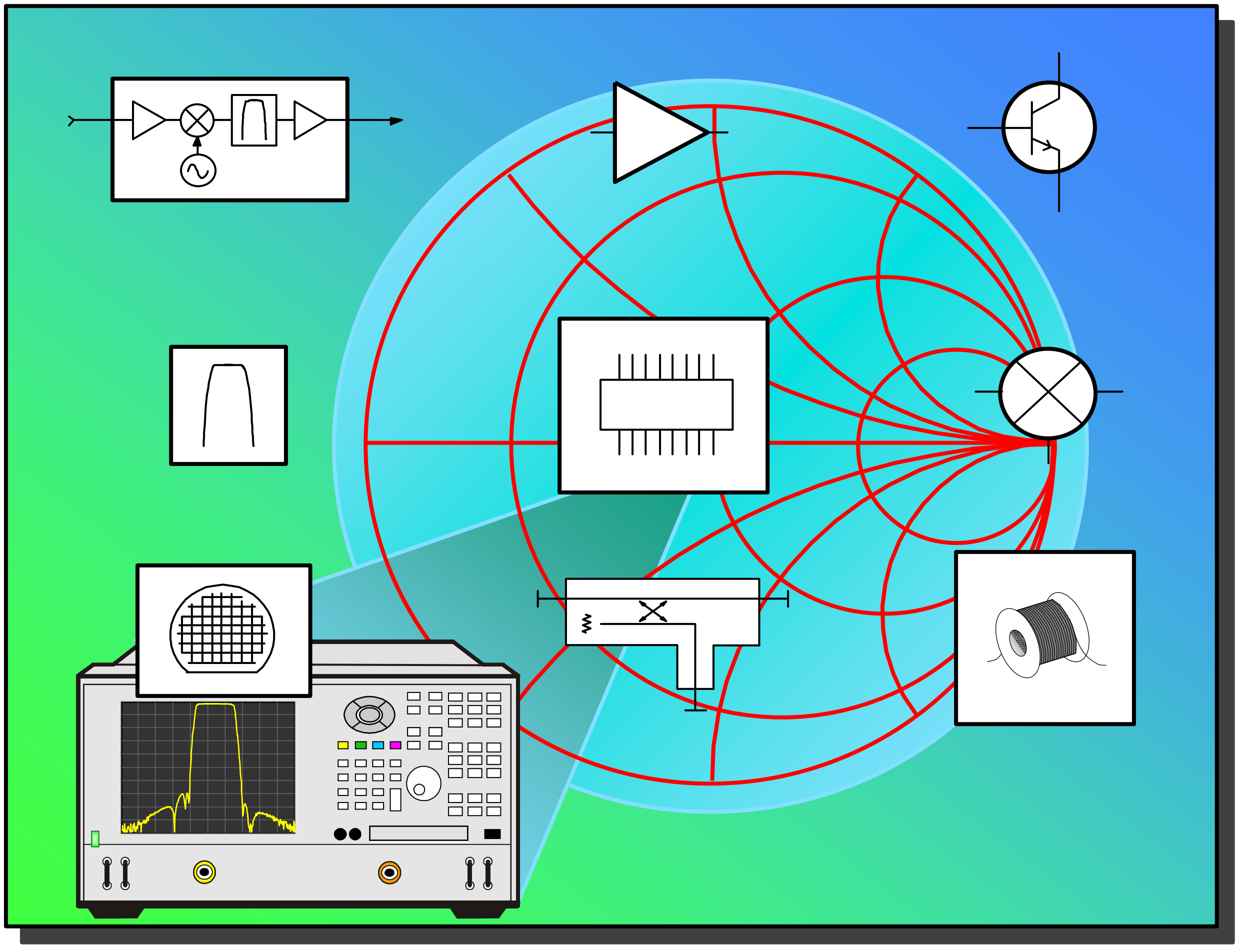
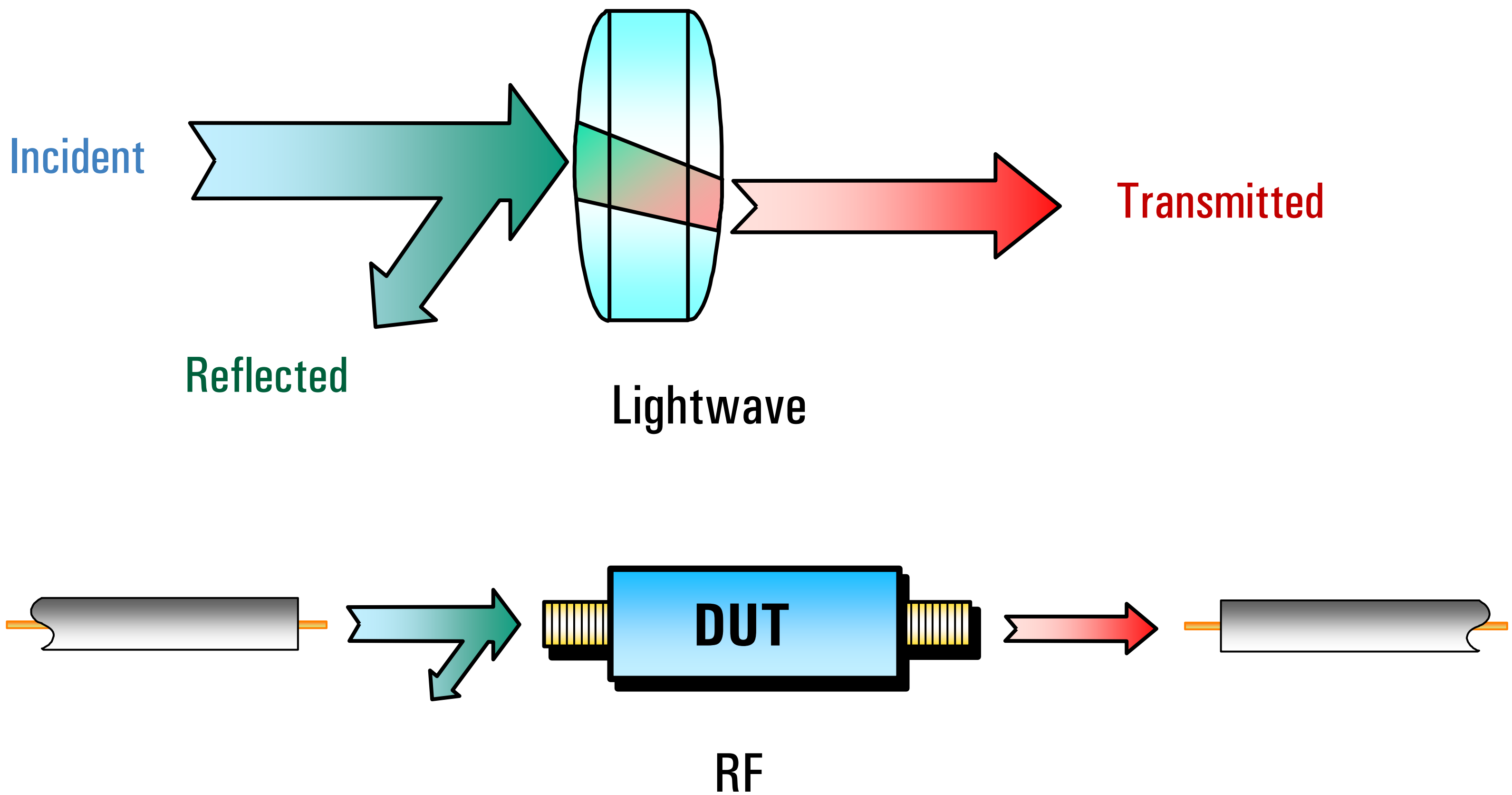
Network Analyzer Basics- EE142 Fall 07

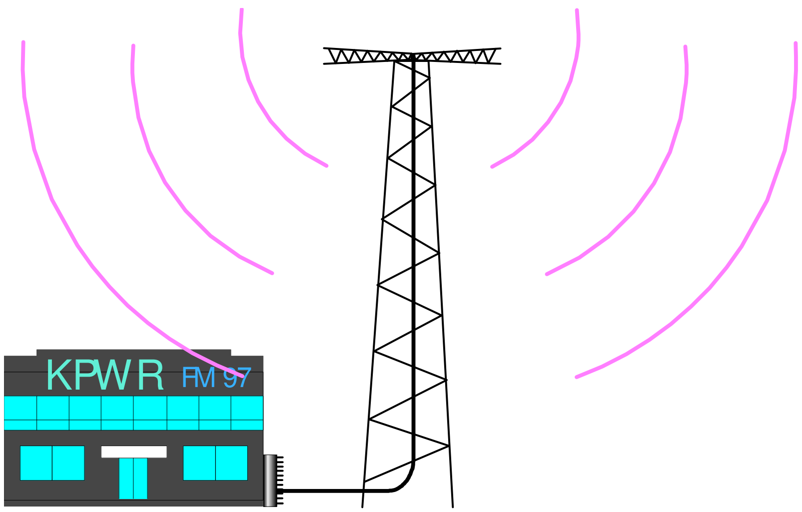


Lightwave Analogy to RF Energy



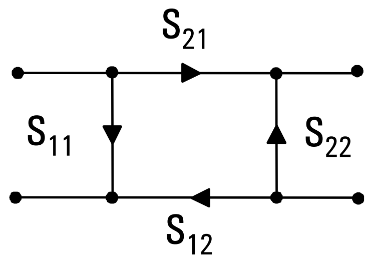
Why Do We Need to Test Components?

- Verify specifications of "building blocks" for more complex RF systems
- Create models for simulation
- Check our simulation models against a real circuit
- Ensure good match when absorbing power (e.g., an antenna)

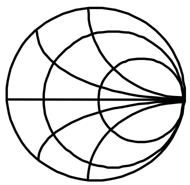


The Need for Both Magnitude and Phase

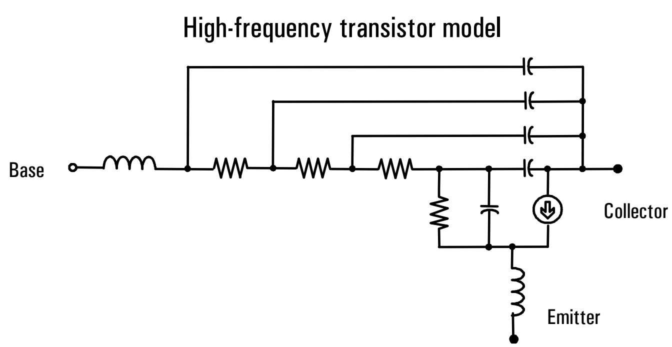
1. Complete characterization of linear networks



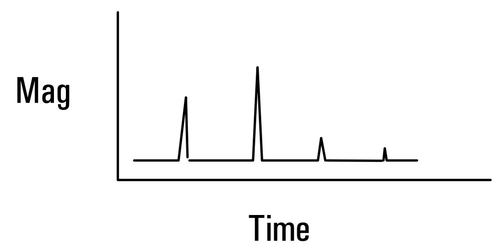
2. Complex impedance needed to design matching circuits



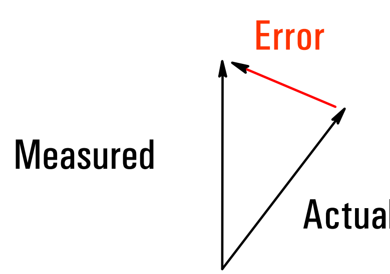
3. Complex values needed for device modeling



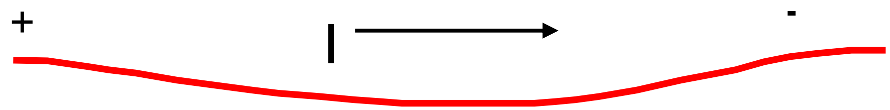
4. Time-domain characterization



5. Vector-error correction

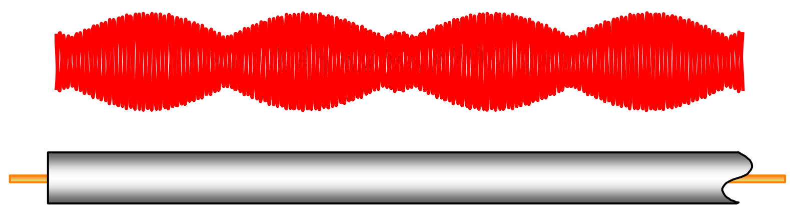


Transmission Line Basics



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

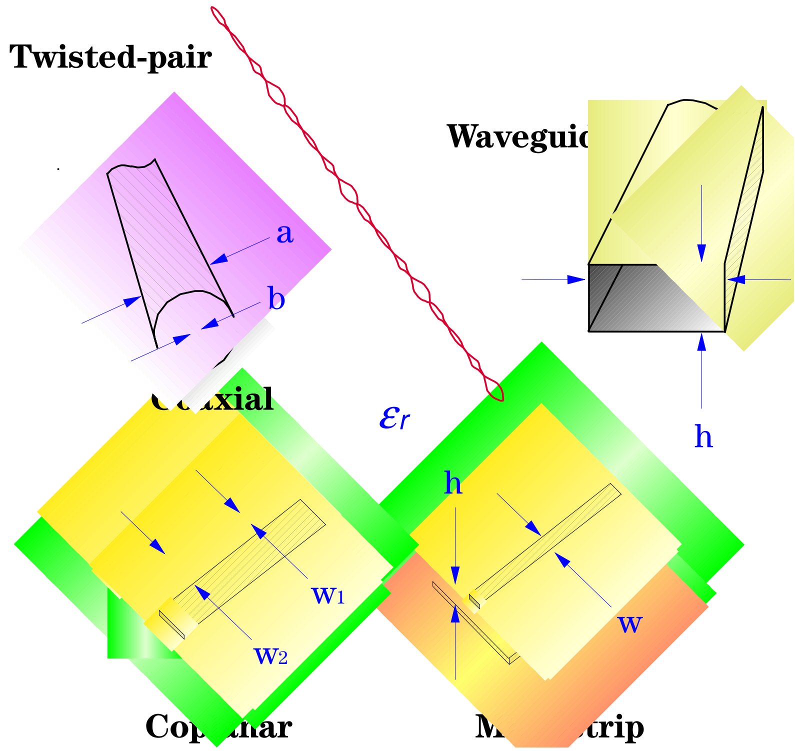


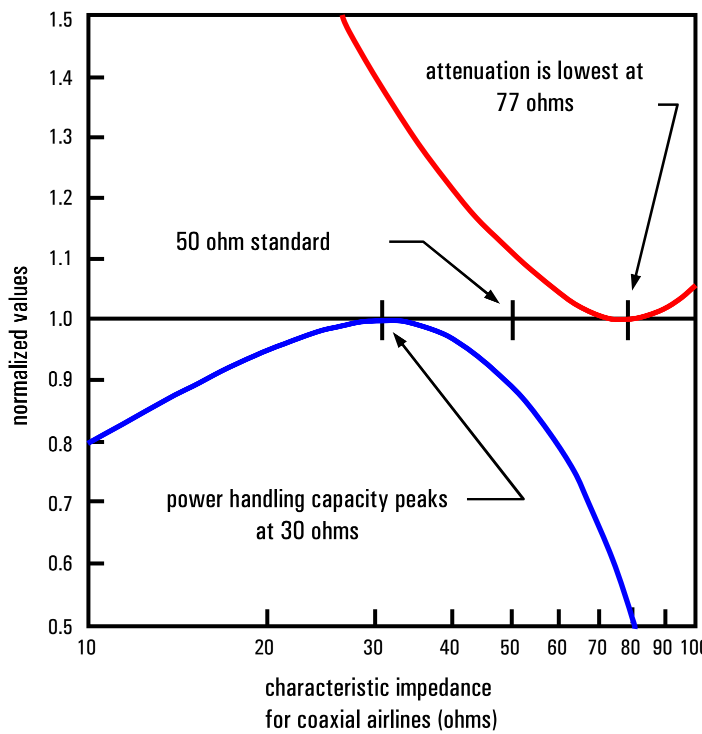
High frequencies

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

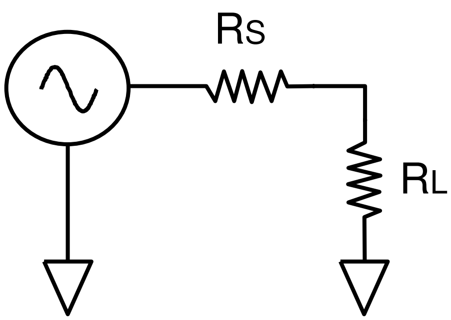
Transmission line Zo

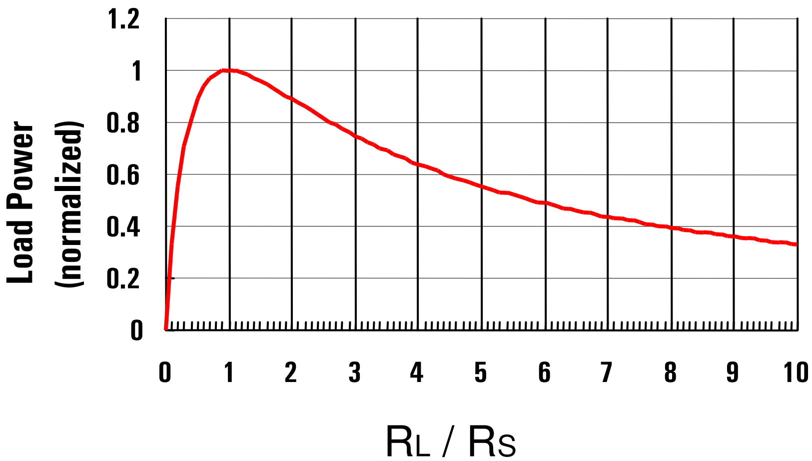
- Zo determines relationship between voltage and current waves
- Zo is a function of physical dimensions and $\mathcal{E}_r$
- Zo is usually a real impedance (e.g. 50 or 75 ohms)





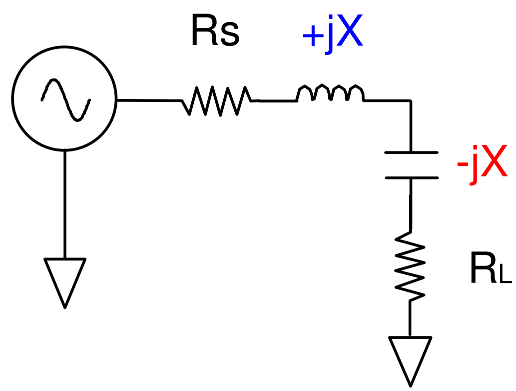
Power Transfer Efficiency



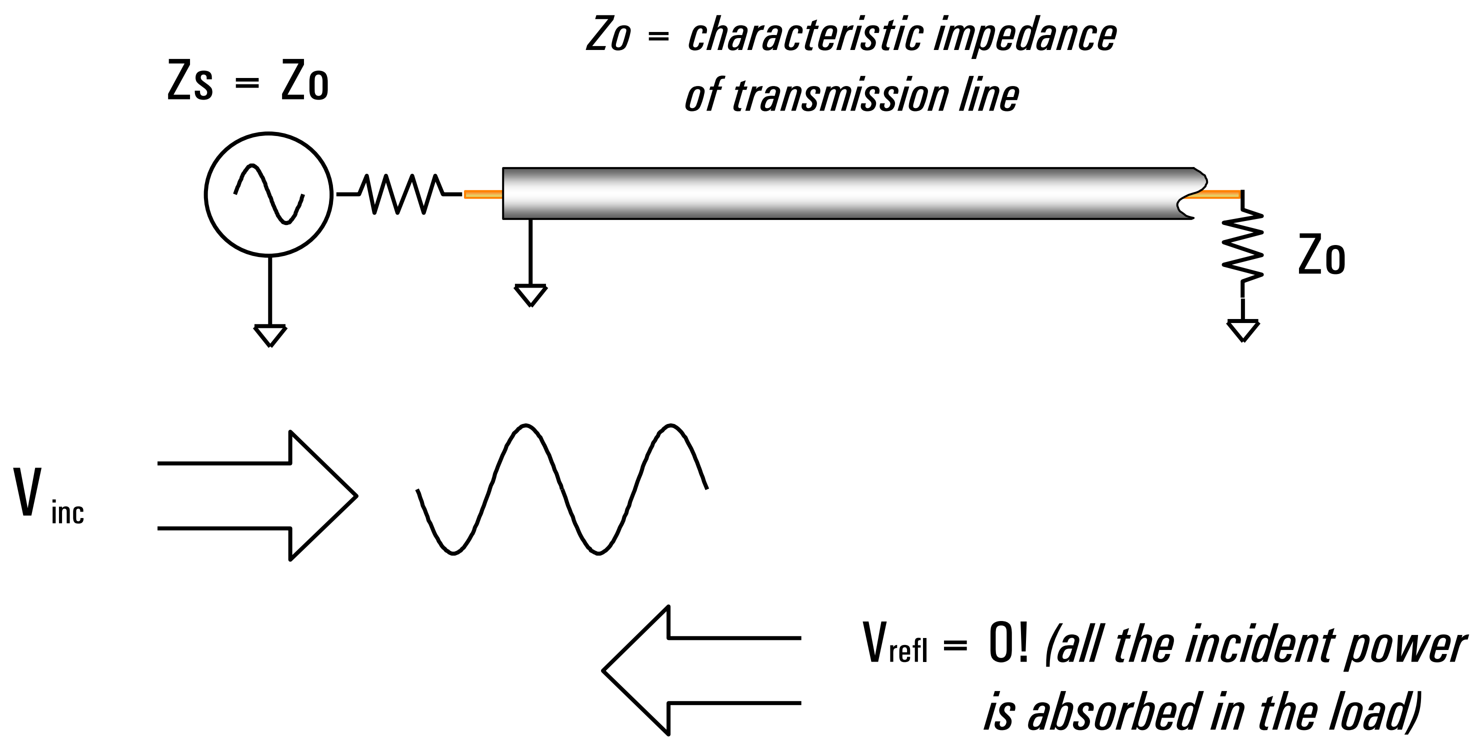


Maximum power is transferred when $R_L = R_S$

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

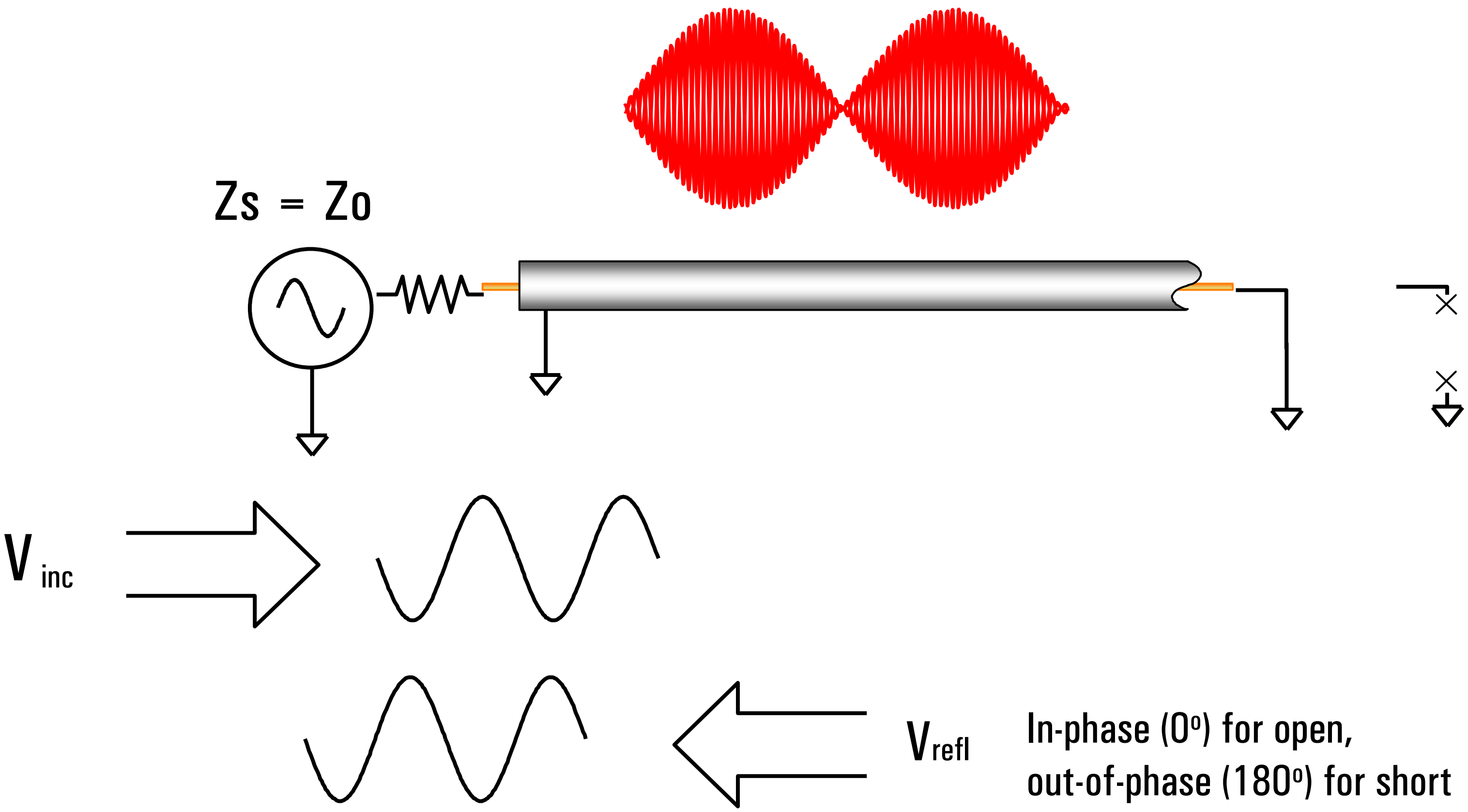


Transmission Line Terminated with Zo



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

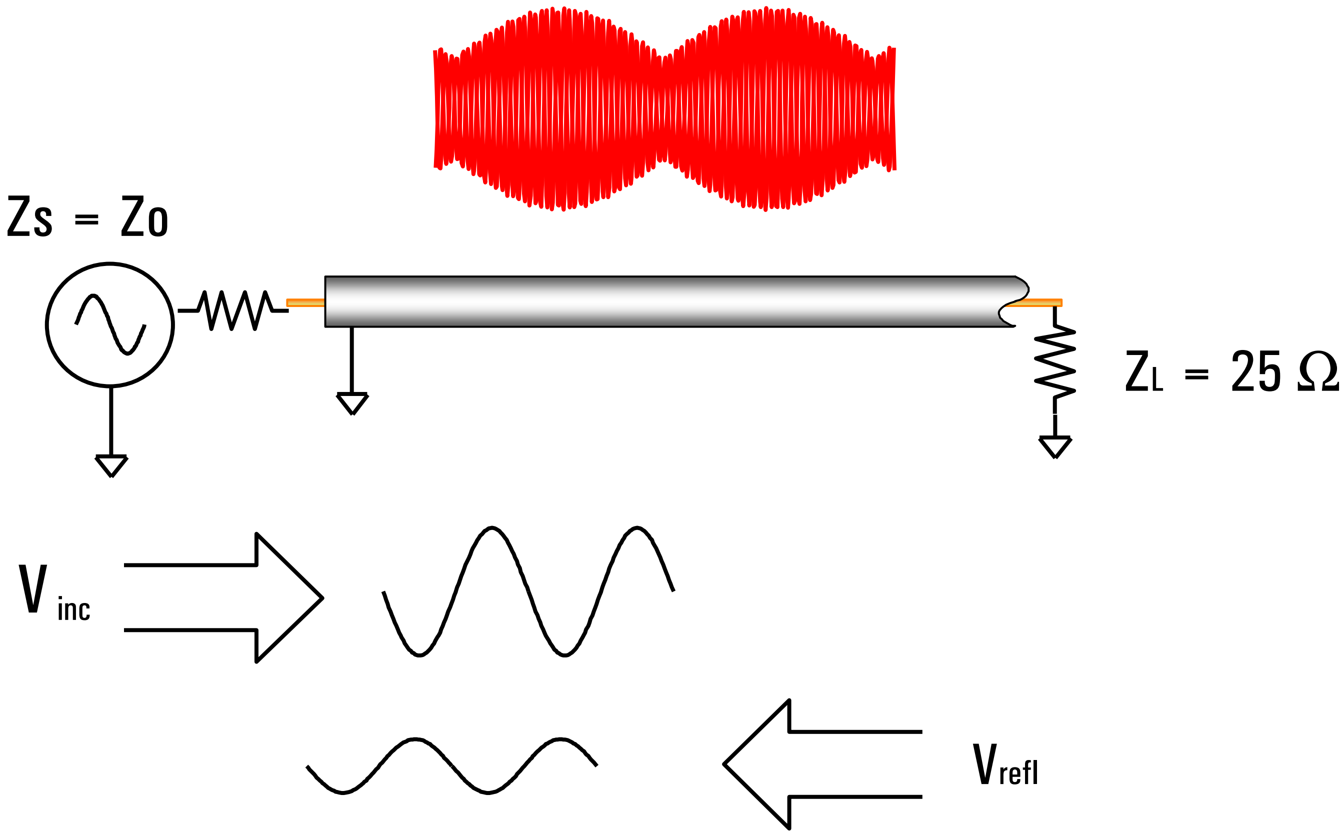
Transmission Line Terminated with Short, Open



In-phase (0^{o}) for open,
out-of-phase (180^{o}) for short

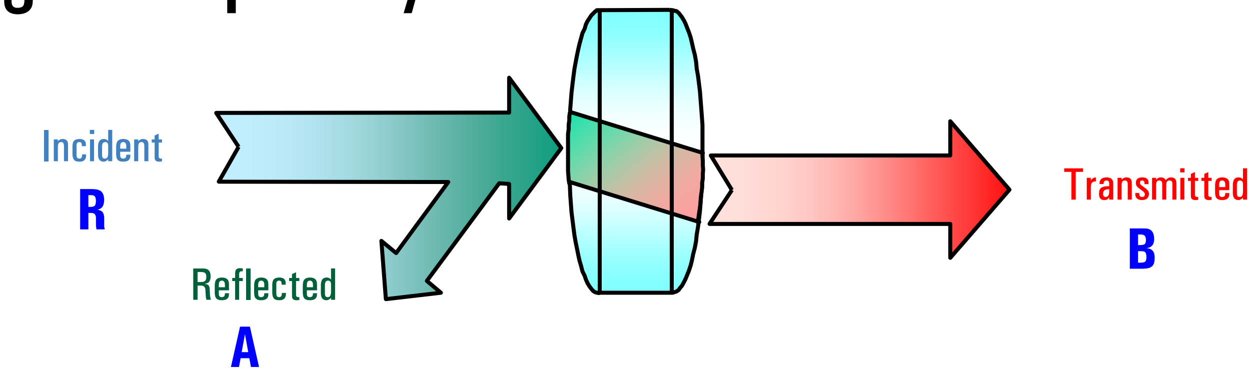
For reflection, a transmission line terminated in a short or open reflects all power back to source

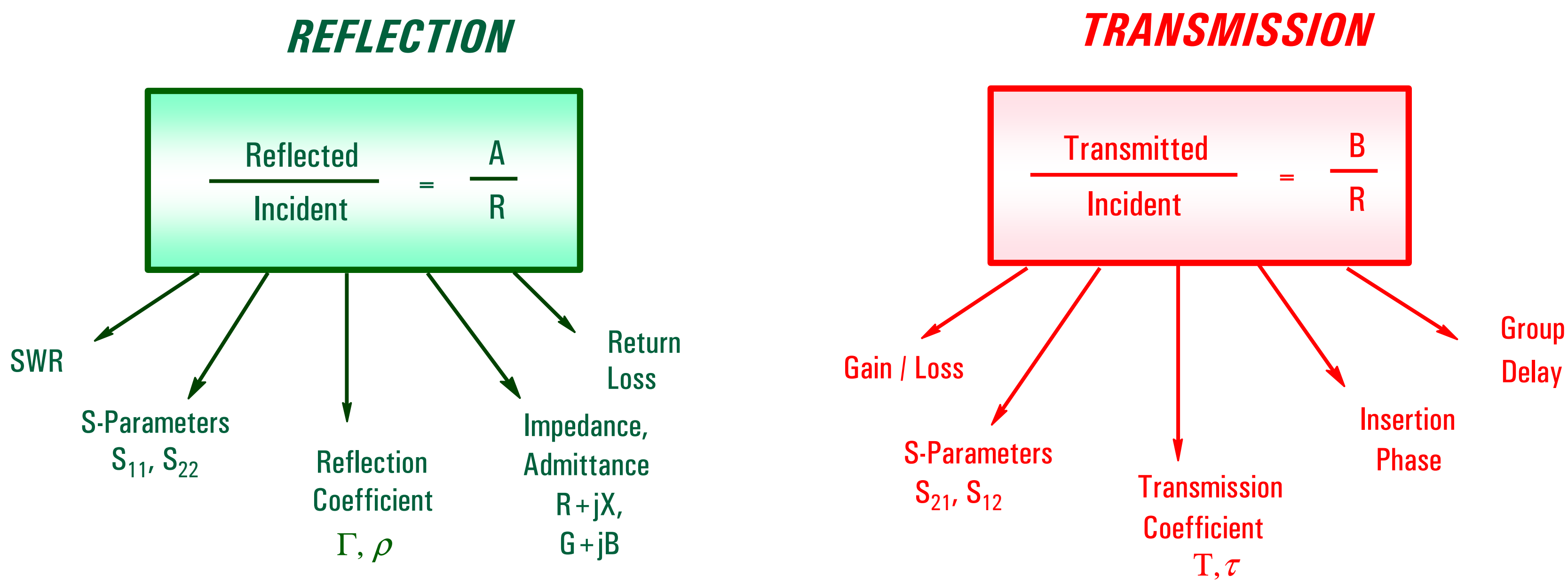
Transmission Line Terminated with 25 Ω



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

High-Frequency Device Characterization

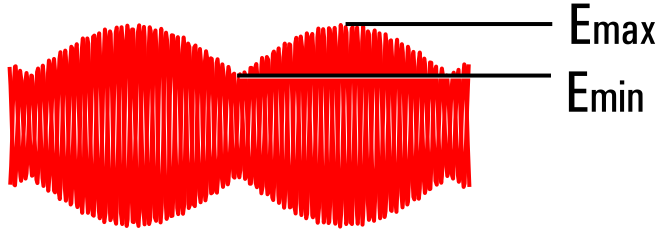




Reflection Parameters

Reflection Coefficient $\Gamma = \dfrac{V_{reflected}}{V_{incident}} = \rho \angle \Phi = \dfrac{Z_L - Z_0}{Z_L + Z_0}$

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

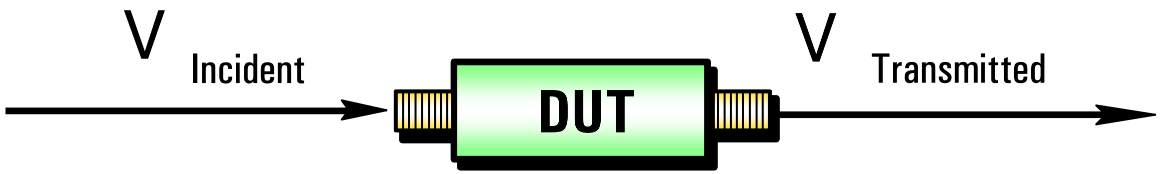


Voltage Standing Wave Ratio

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

No reflection ***($Z_L = Zo$)***		***Full reflection*** ***(Z_L = open, short)***
0	ρ	1
∞ dB	**RL**	0 dB
1	**VSWR**	∞

Transmission Parameters

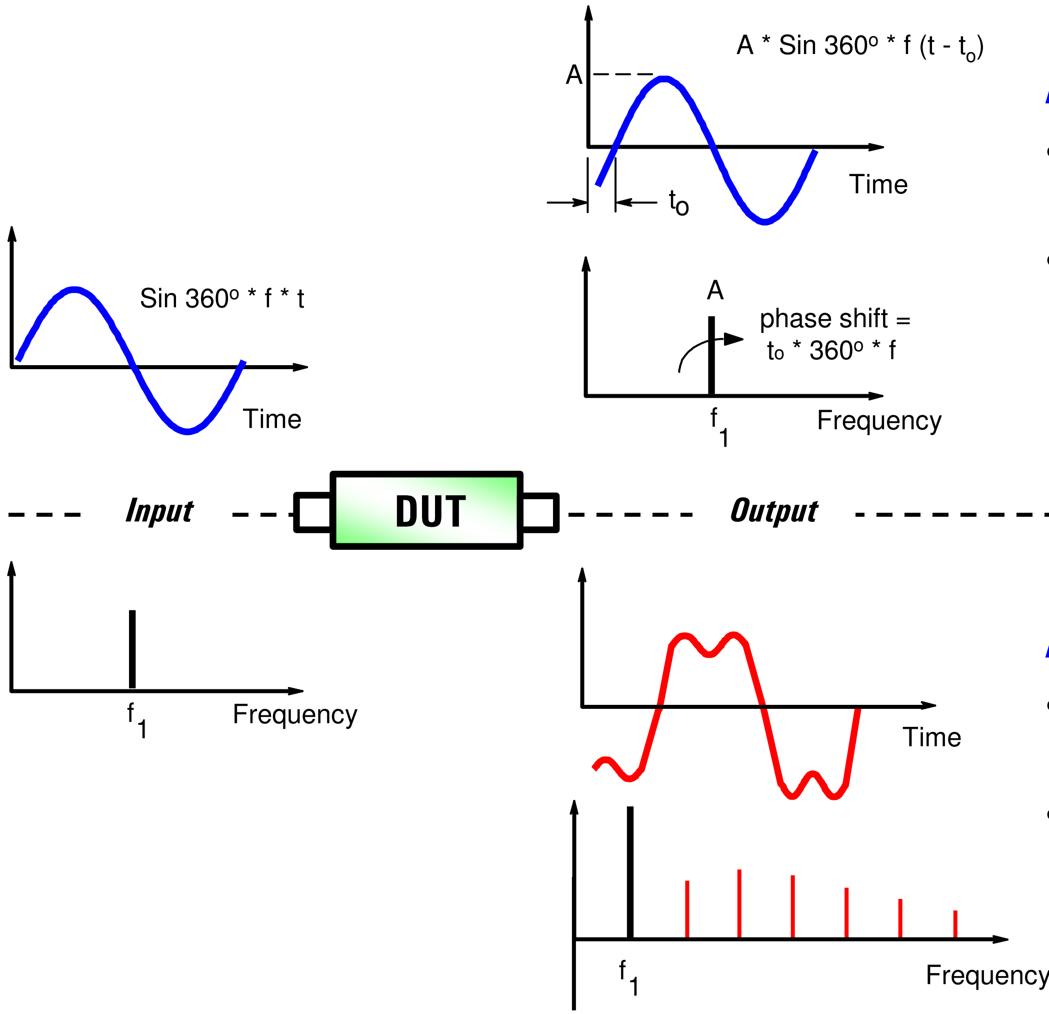


Transmission Coefficient = $T = \dfrac{V_{Transmitted}}{V_{Incident}} = \tau\angle\phi$

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

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

Linear Versus Nonlinear Behavior



Linear behavior:

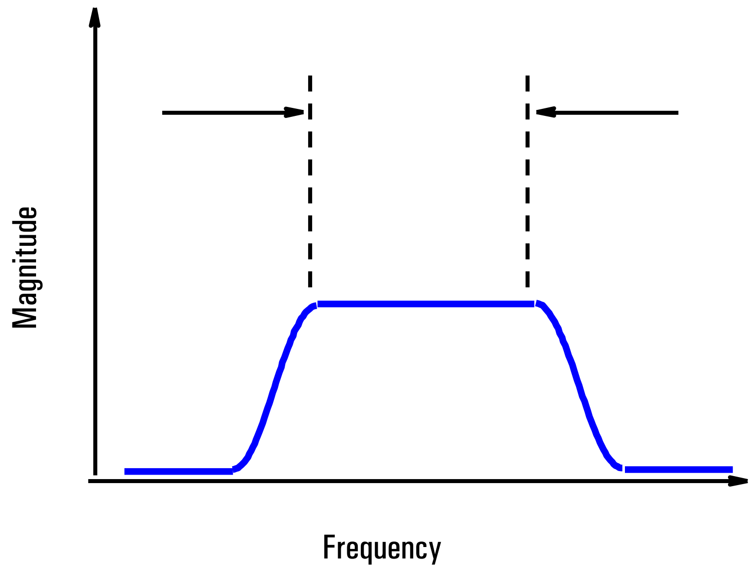
- input and output frequencies are the same (no additional frequencies created)
- output frequency only undergoes magnitude and phase change

Nonlinear behavior:

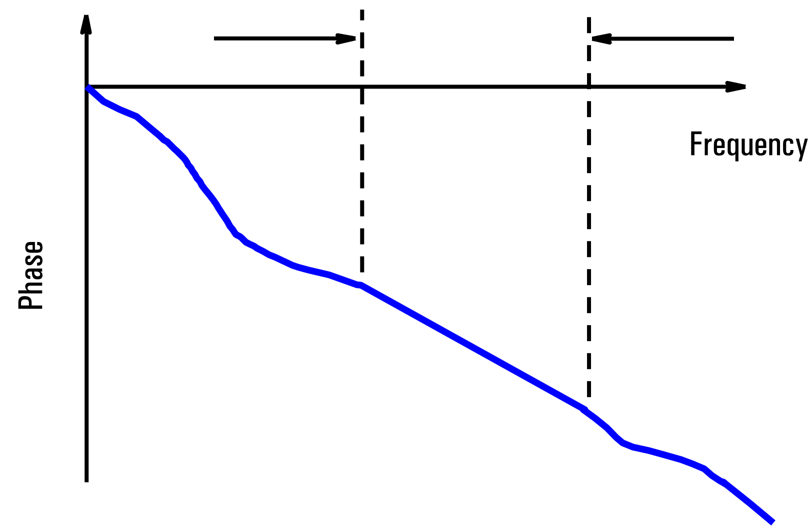
- output frequency may undergo frequency shift (e.g. with mixers)
- additional frequencies created (harmonics, intermodulation)

Criteria for Distortionless Transmission
Linear Networks

Constant amplitude over bandwidth of interest

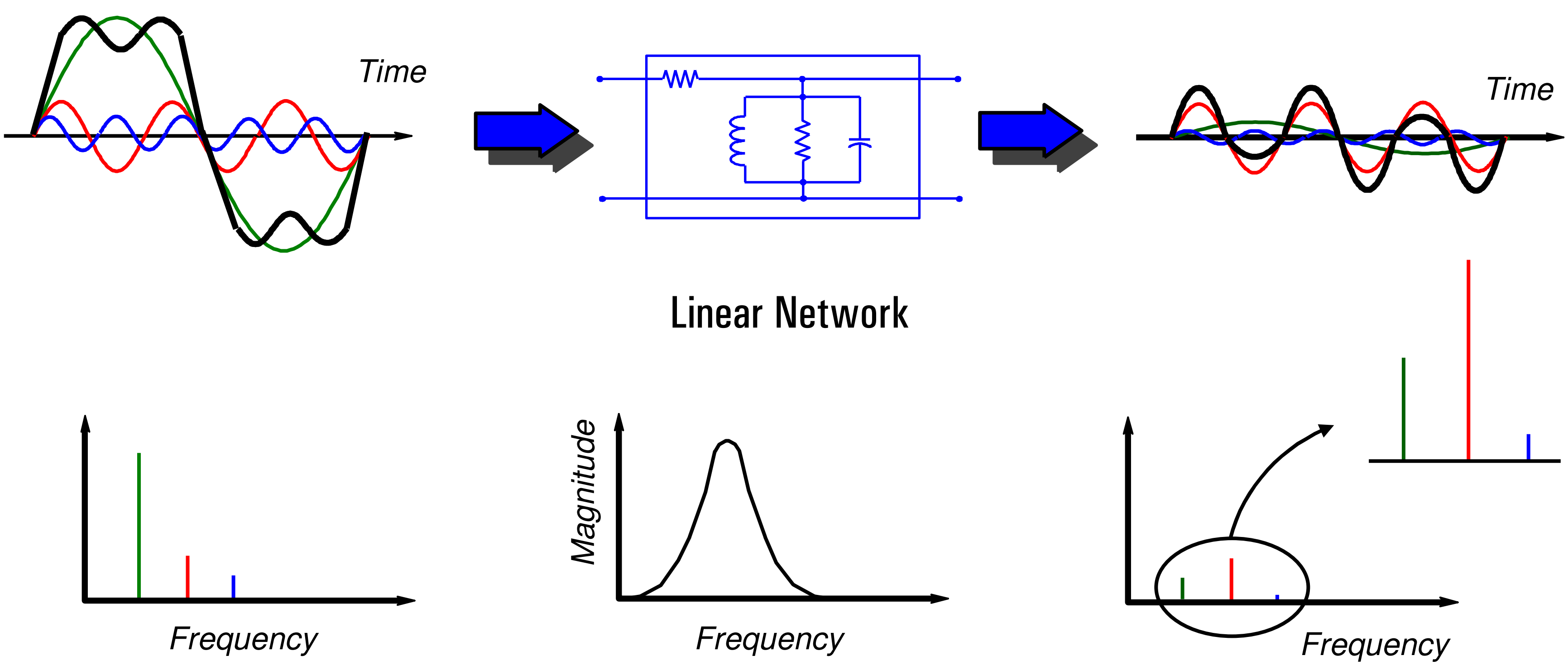


Linear phase over bandwidth of interest



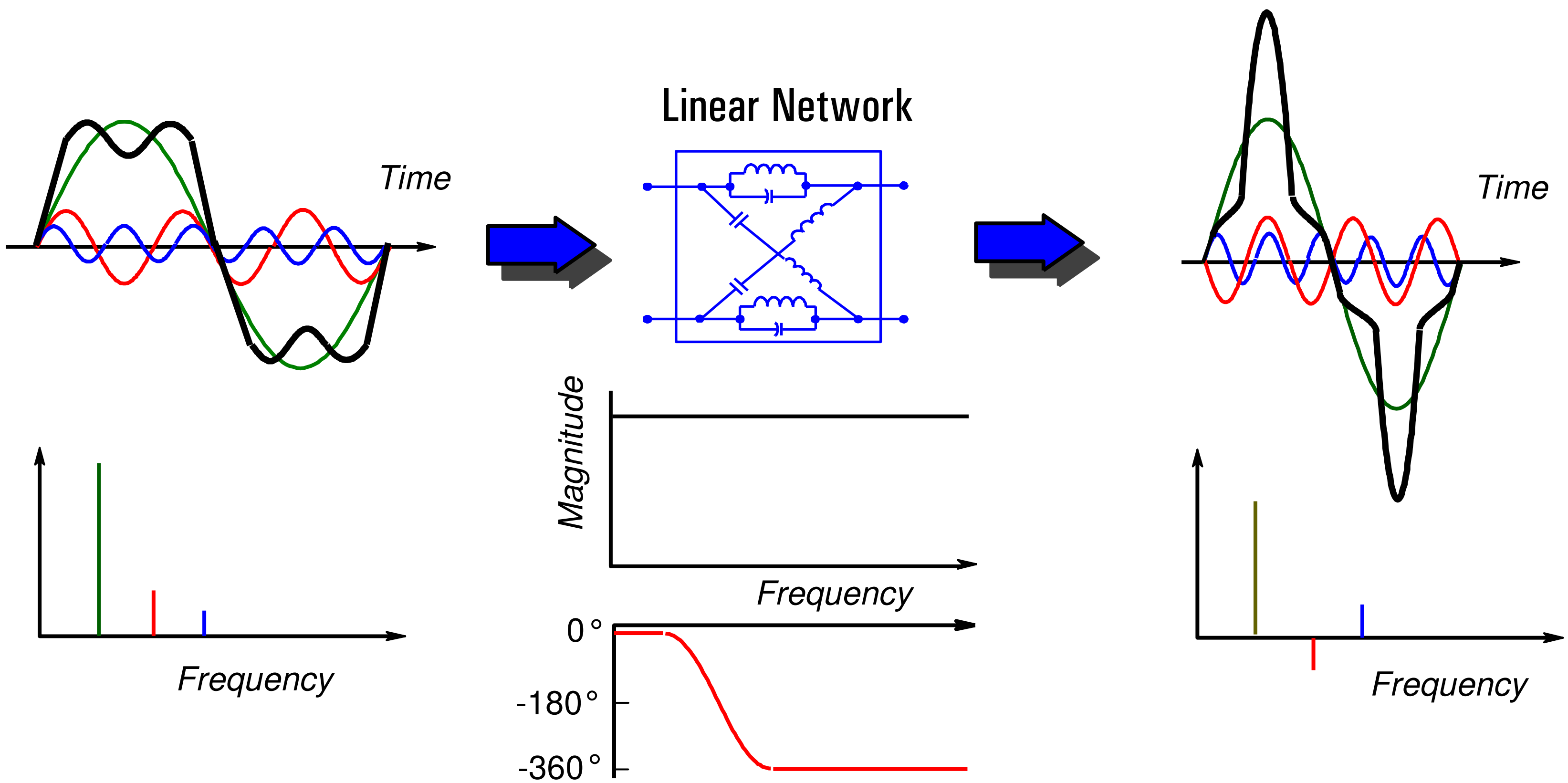
Magnitude Variation with Frequency

F(t) = sin wt + 1/3 sin 3wt + 1/5 sin 5wt



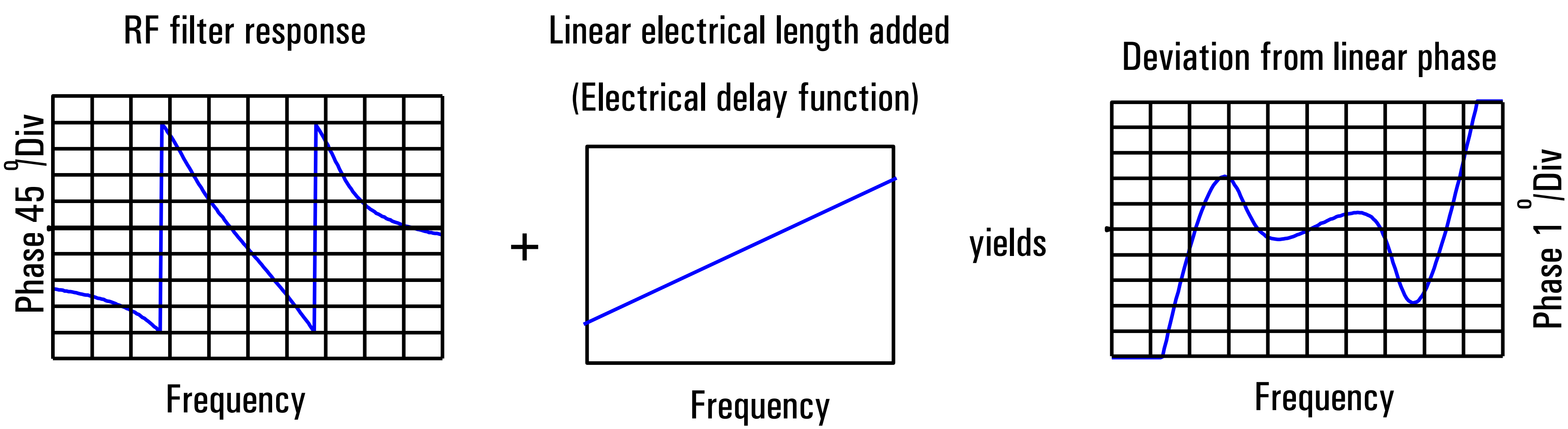
Phase Variation with Frequency

$$F(t) = \sin wt + 1/3 \sin 3wt + 1/5 \sin 5wt$$



Deviation from Linear Phase

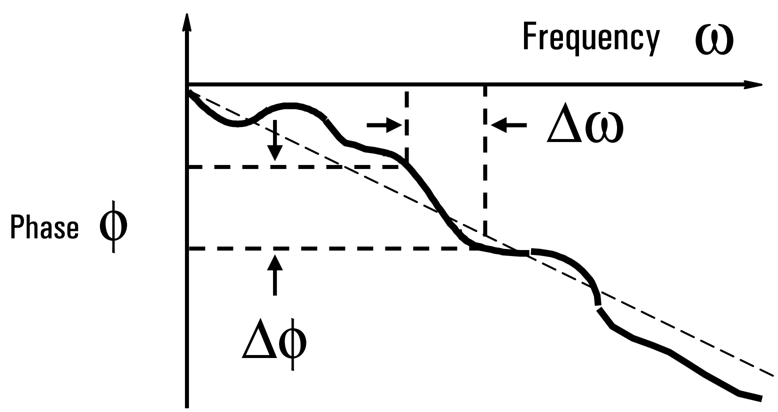
Use electrical delay to remove linear portion of phase response

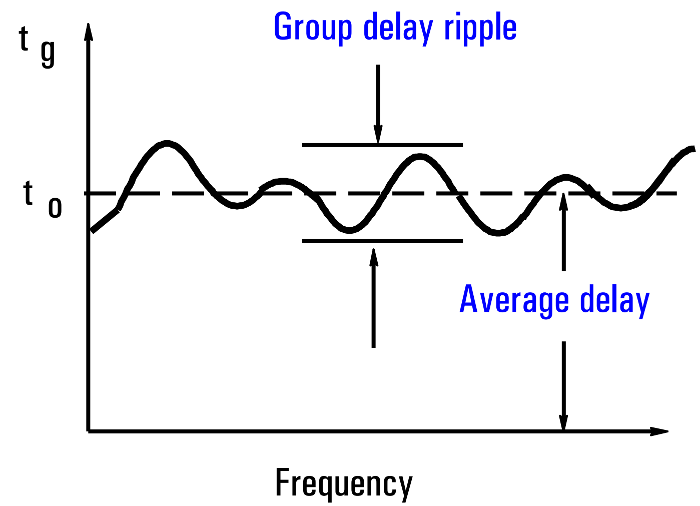


Low resolution

High resolution

Group Delay





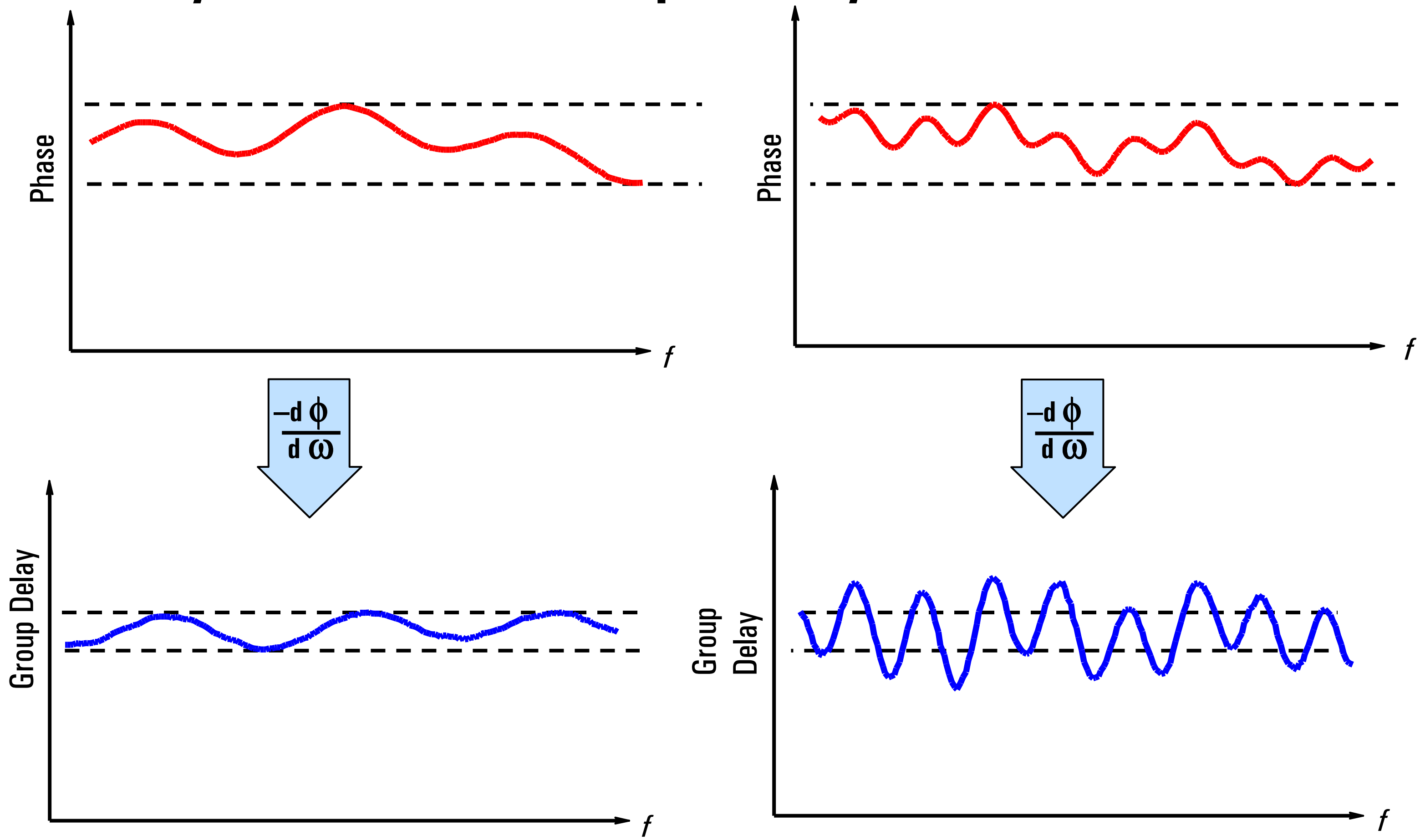
Group Delay (t_g) =

$$\frac{-d\phi}{d\omega} = \frac{-1}{360^{\circ}} * \frac{d\phi}{df}$$

- ϕ in radians
- ω in radians/sec
- ϕ in degrees
- f in Hertz ($\omega = 2\pi f$)

- group-delay ripple indicates phase distortion
- average delay indicates electrical length of DUT
- aperture of measurement is very important

Why Measure Group Delay?



Same p-p phase ripple can result in different group delay

Characterizing Unknown Devices

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

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

H-parameters

$$V_1 = h_{11}I_1 + h_{12}V_2$$
$$I_2 = h_{21}I_1 + h_{22}V_2$$

Y-parameters

$$I_1 = y_{11}V_1 + y_{12}V_2$$
$$I_2 = y_{21}V_1 + y_{22}V_2$$

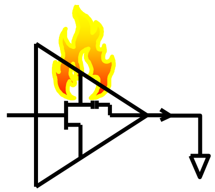
Z-parameters

$$V_1 = z_{11}I_1 + z_{12}I_2$$
$$V_2 = z_{21}I_1 + z_{22}I_2$$

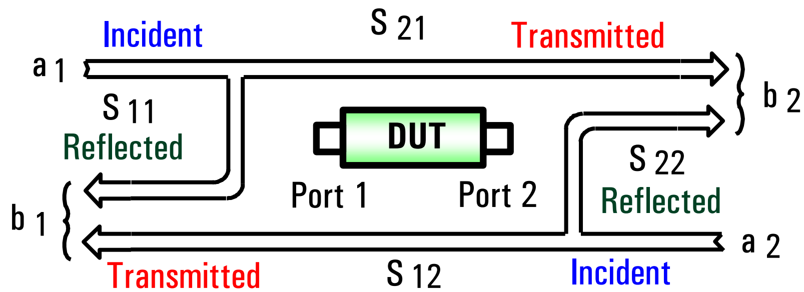
$$h_{11} = \left.\frac{V_1}{I_1}\right|_{V_2=0}$$ *(requires **short circuit**)*

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

Why Use S-Parameters?



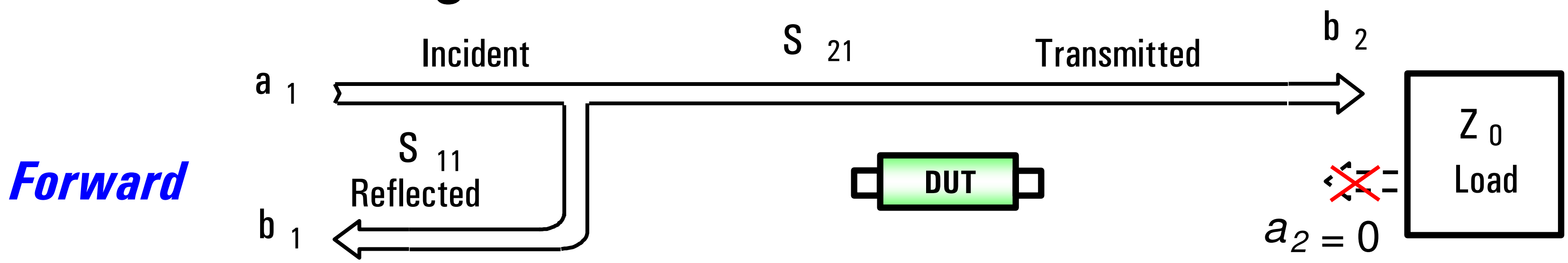
- relatively easy to **obtain** at high frequencies
  - measure voltage traveling waves with a vector network analyzer
  - don't need shorts/opens which can cause active devices to oscillate or self-destruct
- relate to **familiar** measurements (gain, loss, reflection coefficient ...)
- can **cascade** 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

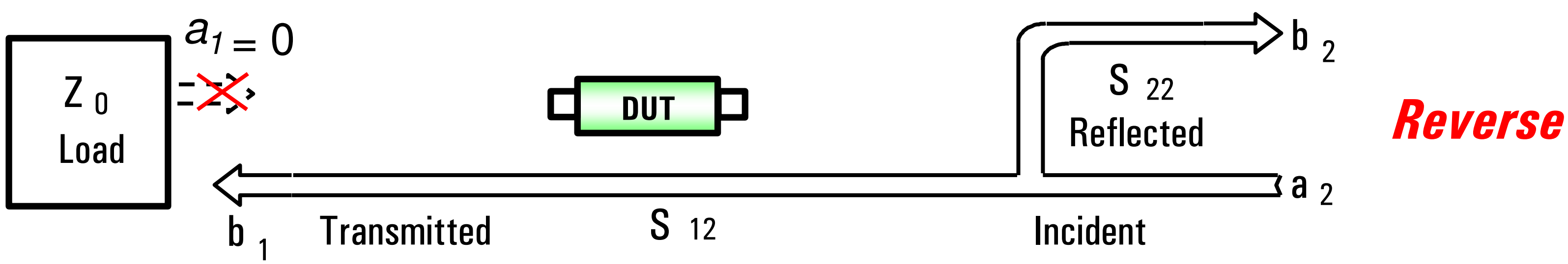


$$S_{11} = \frac{\textit{Reflected}}{\textit{Incident}} = \left.\frac{b_1}{a_1}\right|_{a_2 = 0}$$

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

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

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

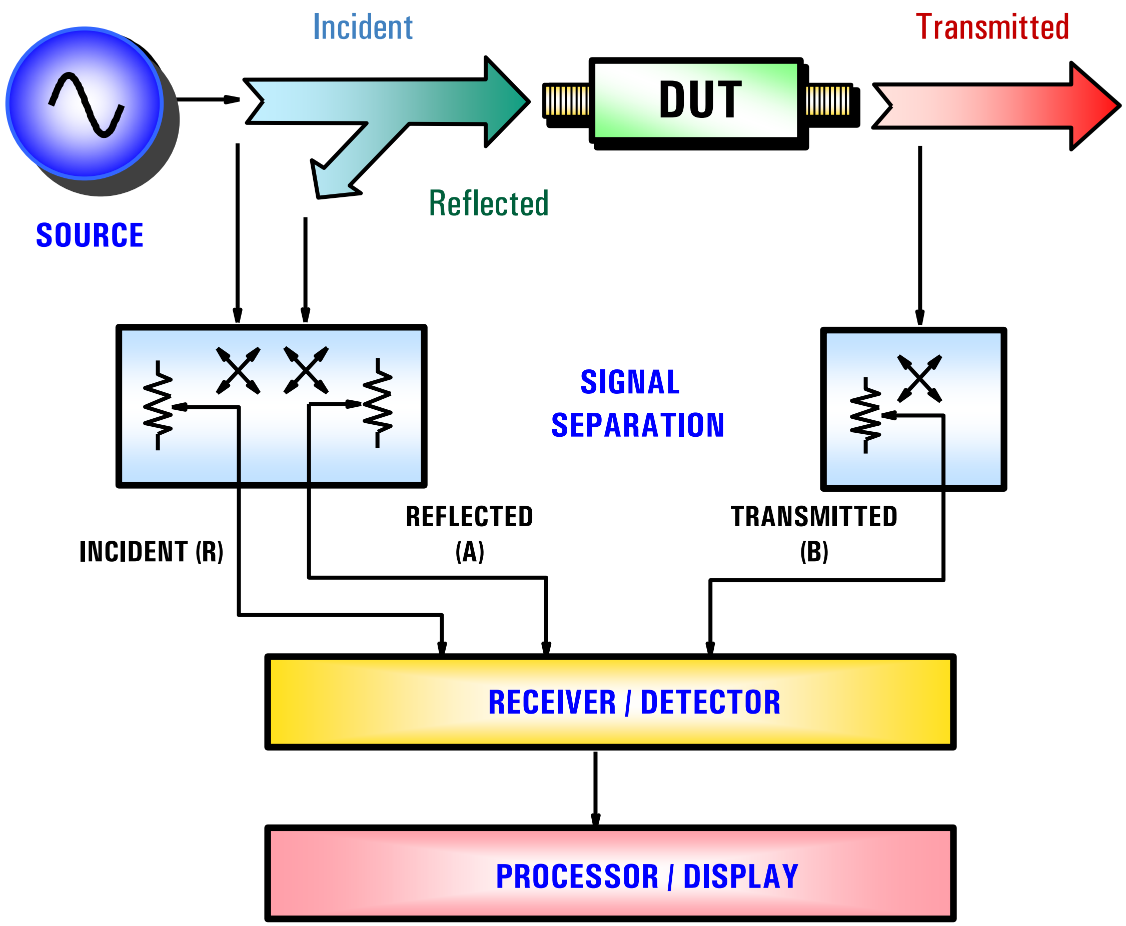


Equating S-Parameters with Common Measurement Terms

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

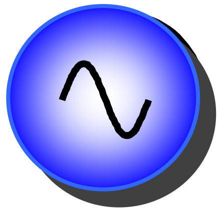
Remember, S-parameters are inherently complex, linear quantities -- however, we often express them in a log-magnitude format

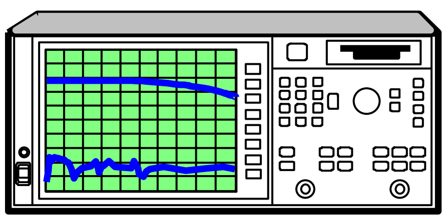
Generalized Network Analyzer Block Diagram

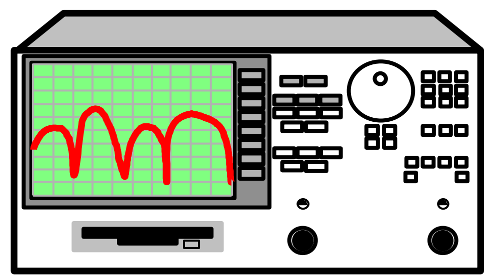


Source

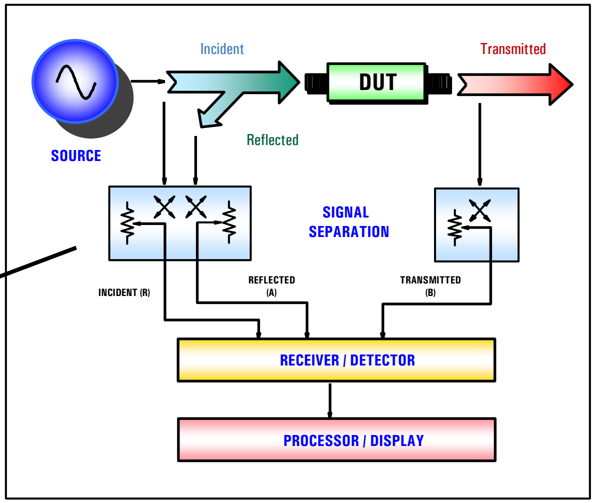
- Supplies stimulus for system
- Swept frequency or power
- Traditionally NAs used separate source
- Most Agilent analyzers sold today have ***integrated, synthesized*** sources





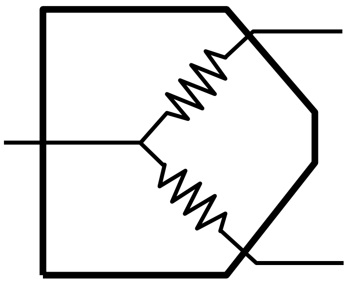


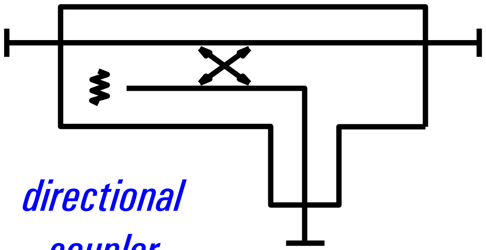
Signal Separation



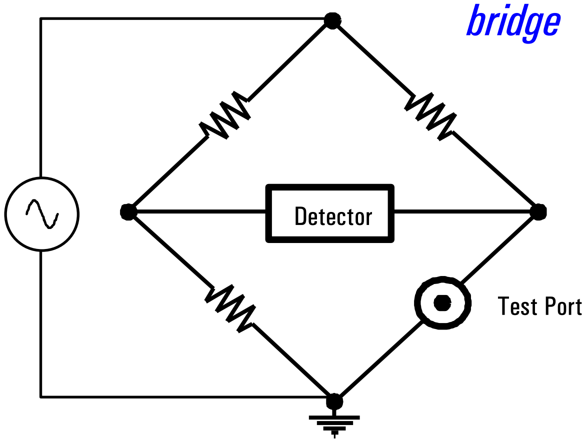
- measure incident signal for reference
- separate incident and reflected signals

splitter





directional coupler

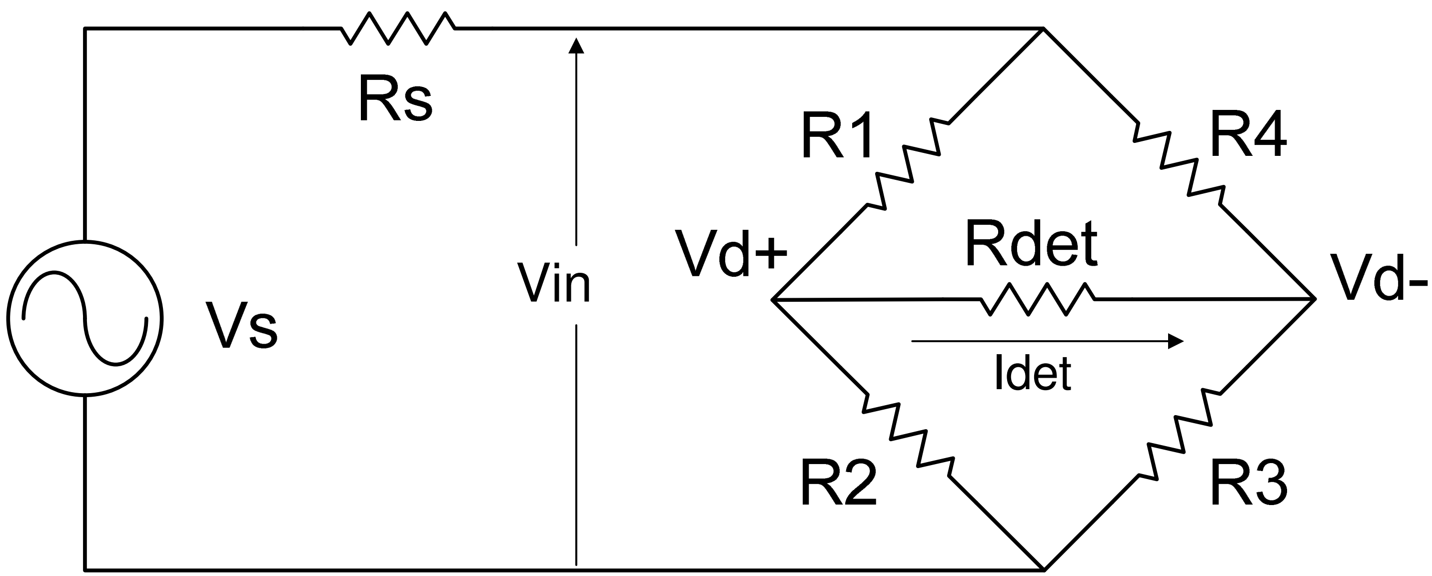


bridge

Consider the Wheatstone Bridge:

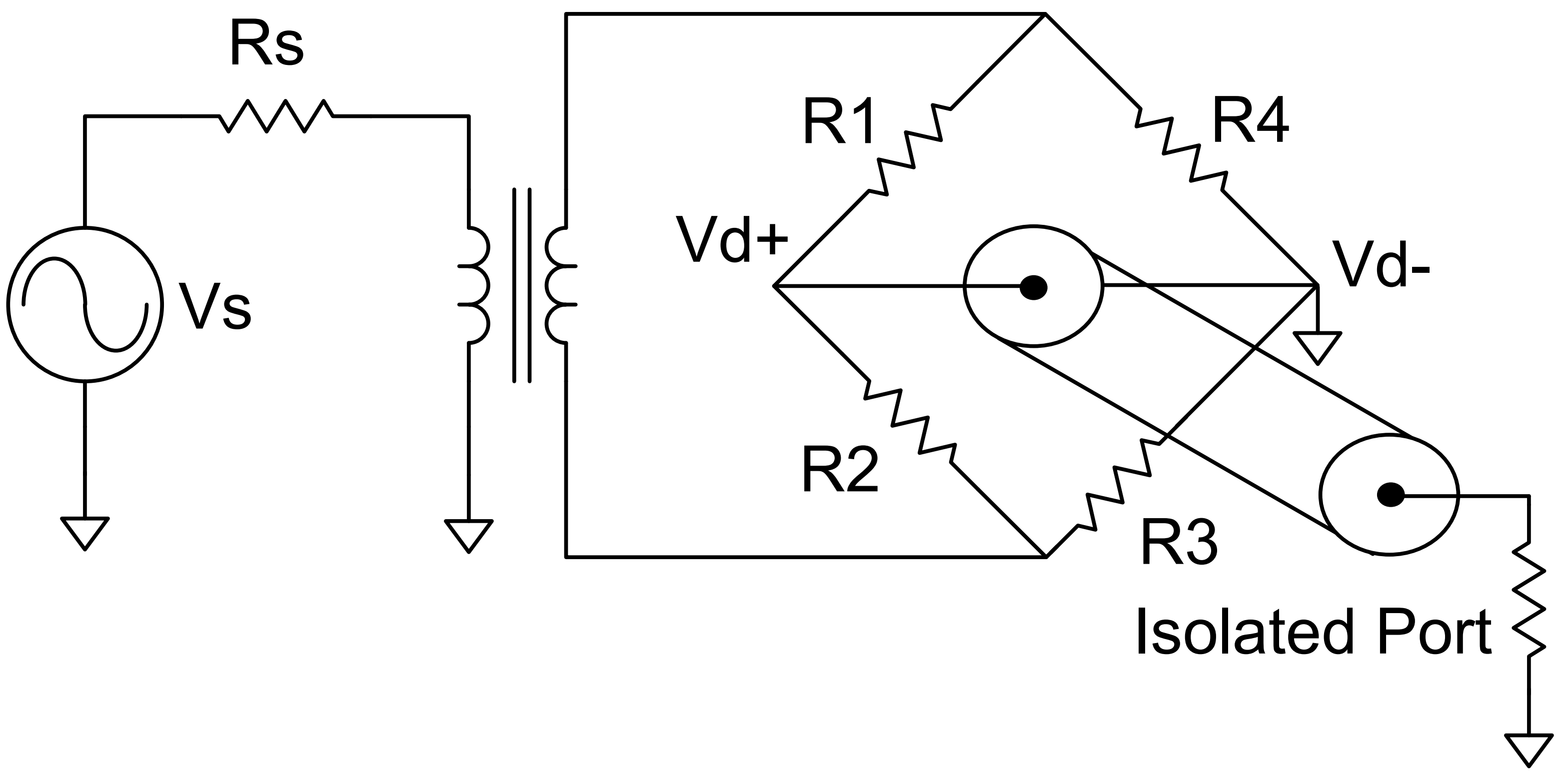
If the bridge is balanced Vd+=Vd-, and Idet = 0

$$Vd- = \frac{R2 \cdot Vin}{R1 + R2}; \quad Vd+ = \left.\frac{R3 \cdot Vin}{R3 + R4}\right|_{I\,det=0} \quad \text{Then} \quad \frac{R1}{R2} = \frac{R4}{R3}$$

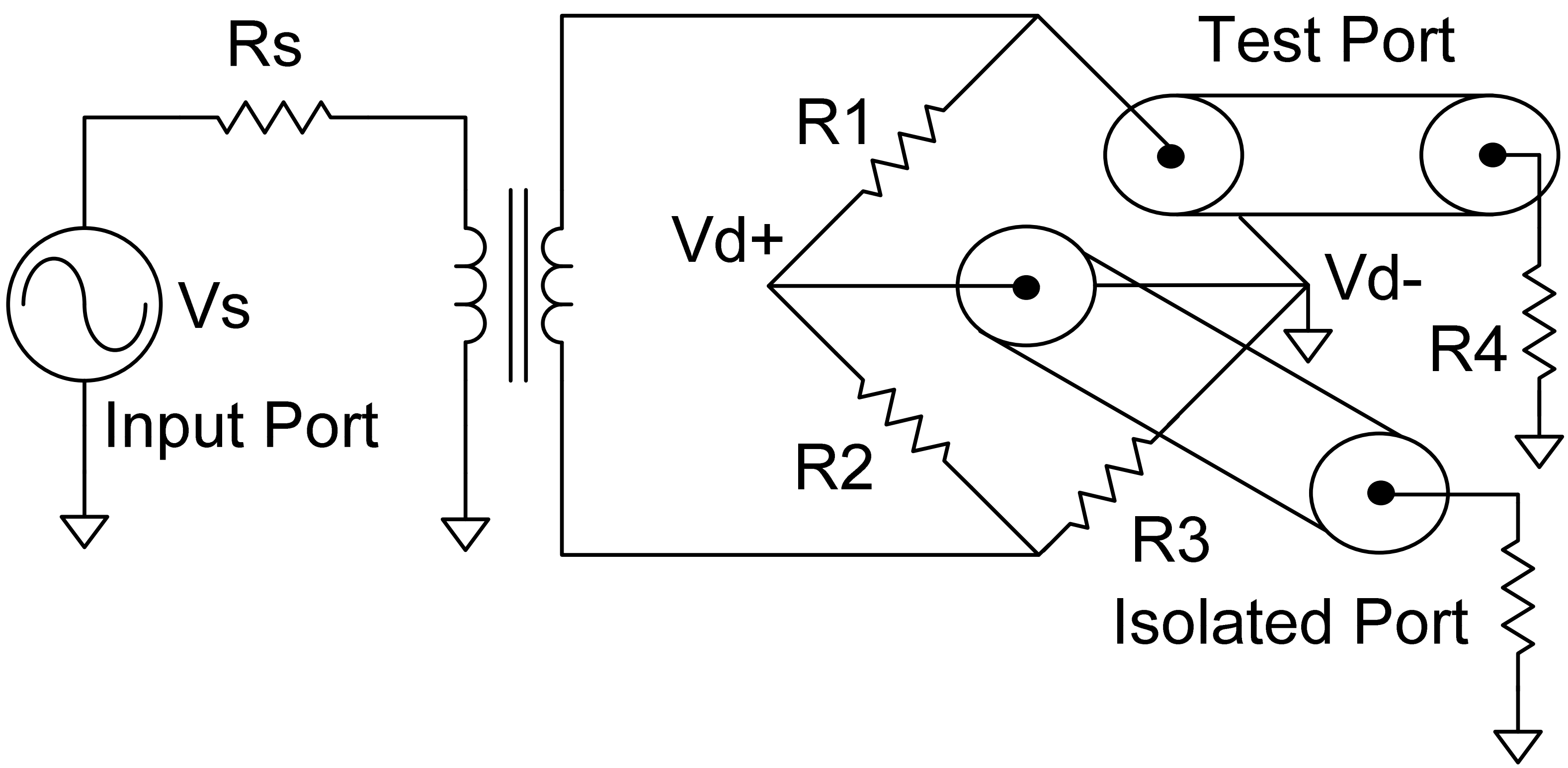


Further, it can be shown, that the input impedance of a balanced bridge follows the equation: $Zin^2 = R1 \cdot R3 = R2 \cdot R4$

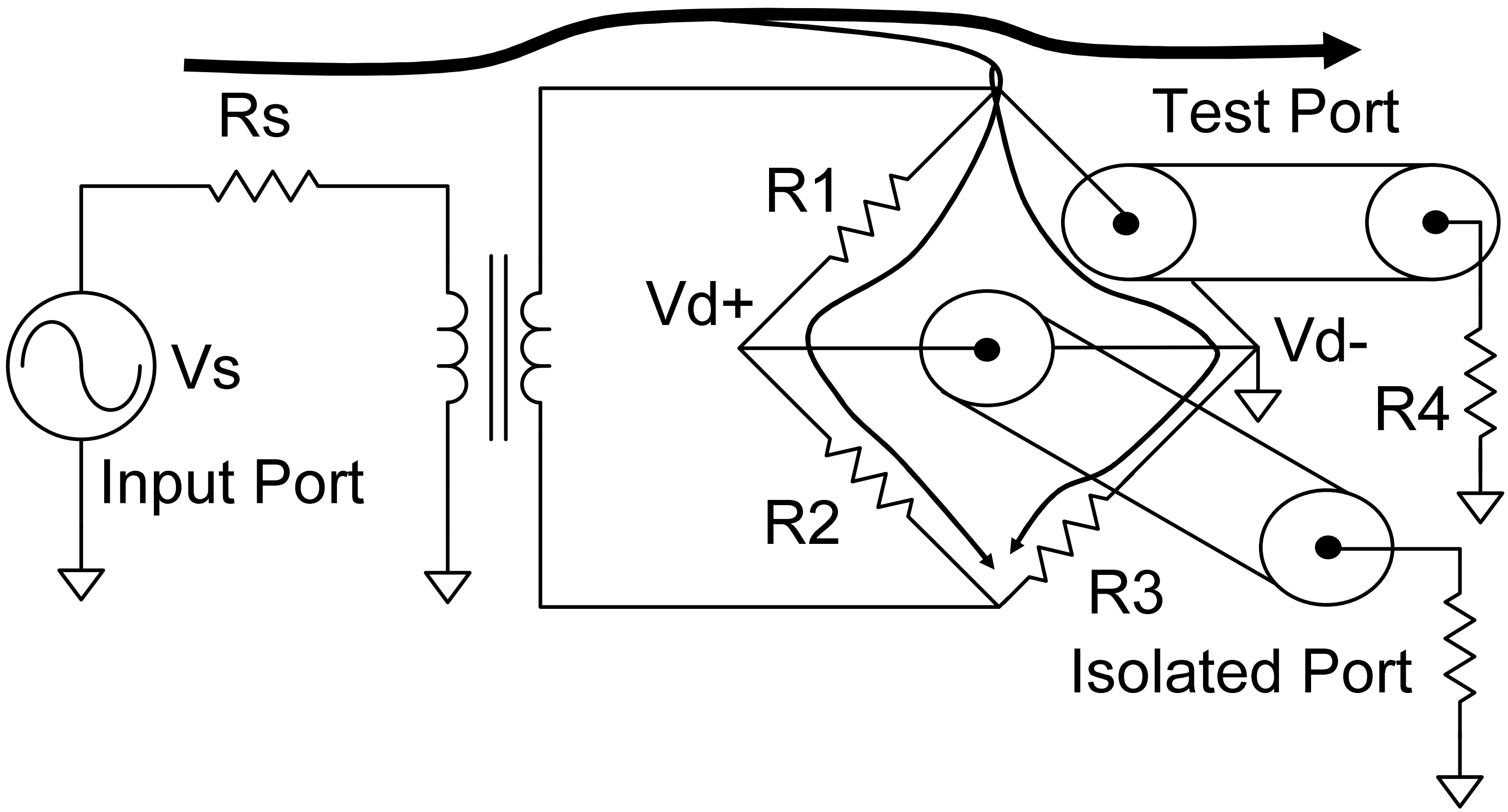
We can morph this Wheatstone Bridge into a "Directional Bridge" with explicit ports by noting that the floating voltage source can be replaced with a transformer coupled port, and Rdet can be connected through a transmission line (representing a cable or port)



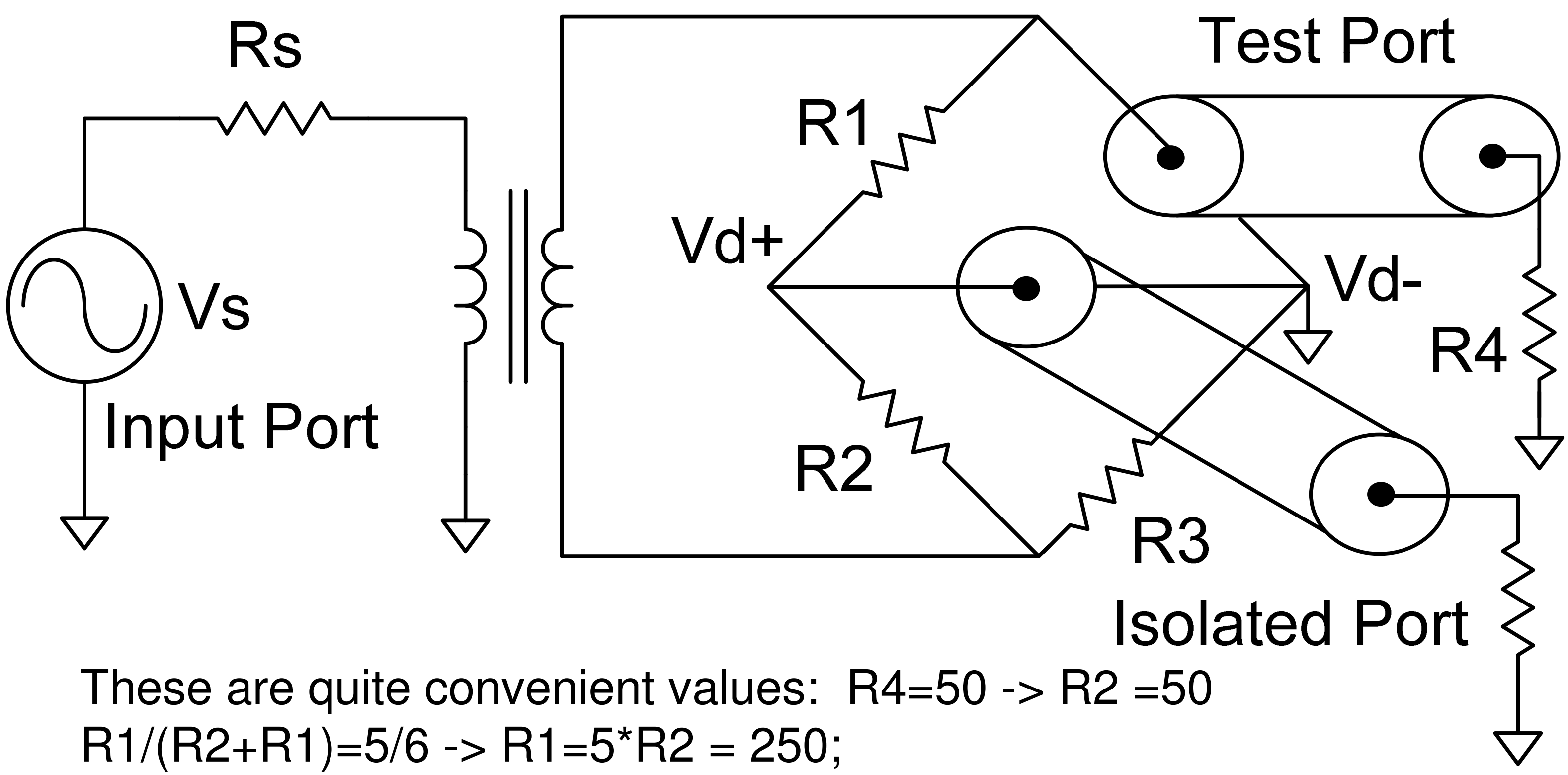
We would like the bridge to be matched so $Rs^2=R1*R3=R2*R4$.
In this condition, Vin=Vs/2.
If we fix R4=Rs, then R2=Rs as well, and we can replace R4 with a transmission line or cable of impedance Rs. Now we have three well defined ports, and we can see that the port replacing the detector port is isolated.



So, in the isolation direction it is clear that no signal appears at the isolated port, as the current divides equally across the bridge, if the test port is terminated in Rs

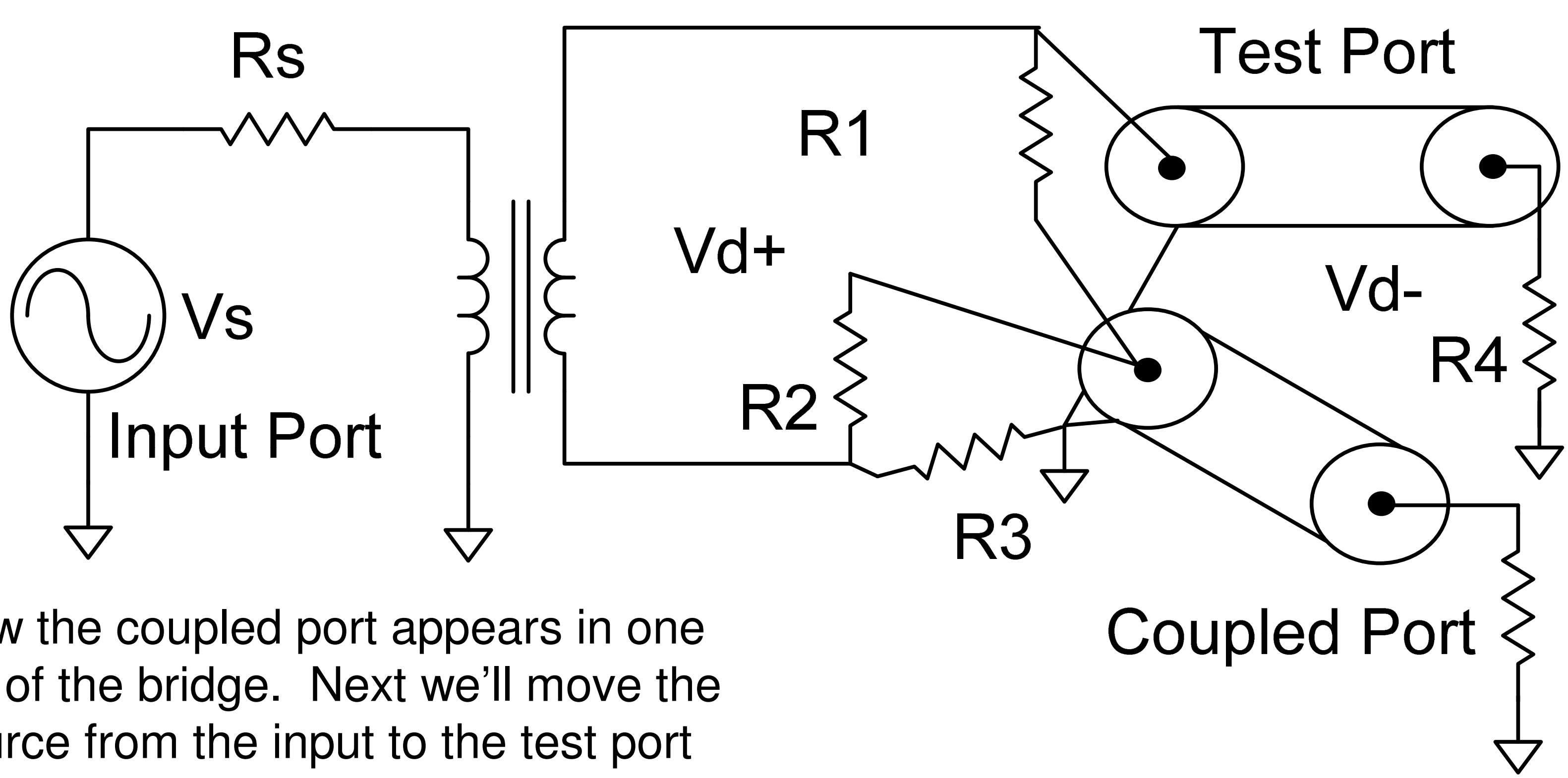


Now we can set the forward loss of the bridge. The voltage on the test port is equal to the voltage across R1. We have complete flexibility to set any ratio we want. In this case let's choose the voltage to be 5/6 of Vin. Then Vd+=Vd-=(1/6)Vin. The loss from Input Port to output port is 20*log(5/6) = -1.58 dB.



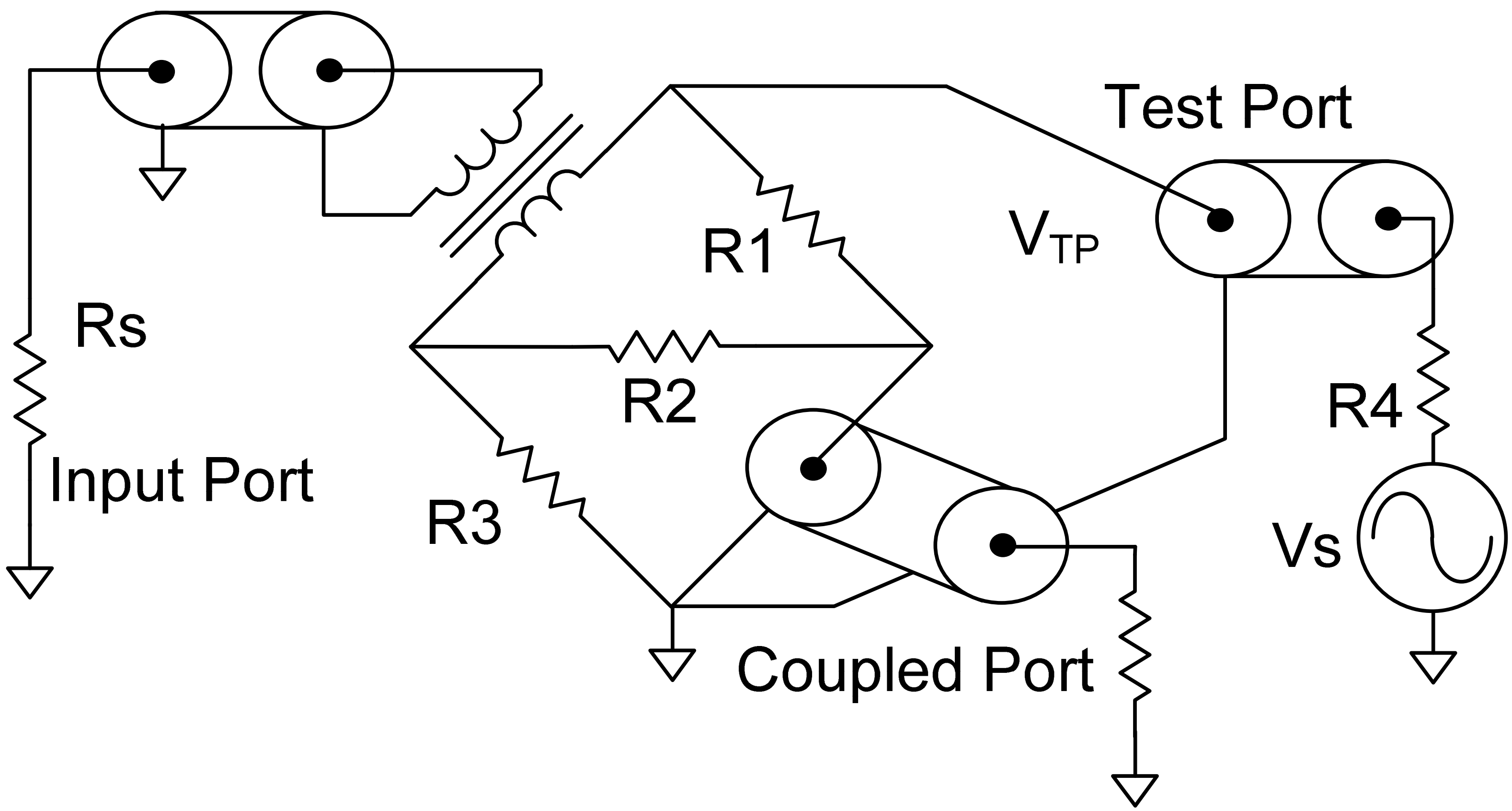
These are quite convenient values: R4=50 -> R2 =50
R1/(R2+R1)=5/6 -> R1=5*R2 = 250;
And because R1*R3=R2*R4 ->R3 = 10;

Now lets look how to “reverse” the power flow, and see what couples into the isolated port (we’ll now call it the Coupled Port) when we put the source at the test port, and redraw the figure (no connection changes) to highlight the coupled port.

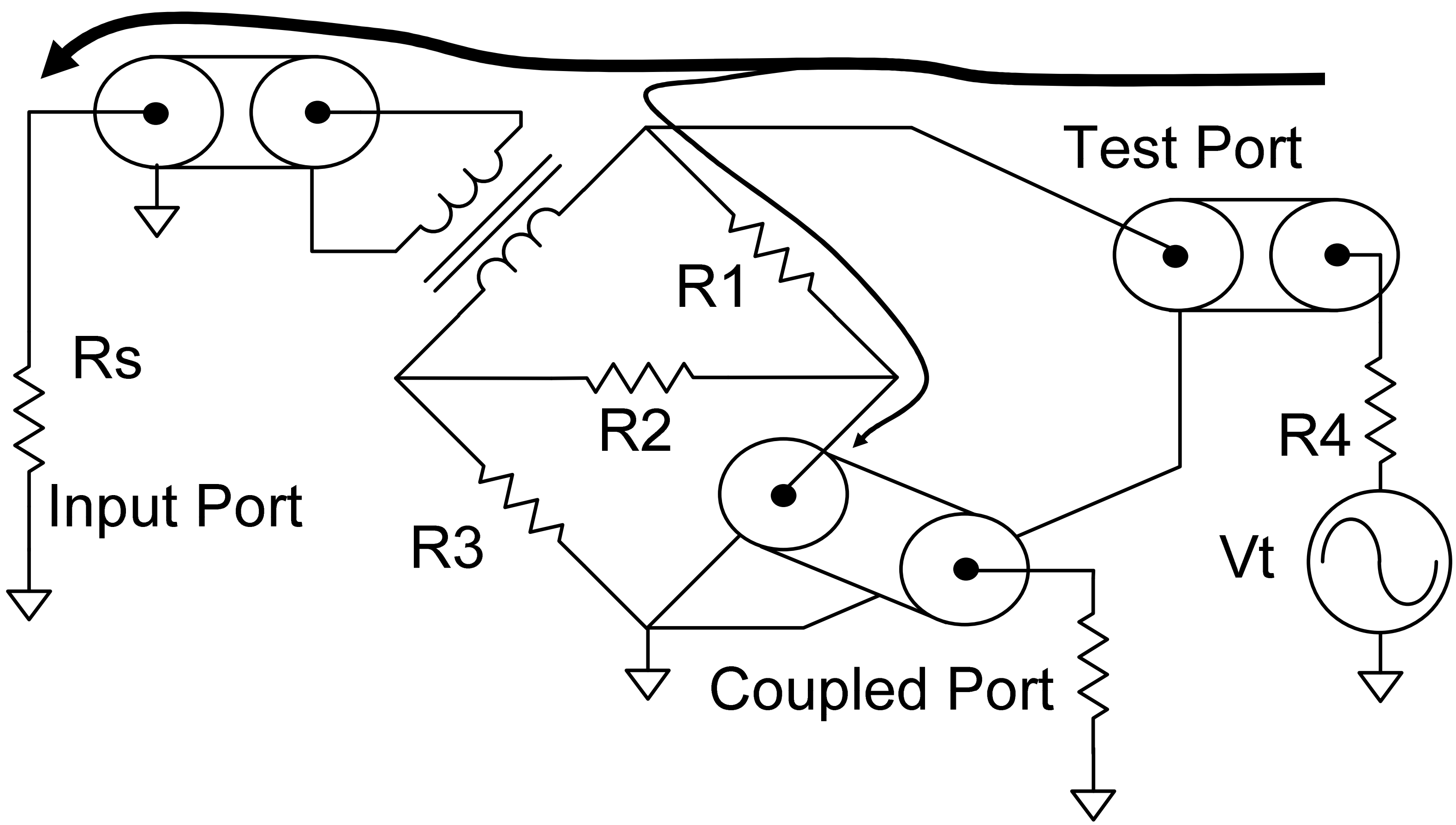


Now the coupled port appears in one leg of the bridge. Next we’ll move the source from the input to the test port (and make the input into a port as well)

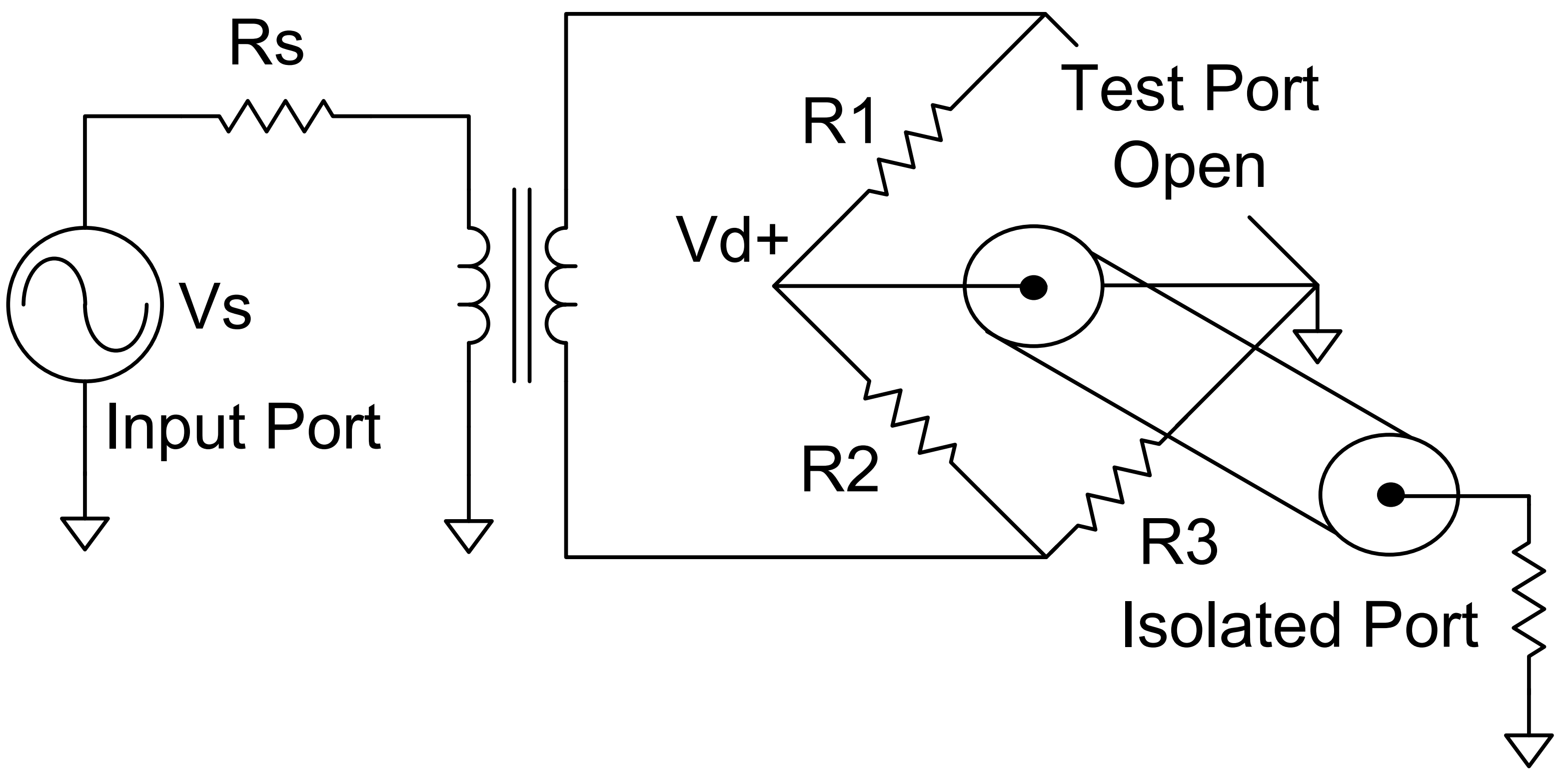
Finally, we can compute the coupling factor of the bridge. In the coupling direction, the voltage across the coupled port is 1/6 *V_{TP}, or -15.5 dB. We can set either the loss of the bridge or the coupling, but once we set one, the other is determined.



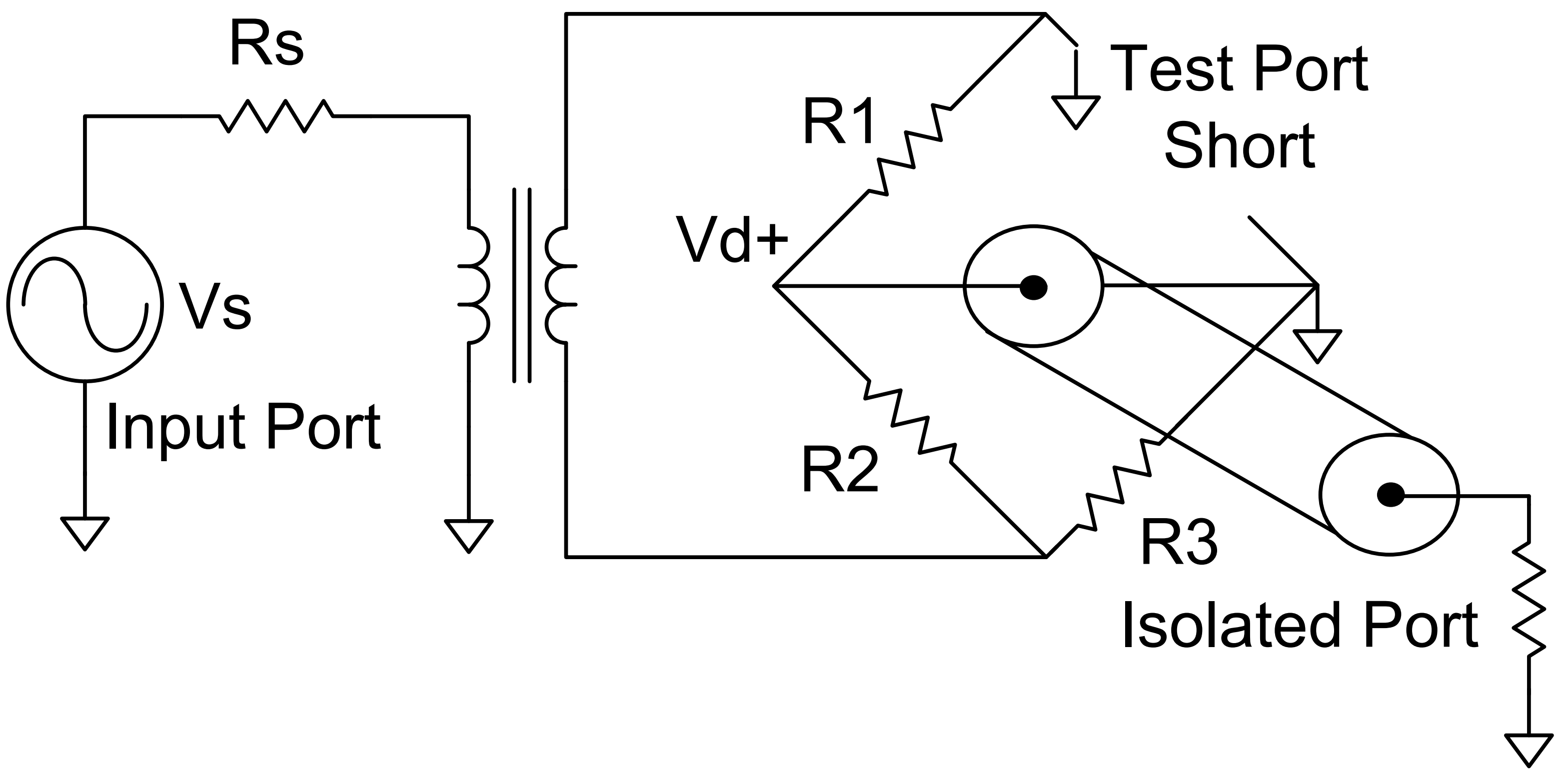
Just as clearly, with the signal driven from the test port, there will be the same loss to the Input Port as there was in the other direction, but now the signal will be coupled to the Coupled Port



Let's check two cases: Assume the test port is open circuit (R4 infinite), then the voltage at the isolated point will be (1/2)*(5/6)*(1/6)*Vs, exactly the same as the combination of loss and coupling, assuming a total reflection at the test port.

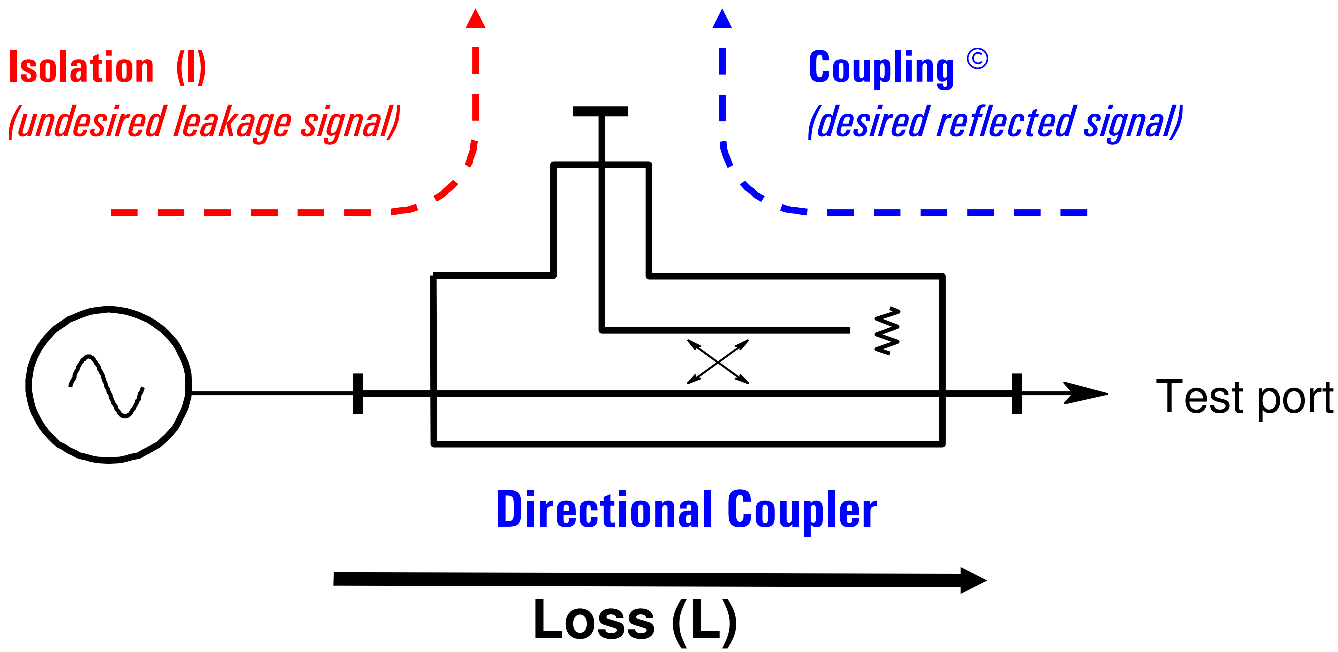


Now Assume the test port is short circuit (R4 =0). Surprisingly (or not, if you're a real electrical engineer) the voltage at the isolated port will be (1/2)*(5/6)*(1/6)*Vs, exactly the same as the open, but with a sign change! Thus it is again the combination of loss and coupling, assuming a total reflection at the test port, but the reflection is negative.

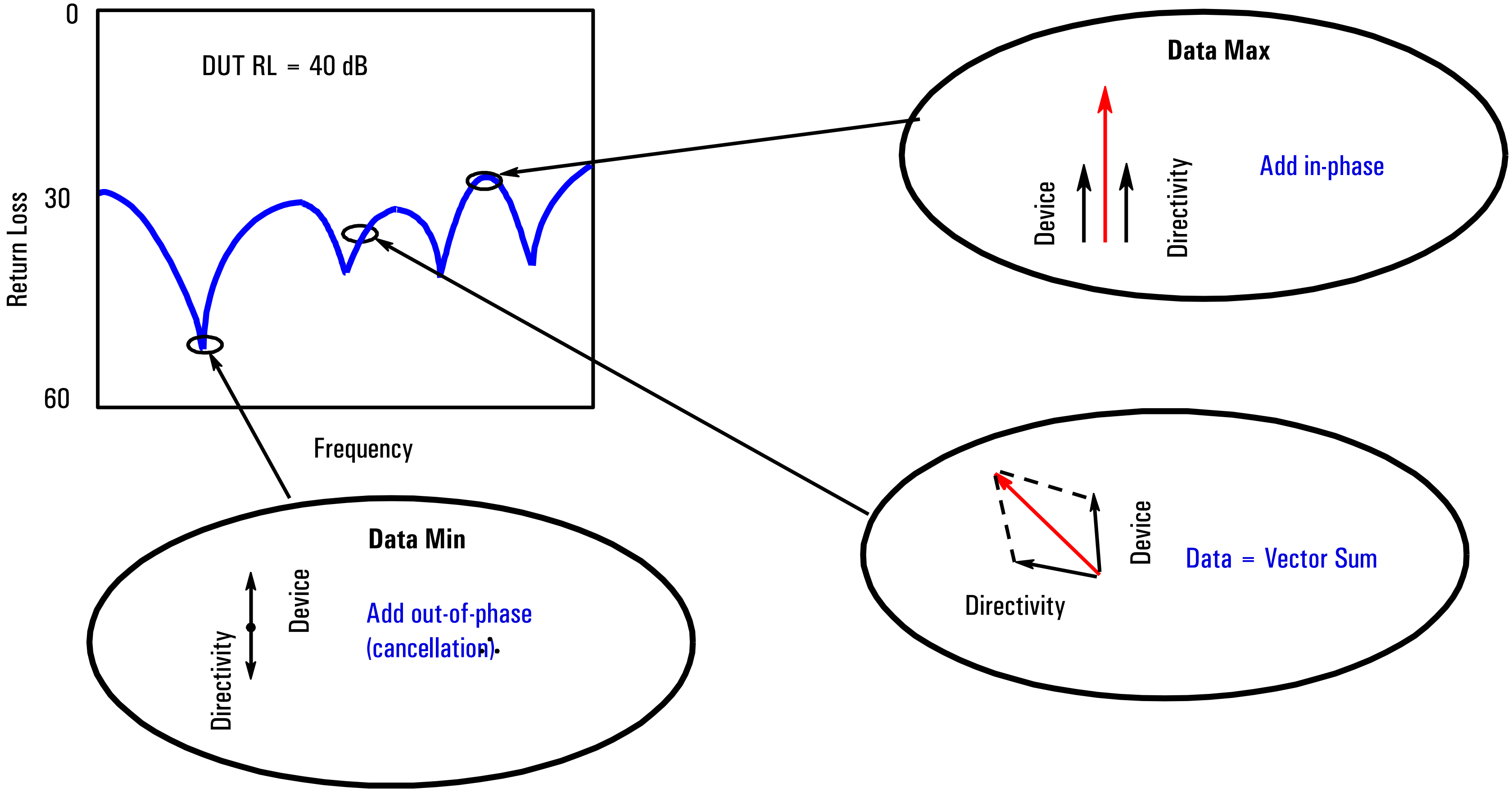


Directivity

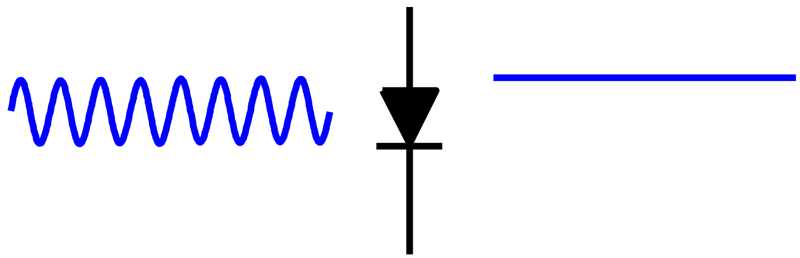
Directivity is a measure of how well a coupler can separate signals moving in opposite directions
D = I/(C * L), I, C, L positive (loss).



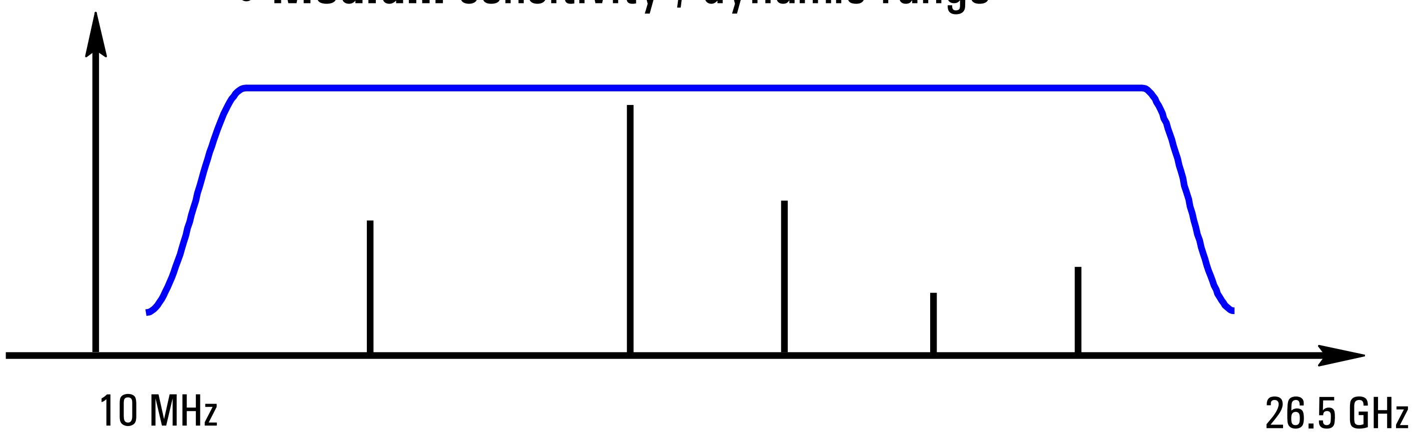
Interaction of Directivity with the DUT (Without Error Correction)



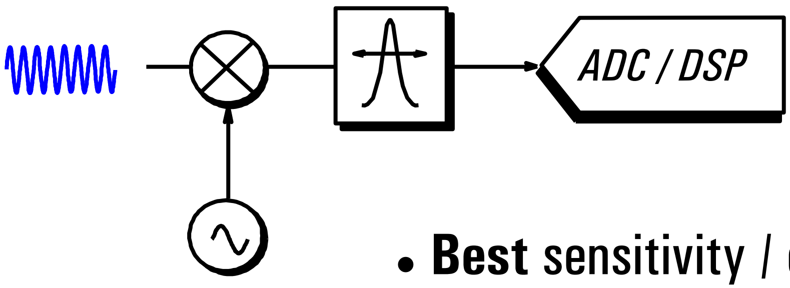
Broadband Diode Detection



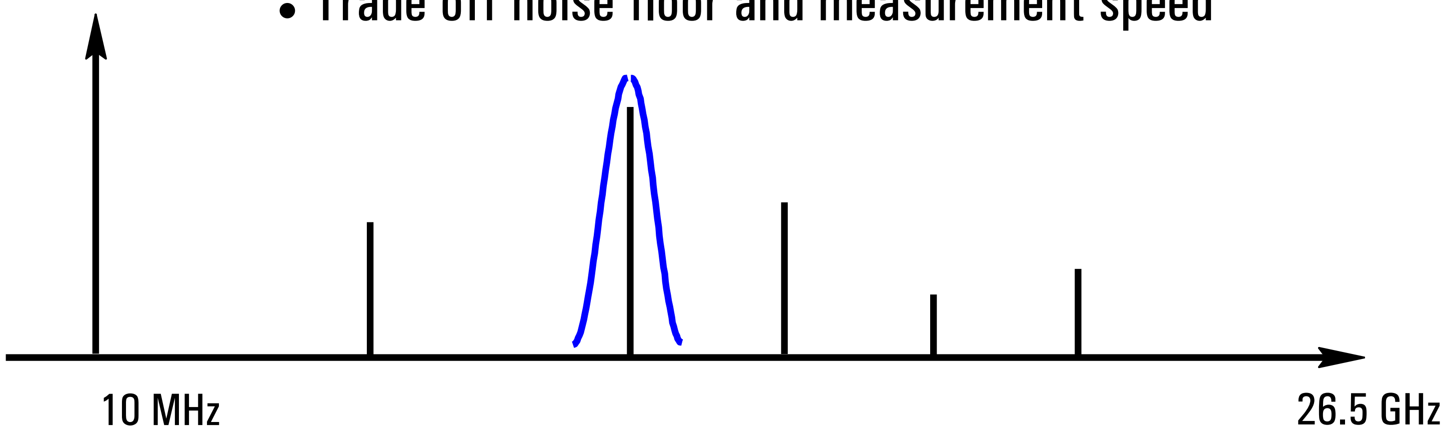
- Easy to make **broadband**
- **Inexpensive** compared to tuned receiver
- Good for measuring frequency-translating devices
- Improve dynamic range by increasing power
- **Medium** sensitivity / dynamic range



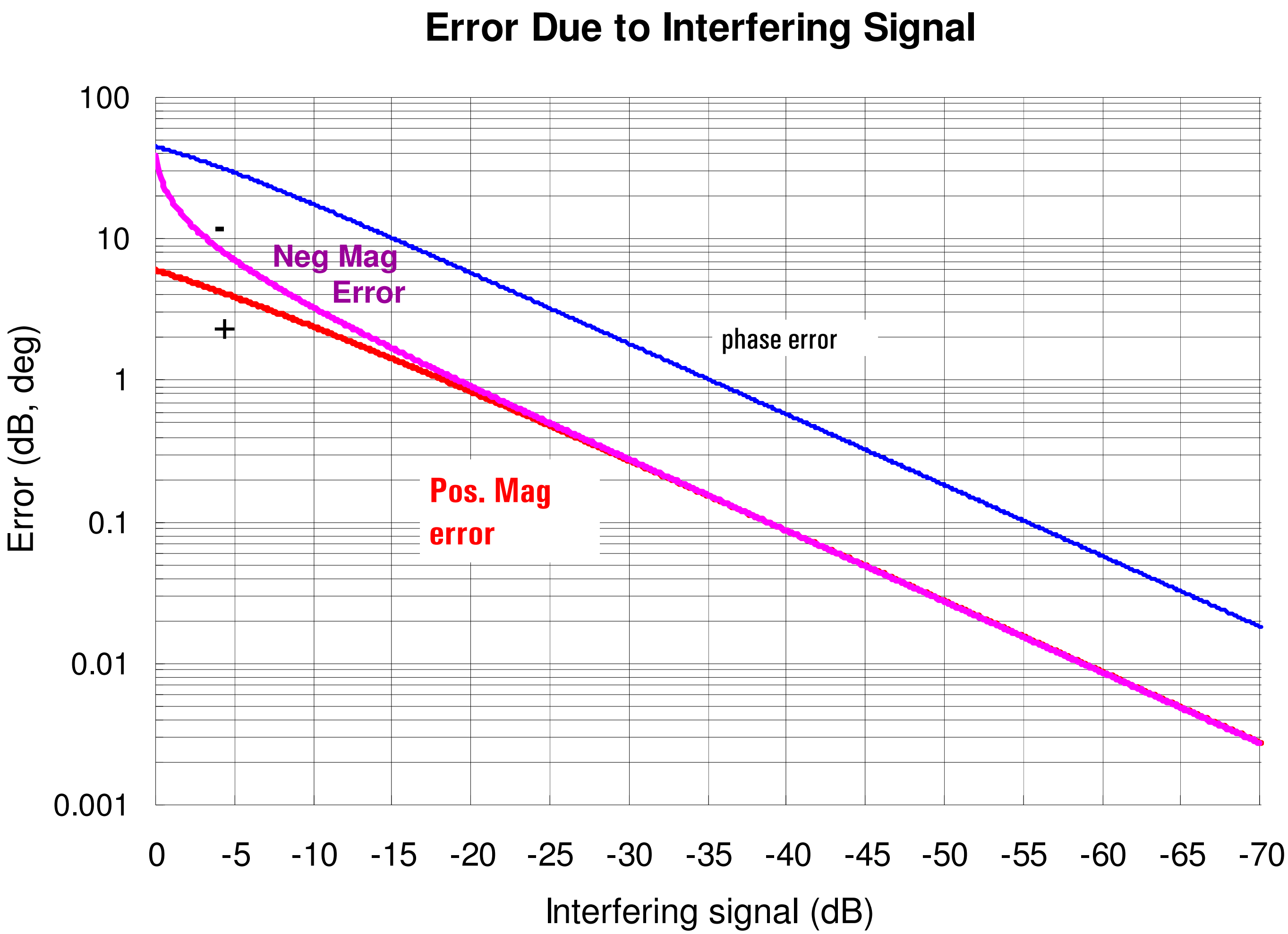
Narrowband Detection – Tuned Receiver



- **Best** sensitivity / dynamic range
- Provides harmonic / spurious signal **rejection**
- Improve dynamic range by increasing **power**, decreasing IF **bandwidth**, or **averaging**
- Trade off noise floor and measurement speed

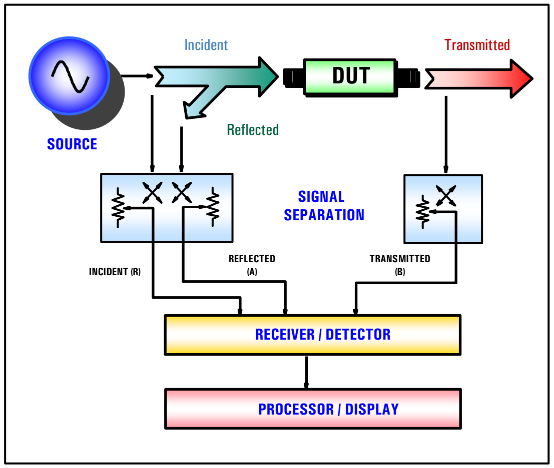


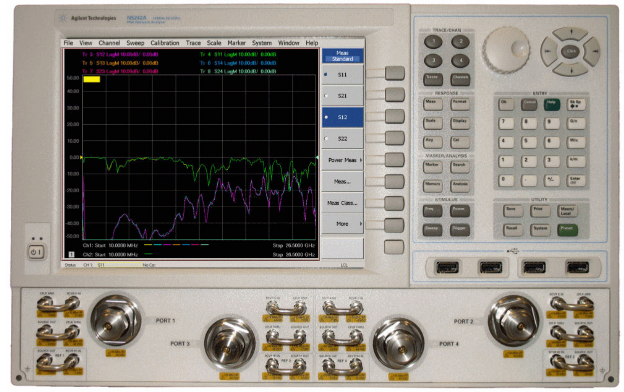
Errors due to reflections, other signals

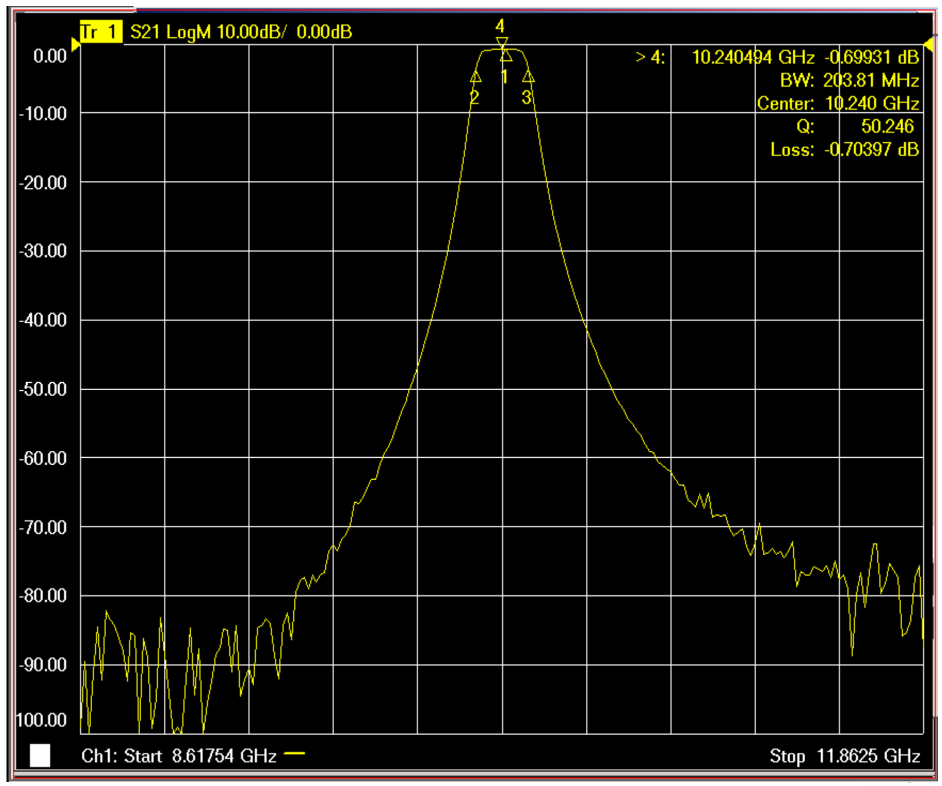


In Log Mag format, the –dB error is larger than the +dB error

Processor/Display







- markers
- limit lines
- pass/fail indicators
- linear/log formats
- grid/polar/Smith charts

Measurement Error Modeling

Systematic errors

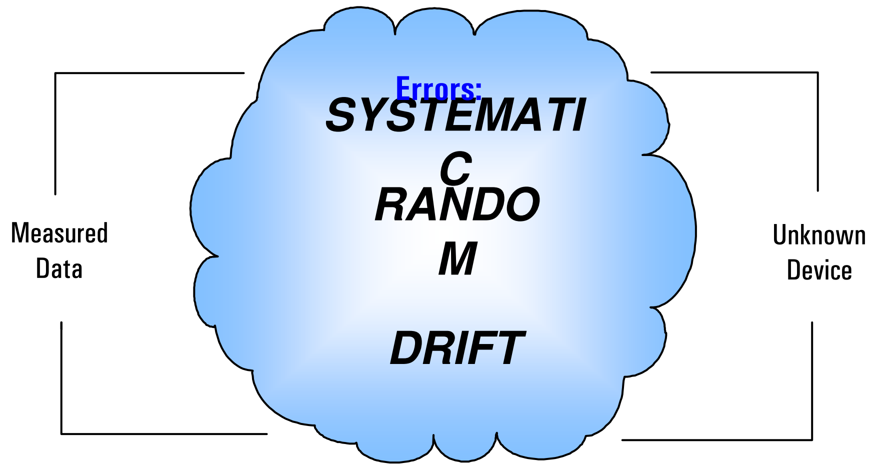
- due to **imperfections** in the analyzer and test setup
- assumed to be **time invariant** (predictable)

Random errors

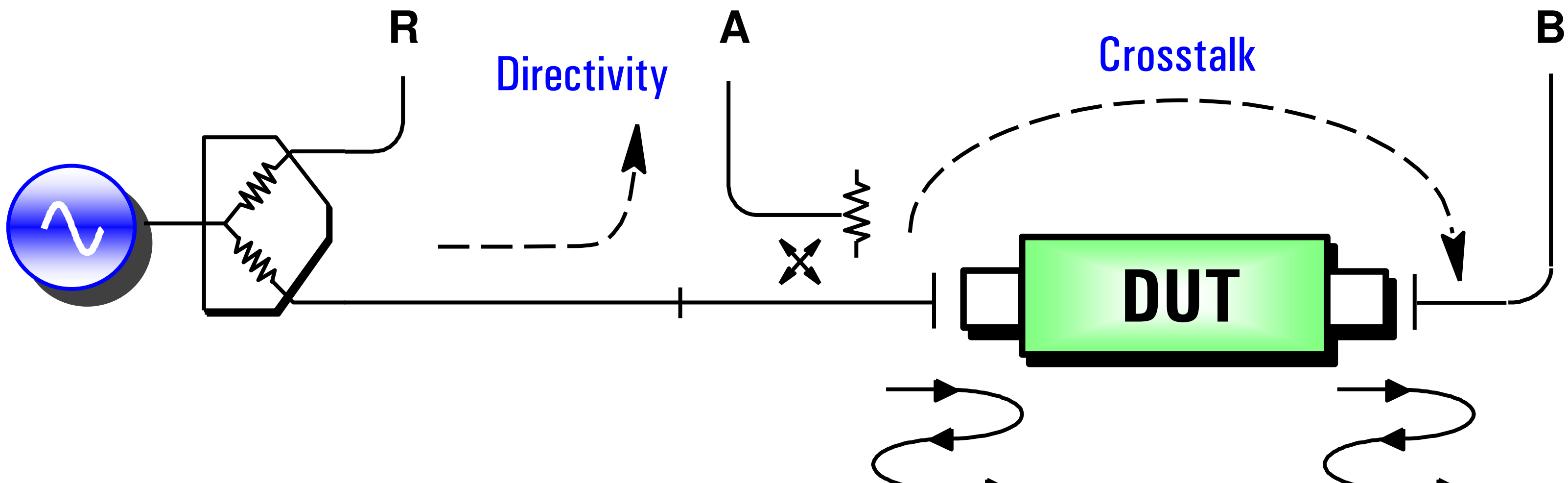
- **vary** with time in random fashion (unpredictable)
- main contributors: instrument **noise,** switch and connector **repeatability**

Drift errors

- due to system performance changing ***after*** a calibration has been done
- primarily caused by **temperature variation**



Systematic Measurement Errors



Frequency response

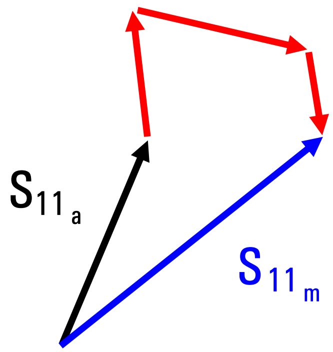
- reflection tracking (A/R)
- transmission tracking (B/R)

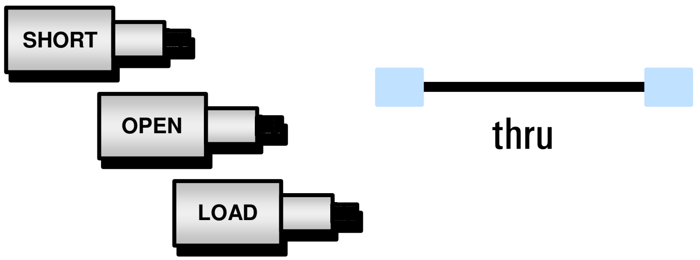
Six forward and six reverse error terms yields 12 error terms for two-port devices

Types of Error Correction

- **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

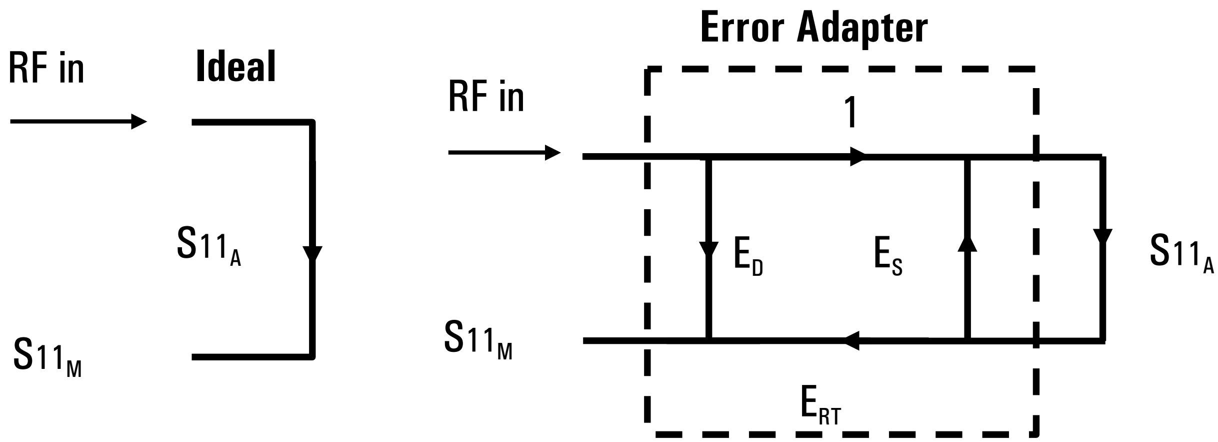




What is Vector-Error Correction?

- 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)
- Standards defined in **cal kit definition** file
  - network analyzer contains standard cal kit definitions
  - **CAL KIT DEFINITION MUST MATCH ACTUAL CAL KIT USED!**
  - User-built standards must be characterized and entered into user cal-kit

Reflection: One-Port Model



E_D = Directivity

E_{RT} = Reflection tracking

E_S = Source Match

$S11_M$ = Measured

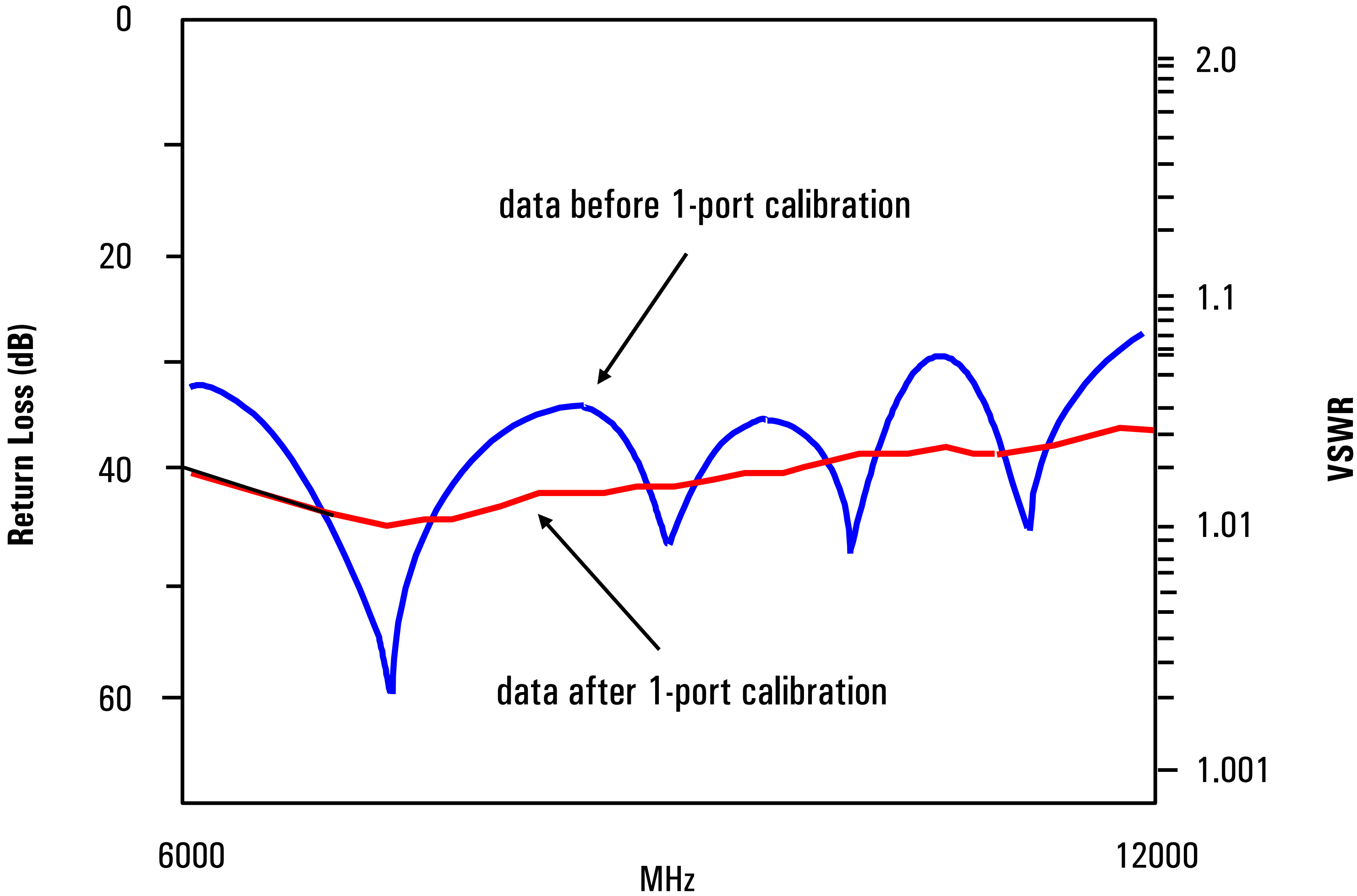
$S11_A$ = Actual

To solve for error terms, we measure 3 standards to generate 3 equations and 3 unknowns

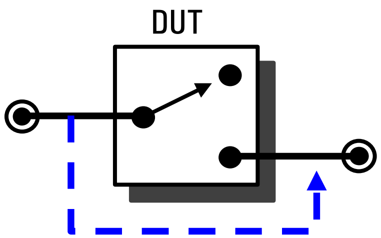
$$S11_M = E_D + E_{RT}\left[\frac{S11_A}{1 - E_S\ S11_A}\right]$$

- Assumes good termination at port two if testing two-port devices
- If using port 2 of NA *and* DUT reverse isolation is low (e.g., filter passband):
  - assumption of good termination is not valid
  - two-port error correction yields better results

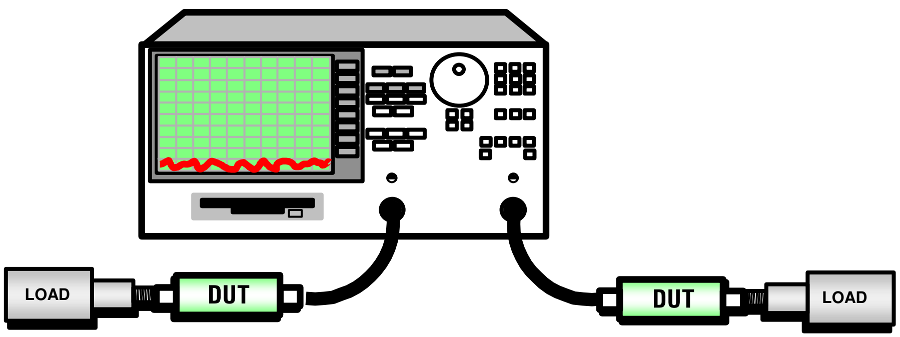
Before and After One-Port Calibration



Crosstalk: Signal Leakage Between Test Ports During Transmission



- 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 near noise floor of system)
  - only perform if really needed (use averaging if necessary)
  - if crosstalk is **independent** of DUT match, use two terminations
  - if **dependent** on DUT match, use DUT with termination on output

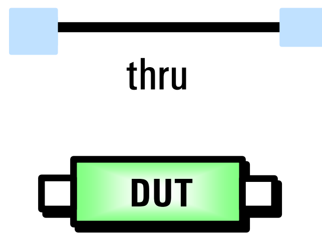


Errors and Calibration Standards

UNCORRECTED

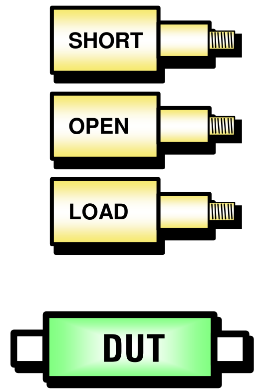
- Convenient
- Generally not accurate
- No errors removed

RESPONSE



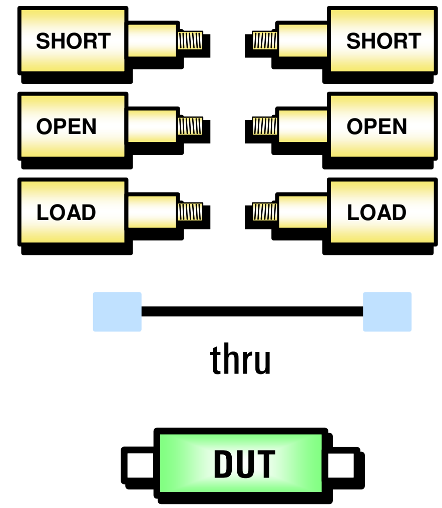
- Easy to perform
- Use when highest accuracy is not required
- Removes frequency response error

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

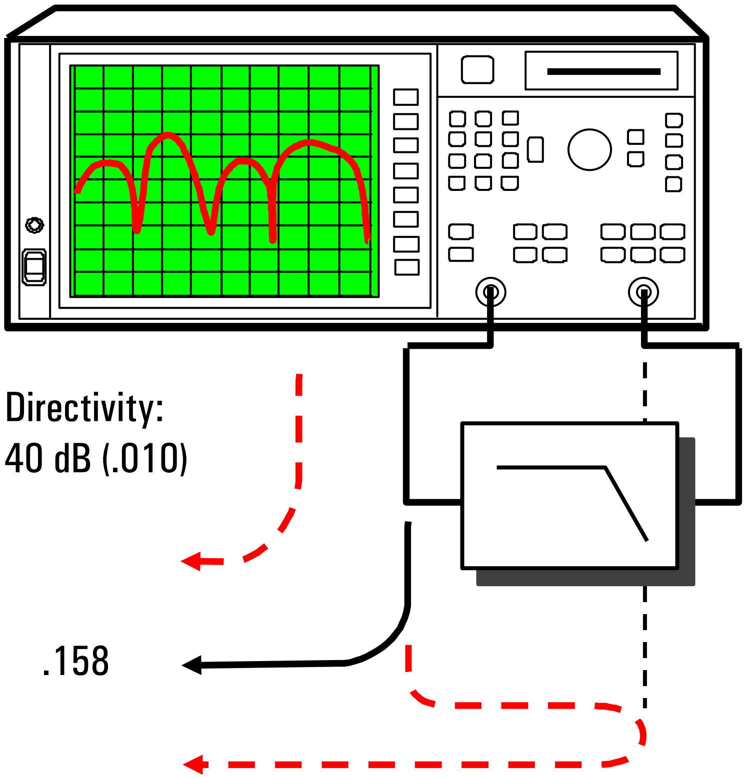


- Highest accuracy
- Removes these errors:
  Directivity
  Source, load match
  Reflection tracking
  Transmission tracking
  Crosstalk

ENHANCED-RESPONSE

- Combines response and 1-port
- Corrects source match for transmission measurements

Reflection Example Using a One-Port Cal



Directivity:
40 dB (.010)

.158

(.891)(.126)(.891) = .100

Load match:
18 dB (.126)

DUT

16 dB RL (.158)
1 dB loss (.891)

Remember: convert all dB values to linear for uncertainty calculations!

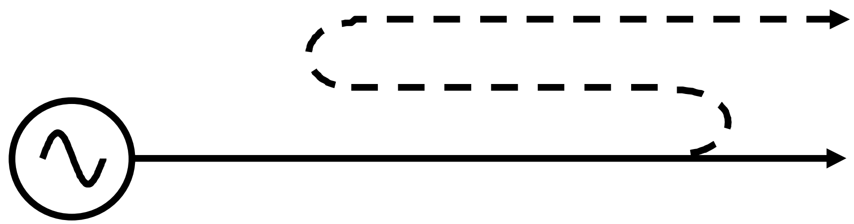
$$\rho \text{ or } loss_{(linear)} = 10^{\left(\frac{-dB}{20}\right)}$$

Measurement uncertainty:

-20 * log (.158 + .100 + .010)
= 11.4 dB (-4.6dB)

-20 * log (.158 - .100 - .010)
= 26.4 dB (+10.4 dB)

Transmission Example Using Response Cal



Thru calibration (normalization) builds error into measurement due to source and load match interaction

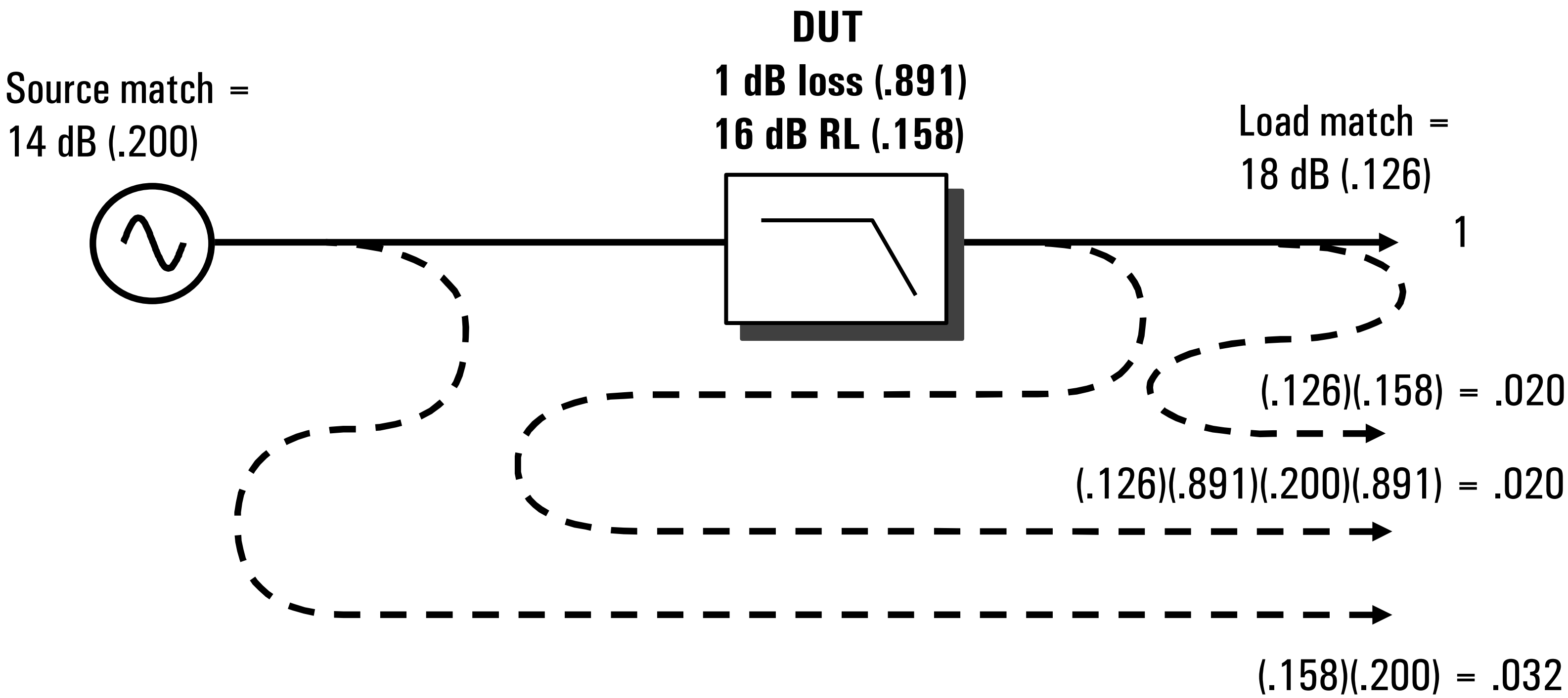
Calibration Uncertainty

$$= (1 \pm \rho_S \rho_L)$$

$$= (1 \pm (.200)(.126)$$

$$= \pm 0.22 \text{ dB}$$

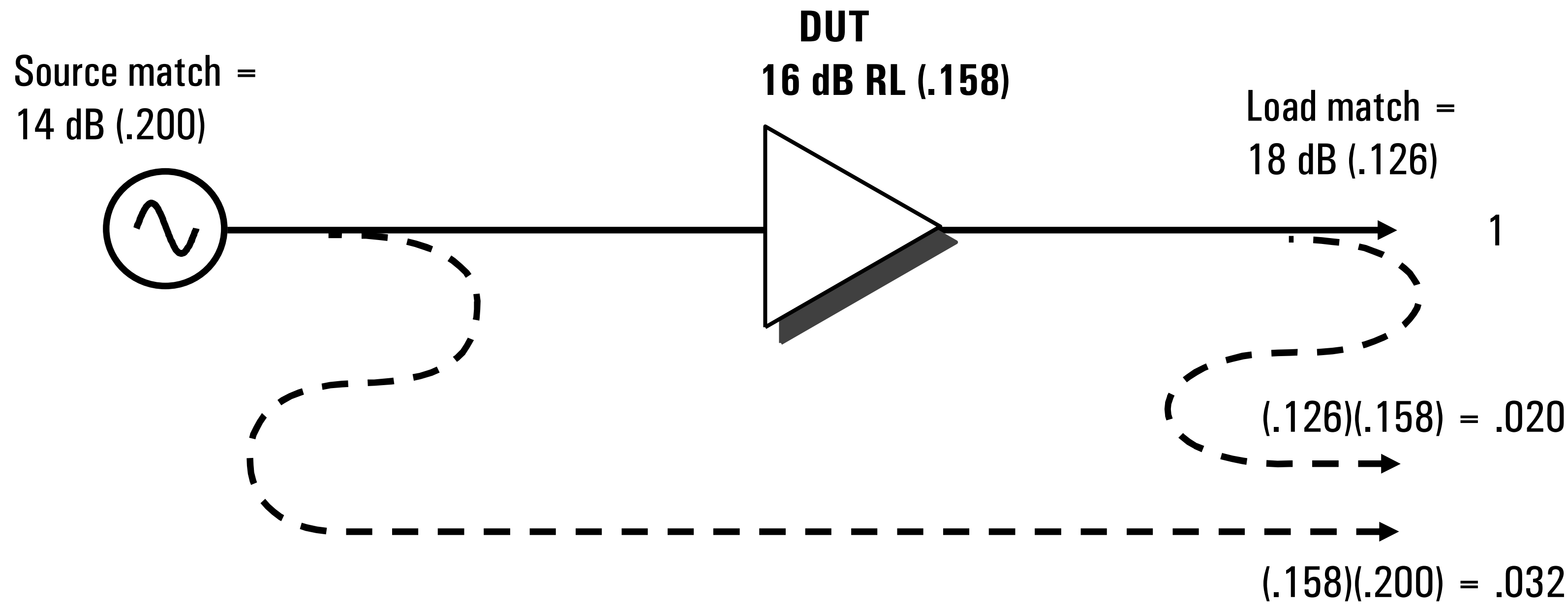
Filter Measurement with Response Cal



Total measurement uncertainty:
+0.60 + 0.22 = + 0.82 dB
-0.65 - 0.22 = - 0.87 dB

Measurement uncertainty
= 1 ± (.020+.020+.032)
= 1 ± .072
= + 0.60 dB
- 0.65 dB

Measuring Amplifiers with a Response Cal

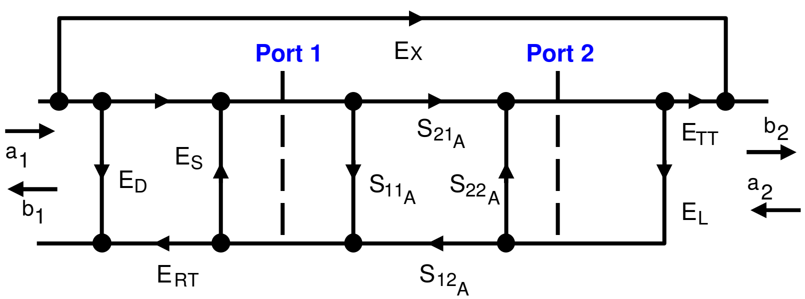


Total measurement uncertainty:
+0.44 + 0.22 = + 0.66 dB
-0.46 - 0.22 = - 0.68 dB

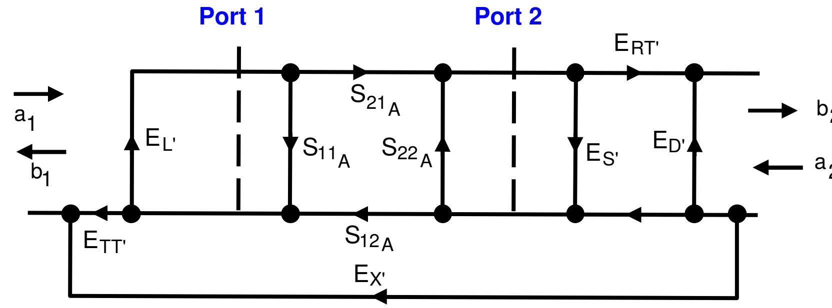
Measurement uncertainty
= 1 ± (.020+.032)
= 1 ± .052
= + 0.44 dB
- 0.46 dB

Two-Port Error Correction

Forward model



Reverse model



E_D = fwd directivity
E_S = fwd source match
E_{RT} = fwd reflection tracking
$E_{D'}$ = rev directivity
$E_{S'}$ = rev source match
$E_{RT'}$ = rev reflection tracking

E_L = fwd load match
E_{TT} = fwd transmission tracking
E_X = fwd isolation
$E_{L'}$ = rev load match
$E_{TT'}$ = rev transmission tracking
$E_{X'}$ = rev isolation

- Each actual S-parameter is a function of all four measured S-parameters
- Analyzer must make forward *and* reverse sweep to update any one S-parameter
- Luckily, you don't need to know these equations to ***use*** network analyzers!!!

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

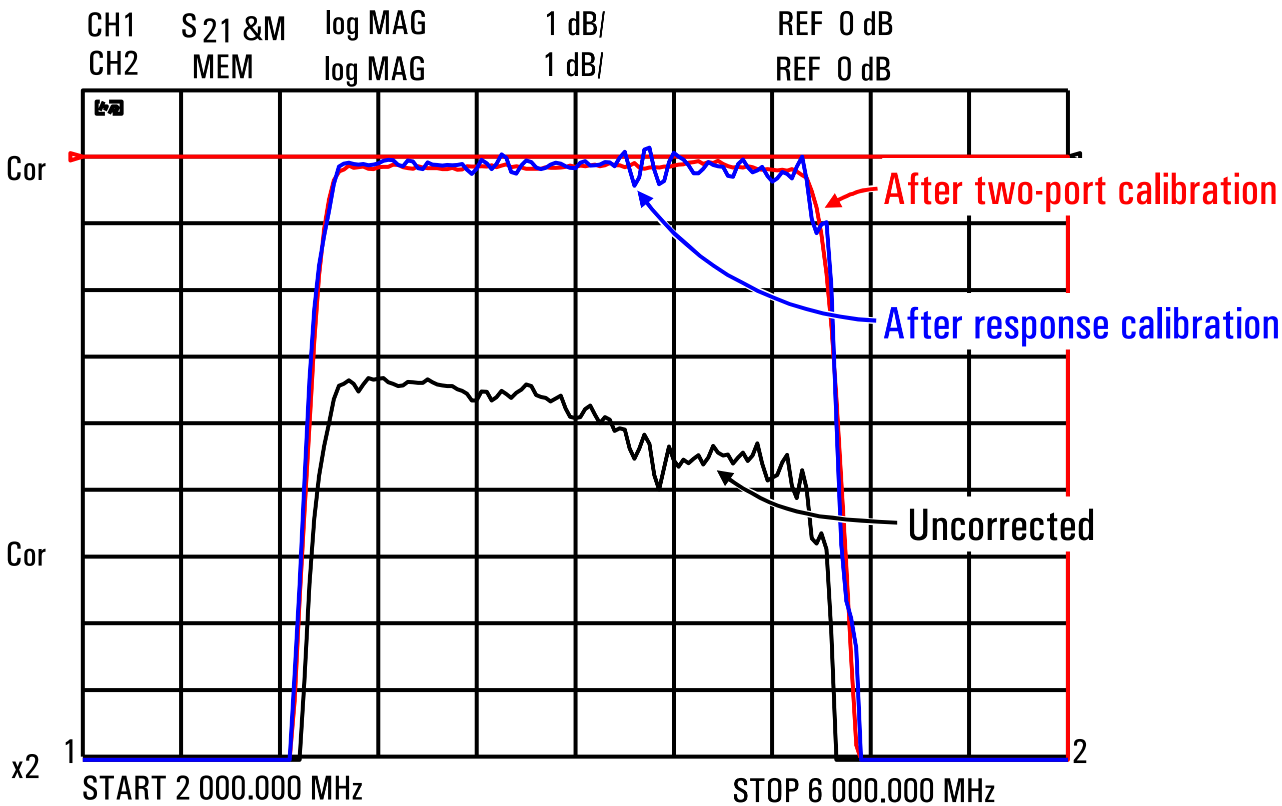
$$S_{21a} = \frac{\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(1+\frac{S_{22m}-E_D'}{E_{RT}'}(E_S'-E_L)\right)}{\left(1+\frac{S_{11m}-E_D}{E_{RT}}E_S\right)\left(1+\frac{S_{22m}-E_D'}{E_{RT}'}E_S'\right) - E_L'E_L\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(\frac{S_{12m}-E_X'}{E_{TT}'}\right)}$$

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

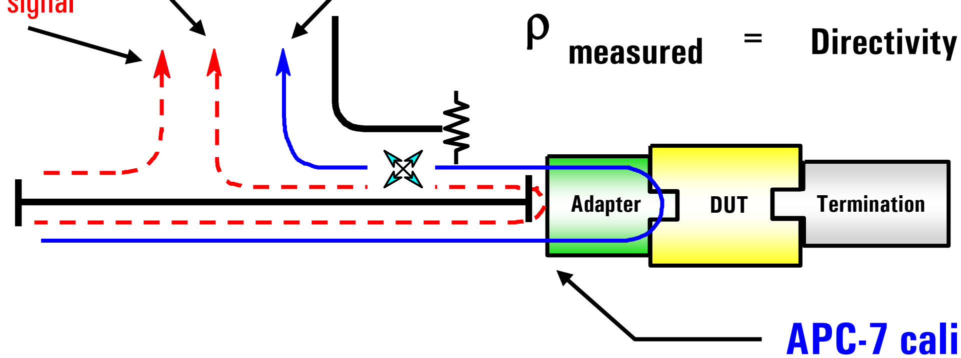
$$S_{22a} = \frac{\left(\frac{S_{22m}-E_D'}{E_{RT}'}\right)\left(1+\frac{S_{11m}-E_D}{E_{RT}}E_S\right) - E_L'\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(\frac{S_{12m}-E_X'}{E_{TT}'}\right)}{\left(1+\frac{S_{11m}-E_D}{E_{RT}}E_S\right)\left(1+\frac{S_{22m}-E_D'}{E_{RT}'}E_S'\right) - E_L'E_L\left(\frac{S_{21m}-E_X}{E_{TT}}\right)\left(\frac{S_{12m}-E_X'}{E_{TT}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

Response versus Two-Port Calibration

Measuring filter insertion loss



Adapter Considerations



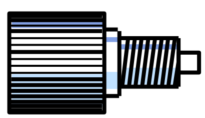
$$\rho_{measured} = \text{Directivity} + \rho_{adapter} + \rho_{DUT}$$

Coupler directivity = 40 dB

Worst-case
System Directivity

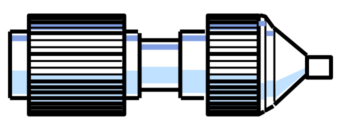
Adapting from APC-7 to SMA (m)

28 dB



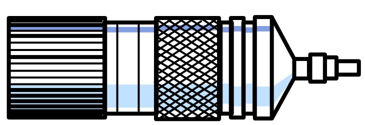
APC-7 to SMA (m)
SWR:1.06

17 dB



APC-7 to N (f) + N (m) to SMA (m)
SWR:1.05 SWR:1.25

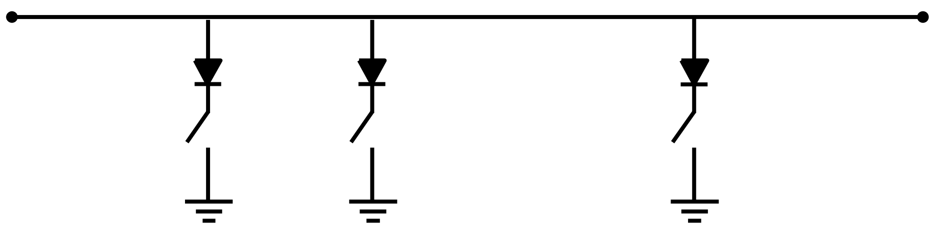
14 dB



APC-7 to N (m) + N (f) to SMA (f) + SMA (m) to (m)
SWR:1.05 SWR:1.25 SWR:1.15

ECal: Electronic Calibration (85060/90 series)

- Variety of modules cover 300 kHz to 26.5 GHz
- 2 and 4-port versions available
- Choose from six connector types (50 Ω and 75 Ω)
- Mix and match connectors (3.5mm, Type-N, 7/16)
- Single-connection
  - reduces calibration time
  - makes calibrations easy to perform
  - minimizes wear on cables and standards
  - eliminates operator errors
- Highly repeatable temperature-compensated terminations provide excellent accuracy



Microwave modules use a transmission line shunted by PIN-diode switches in various combinations or use custom GaAs switches

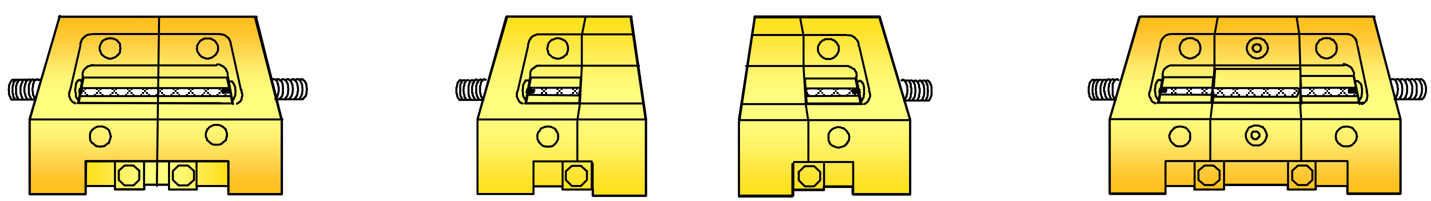
Thru-Reflect-Line (TRL) Calibration

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
- Developed from the "8 term error model"
- Uses practical calibration standards that are easily fabricated and characterized
- Two variations: TRL (requires 4 receivers) and TRL* (only three receivers needed)
- Other variations: Line-Reflect-Match (LRM), Thru-Reflect-Match (TRM), plus many others

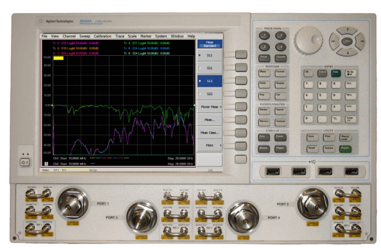
*TRL was developed for **non-coaxial microwave** measurements*



TAKE CARE of YOUR NETWORK ANALYZER

- Always use an adpater on the port of the analyzer
- Never drive too much power into the Network Analyzer
- Watch out for running too much bias current through the NA
- Never drive too much power into the Network Analzyer
- Don't hood up DC voltage directly to the NA (use the bias tees)
- Touch the case of the NA first before touching the cable ends (discharge your ESD).
- Did I say "Don't drive too much power into the NA"?

=



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In Class Demo: Setting up and using the NA

- Start by setting up the start/stop/number of points for your measurement, under the Stimulus block
- Set the IF BW: 1 KHz for precise measurements, 10 kHz for fast.
- Set the power if you're measuring an active device, to avoid over driving the NA
- Select the traces: on the ENA select "display traces" to change then number of traces shown.
- Hit the Meas key to select what parameter to display
- Hit the MARKER key to put one (or more) markers on the screen

In Class Demo: Setting up and using the NA

- Use the FORMAT to change between Log and Linear
- Use the Scale key to bring up the scale. Use autoscale or select the scale in dB/div, the reference live value, and reference line position
- Use the Data->Memory and Data&Mem to save compare traces (DISPLAY)
- Save your data using "Save S2P"
- Use the equation editor to change the value of your trace
- Use Save/Recall to save your setups