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RF Network Analysis Basics

May 24, 2001

presented by:

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RF Network Analysis Basics

HP 416A Signal Ratio Meter
1955

HP 8410 Network Analyzer
1967

Agilent Vector Network Analyzer
2001

What is Network Analysis?

Not about Computer Networks

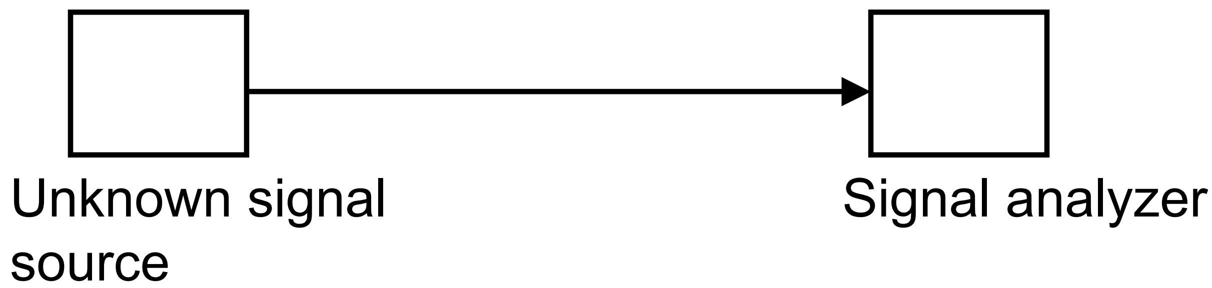
Networks are analog circuits, not computer communication paths.

Testing filters, attenuators, splitters, couplers, amplifiers, receivers, duplexers, mixers, and many more device types

Network analysis is the characterization of a device, circuit, or system derived by comparing a signal coming out of the device with a signal applied to the device.

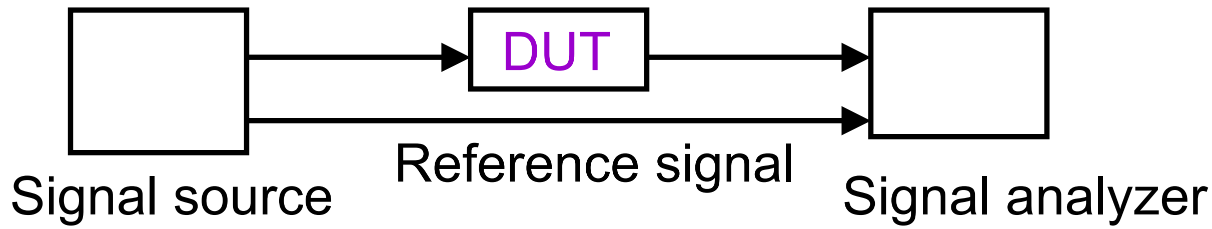
Network vs Signal Analysis

Signal Analysis Characterizes an Unknown Signal

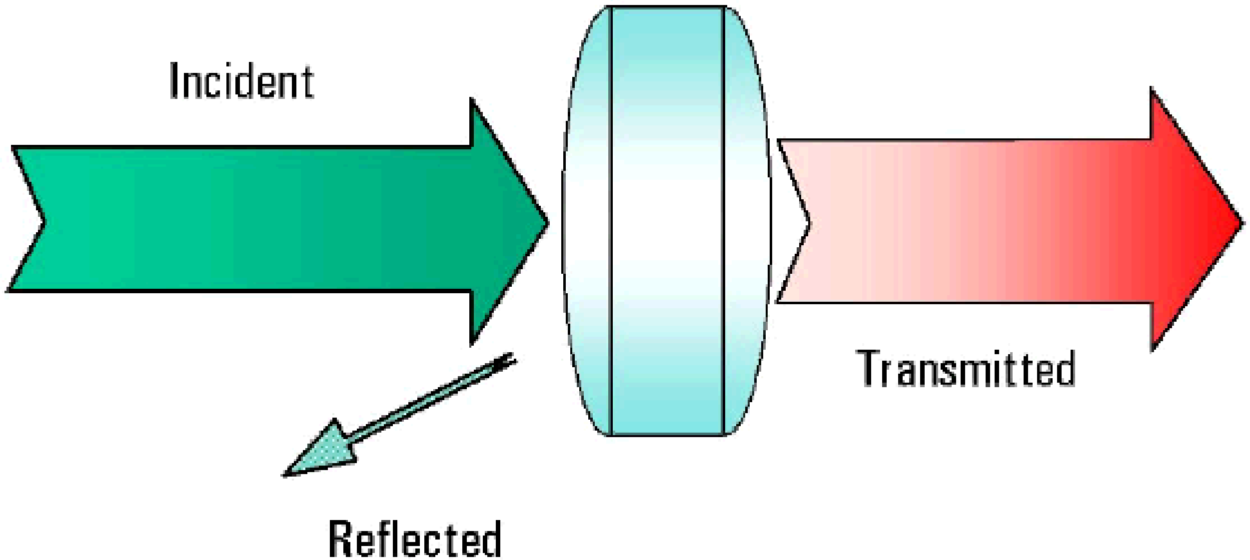


Network Analysis Characterizes an Unknown Circuit

(Device Under Test)



Device Characteristics



Why do we characterize devices?

Verify building block performance — Test before RF system installation

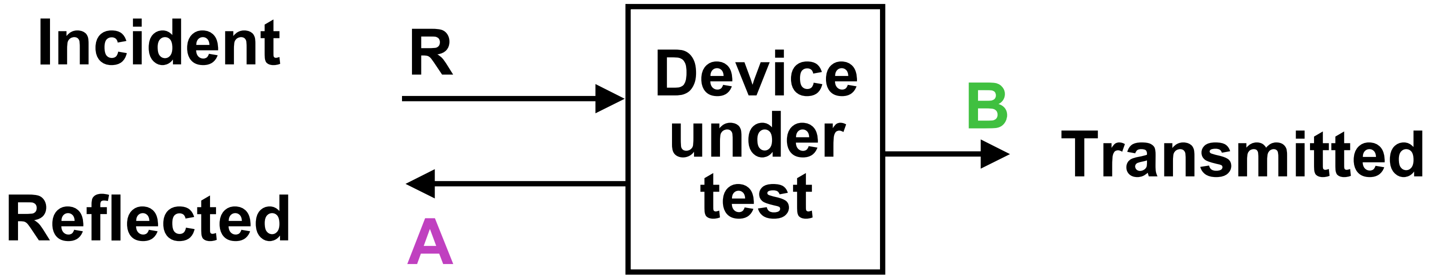
Ensure distortionless signal transmission
- Test for linear and non-linear distortion
- Flat frequency response
- Gain compression
- AM-PM conversion errors

Ensure good impedance match — Efficient power transfer

How do we characterize devices?

1

Utilize a stimulus/response test system.



Network analyzer receivers R, A, and B

Reverse tests: Move stimulus to other port

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How do we characterize devices?

2 Measure the amplitude and phase ratios over the device's frequency.

Forward and Reverse
Transmitted and Reflected

$$\frac{\text{Transmitted}}{\text{Incident}} = \frac{B}{R}$$

$$\frac{\text{Reflected}}{\text{Incident}} = \frac{A}{R}$$

vs frequency

How do we characterize devices?

3 Calculate application parameters from the ratio data.

Transmission Parameters

Transmission coefficient, Τ and τ

Insertion gain and loss

S-parameters S21 and S12

Insertion phase

Group delay

Reflection Parameters

Reflection coefficient, Γ and ρ

Return loss

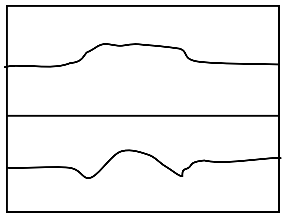
S-parameters S11, S22

Impedance, Z, R+jX
Admittance, A, G+jB

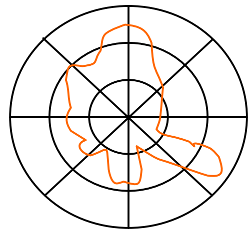
Standing wave ratio, SWR

How do we characterize devices?

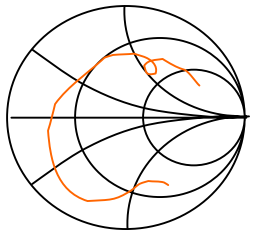
4 Present the results as numerical, graphical, or data objects.



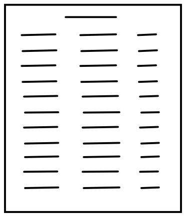
XY plot



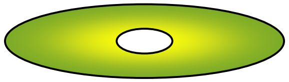
Polar plot



Smith chart



Printed table



Data file

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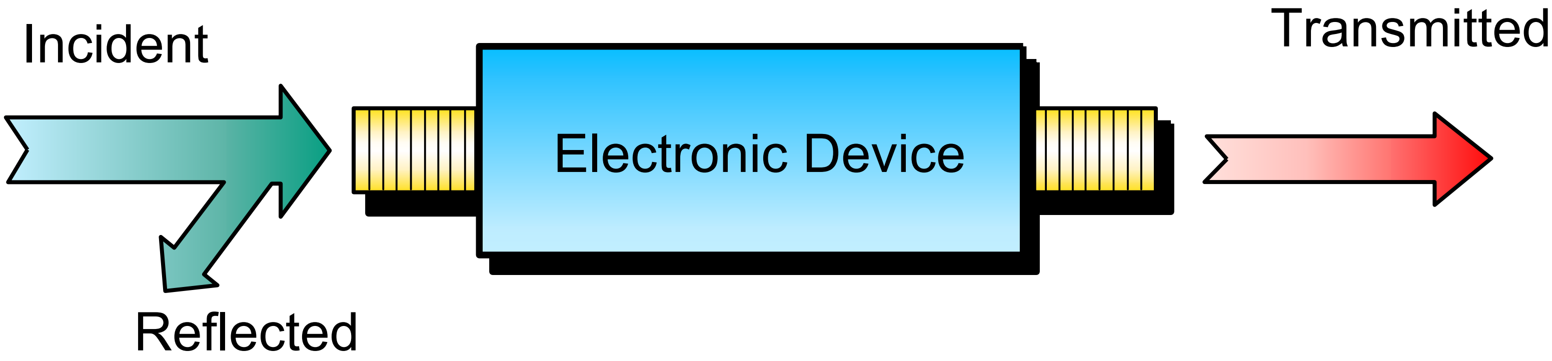
Electronic Device Characteristics



A vector network analyzer measures relative amplitude and phase:

$$\frac{\text{Reflected}}{\text{Incident}} \quad \text{and} \quad \frac{\text{Transmitted}}{\text{Incident}}$$

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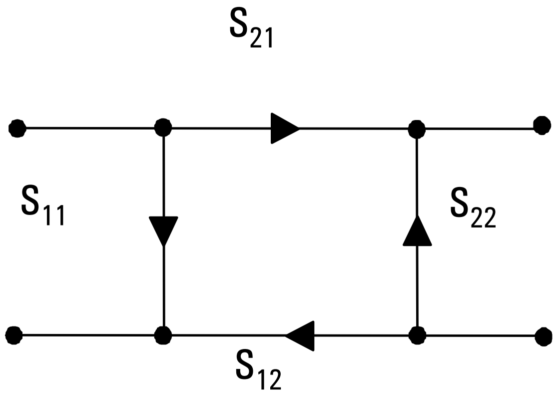
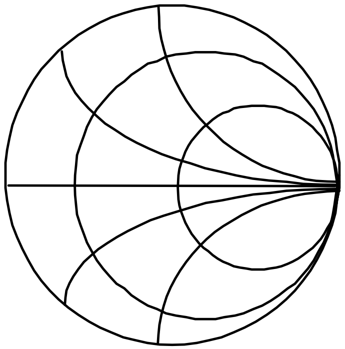
Reasons to Measure Amplitude and Phase

1. Complete characterization of linear networks

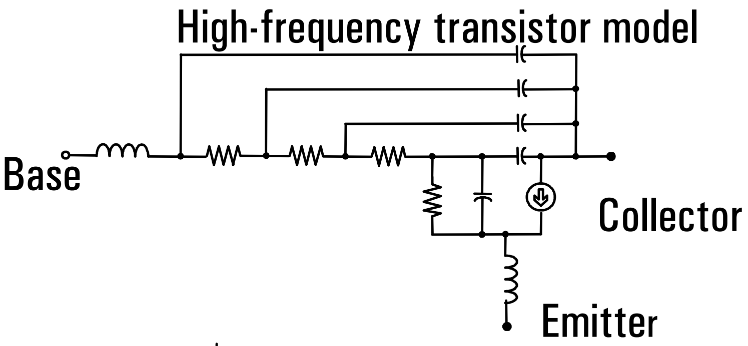


2. Complex impedance needed to design matching circuits

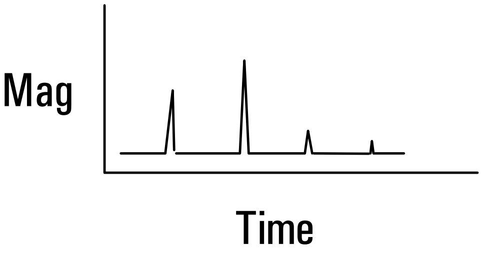


Reasons to Measure Amplitude and Phase

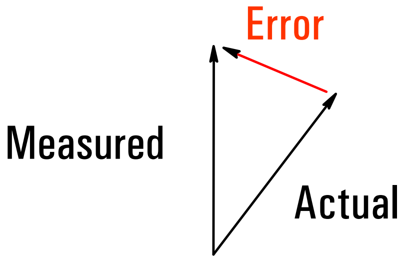
3. Complex values needed for device modeling



4. Time-domain characterization



5. Vector-error correction



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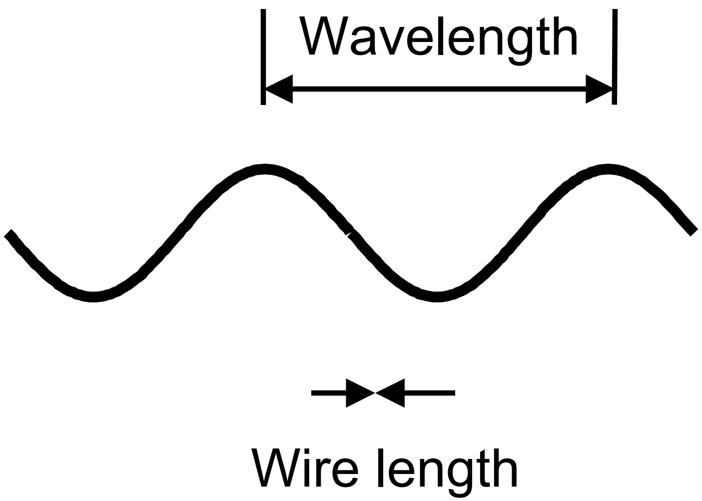
Transmission Line Basics

Low frequencies (< 100 MHz)

Wavelengths are much longer than the wire length.

Current travels down wires easily for efficient power transmission.

Voltage and current magnitude and phase are not dependent upon the position along the wire.



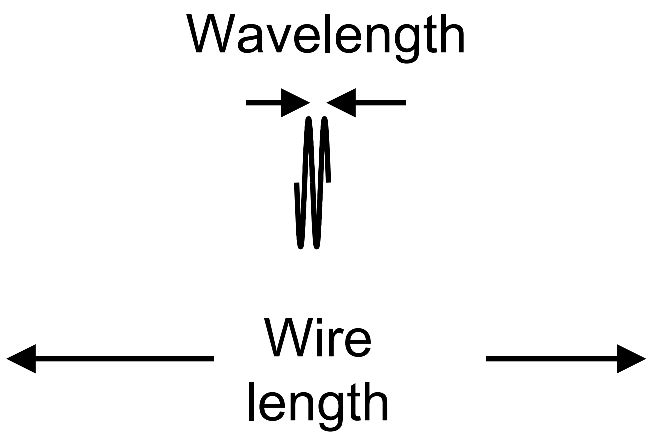
Transmission Line Basics

High frequencies (> 100 MHz)

Wavelength is less than the length of transmission medium.

Match the load and source to the line's characteristic impedance (Z_o) for maximum power transfer.

When poorly matched, the voltage and phase are dependent upon the position along the line.



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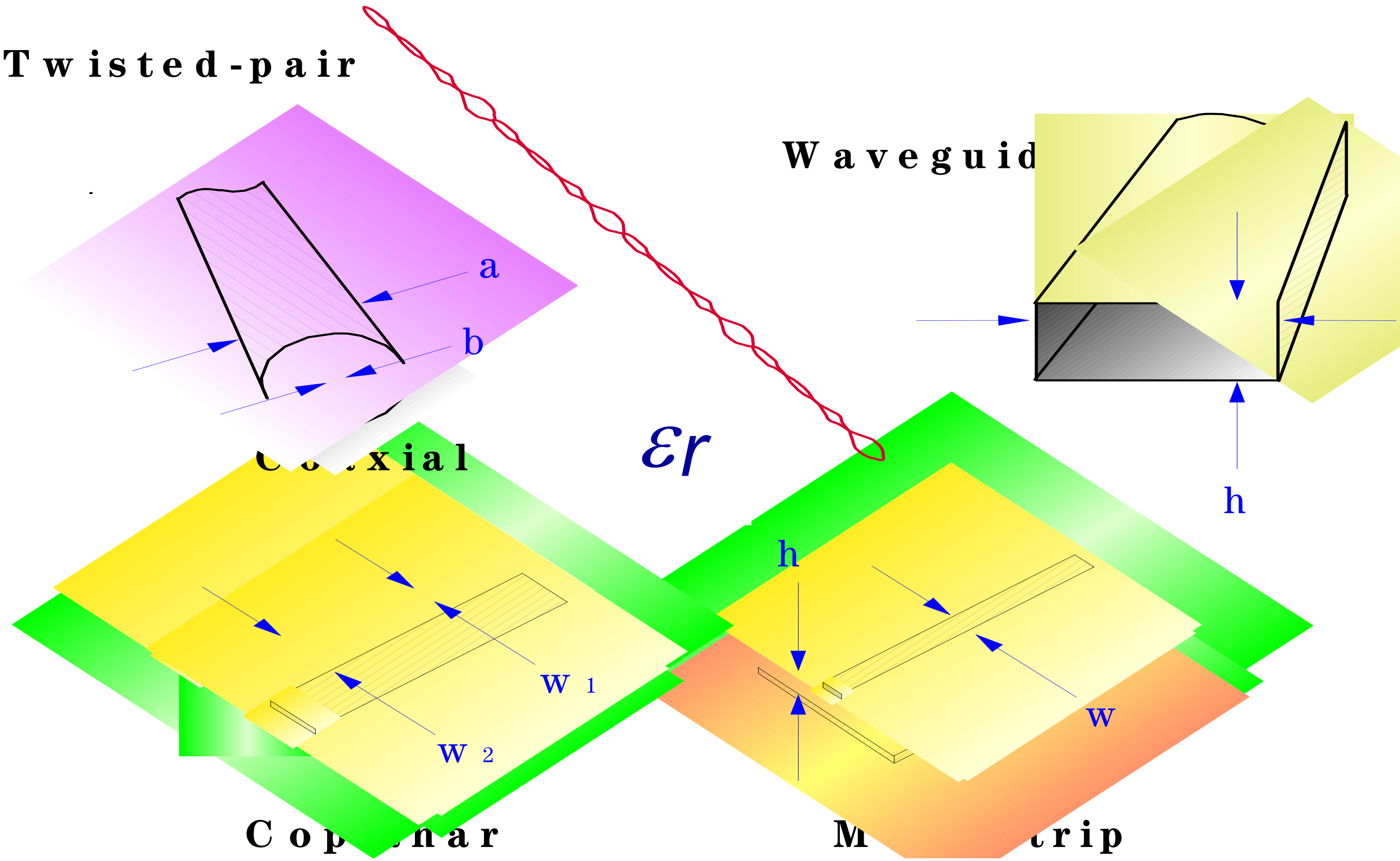
Transmission Lines Come in Many Forms



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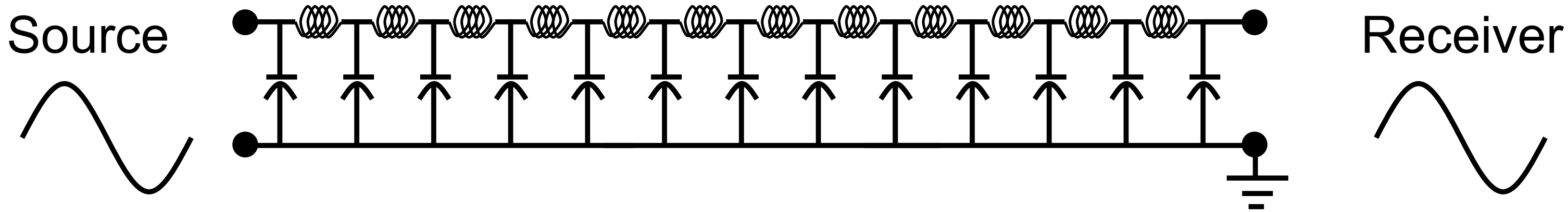
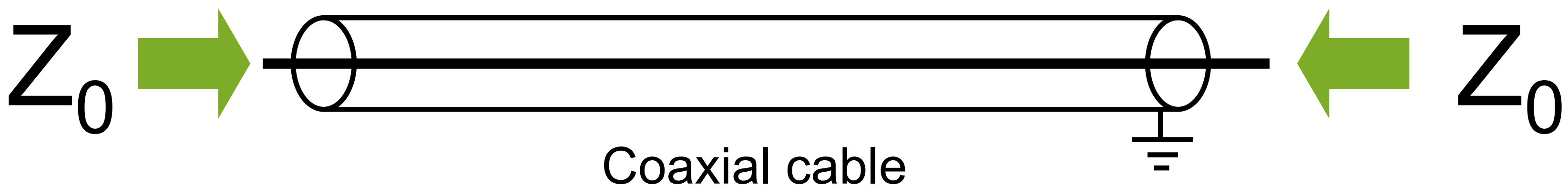
Transmission Lines



Equivalent circuit of an ideal transmission line

Loss
Impedance
Delay



Coaxial cable

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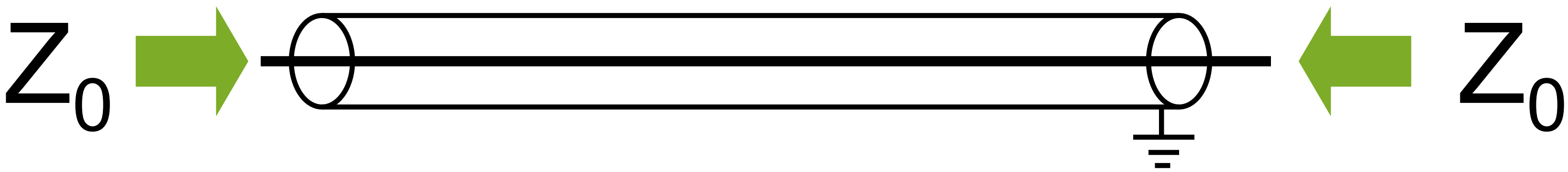
Characteristic Impedance



Has common values: 50 Ω (Ohms) and 75 Ω

Describes the relationship between the voltage and current traveling waves

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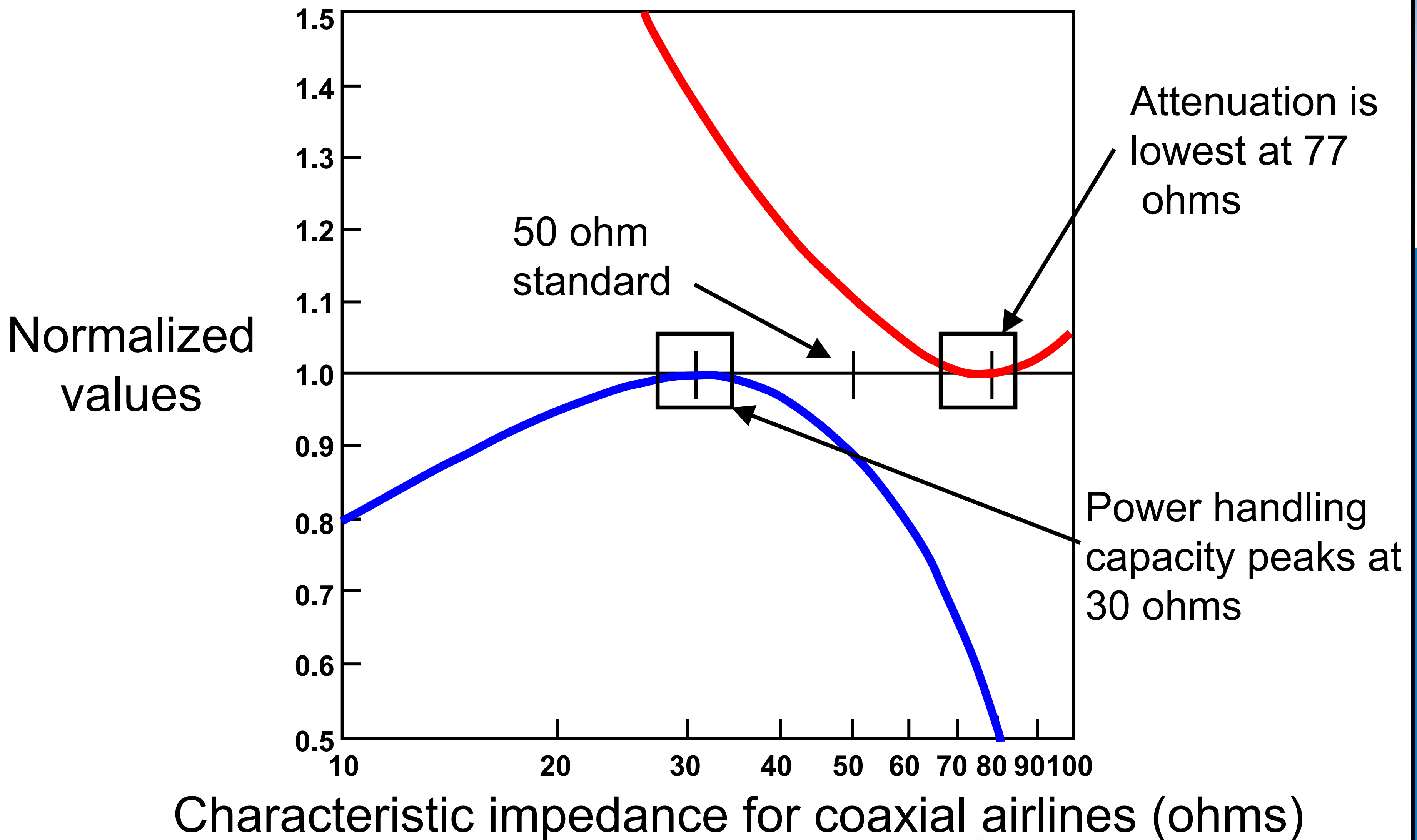
Why 50 Ohms and 75 Ohms?



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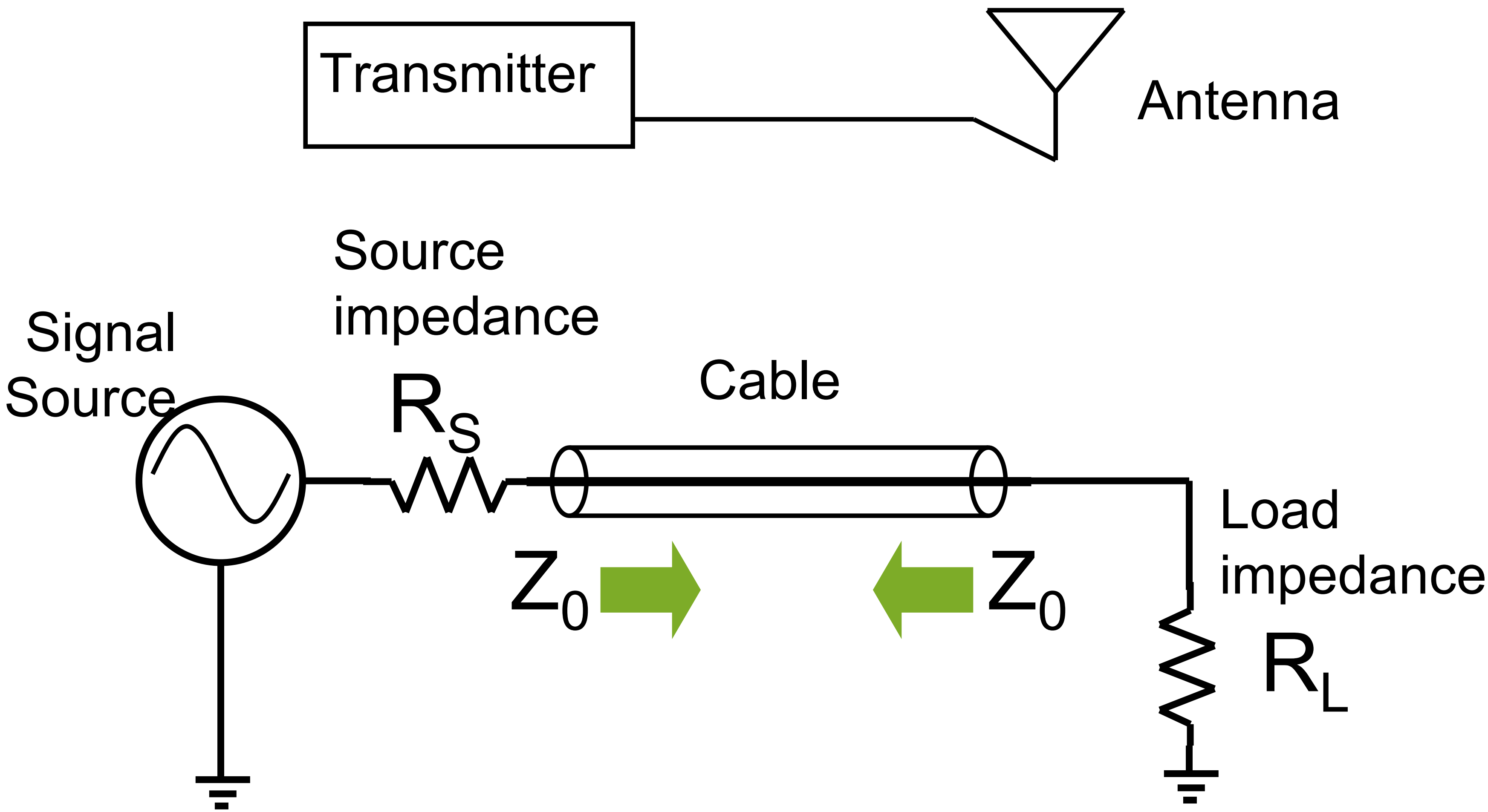
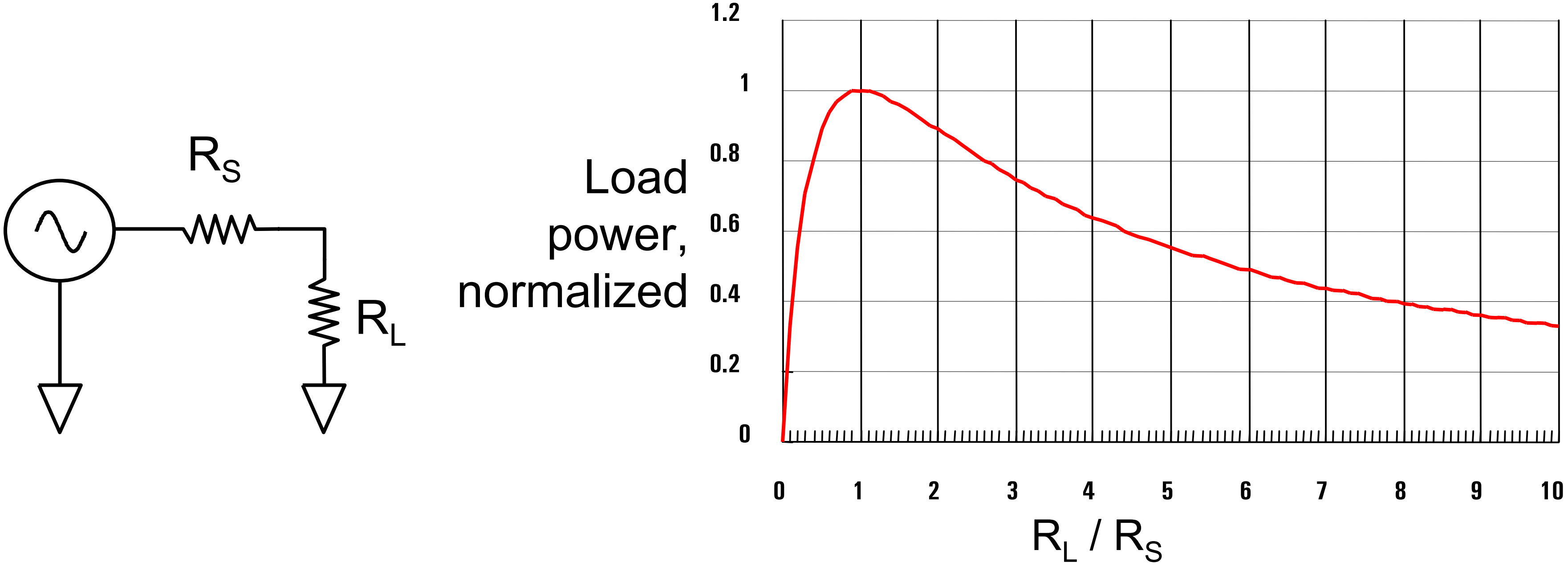
Optimizing Power Transfer



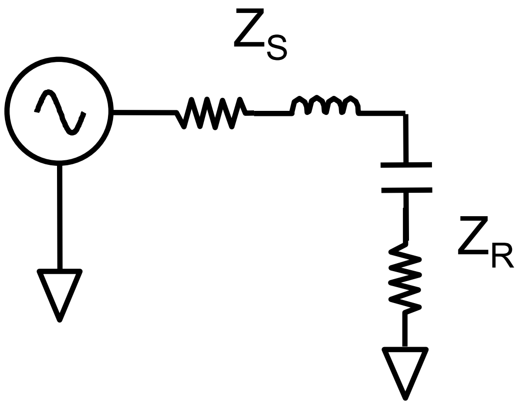
Good match: $R_S = Z_0 = R_L$

Power Transfer Efficiency



Maximum power is transferred when $R_L = R_S$

Power Transfer Efficiency



Maximum power transfer for complex impedance requires a conjugate match.

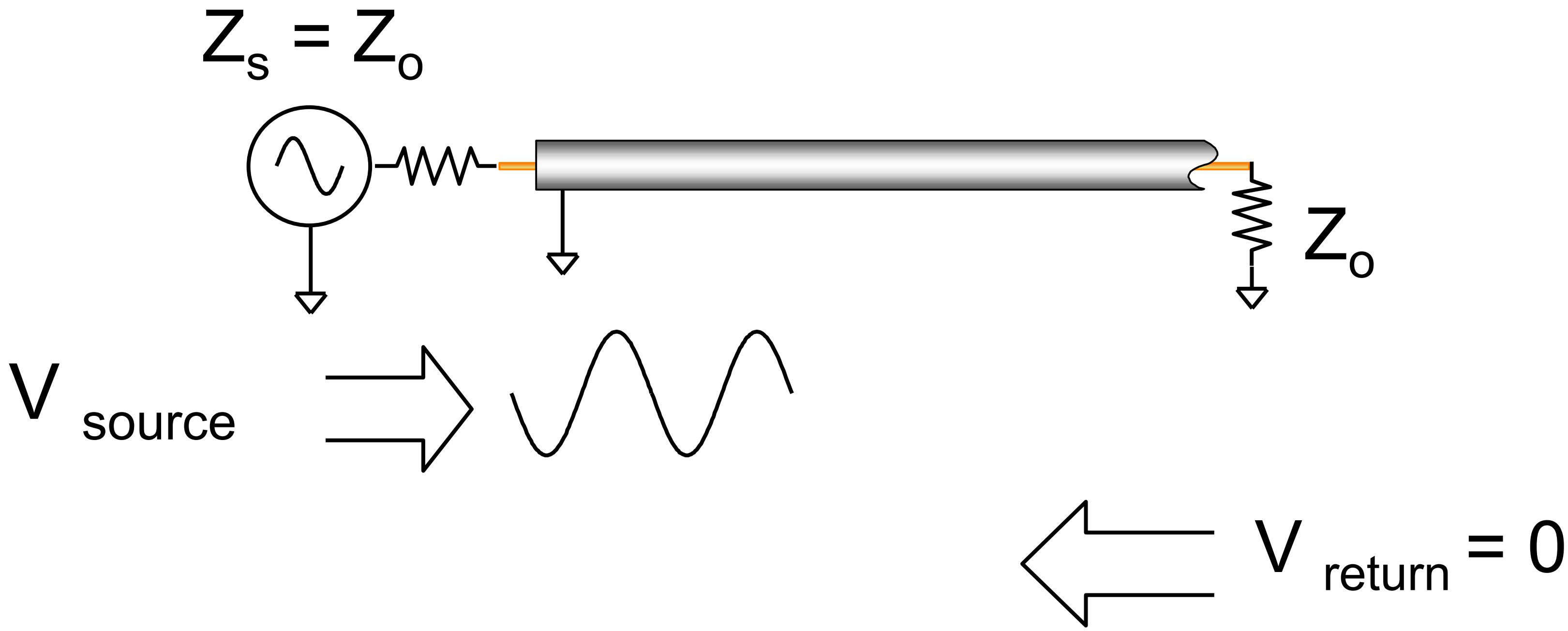
$$Z_S = R_S + jX \qquad Z_R = R_R - jX$$

$$Z_S = Z_L^*$$

$$Z_R = 0.6 + j0.3$$

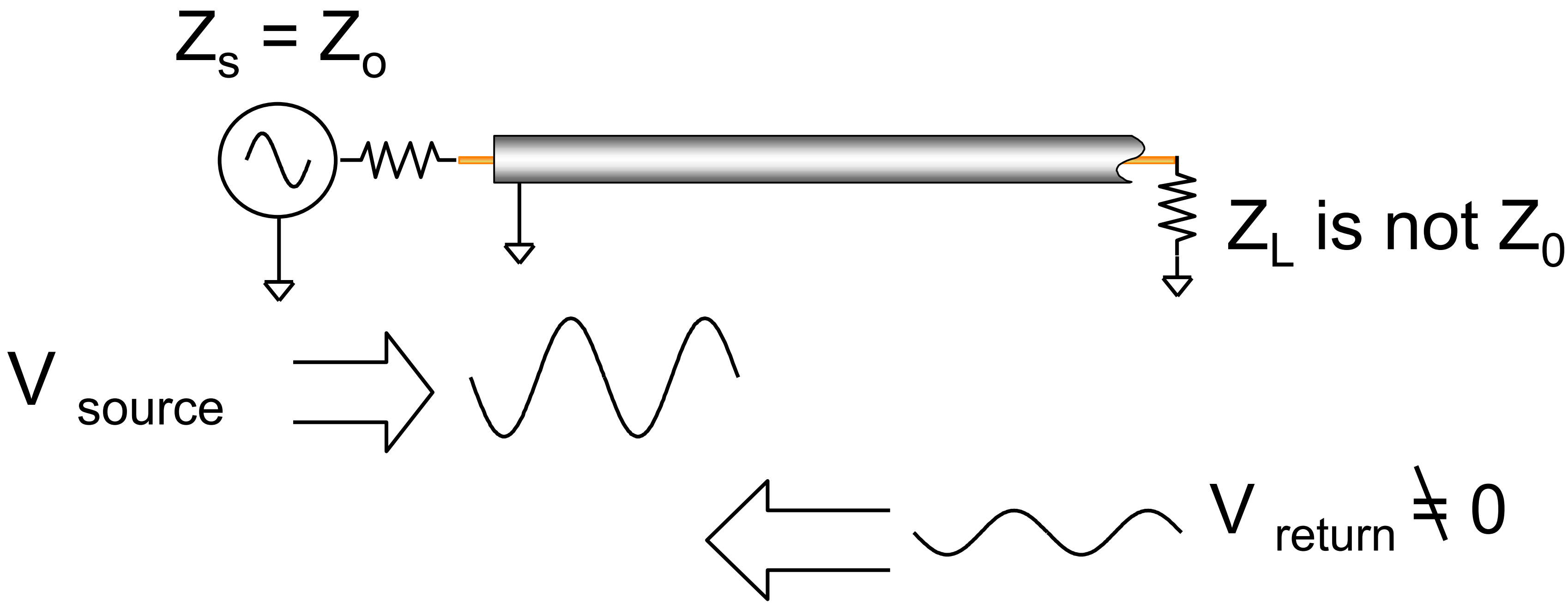
$$Z_L^* = 0.6 - j0.3$$

Transmission Line Terminated with Z_o



The load match is perfect and no signal is reflected back to the source.

Transmission Line Not Terminated with Z_o



The load match is not perfect and a signal is reflected back to the source.

Characterizing Complex RF and Microwave Devices

Low frequency techniques don't work

The parameters H, Y, and Z
require open and short circuits

Complex impedance computation is required

Matching devices over wide
frequency ranges is tough

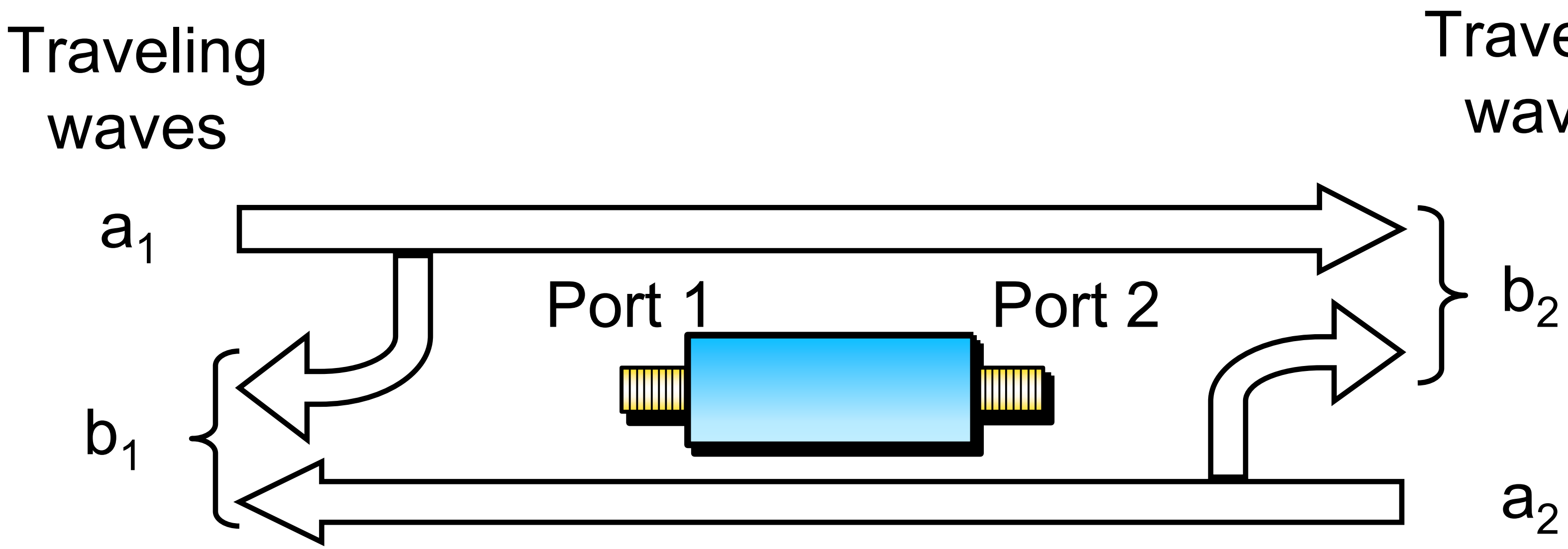
Scattering parameters characterize RF and microwave devices

Why Use S-parameters?

- Measured using a network analyzer
- Relate to familiar measurements
- Cascade to measure system performance
- Used in device simulation

S-parameters are the most efficient tools for characterizing complex devices at high frequencies.

S-parameters Defined

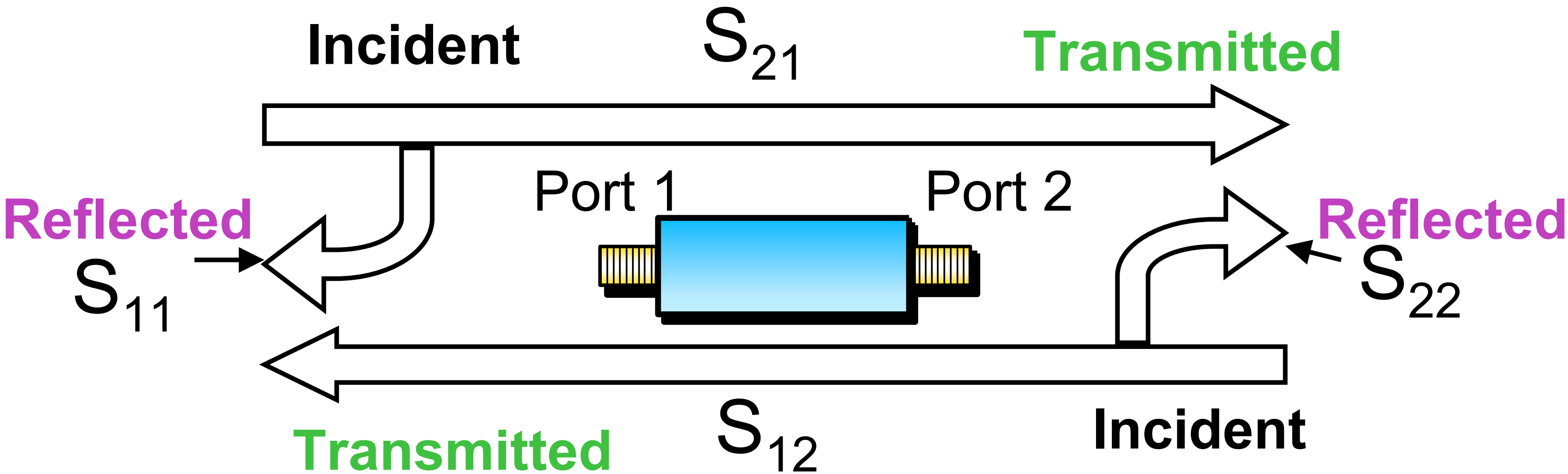


$$S_{21}$$

First number - port where signal emerges (to)

Second number - port where signal is applied (from)

S-parameters Defined



Equating S-parameters with Common Measurement Terms

S11 = forward reflection coefficient ***(input match)***
S22 = reverse reflection coefficient ***(output match)***
S21 = forward transmission coefficient ***(gain or loss)***
S12 = reverse transmission coefficient ***(isolation)***

Example: The magnitude of S21 is gain or loss

S-parameters are

- Complex numbers
- Linear values
- Expressed in dB to see wide range of values

S-parameters Allow Designers to Optimize Power Transfer

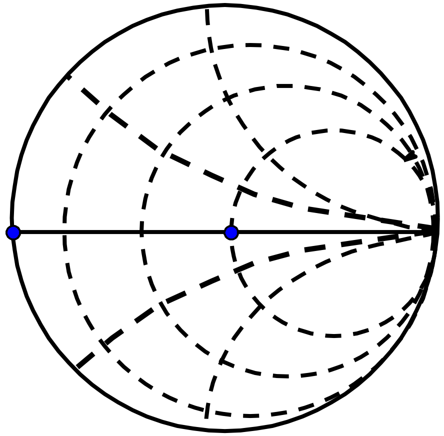
Optimum power transfer between mismatched devices

Requires

S-parameters

S11 and S22

Smith chart



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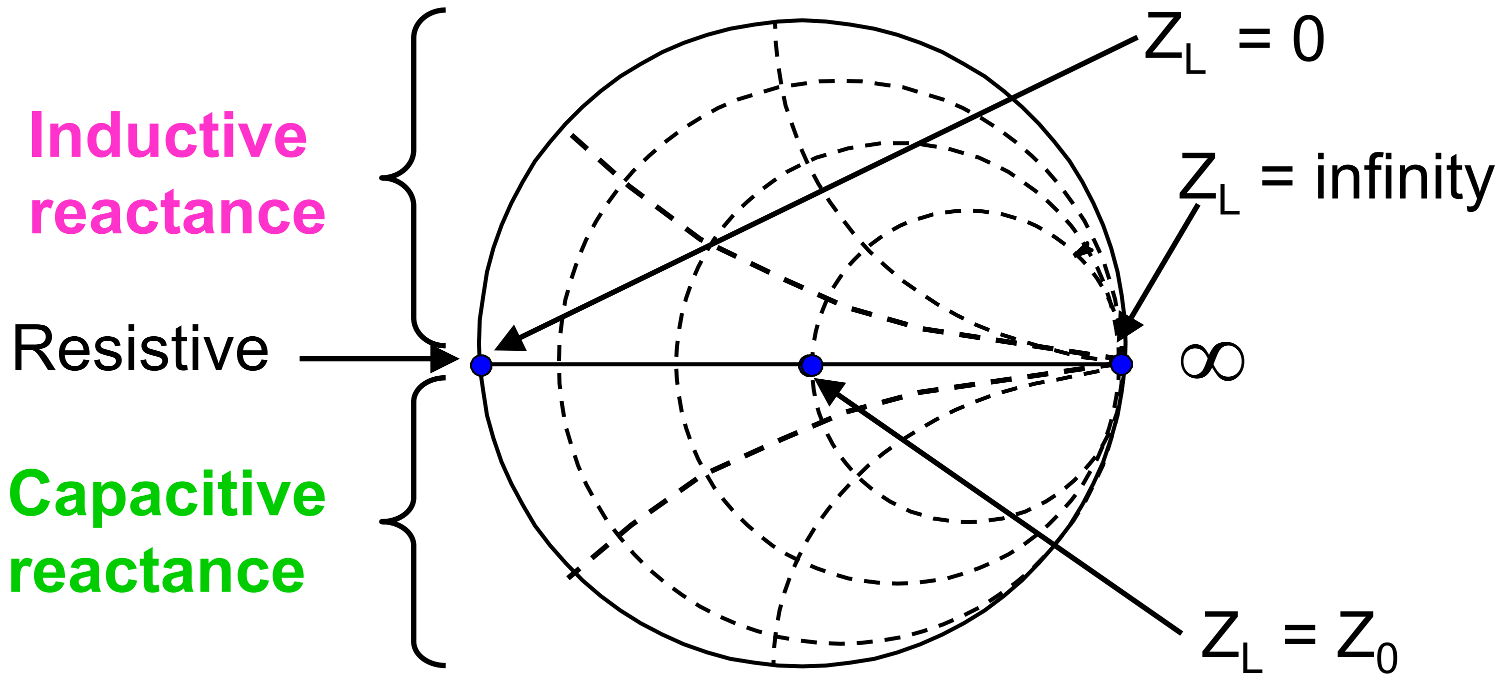
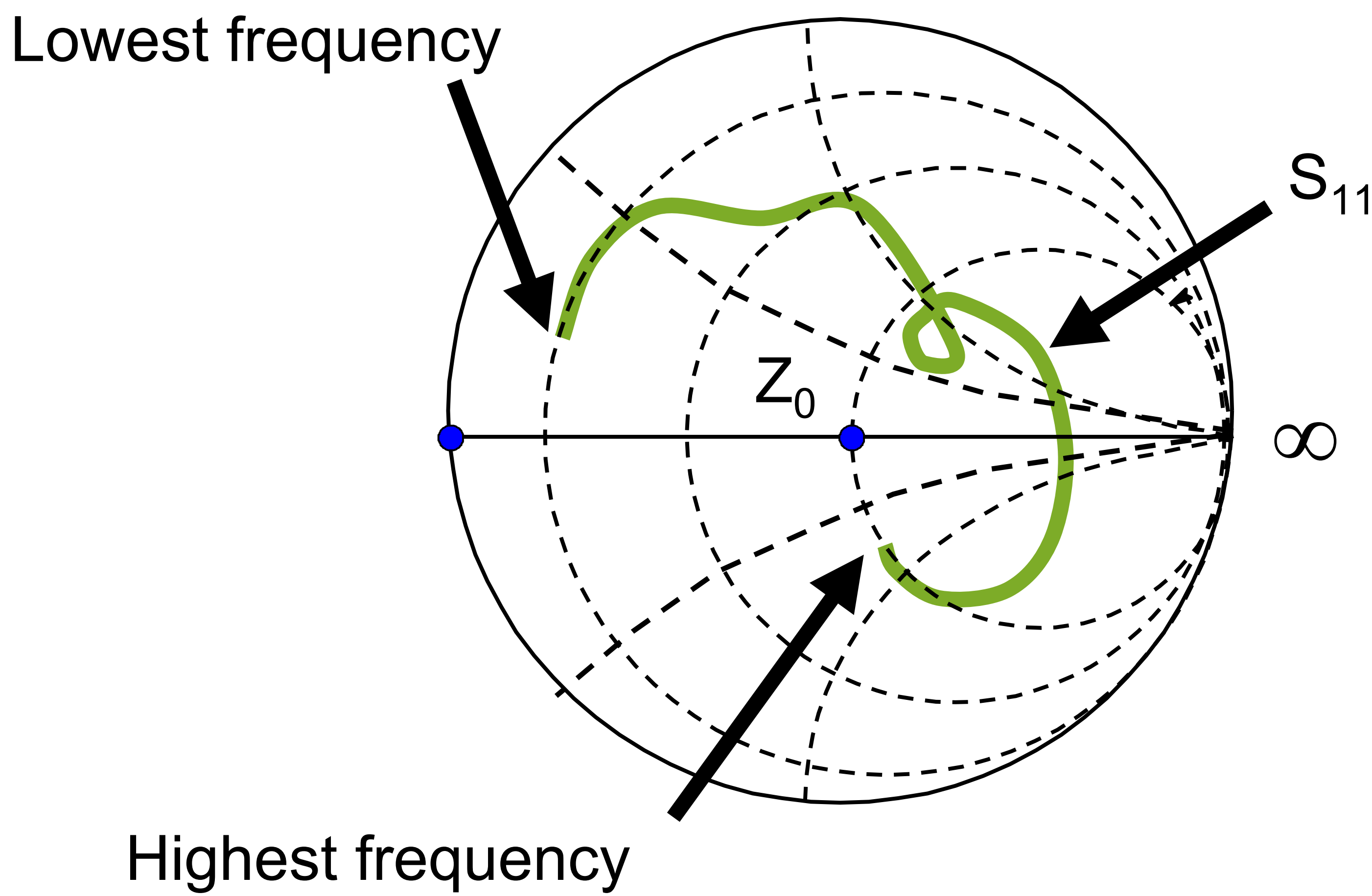
The Smith Chart Maps

Rectilinear Impedance onto a Polar Plane



Circles = constant resistance
Arcs = constant reactance

Impedance Plotted Over Frequency



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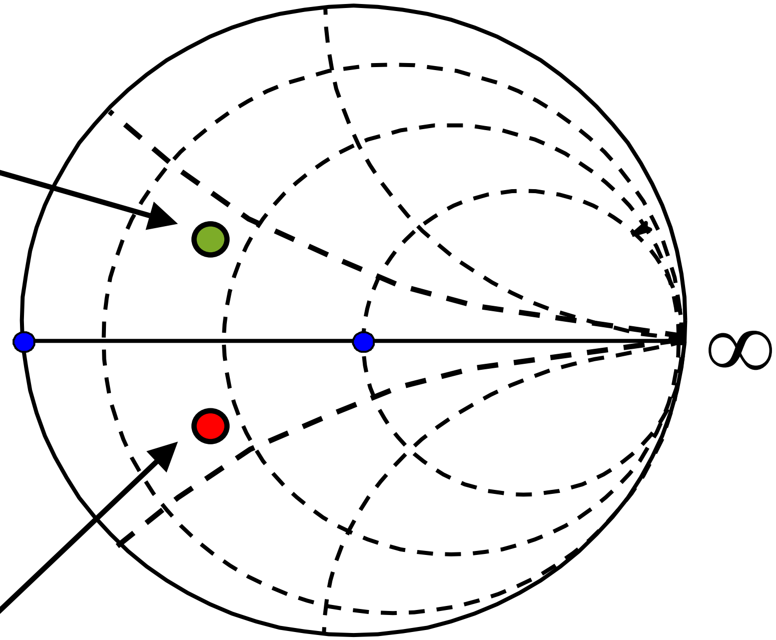
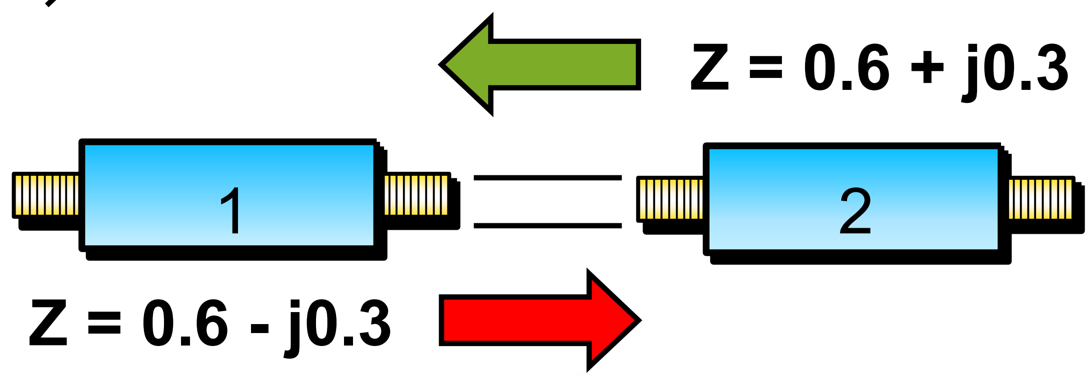
Conjugate Matching for Optimum Power Transfer

Device output impedance
= 0.6 + j0.3



The conjugate match: the numbers are the same, but the reactance sign is opposite

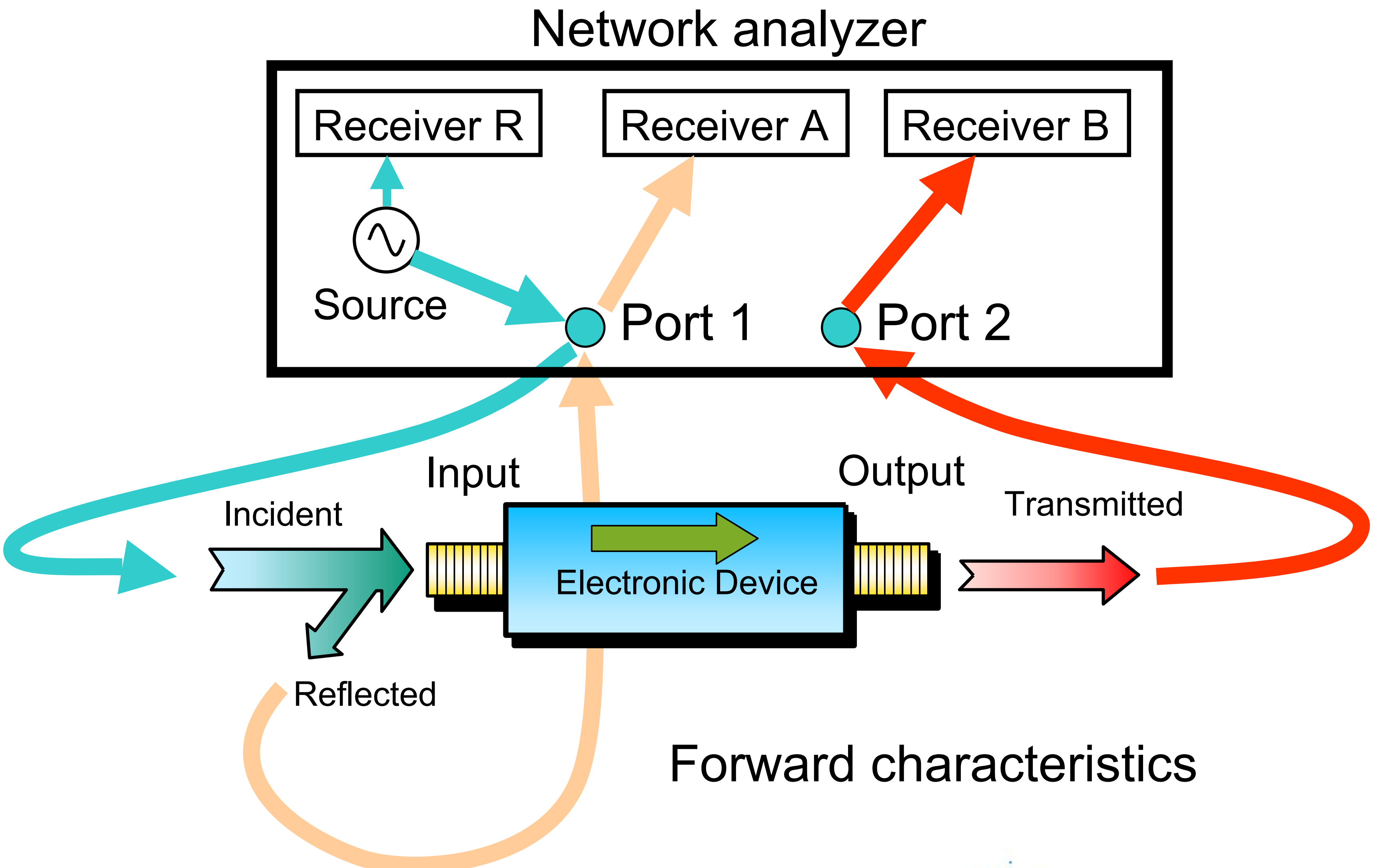
Conjugate impedance
= 0.6 - j0.3



Let's take a Break

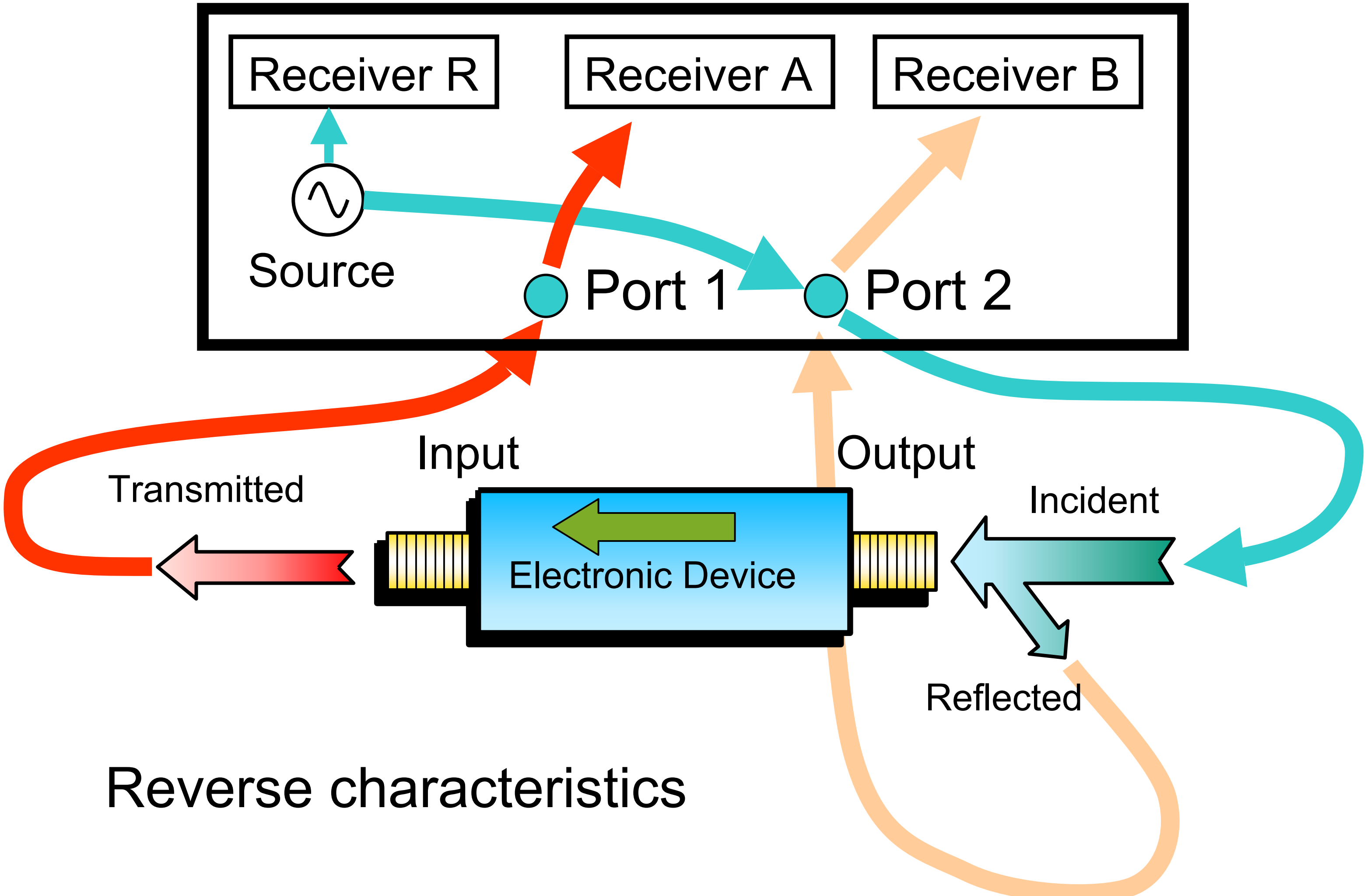
Questions and Answers

Network Analyzer Operation



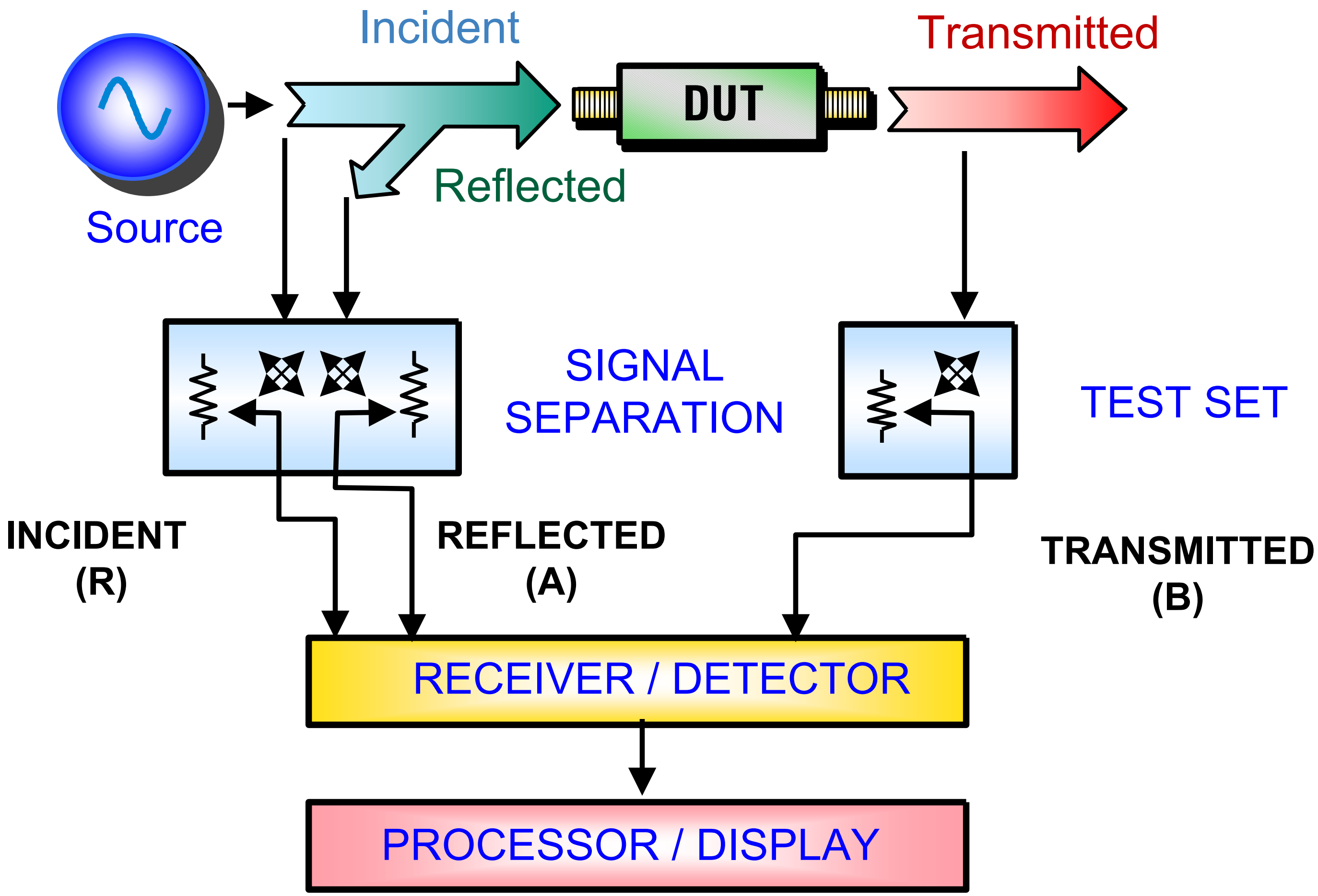
Forward characteristics

Network Analyzer Operation



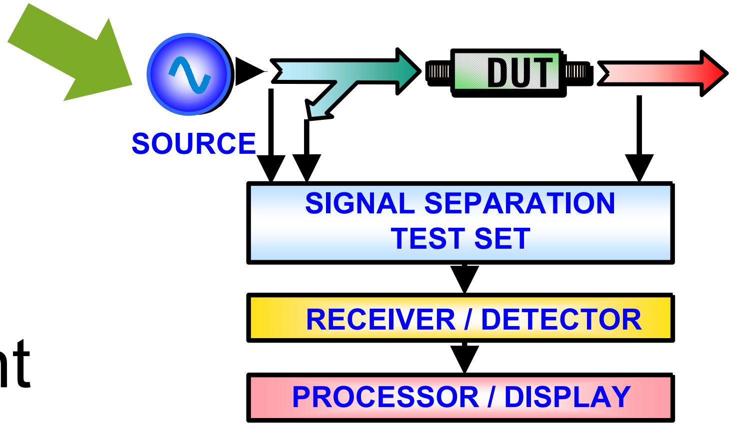
Reverse characteristics

Generalized Network Analyzer Block Diagram

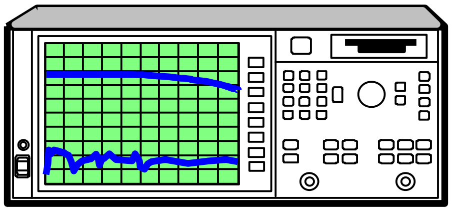


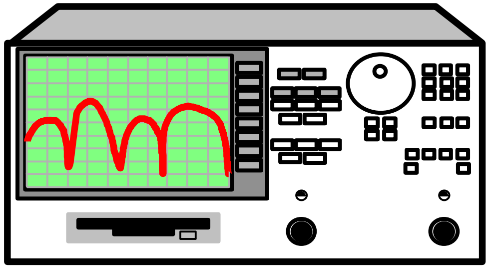
Source

Provides DUT Stimulus

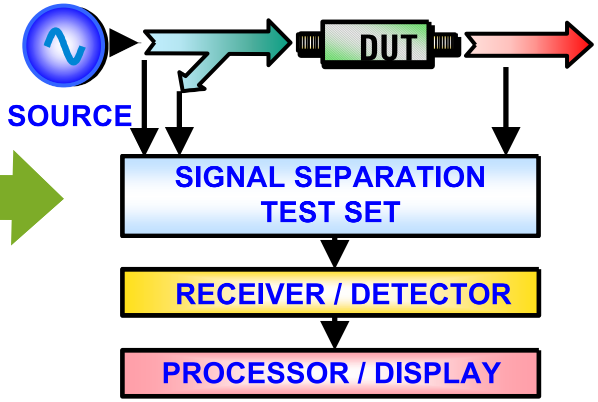


- Supplies stimulus, or incident signal, for testing
- Swept frequency or power
- Most analyzers sold today have ***integrated, synthesized*** sources



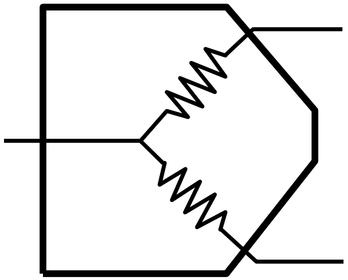


Signal Separation



- Measures the incident signal for a reference
- Separates the incident and reflected signals

Splitter

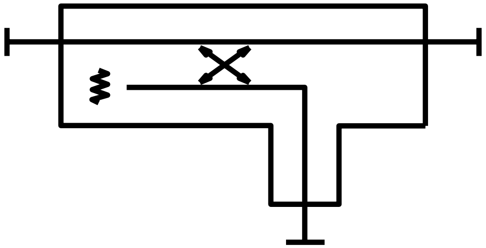


Non-directional

Broadband

6 dB loss

Directional coupler

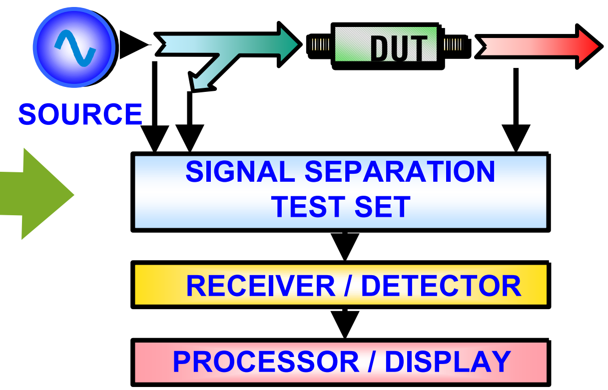


Directional

Microwave

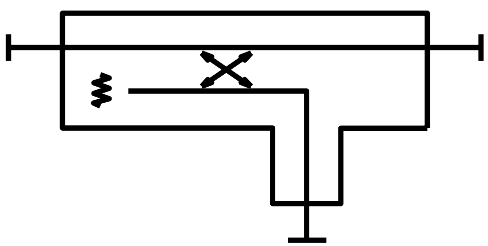
Low losses

Signal Separation



- Measures the incident signal for a reference
- Separates the incident and reflected signals

Directional coupler

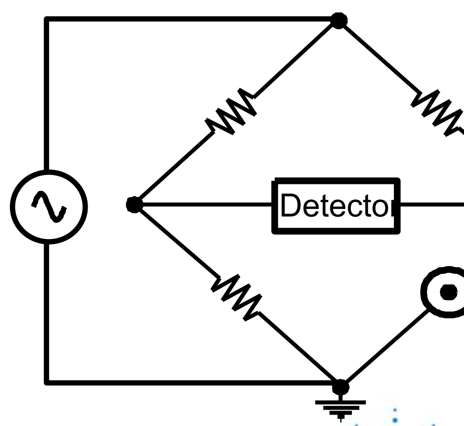


Directional

Microwave

Low losses

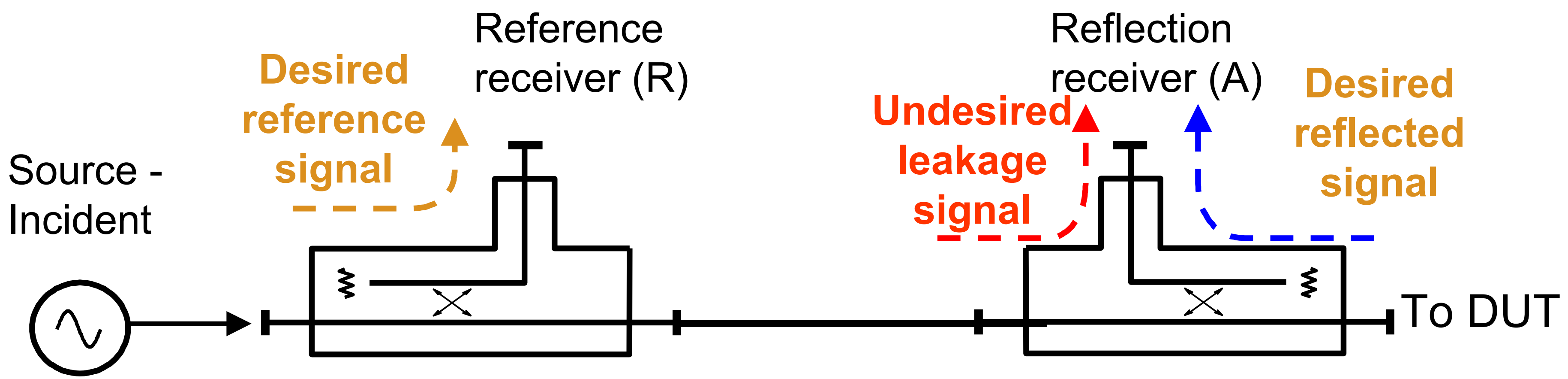
Bridge



Broadband

Some loss

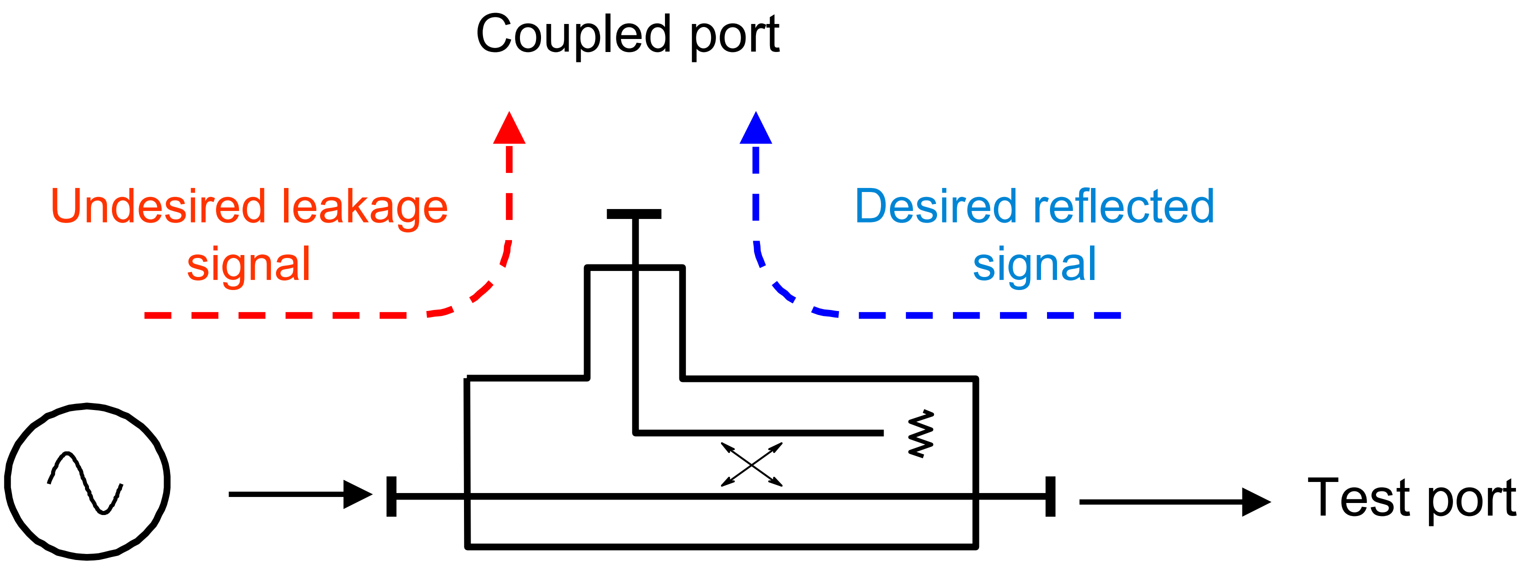
Directional Coupler Use



Sends a small part of the incident signal to R

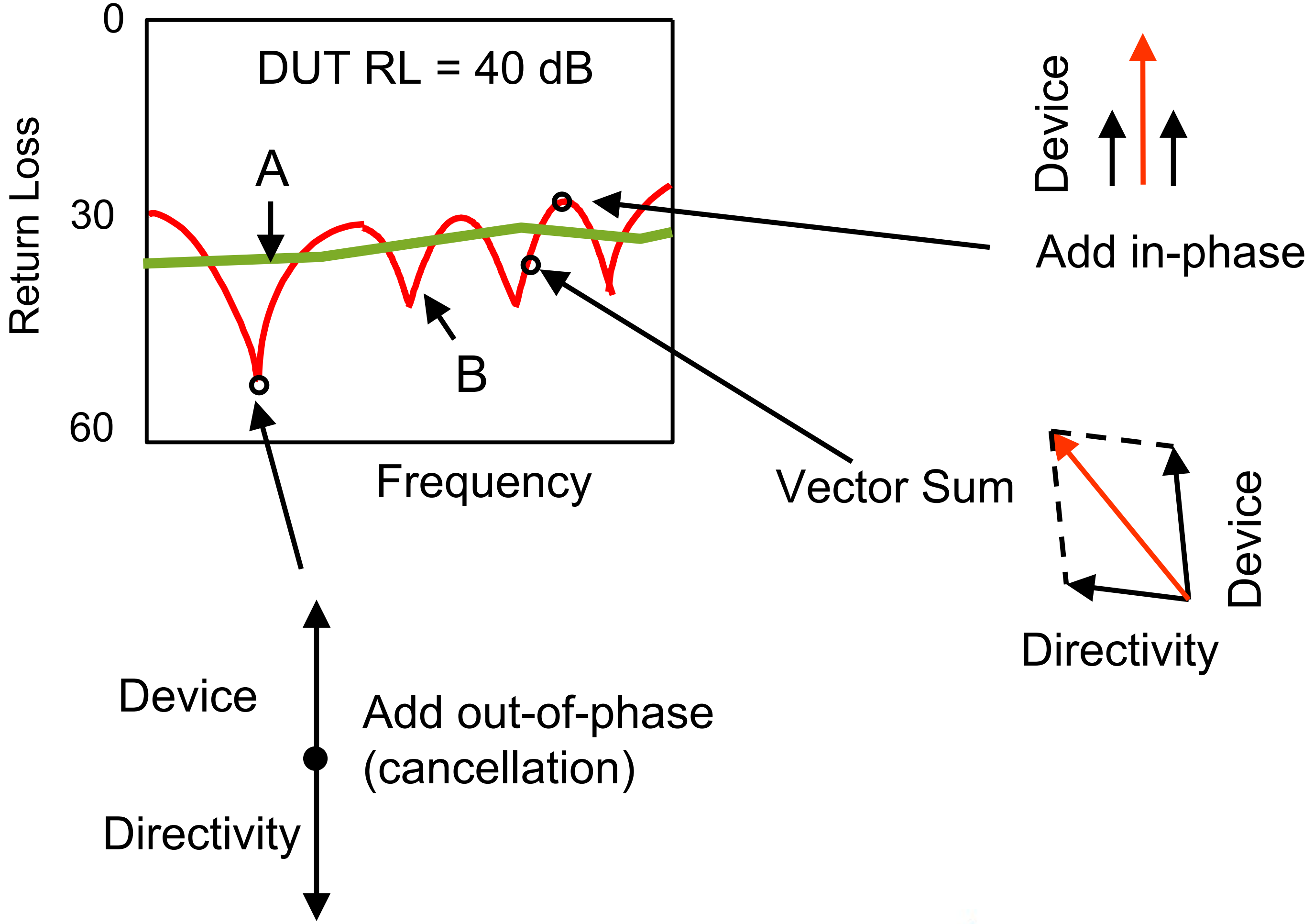
Sends a small part of the reflected signal to A

Directivity Measures Coupler Performance



Directivity is a measure of how well a coupler can separate signals moving in opposite directions

Directivity's Affect on Return Loss



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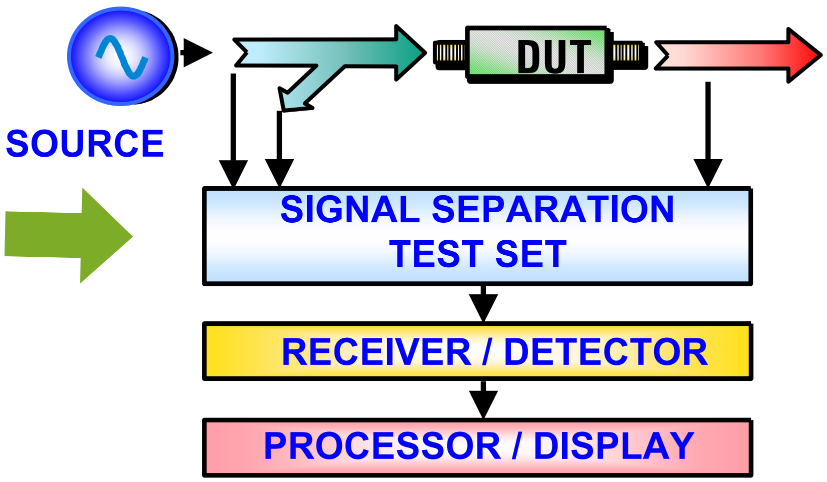
Test Sets

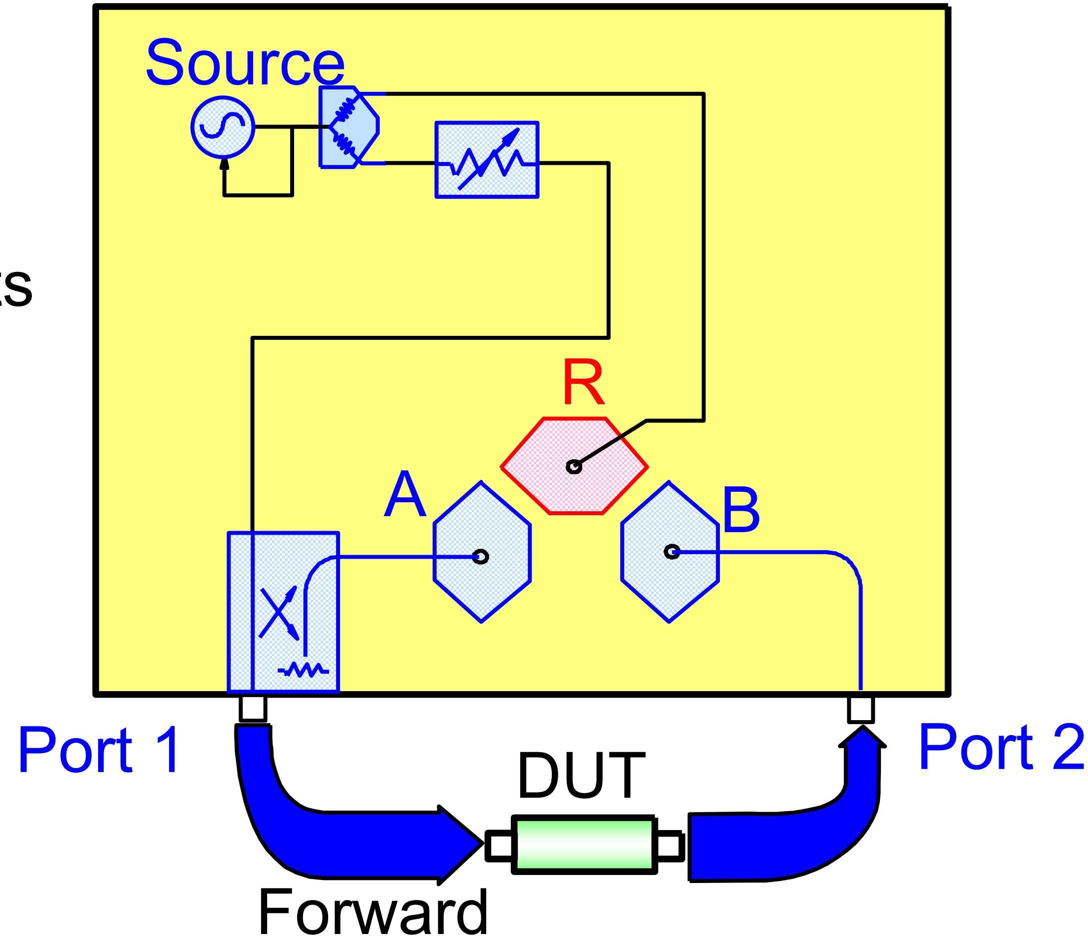


Transmission Test Set (T/R)

S-parameter Test Set

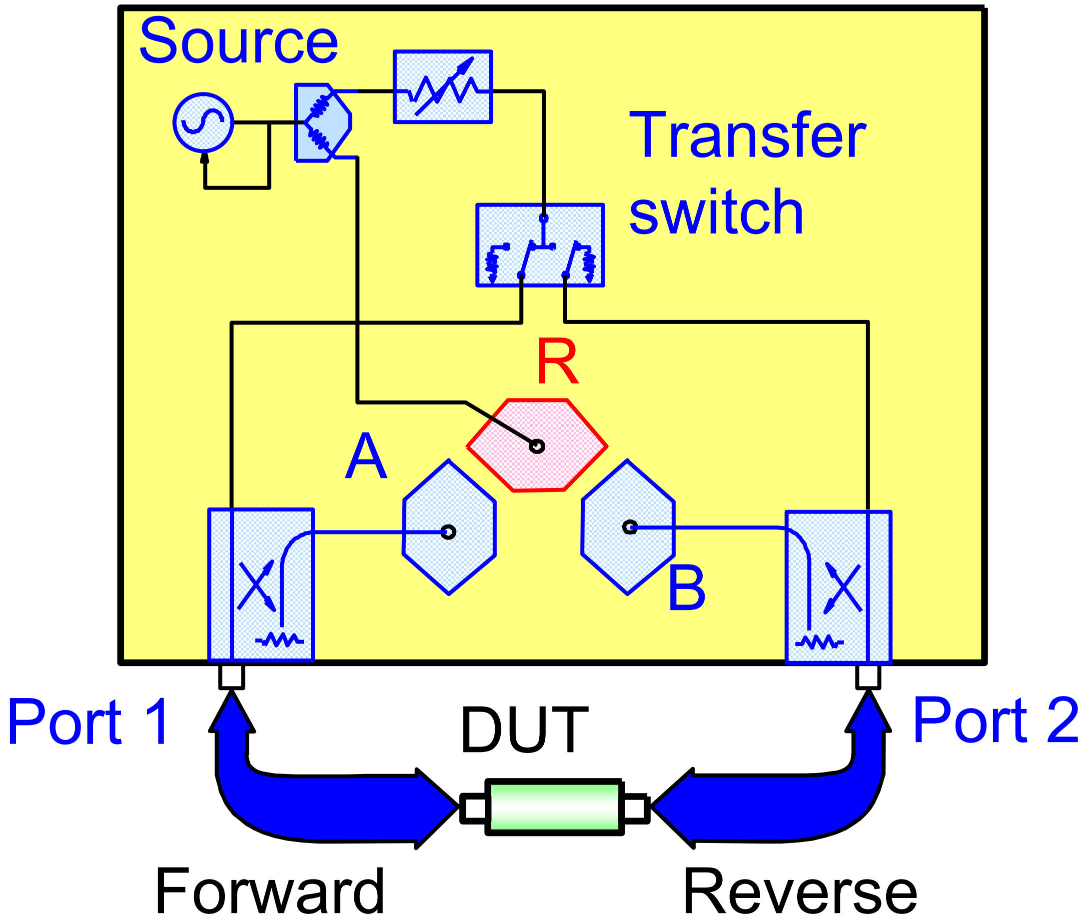
Transmission/ Reflection Test Set

- Forward measurements only
- Limited calibration

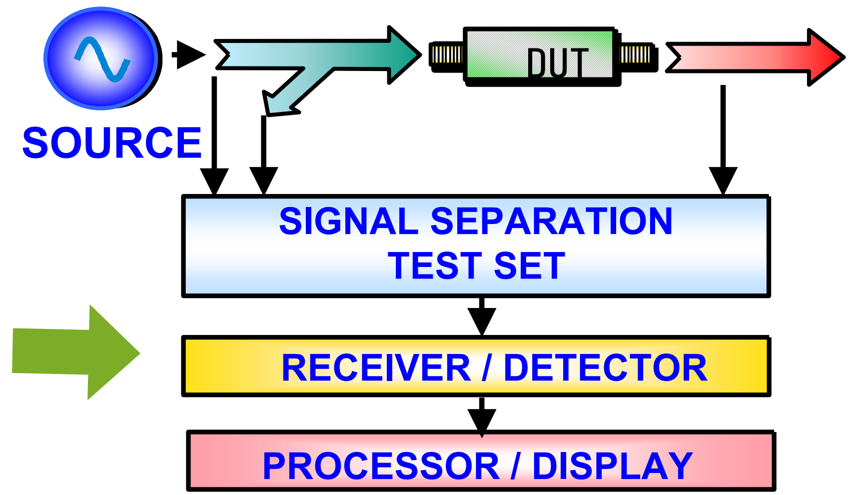


S-parameter Test Set

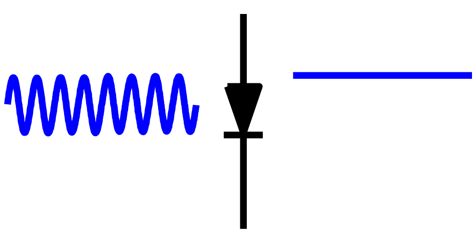
- Forward and reverse measurements
- Extensive calibration possible



Receiver and Detector

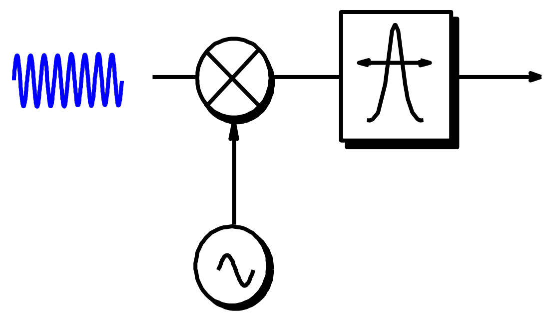


Scalar Network Analyzer



Broadband

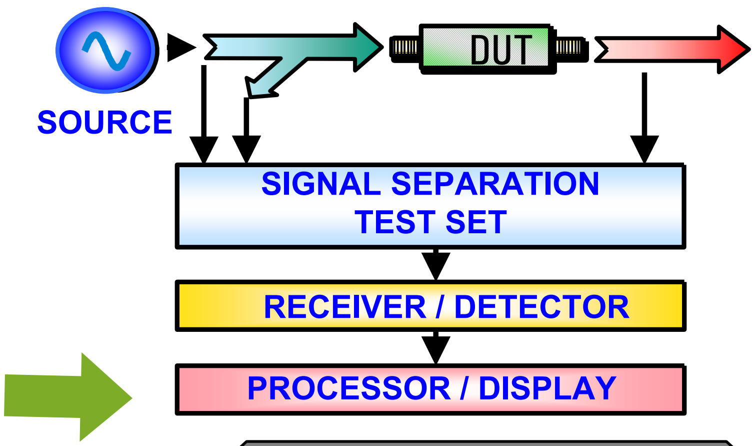
Vector Network Analyzer

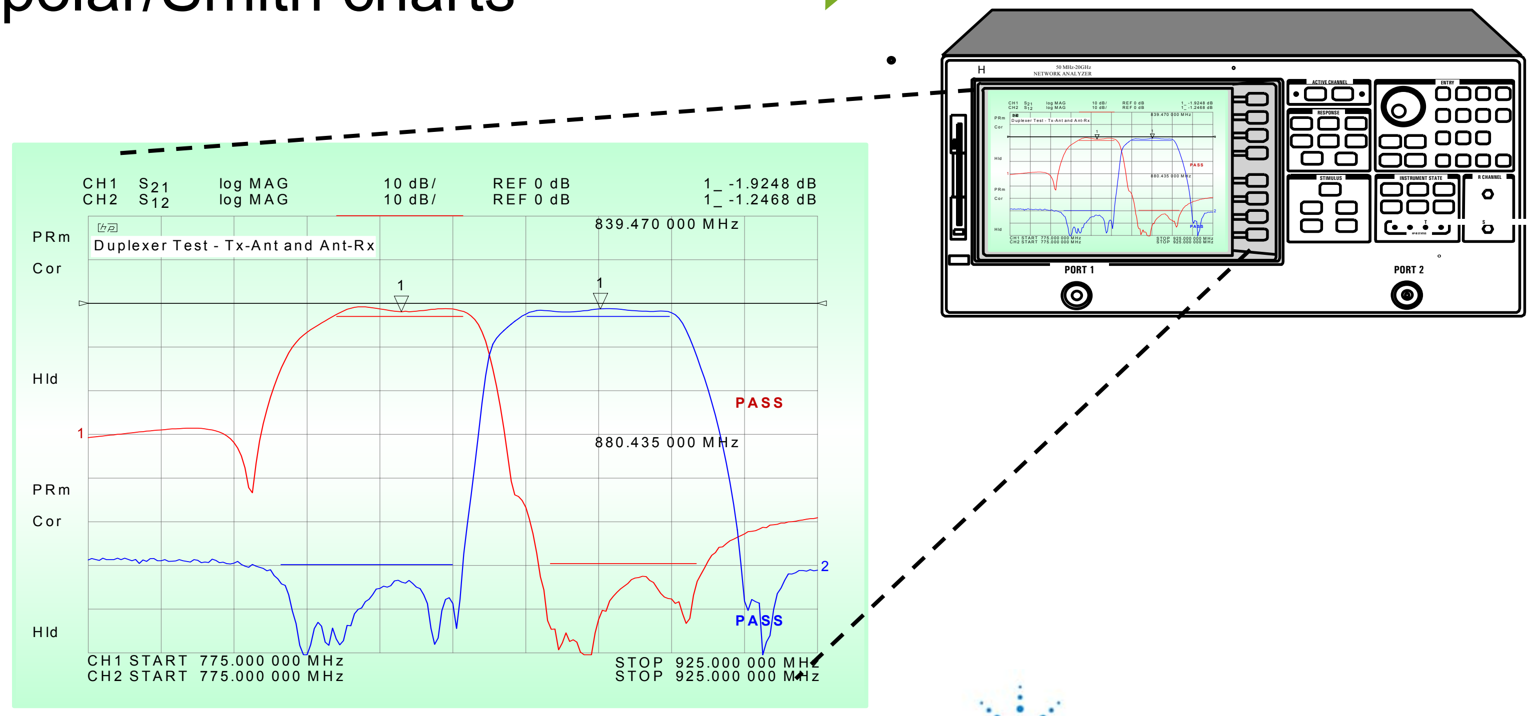


Narrowband

Processor and Display

- Markers
- Limit lines
- Pass/fail indicators
- Linear/log formats
- Grid/polar/Smith charts





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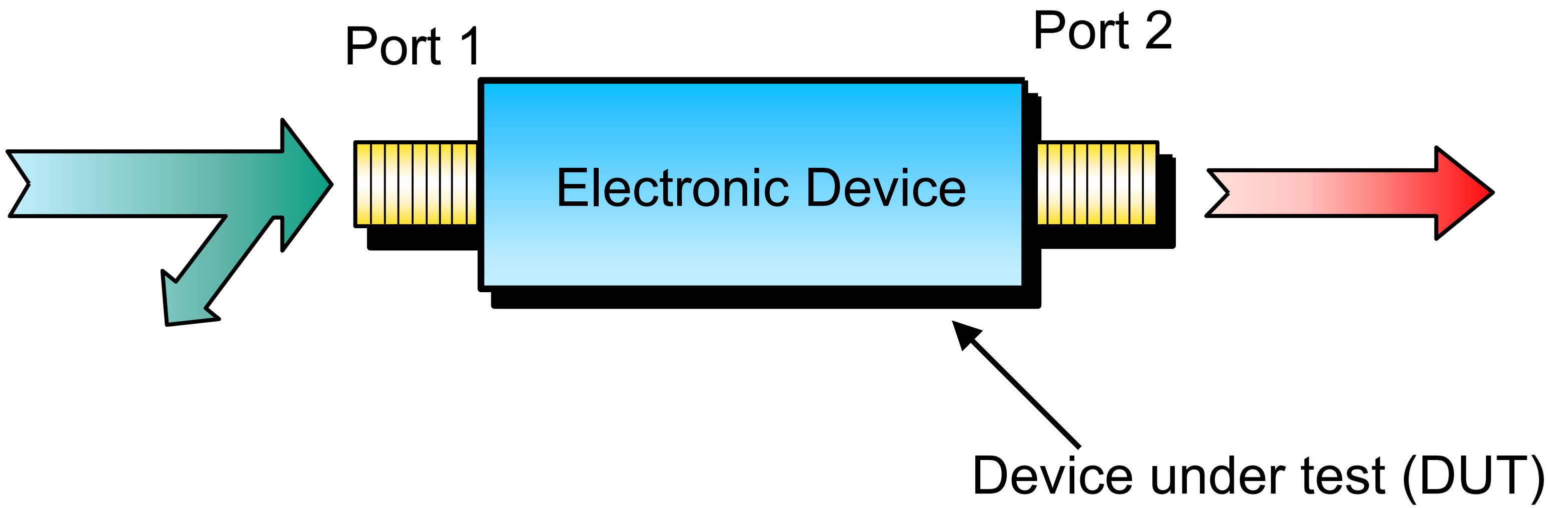
Testing a Device

Where do we start?

- Understand the application requirements
- List the measurement parameters required
- Specify the minimum test equipment set

What Type of Device Are You Testing?



- Two port device
- Active or passive
- Linear or non-linear performance
- Wide or narrow frequency response

Which Test Parameters?

S-parameters S_{21} and S_{12}

Insertion gain and loss

Group delay

Transmission coefficient, T and τ

Insertion phase

Return loss

Impedance, Z

S-parameters S_{11} and S_{22}

Reflection coefficient, Γ and ρ

Standing wave ratio, SWR

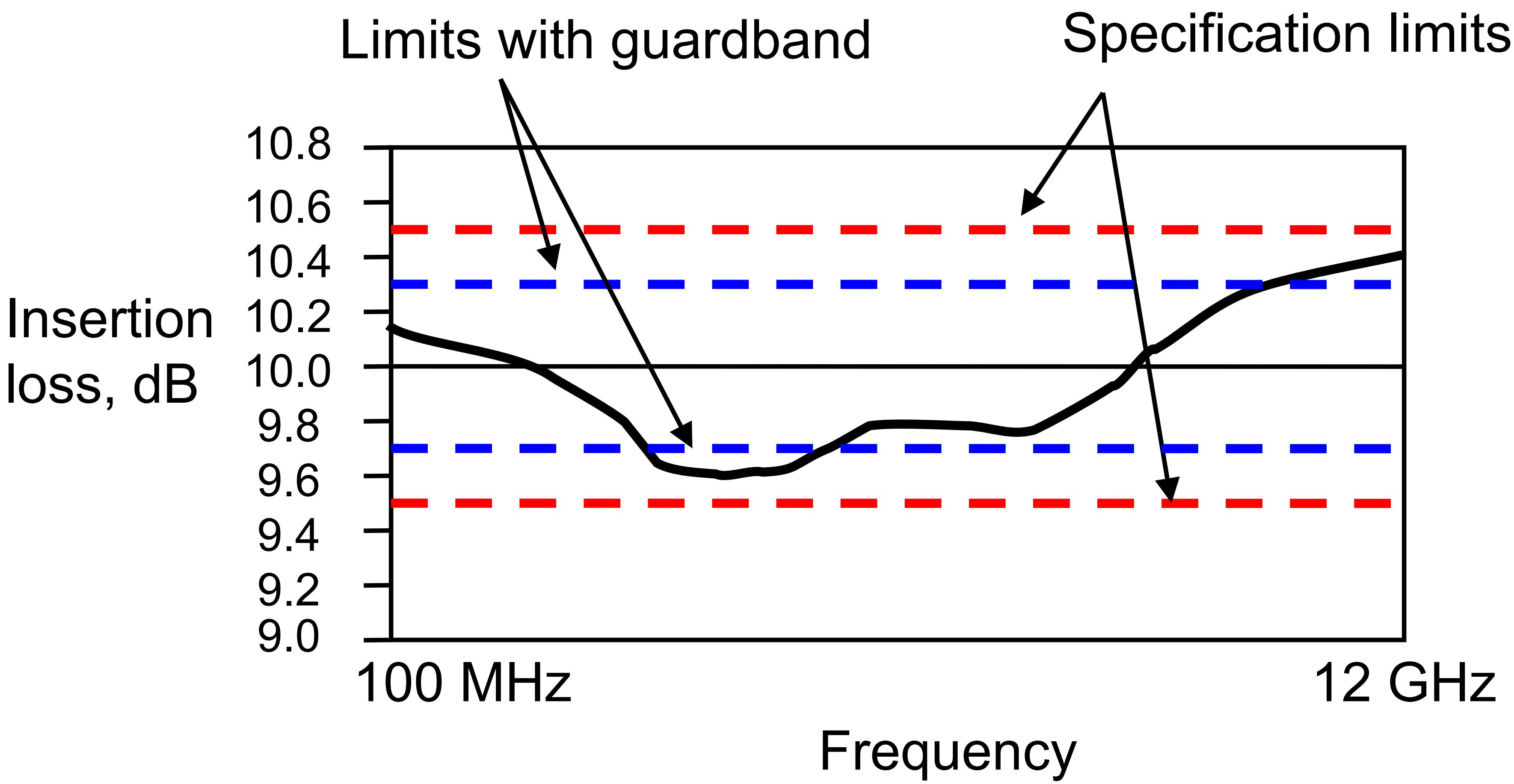
Transmission Loss

$$\textbf{Insertion Loss (dB)} = -10\text{Log}\left|\frac{\text{Power Transmitted}}{\text{Power Incident}}\right|$$

$$= -10\ \text{Log}\left|\frac{V_{\text{Transmitted}}}{V_{\text{Incident}}}\right|^2 = -20\ \text{Log}\left|\frac{V_{\text{Transmitted}}}{V_{\text{Incident}}}\right|$$

$$= \mathbf{-20\ Log}\ \tau$$

Transmission Loss



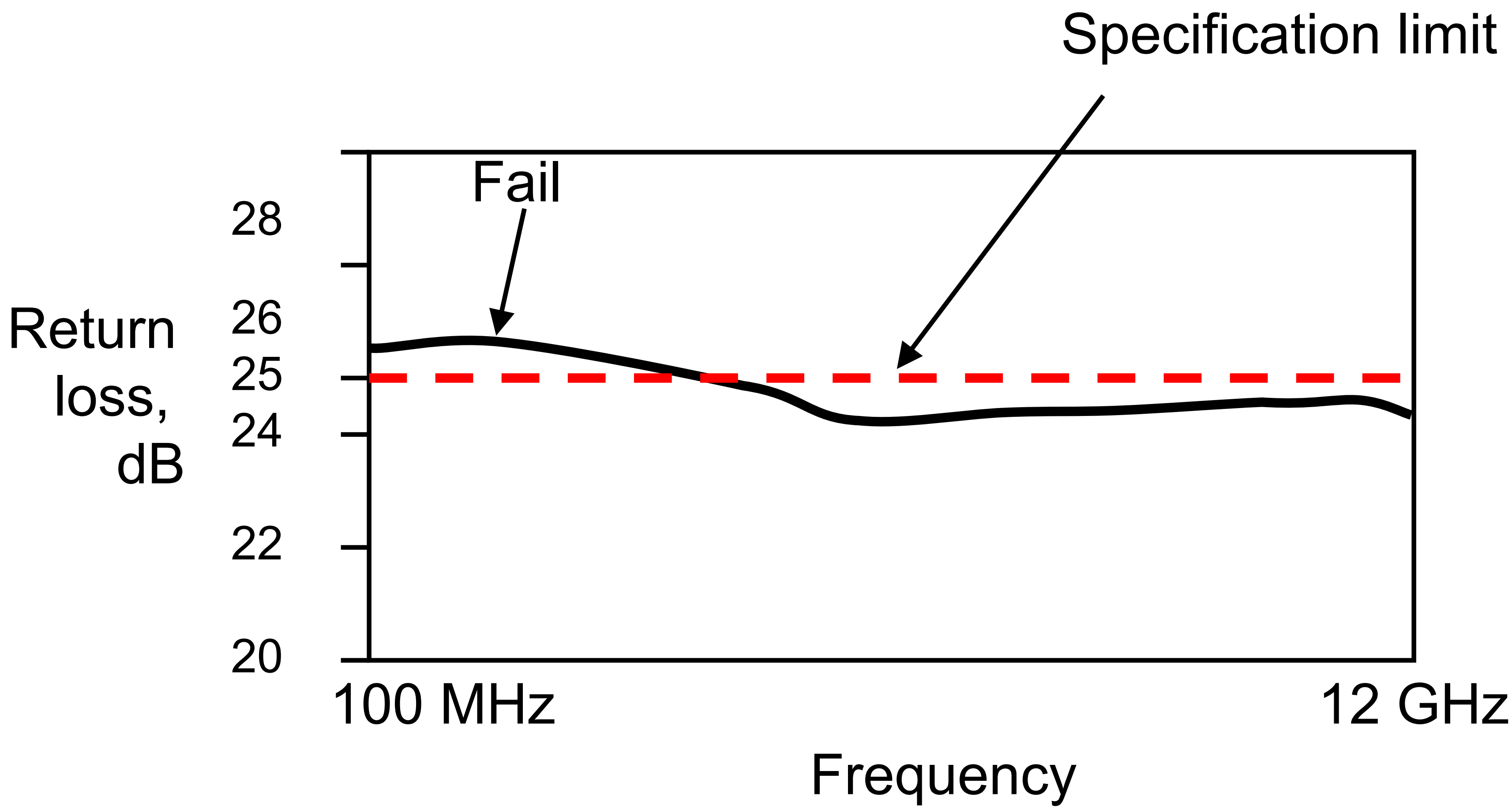
Return Loss

$$\textbf{Return loss (dB)} = -20 \text{ Log} \left| \frac{\text{Voltage Reflected}}{\text{Voltage Incident}} \right|$$

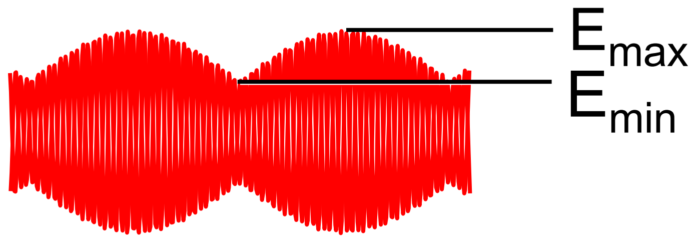
$$= \mathbf{-20\ Log(\rho)}$$

$$\text{where } \rho = \left| \frac{\text{Voltage Reflected}}{\text{Voltage Incident}} \right|$$

Return Loss

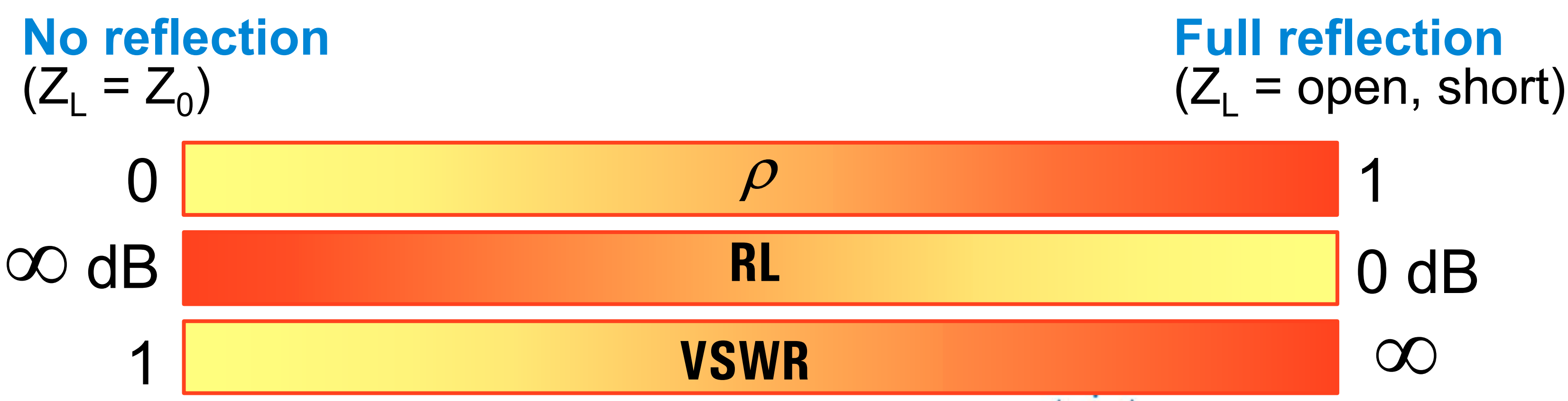

Specification limit
Fail
Return loss, dB
28
26
25
24
22
20
100 MHz
12 GHz
Frequency

Reflection Parameters



Standing wave ratio or Voltage Standing Wave Ratio

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



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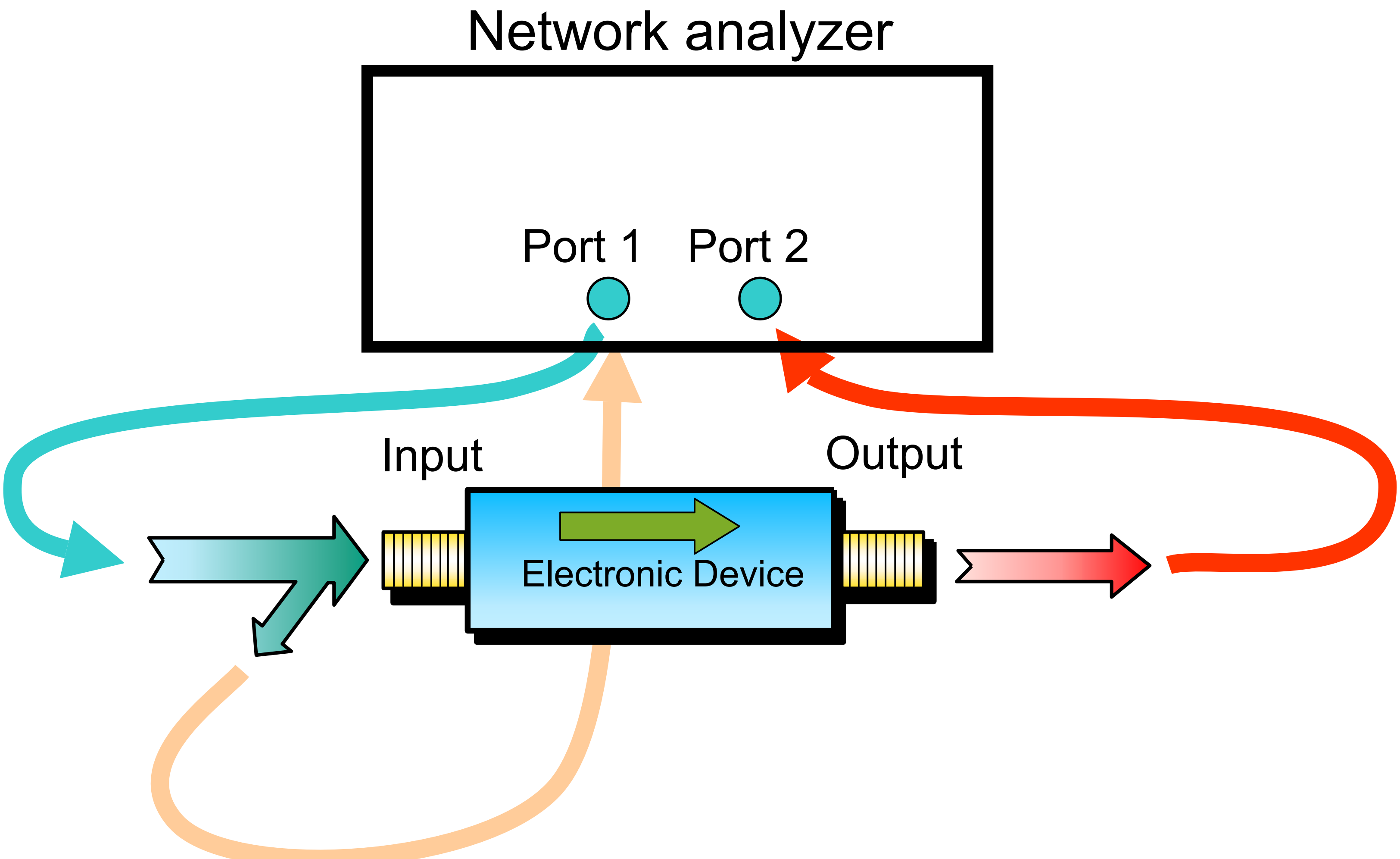
Forward and Reverse Measurements



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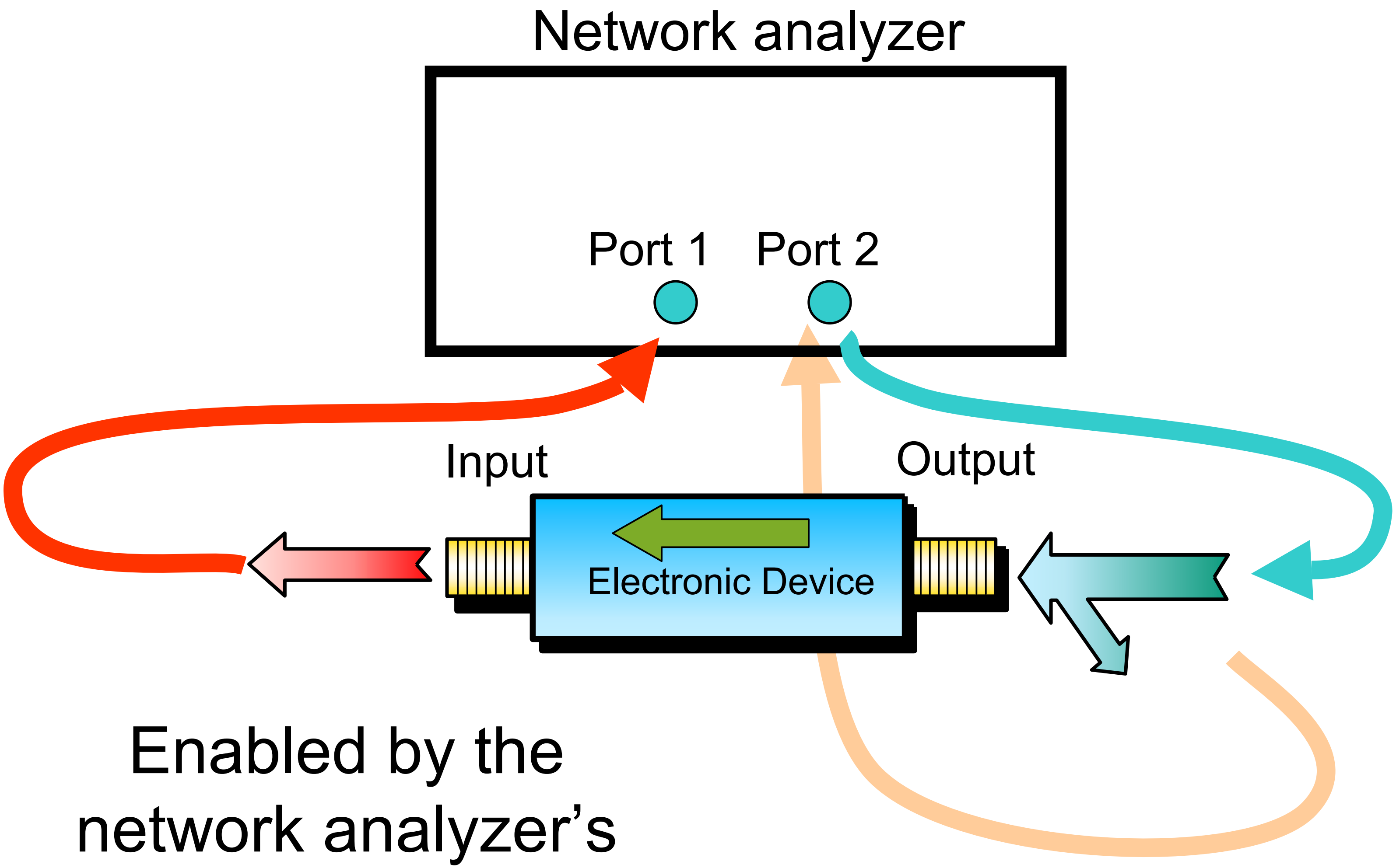
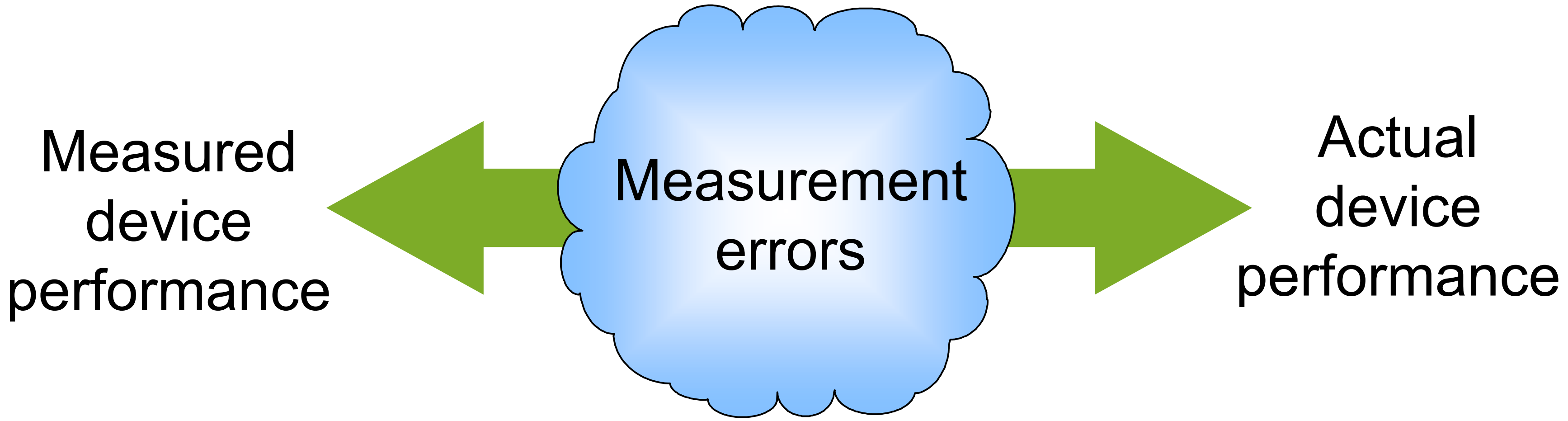
Forward and Reverse Measurements



Enabled by the network analyzer's internal test set.

Accuracy and Error Correction



Types of Measurement Errors

Calibration

Systematic

Predictable

Uncorrected

Random

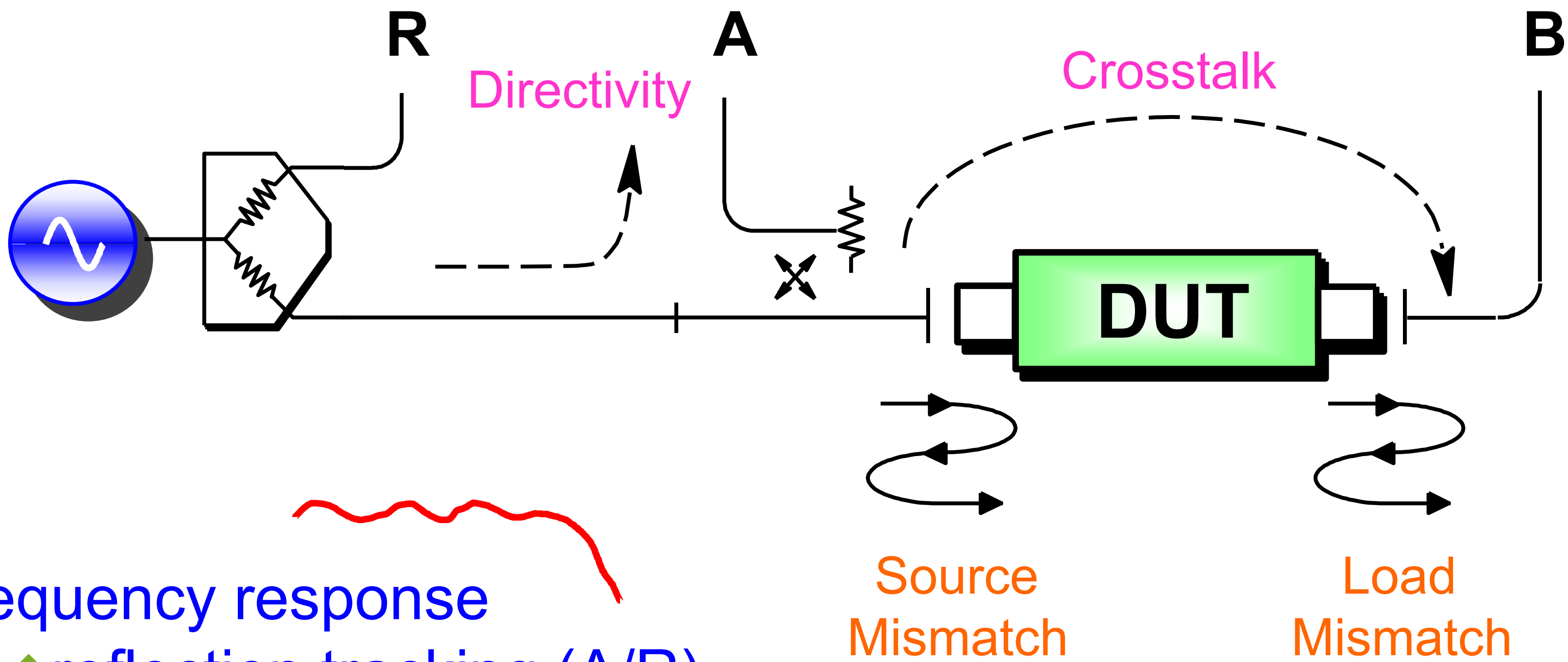
Unpredictable

Re-calibration

Drift

System changes after calibration
Can be fixed

Systematic Errors



Frequency response

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

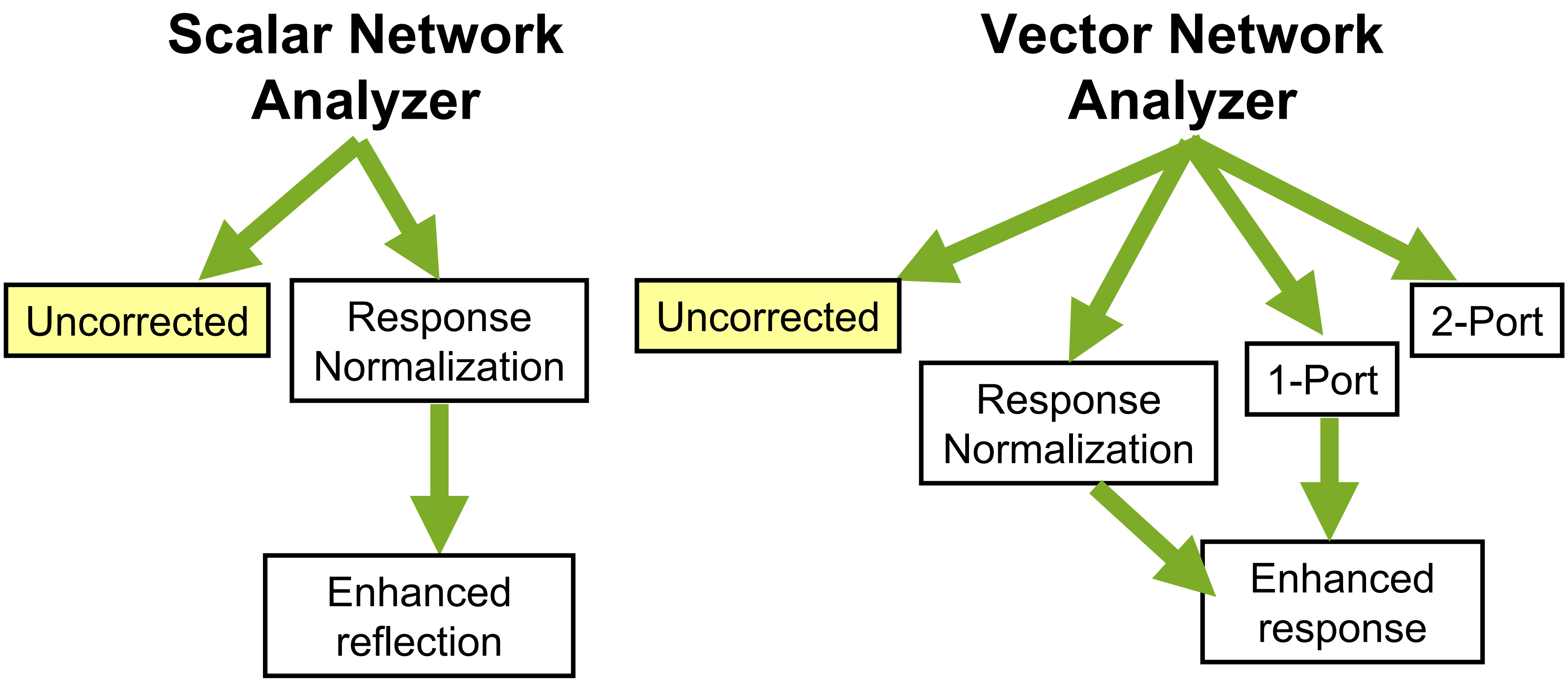
Systematic Errors

Six Error Terms

- Directivity
- Crosstalk
- Source match
- Load match
- Transmission frequency response
- Reflection frequency response

Complete characterization of a two port device requires ***forward and reverse*** measurements, for a total of 12 error terms.

Error Correction Possibilities



Error Correction Process

1. Measure the calibration (impedance) standards.

2. Compute and store the error-correction terms.

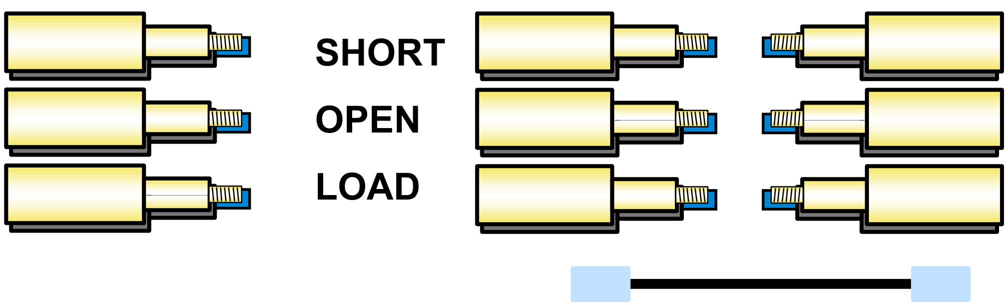
3. Measure the DUT and apply the correction data.

Calibration standards are devices whose characteristics are precisely known.

Vector Error Correction Requirements

- Requires many standards in a cal kit
- One port - for reflection calibration
- Two port - for full reflection and transmission calibration

A Typical Cal Kit



One port cal

Two port cal

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Response Error Correction

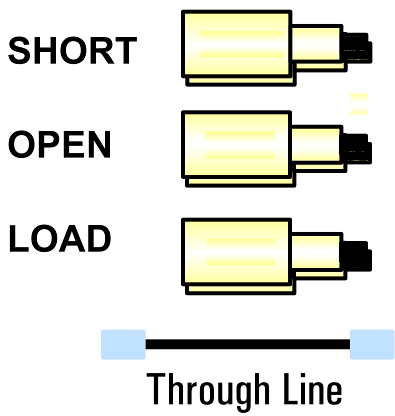
(Normalization)

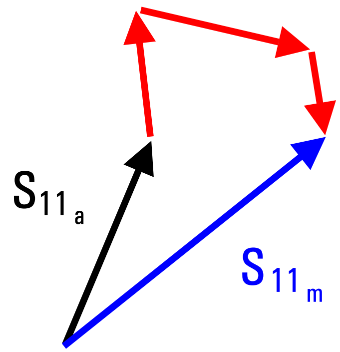
- Simple to perform
- Only corrects for tracking errors
- Stores the reference trace in memory.
  Divides measurement data by reference data.

Vector Error Correction

1- Port or 2 - Port

- Must measure amplitude and phase
- Requires more calibration standards
- Accounts for all major sources of systematic error



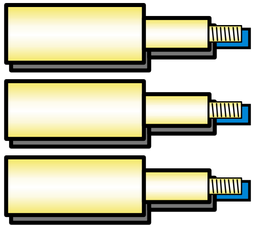


One Port Vector Error Correction

Reflection Measurements

- **Directivity**
- **Source match**
- **Reflection tracking**

SHORT
OPEN
LOAD



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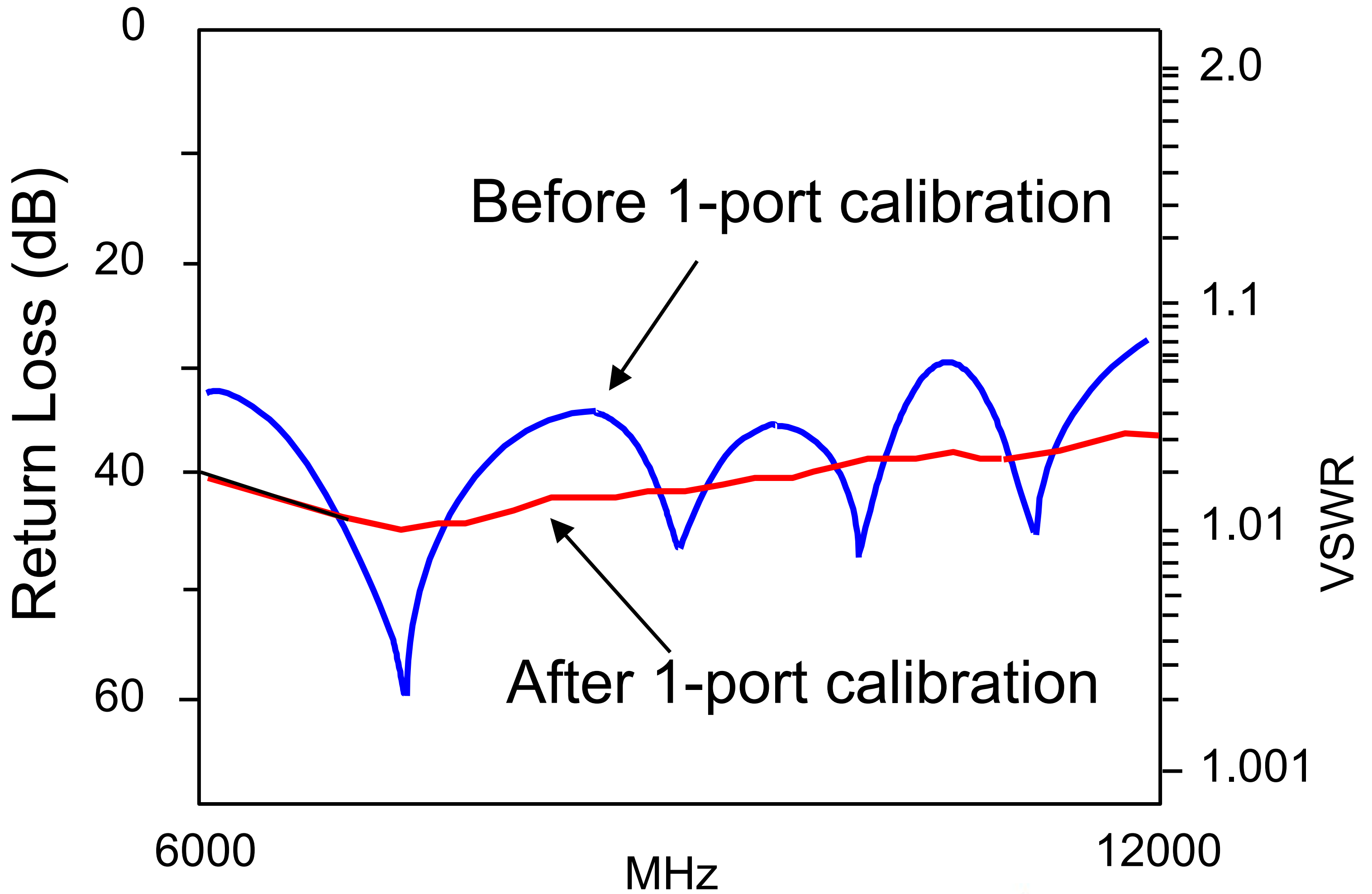
Return Loss Measurement With

One-Port Calibration



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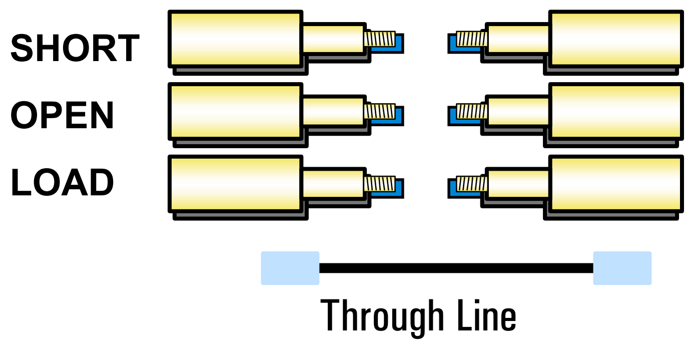
Full Two Port Vector Error Correction

Forward Measurements		Reverse Measurements
1	Directivity	7
2	Crosstalk	8
3	Source match	9
4	Load match	10
5	Transmission frequency response	11
6	Reflection frequency response	12



Twelve Term Error Correction Equations

$$S_{11a} = \frac{\left(\frac{S_{11m} - E_D}{E_{RT}}\right)\left(1 + \frac{S_{22m} - E_D'}{E_{RT}'} E_S'\right) - E_L\left(\frac{S_{21m} - E_X}{E_{TT}}\right)\left(\frac{S_{12m} - E_X'}{E_{TT}'}\right)}{\left(1 + \frac{S_{11m} - E_D'}{E_{RT}} E_S\right)\left(1 + \frac{S_{22m} - E_D'}{E_{RT}'} E_S'\right) - E_L' E_L\left(\frac{S_{21m} - E_X}{E_{TT}}\right)\left(\frac{S_{12m} - E_X'}{E_{TT}'}\right)}$$

$$S_{21a} = \frac{\left(\frac{S_{21m} - E_X}{E_{TT}}\right)\left(1 + \frac{S_{22m} - E_D'}{E_{RT}'} (E_S' - E_L)\right)}{\left(1 + \frac{S_{11m} - E_D}{E_{RT}} E_S\right)\left(1 + \frac{S_{22m} - E_D'}{E_{RT}'} E_S'\right) - E_L' E_L\left(\frac{S_{21m} - E_X}{E_{TT}}\right)\left(\frac{S_{12m} - E_X'}{E_{TT}'}\right)}$$

$$S_{12a} = \frac{\left(\frac{S_{12m} - E_X'}{E_{TT}'}\right)\left(1 + \frac{S_{11m} - E_D}{E_{RT}} (E_S - E_L')\right)}{\left(1 + \frac{S_{11m} - E_D}{E_{RT}} E_S\right)\left(1 + \frac{S_{22m} - E_D'}{E_{RT}'} E_S'\right) - E_L' E_L\left(\frac{S_{21m} - E_X}{E_{TT}}\right)\left(\frac{S_{12m} - E_X'}{E_{TT}'}\right)}$$

$$S_{22a} = \frac{\left(\frac{S_{22m} - E_D'}{E_{RT}'}\right)\left(1 + \frac{S_{11m} - E_D}{E_{RT}} E_S\right) - E_L'\left(\frac{S_{21m} - E_X}{E_{TT}}\right)\left(\frac{S_{12m} - E_X'}{E_{TT}'}\right)}{\left(1 + \frac{S_{11m} - E_D}{E_{RT}} E_S\right)\left(1 + \frac{S_{22m} - E_D'}{E_{RT}'} E_S'\right) - E_L' E_L\left(\frac{S_{21m} - E_X}{E_{TT}}\right)\left(\frac{S_{12m} - E_X'}{E_{TT}'}\right)}$$

To determine any one of these four values on the left, **all must be measured**.
Luckily, you don't need to know these equations to use vector network analyzers.

Advanced Calibration Topics

- Measuring non-insertable devices
- Adapter substitution and adapter removal
- Enhanced response calibration
- Calculating measurement uncertainty after two port calibration
- Electronic calibration
- TRL calibration

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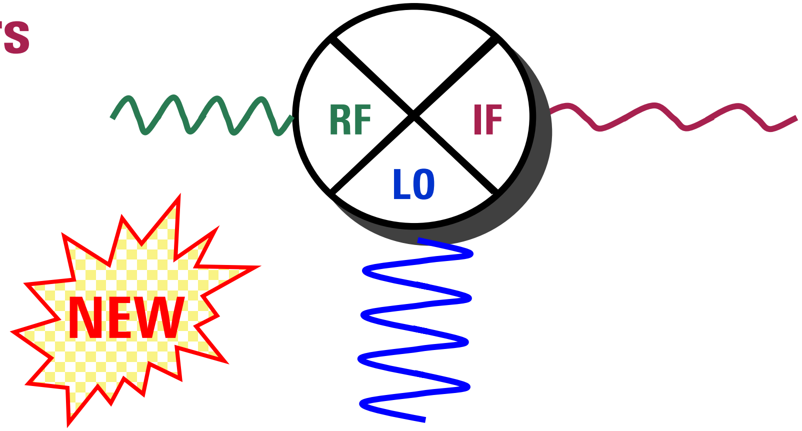
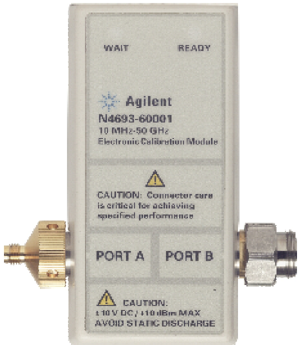
New for the PNA

- **Extended frequency range to 70 GHz!**
  - Fully integrated solution
  - 10 MHz to 67 GHz specified performance
  - 67-70 GHz typical performance
  - Dynamic range > 96 dB at 67 GHz
  - Test on-wafer or in-fixture devices
  - Plus all PNA platform benefits
- **Test mixers and frequency converters**
- **Microwave ECal electronic calibration to 67 GHz**





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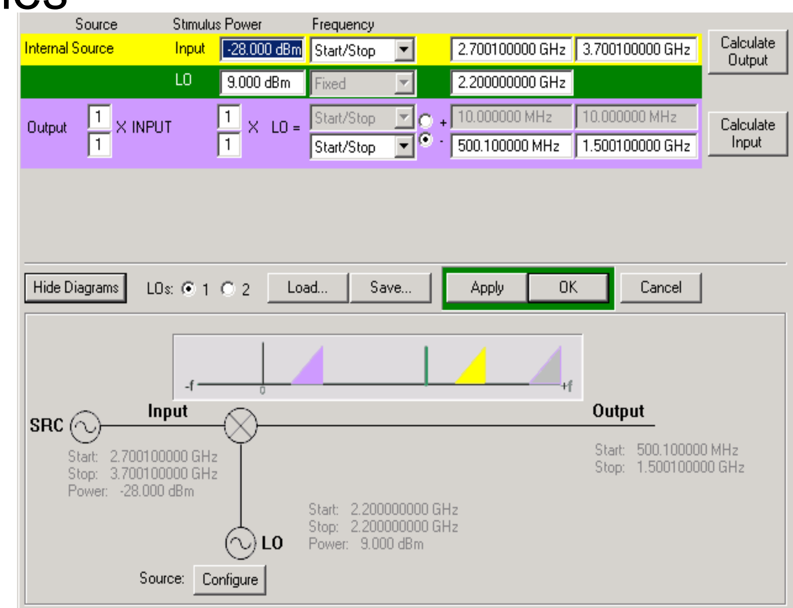
PNA Frequency Converter Measurements

NEW

- **Highest Accuracy**
  - Industry's only fully match-corrected power calibration
  - Industry's only vector-mixer calibration
- **Convenient**
  - Intuitive user interface
  - Eliminates source phase-lock difficulties
  - Eliminates external attenuators
  - External LO's controlled by VNA
- **Fast**
  - SNA speed with VNA accuracy
  - Much faster than using spectrum analyzers or power meters



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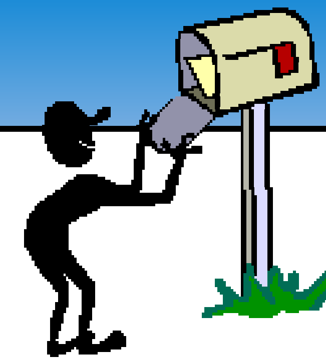

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