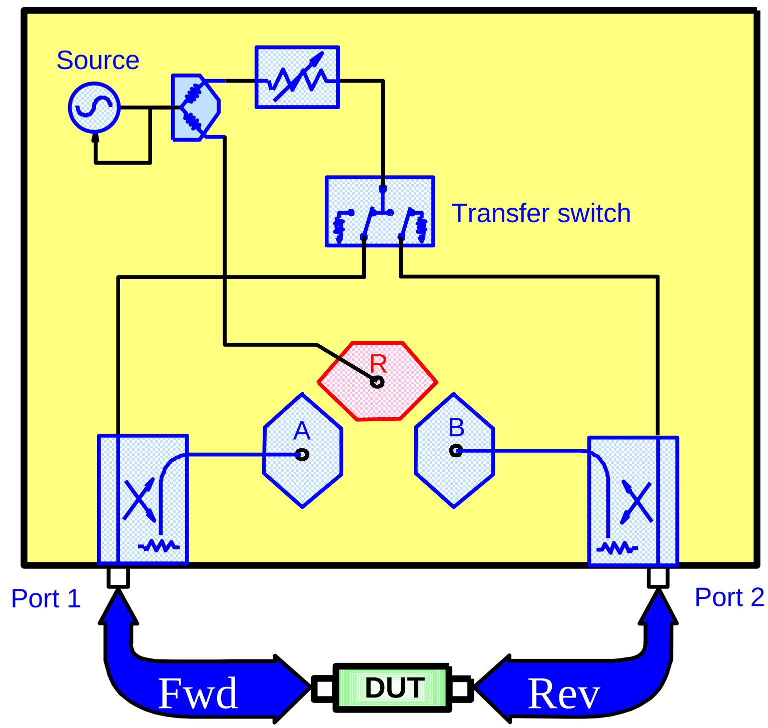


T/R Versus S-Parameter Test Sets

Transmission/Reflection Test Set



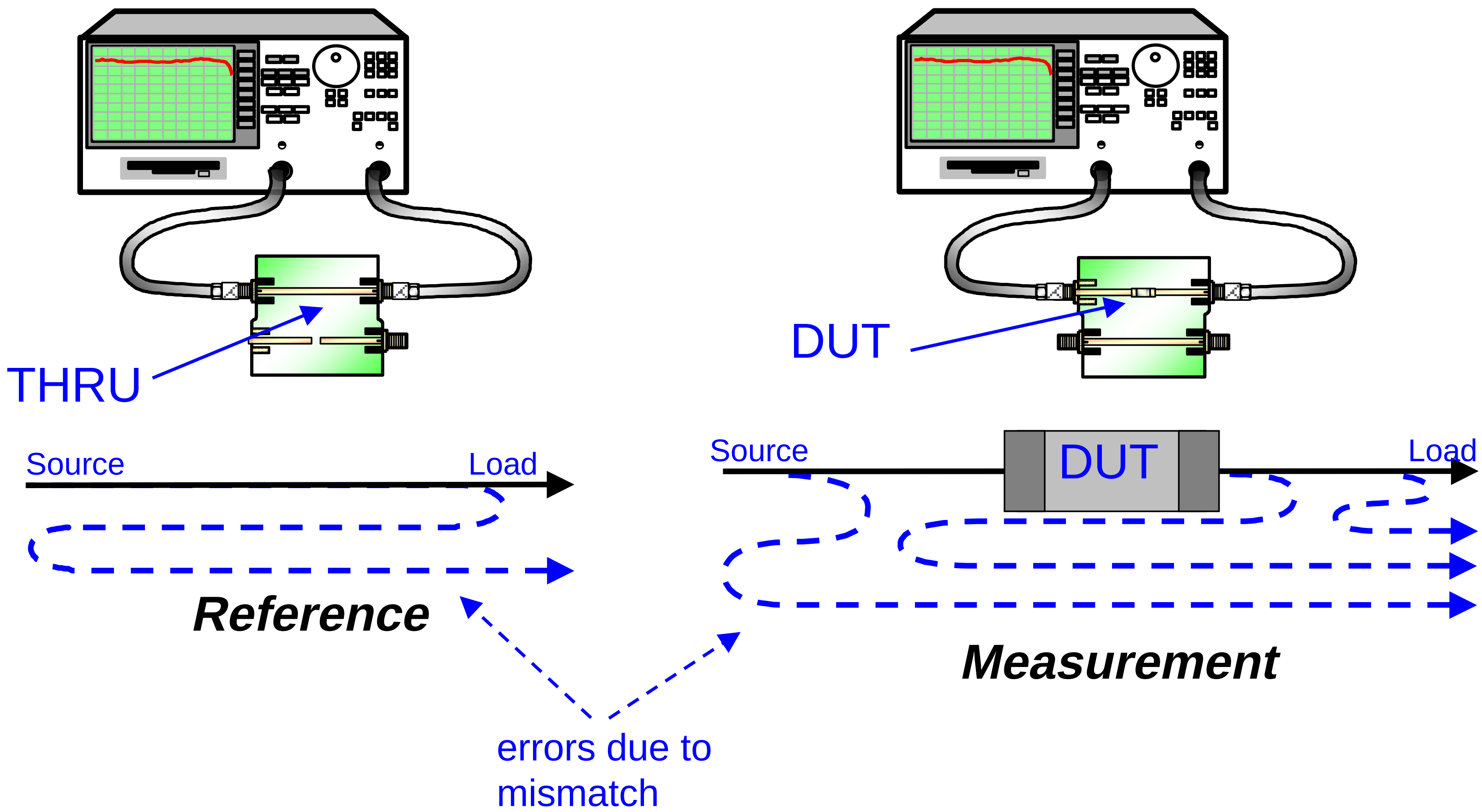
S-Parameter Test Set



- RF always comes out port 1
- port 2 is always receiver
- **response**, **one-port** cal available

- RF comes out port 1 or port 2
- forward and reverse measurements
- **two-port** calibration possible

Response Calibration



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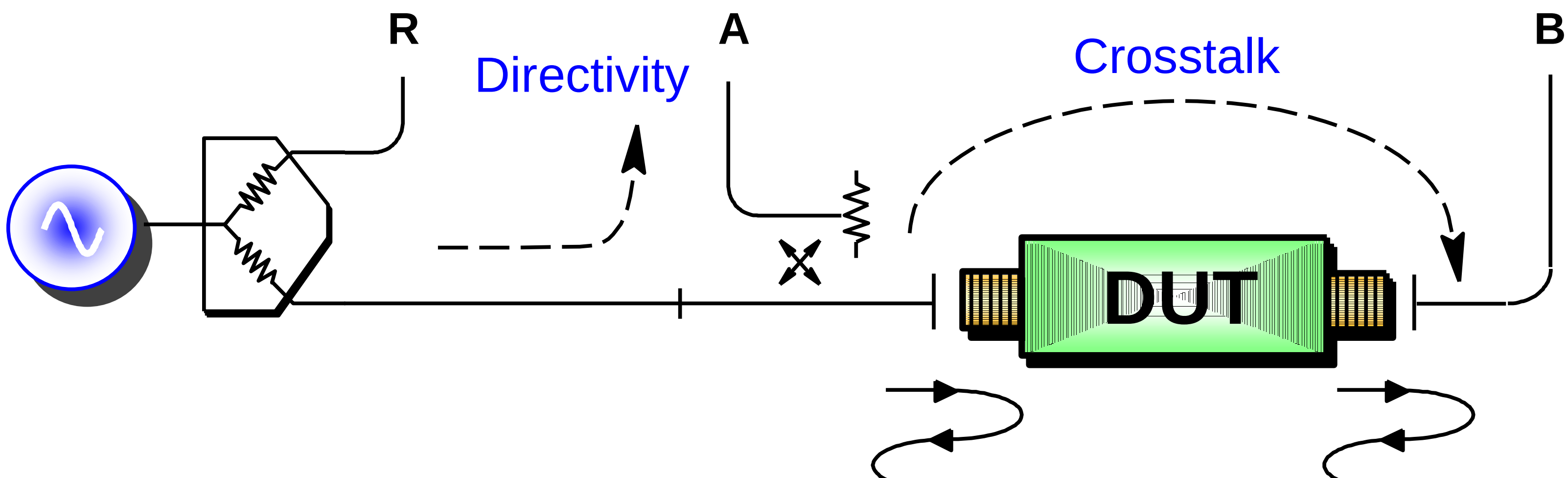
Two-Port Calibration

Two-port calibration corrects for all major sources of 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

Thru-Reflect-Line (TRL) Calibration

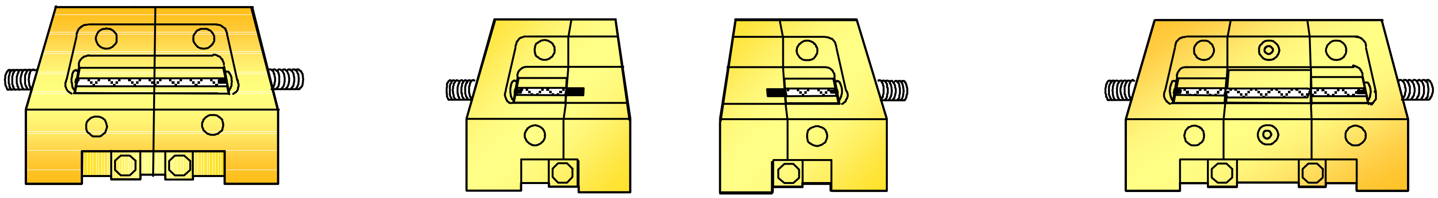
TRL calibration was developed for non-coaxial microwave measurements

Advantages

- microwave cal standards **easy** to make (no open or load)
- based on **transmission line** of known length and impedance
- do not need to know characteristics of **reflect** standard

Disadvantages

- impractical **length** of RF transmission lines
- fixtures usually more **complicated** (and expensive)
- 8:1 BW **limitation** per transmission line



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Characterizing Unknown Devices

Using parameters (H, Y, Z, S) to characterize devices:

- gives us a linear behavioral model of our device
- measure parameters (e.g. voltage and current) versus frequency unde various source and load conditions (e.g. short and open circuits)
- compute device parameters from measured data
- now we can predict circuit performance under any source and load conditions

<u>H-parameters</u>

$V_1 = h_{11}I_1 + h_{12}V_2$

$I_2 = h_{21}I_1 + h_{22}V_2$

$$h_{11} = \left.\frac{V_1}{I_1}\right|_{V_2=0}$$ *(requires* ***short circuit)***

$$h_{12} = \left.\frac{V_1}{V_2}\right|_{I_1=0}$$ *(requires* ***open circuit)***

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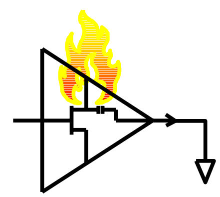
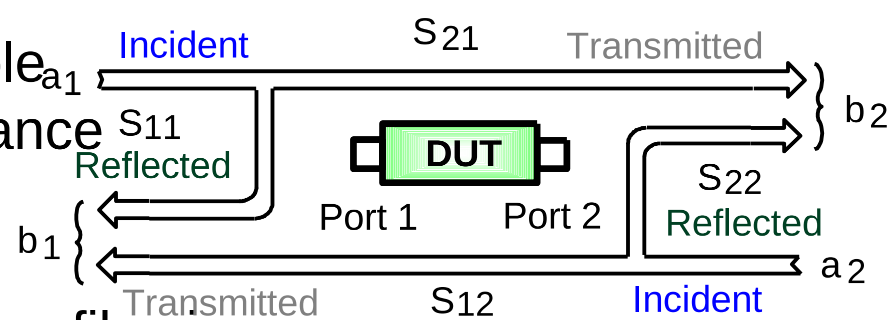
Why Use S-Parameters?

- relatively easy to **obtain** at high frequencies
  - measure voltage traveling waves with a vector network analyzer
  - don't need shorts/opens which can cause active devices to oscillate or self-destruct
- relate to **familiar** measurements (gain, loss, reflection coefficient ...)
- can **cascade** S-parameters of multiple devices to predict system performance
- can **compute** H, Y, or Z parameters from S-parameters if desired
- can easily import and use S-parameter files in our **electronic-simulation** tools



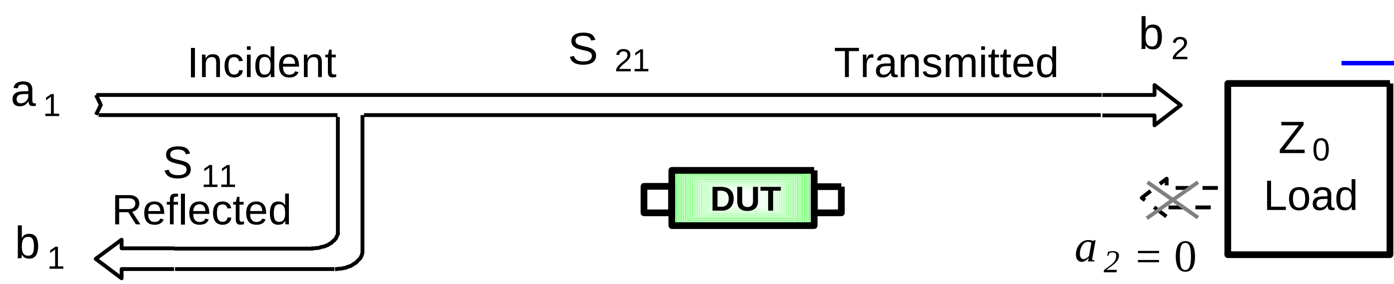


$$b_1 = S_{11} a_1 + S_{12} a_2$$

$$b_2 = S_{21} a_1 + S_{22} a_2$$

Measuring S-Parameters

Forward

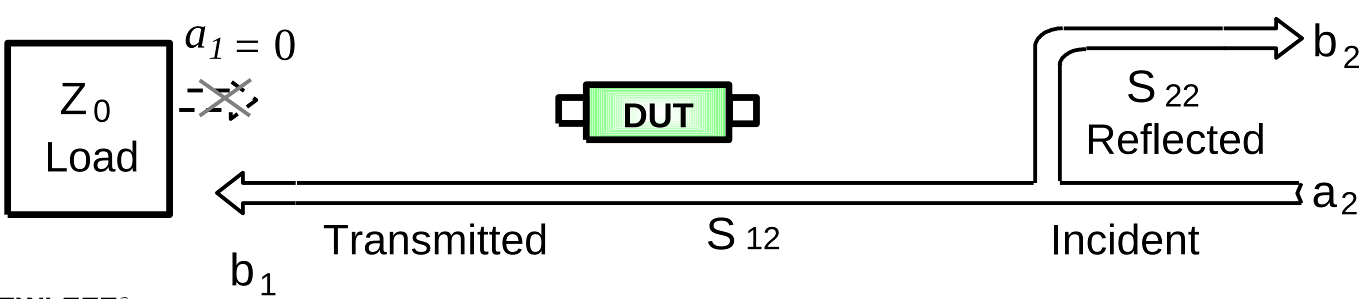


$$S_{11} = \frac{\textit{Reflected}}{\textit{Incident}} = \left.\frac{b_1}{a_1}\right|_{a_2 = 0}$$

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

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

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



Reverse

Equating S-Parameters with Common Measurement Terms

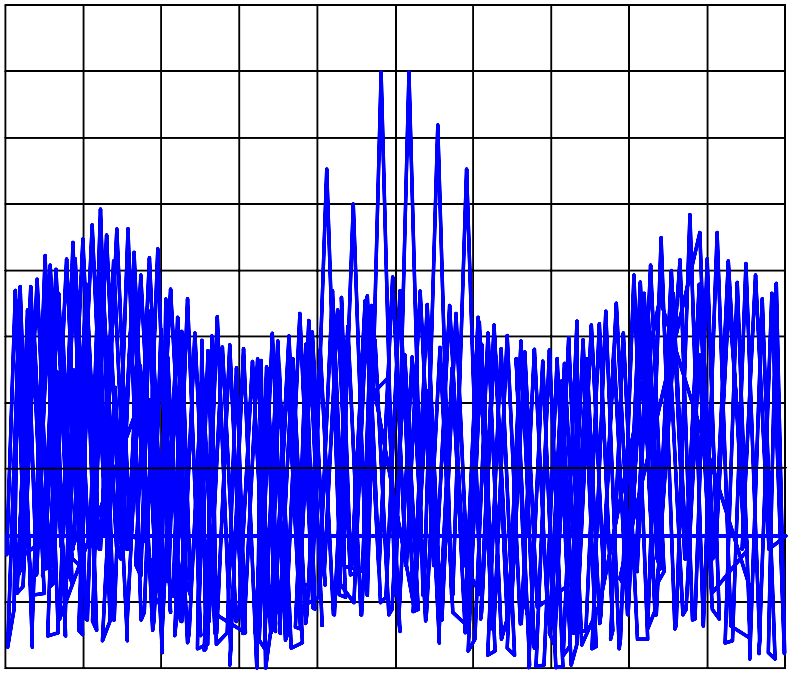
S_{11} = forward reflection coefficient ***(input match)***
S_{22} = reverse reflection coefficient ***(output match)***
S_{21} = forward transmission coefficient ***(gain or loss)***
S_{12} = reverse transmission coefficient ***(isolation)***

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

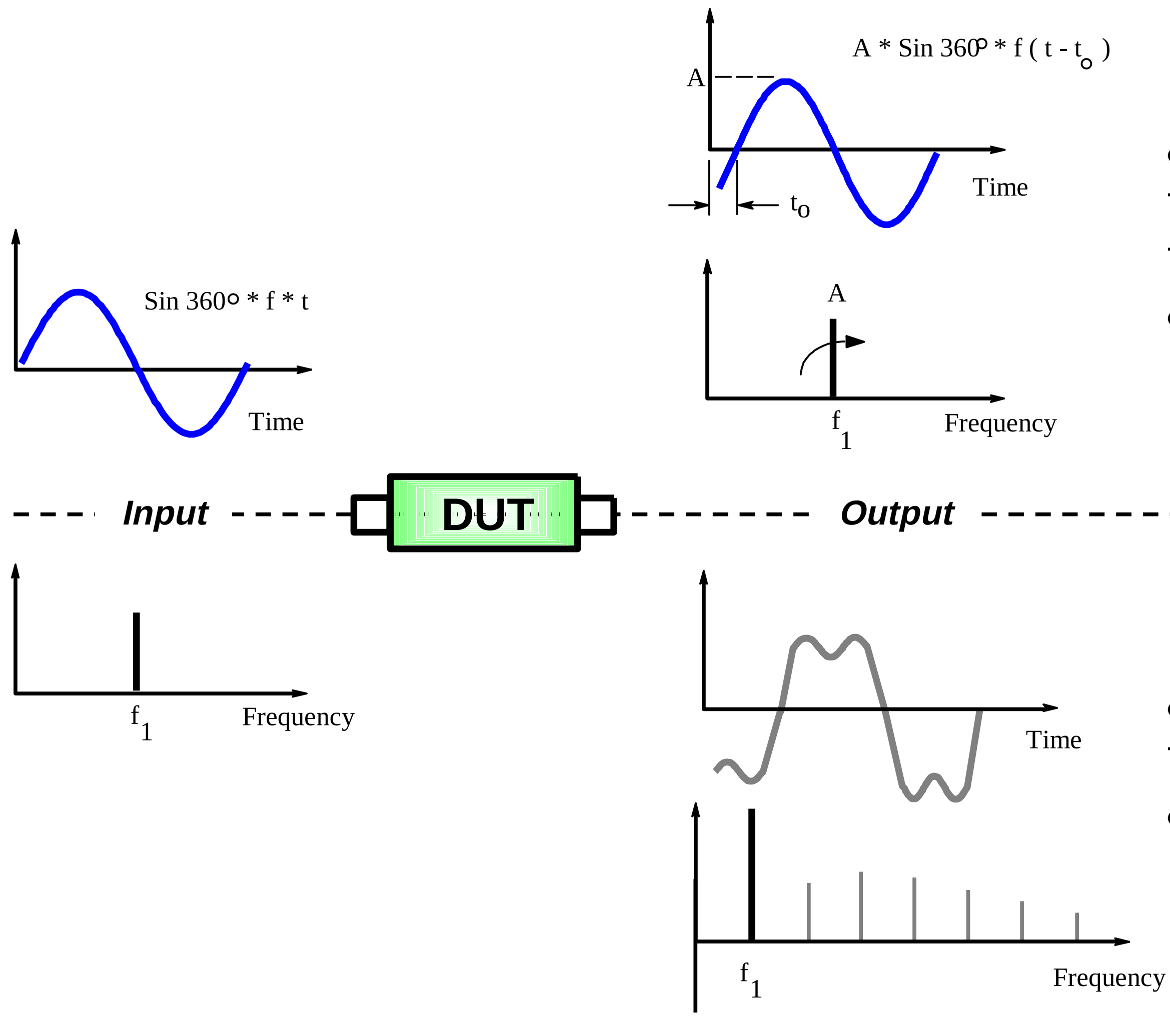
Going Beyond Linear Swept-Frequency Characterization

So far, we've only talked about linear swept-frequency characterization (used for passive and active devices). Two other important characterizations for active devices are:

- nonlinear behavior
- noise figure



Linear Versus Nonlinear Behavior



Linear behavior:

- input and output frequencies are the same (no additional frequencies created)
- output frequency only undergoes magnitude and phase change

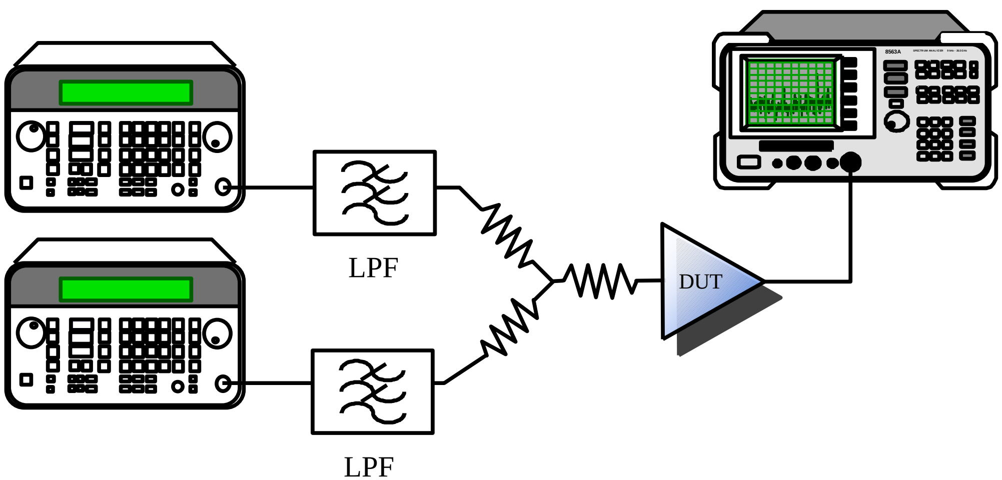
Nonlinear behavior:

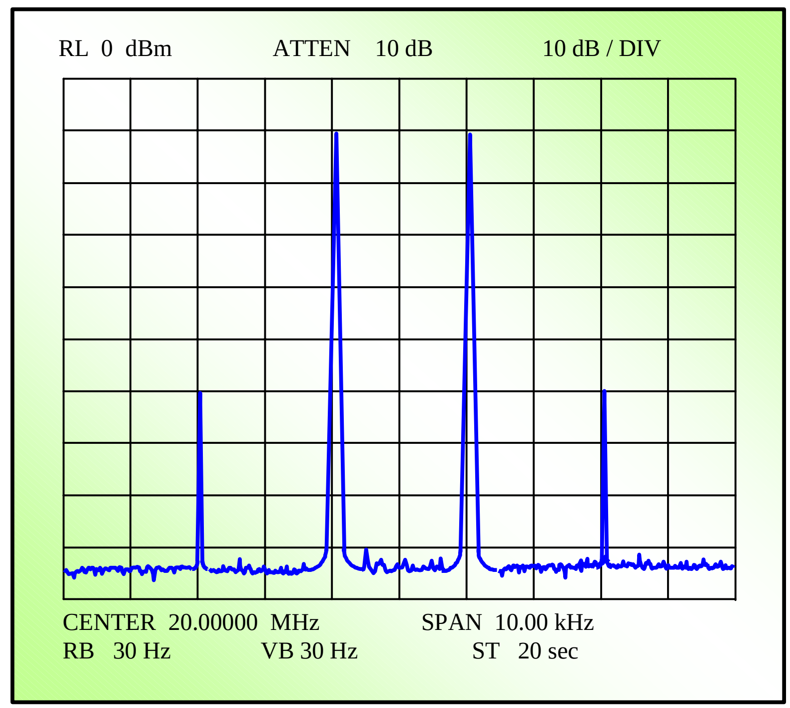
- output frequency may undergo frequency shift (e.g. with mixers)
- additional frequencies created (harmonics, intermodulation)

Measuring Nonlinear Behavior

Most common measurements:

- using a ***spectrum analyzer*** + source(s)
  - harmonics, particularly second and third
  - intermodulation products resulting from two or more RF carriers
- using a ***network analyzer*** and power sweeps
  - gain compression
  - AM to PM conversion





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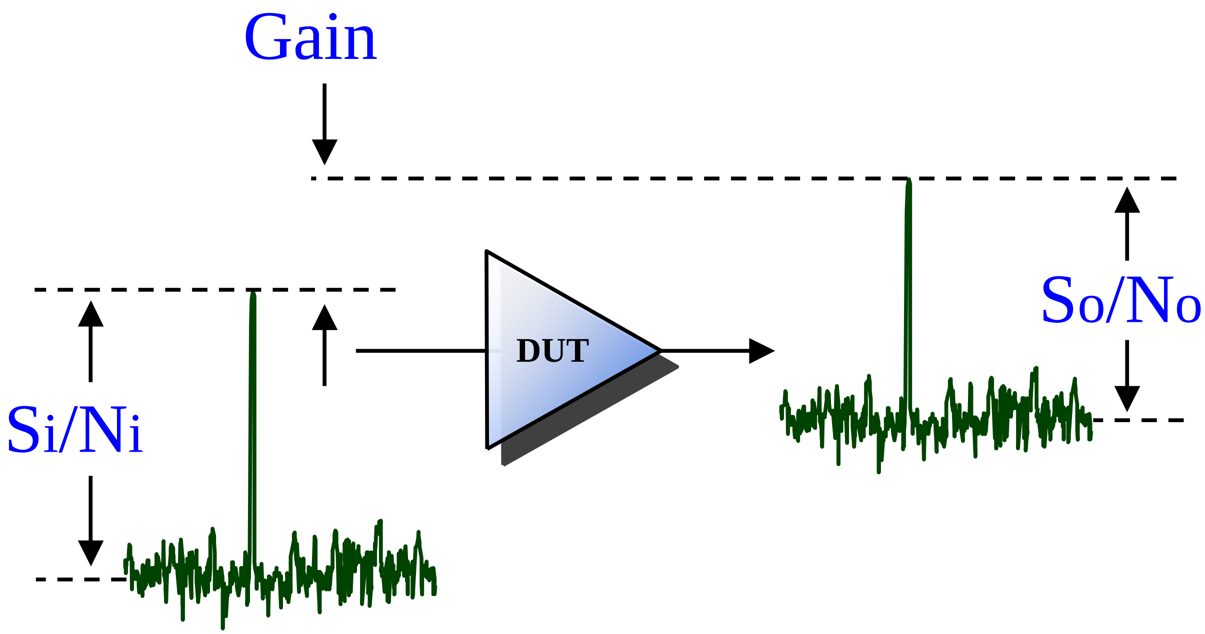
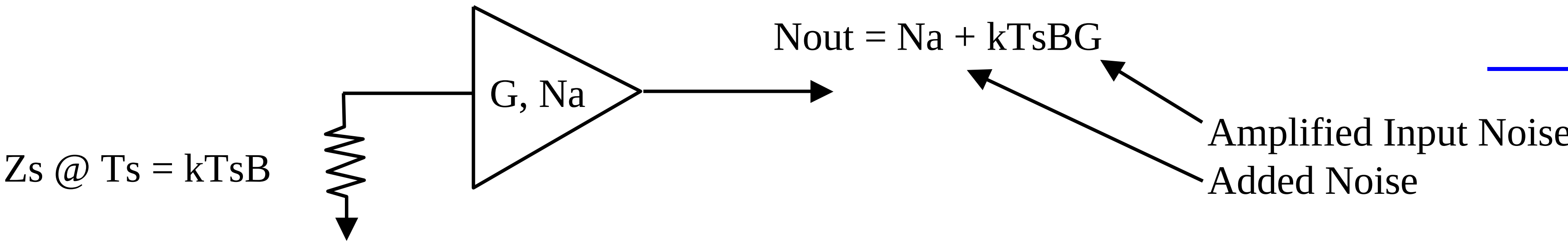
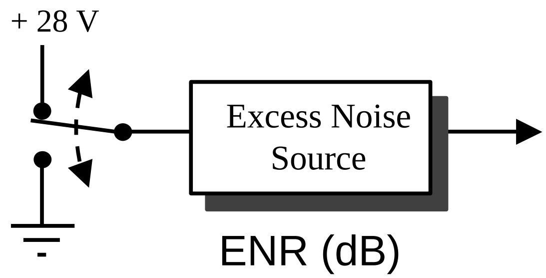
Noise Figure (NF)



- Measure of noise added by amplifier
- NF = 10 log [(S_i/N_i) / (S_o/N_o)]
- Perfect amp would have 0 dB NF

Y-factor Technique for NF Measurements



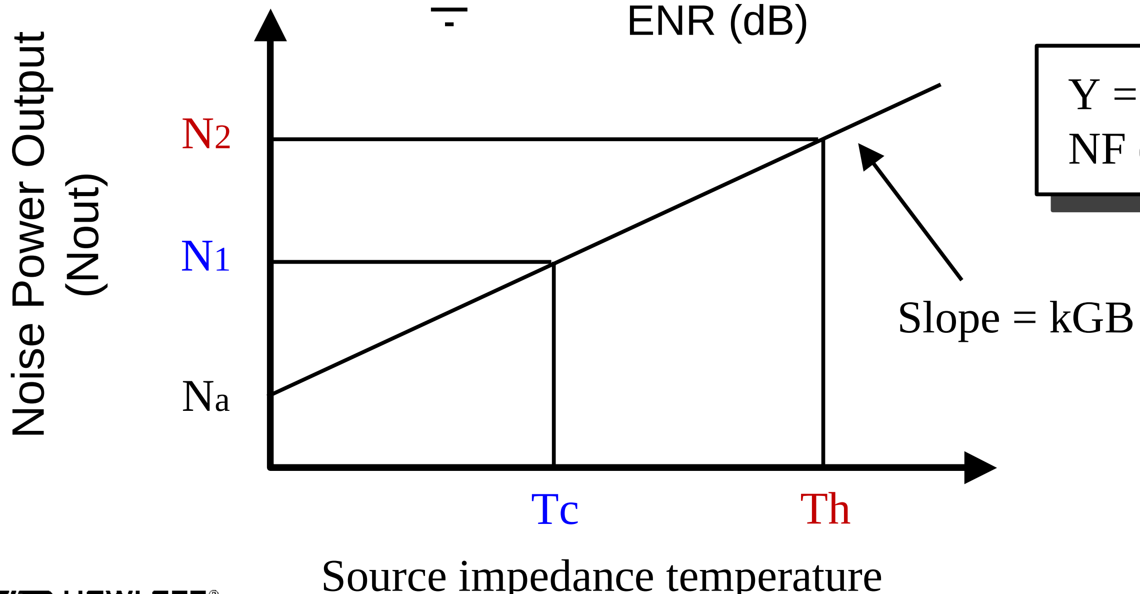


Th (noise source on) => N_2 (at amplifier output)

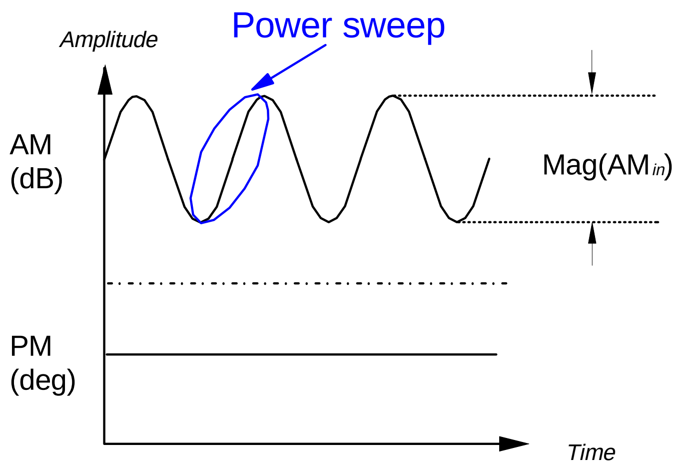
Tc (noise source off) => N_1 (at amplifier output)

$Y = N_2/N_1$

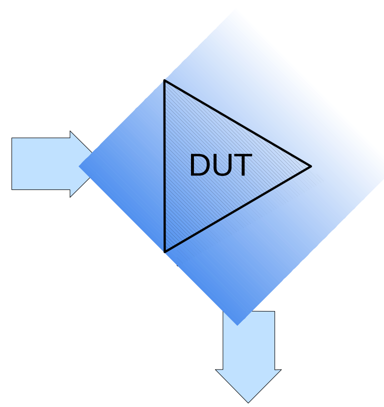
NF (dB) = ENR (dB) - 10 log (Y-1)



AM to PM Conversion



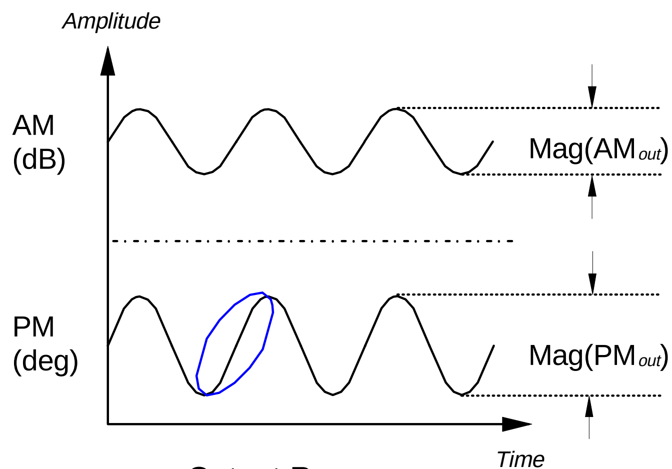
Test Stimulus



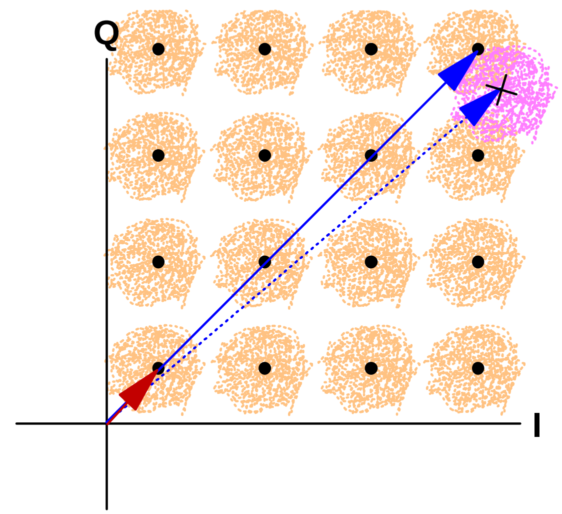
- undesired AM:
  supply ripple, fading, thermal
- desired AM:
  modulation (e.g. QAM)

AM - PM Conversion =

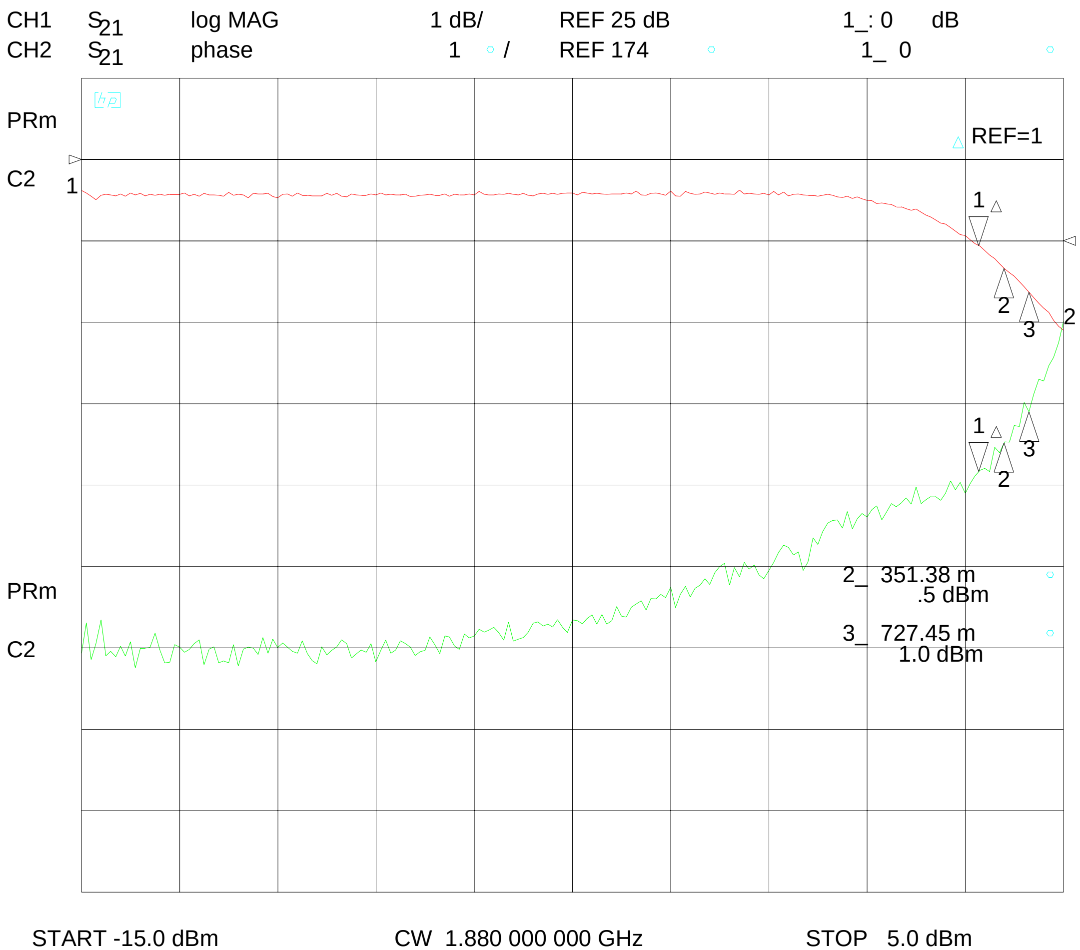
$$\frac{\text{Mag}(PM_{out})}{\text{Mag}(AM_{in})} \quad \text{(deg/dB)}$$



Output Response



Measuring AM to PM Conversion



- use transmission setup with a power sweep
- display phase of S21
- AM to PM = 0.727deg/dB

HEWLETT® PACKARD

Heat Sinking

- for power devices, a heat sink is essential to keep $T_{junction}$ low
- heat sink size depends on material, power dissipation, air flow, and $T_{ambient}$
- ridges or fins increase surface area and help dissipate heat
- usually device attaches directly to heat sink (flange mounts help)
- bolt device in place first, then solder