FUNDAMENTALS OF VNA MEASUREMENTS

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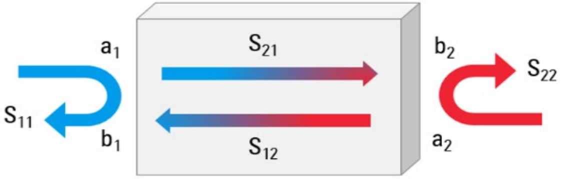
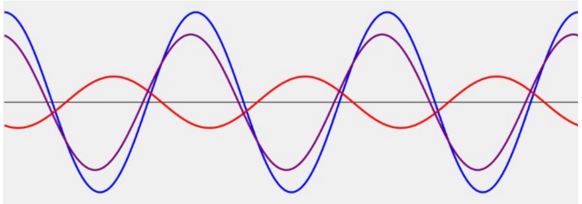
ROHDE&SCHWARZ

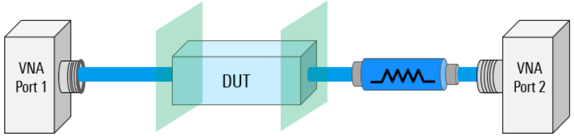
Make ideas real

CONTENTS

- ► S-Parameters
- ► VSWR & Return Loss
- ► Calibration Basics

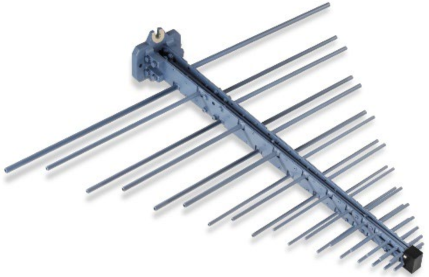






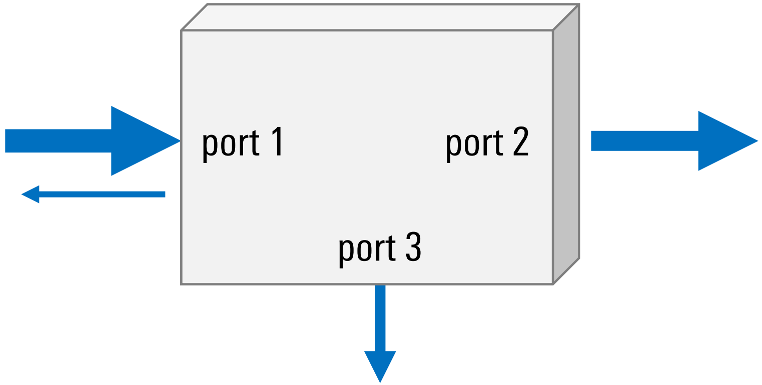
What is a network?

- A **network** is a device with one or more **ports**
- Each port can pass, absorb, and/or reflect RF energy.
- Examples:
  - 1 port : antenna, dummy load
  - 2 port : filter, amplifier
  - 3 port : directional coupler, mixer



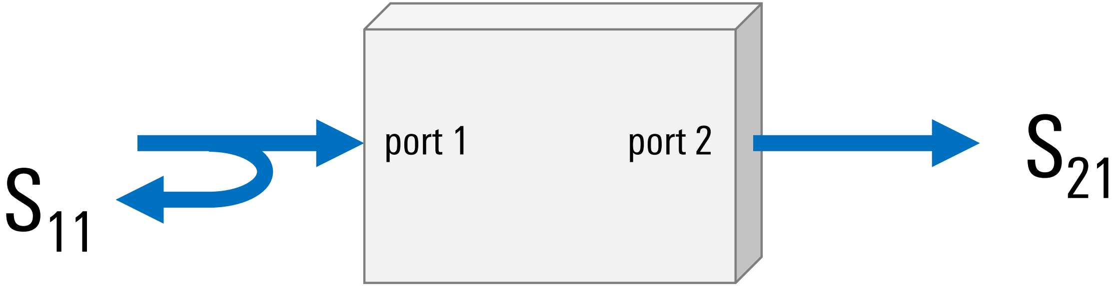
Analyzing networks

- Networks can be analyzed by:
  - injecting RF into a given port
  - measuring the level of RF appearing
    - at that port (reflected)
    - at other ports
- Usually only one signal is injected into one port at one time
- Usually measured over a range of frequencies
- Networks are typically analyzed using an instrument called a **network analyzer**



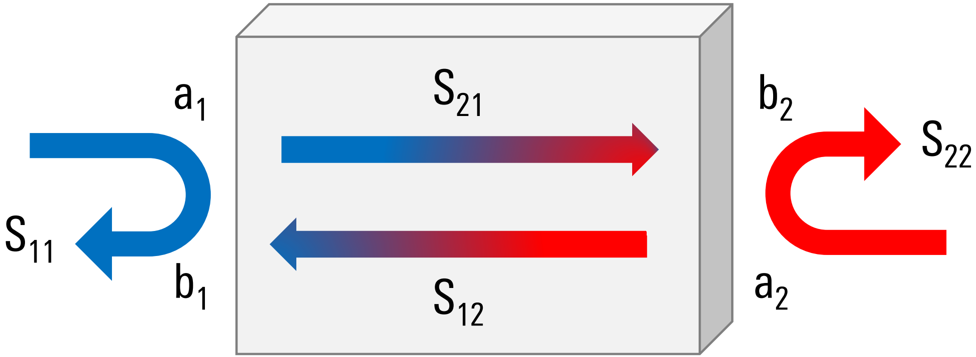
What are S-parameters?

- S-parameters are the most common way of representing these measurements
- Named using the letter ‘S’ and a pair of subscripts (S_{xy})
  - First subscript : port where the energy emerges (output port)
  - Second subscript : port where the energy enters (input port)



Example – Two port network

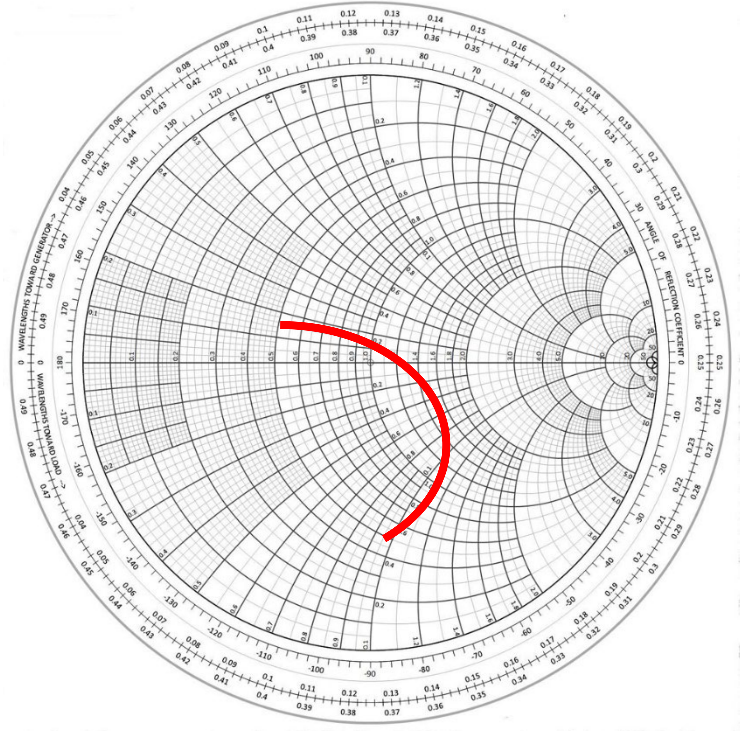
► In a two port network there are four S-parameters: S_{11}, S_{21}, S_{12}, and S_{22}.



$$S_{11} = b_1/a_1$$
$$S_{21} = b_2/a_1$$
$$S_{12} = b_1/a_2$$
$$S_{22} = b_2/a_2$$

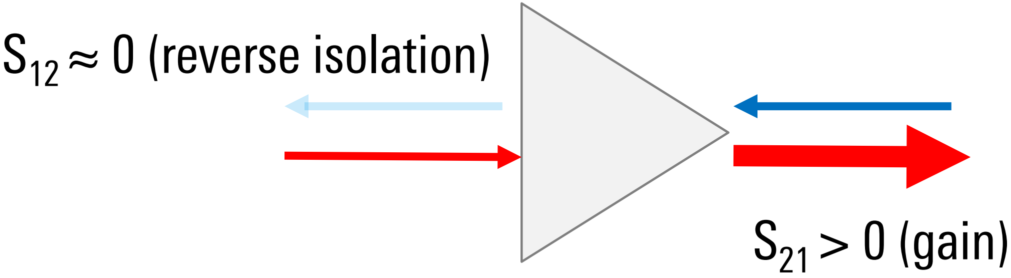
More about S-parameters

- S-parameters can also be represented as N-by-N matrices
  - N = number of ports
- S-parameters are complex values with:
  - Magnitude
  - Phase
- Reflection coefficients (S_{xx}) can be plotted on a Smith Chart
- S-parameters can be cascaded to predict overall system response



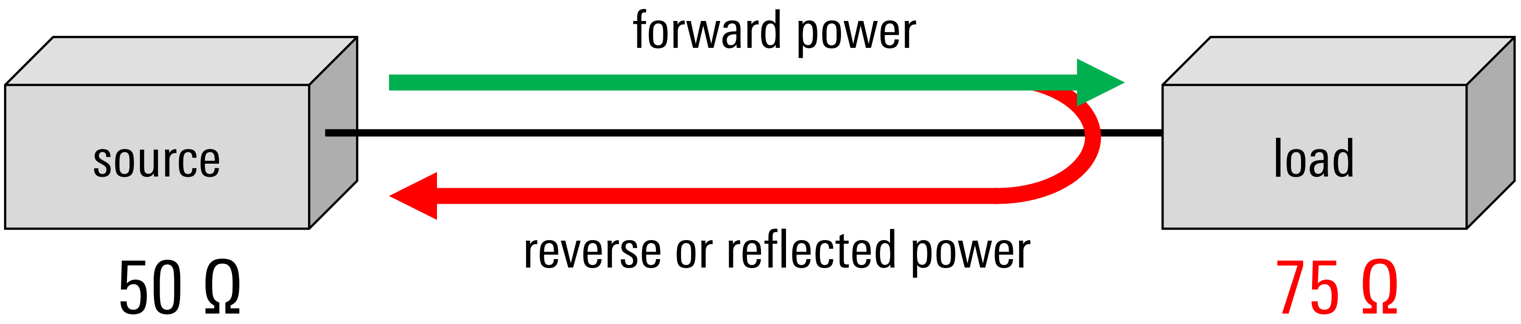
Mapping S-parameters to common names

- Reflection coefficients
  - S_{11}
  - S_{22}
- Transmission coefficients
  - S_{21} – gain or loss
  - S_{12} – reverse isolation



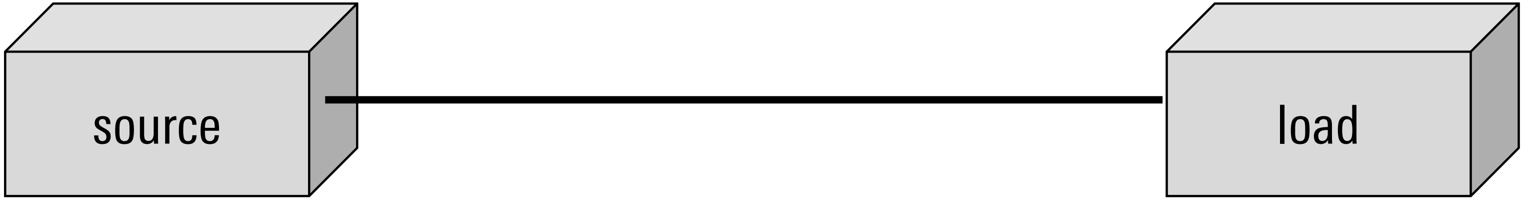
Transferring RF power – matched impedances

Transferring RF power – mismatched impedances



Transferring RF power – complex impedances

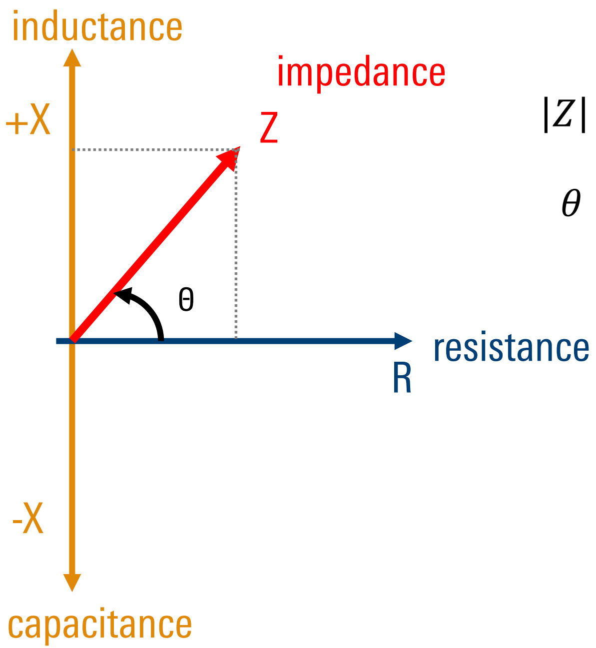
35 + j6 Ω ⟷ match ⟷ 35 - j6 Ω



Source	Load
R + jX Ω	R + jX Ω
50 Ω	50 Ω
resistive (real) / reactive (imaginary)	resistive (real) / reactive (imaginary)

A brief refresher on impedance

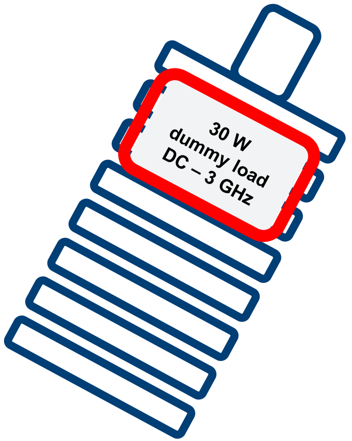
- An impedance is a complex value (Z) that consists of:
  - Resistance (R) – does **not** change with frequency
  - Reactance (X) – **does** change with frequency. Two types:
    - Capacitive (C)
    - Inductive (L)
- Remember: impedance (Z) varies by frequency.

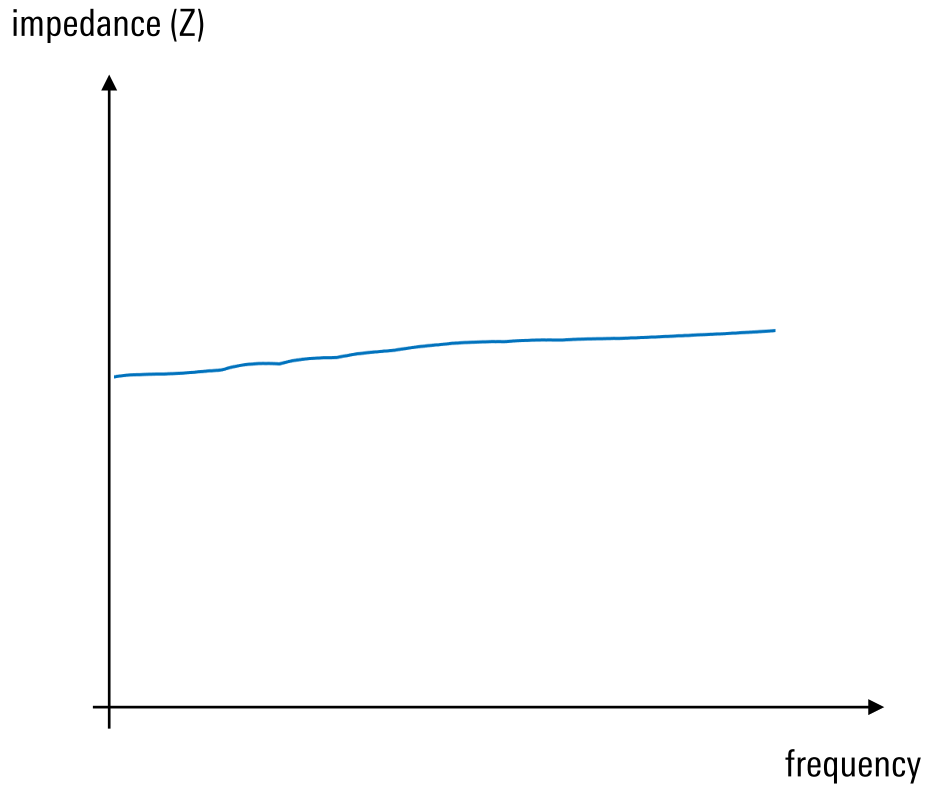


$$|Z| = \sqrt{R^2 + X^2}$$

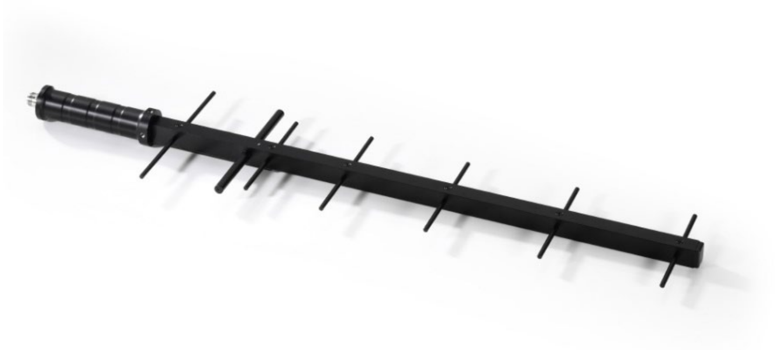
$$\theta = arctan\frac{X}{R}$$

Real world examples

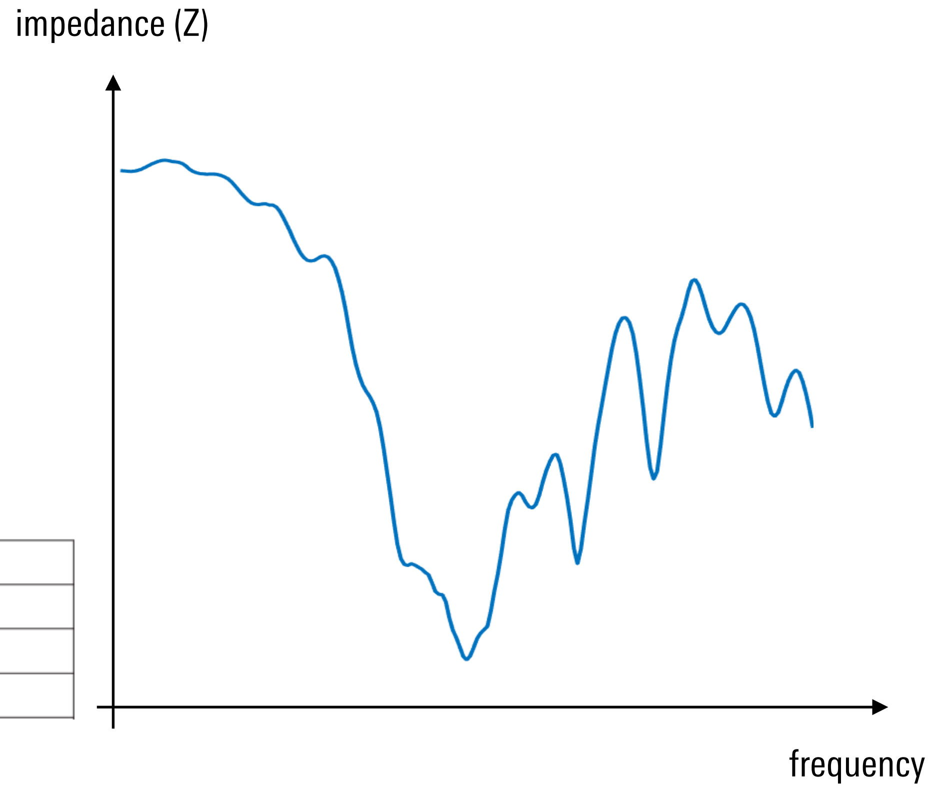




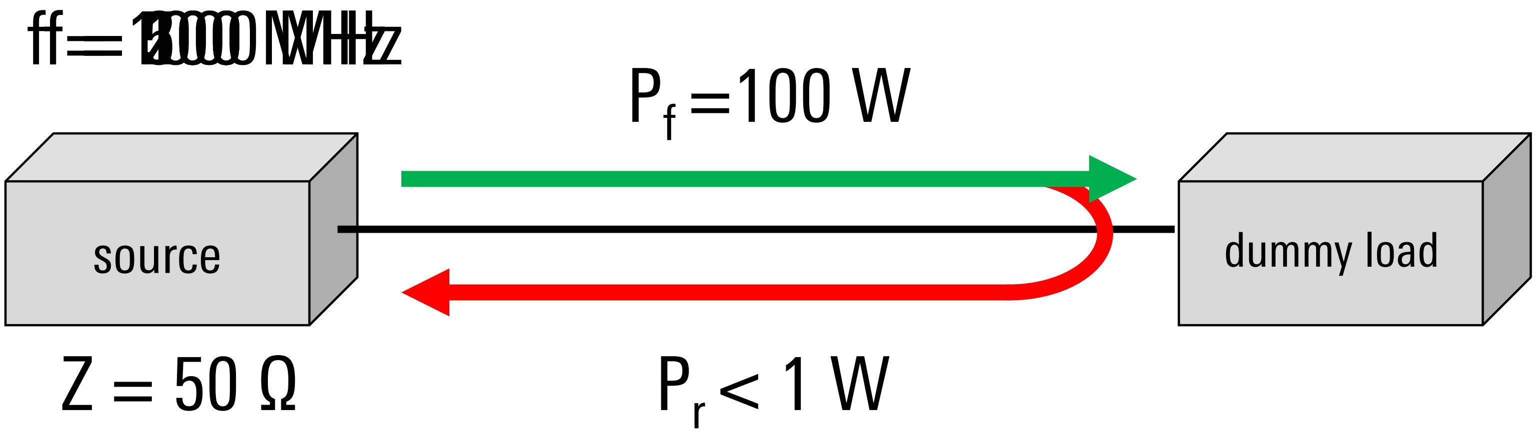
Real world examples



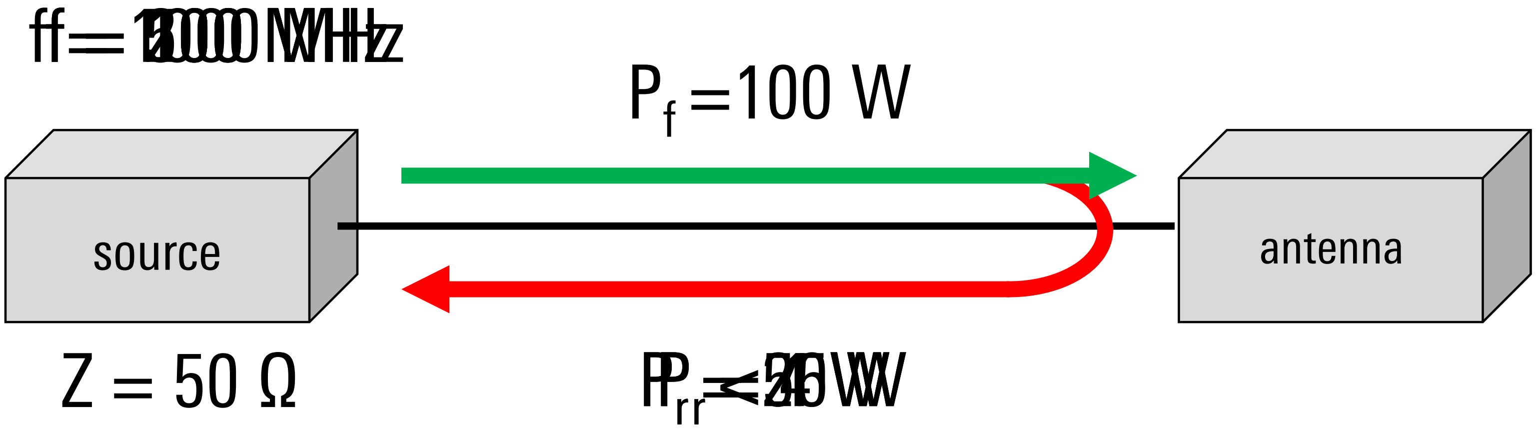
Frequency range	1710 MHz - 1990 MHz
Gain	13 dBi (typ.)
Impedance	50 Ω
VSWR	< 2.5:1



Reflected power vs. frequency : dummy load

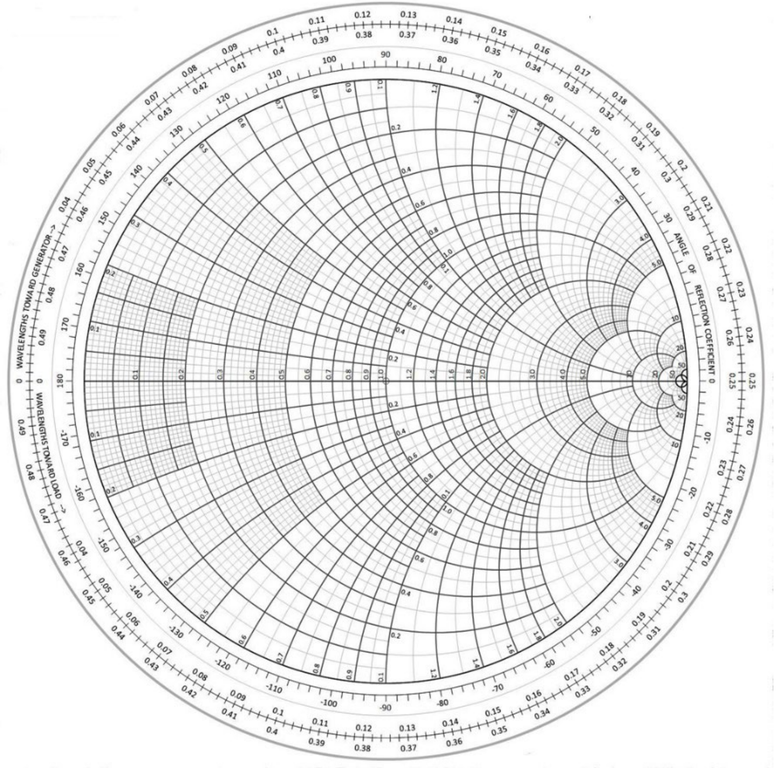


Reflected power vs. frequency : antenna



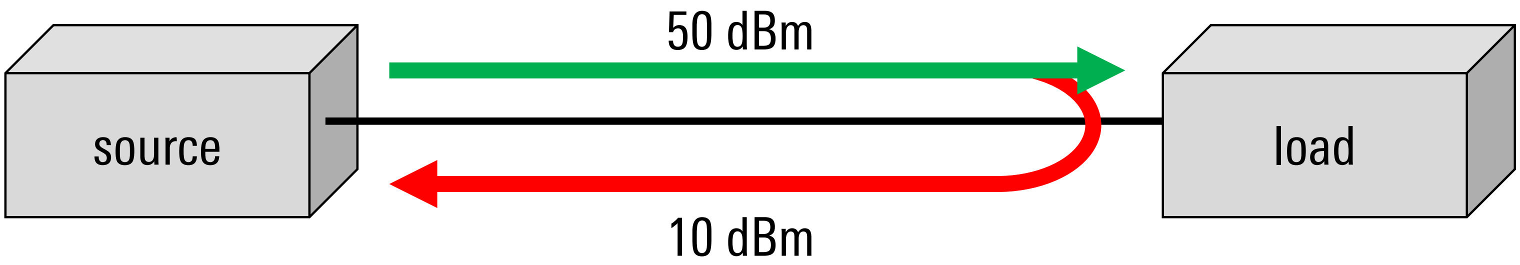
Quantifying reflected power

- ► Need to quantify level of reflected power
  - – Relative to forward power
- ► Two methods of expressing reflected power:
  - – Return loss
  - – Voltage Standing Wave Ratio (VSWR)



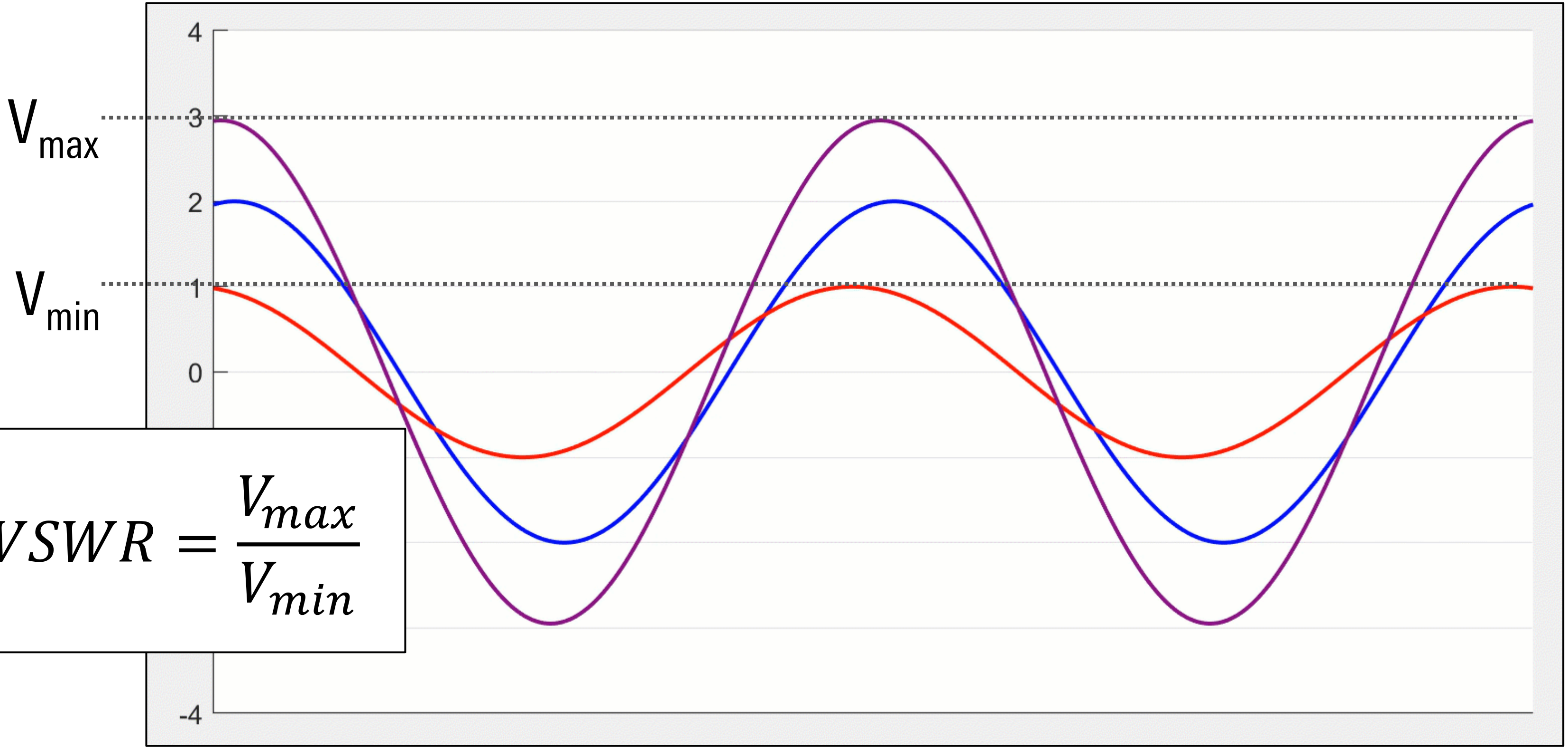
Return loss

- Return loss is the difference in dB between the forward and reflected power
  - Forward power – reflected power = return loss
- Larger values of return loss = less reflected power
  - Always a positive number



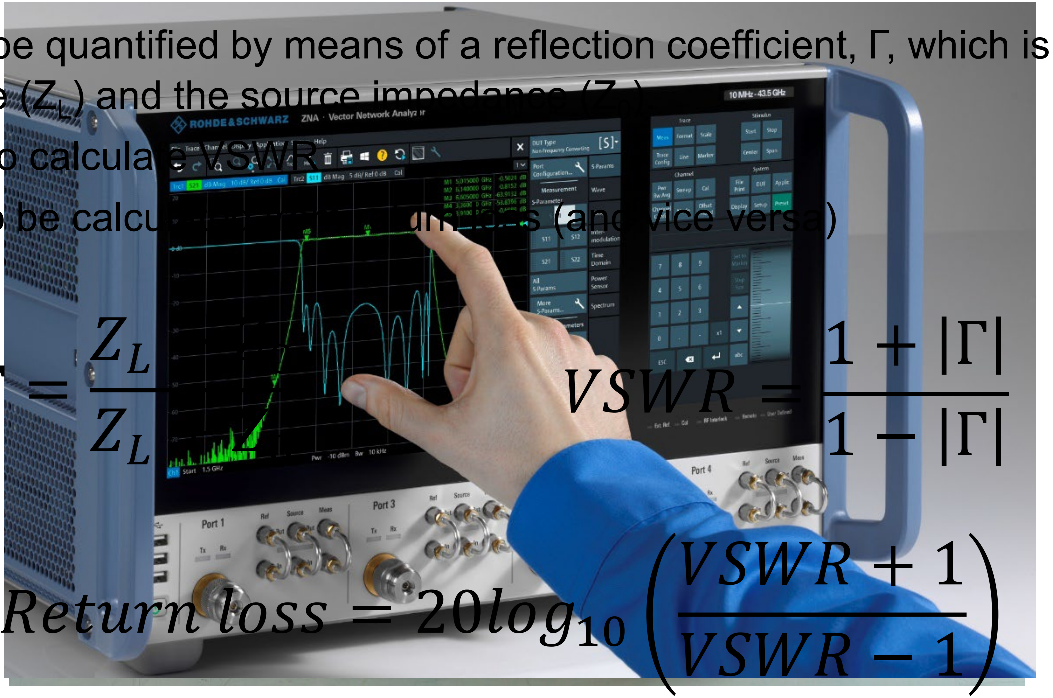
Return loss = 40 dB

Standing waves and VSWR



$$VSWR = \frac{V_{max}}{V_{min}}$$

Calculating VSWR



- Reflection can be quantified by means of a reflection coefficient, Γ, which is a function of the load impedance (Z_L) and the source impedance (Z_0)
- Γ is then used to calculate VSWR
- VSWR can also be calculated from return loss (and vice versa)

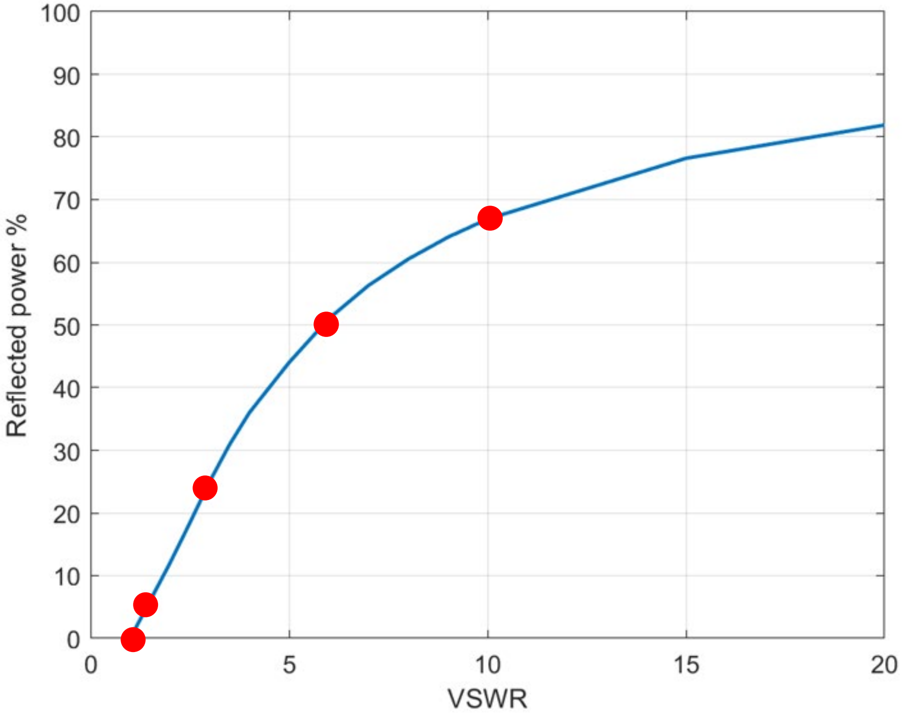
$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0}$$

$$VSWR = \frac{1 + |\Gamma|}{1 - |\Gamma|}$$

$$Return\ loss = 20log_{10}\left(\frac{VSWR + 1}{VSWR - 1}\right)$$

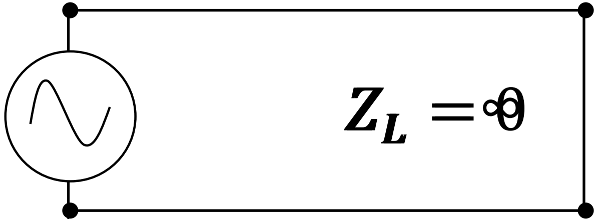
VSWR and % reflected power

VSWR	(Γ)	% reflected power
1.0	0.000	0.00
1.5	0.200	4.0
2.0	0.333	11.1
3.0	0.500	25.0
4.0	0.600	36.0
5.0	0.667	44.0
6.0	0.714	51.0
7.0	0.750	56.3
8.0	0.778	60.5
9.0	0.800	64.0
10.0	0.818	66.9
15.0	0.875	76.6
20.0	0.905	81.9



Two special VSWR cases

- Two special cases:
  - short circuit
  - open circuit
- In both cases VSWR = ∞ (infinity), or 100% reflected power

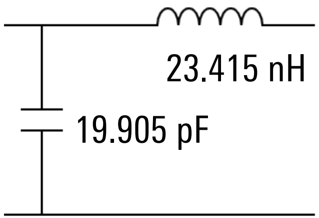


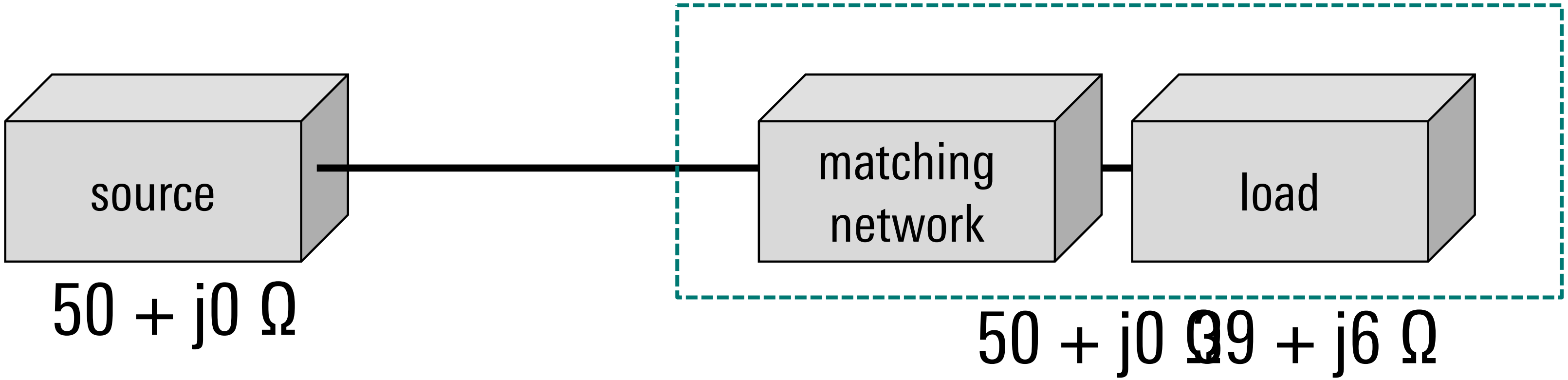
$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0}, \quad \Gamma = \frac{0 - Z_0}{0 + Z_0} = -1, \quad \Gamma = \frac{\infty - Z_0}{\infty + Z_0} = 1$$

$$VSWR = \frac{1 + |\Gamma|}{1 - |\Gamma|} = \infty$$

Dealing with reflected power – matching networks

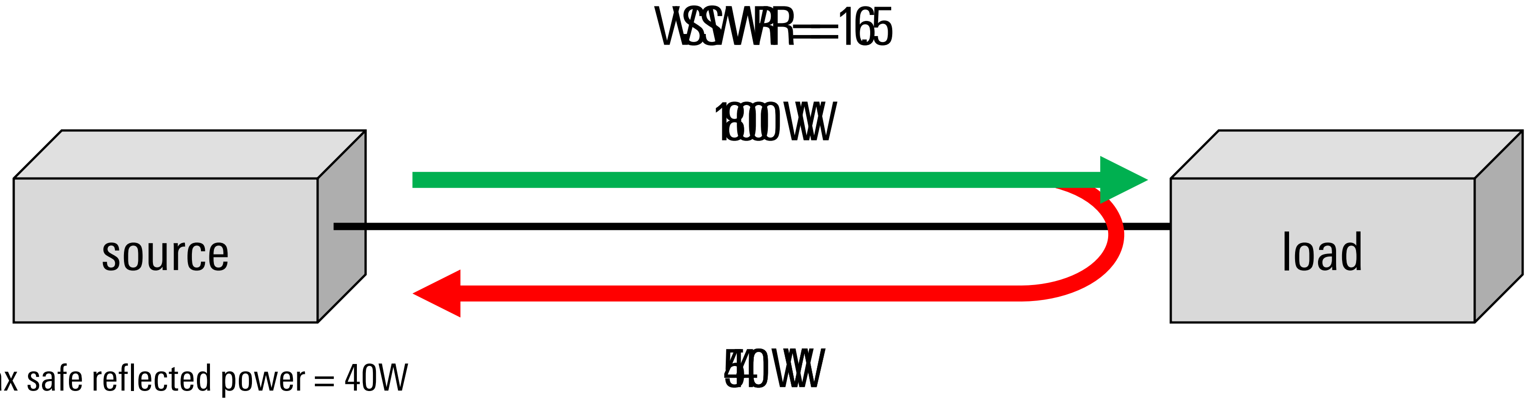
- A matching network can be placed between source and load
- Adds impedances (capacitance and inductance) to “match” source and load impedance





Dealing with reflected power – foldback

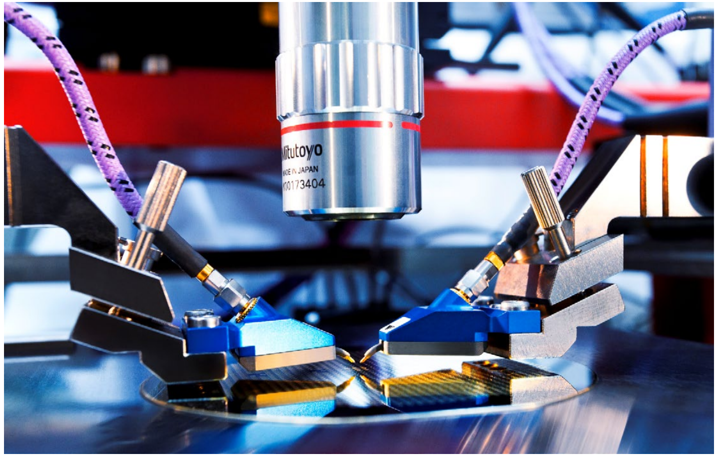
- Reducing forward power also reduces reflected power
  - This is called foldback
  - Primarily used in high(er) power sources, such as broadband amplifiers
- Protects the source from dangerous levels of reflected power



Max safe reflected power = 40W

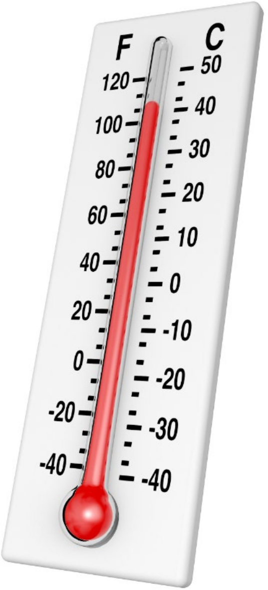
Errors in network measurements

- ► Of all the instruments in the RF world, VNA measurements typically require the highest accuracy and repeatability
- ► Three different types or sources of errors in VNA measurements:
  - – Drift errors
  - – Random errors
  - – Systematic errors
- ► Errors are inaccuracies in both amplitude and phase (vector quantities)



About drift errors

- ► Drift errors are caused by changes in the environment after calibration
  - – Primarily changes in temperature
- ► Minimized by controlling test environment / allowing the instrument to warm up
- ► Can also be reduced through additional calibration
- ► Drift errors cannot be removed, only minimized



About random errors

- Random errors are primarily caused by the test setup
  - Instrument noise
  - Measurement practices
  - Cables, connectors, etc.
- Vary over time, not repeatable, not predictable
- Minimized by high quality equipment and good measurement practices
- Random errors cannot be removed, only minimized

About systematic errors

- Systematic errors occur in a reproducible, predictable, and do not vary over time
- Due to non-ideal components in the VNA and test setup, e.g.
  - Imperfections in the VNA
  - Cable loss
  - Impedance mismatches
- **Systematic errors can be (almost) entirely removed with calibration**

What is calibration?

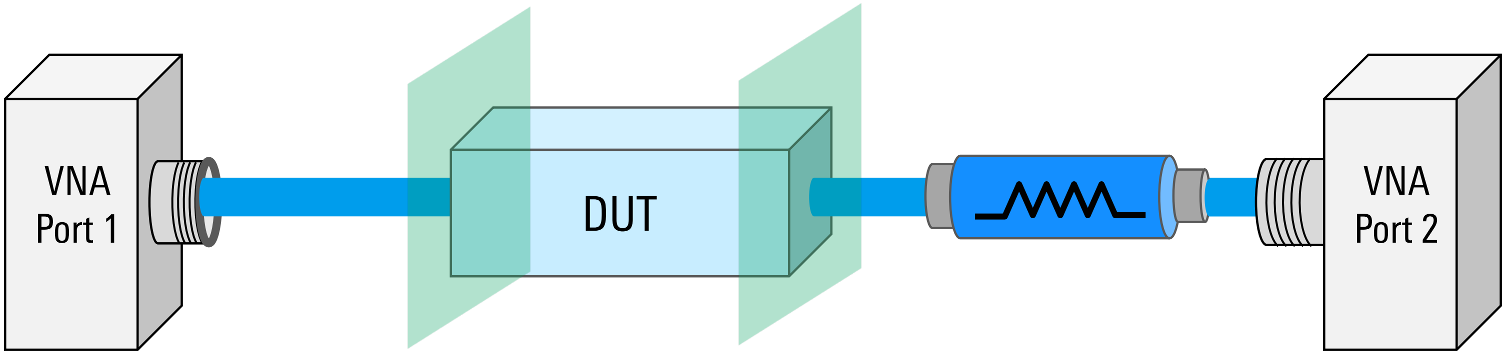
- Calibration removes systematic errors from measurement results
- Steps in calibration:
  - Select a **calibration type** based on measurement setup and desired results
  - Connect **calibration standards** at the appropriate points
  - Run calibration routine and measure response
    - Usually requires multiple steps
  - Calibration data is used to correct results when measuring the DUT

Measurement calibration vs. instrument calibration

- Measurement calibration is **not** the same as instrument calibration
- Measurement calibration
  - Removes systematic errors
  - Performed by the user
  - Usually repeated frequently
- Instrument calibration
  - Verifies instrument performance is within spec
  - Performed by a service or calibration center
  - Usually repeated every few years

Calibration or reference plane

- The calibration (or "reference") plane is where calibration occurs
- Device under test is usually not connected directly to the VNA ports
- Calibration removes the influence of everything up to the calibration or reference plane

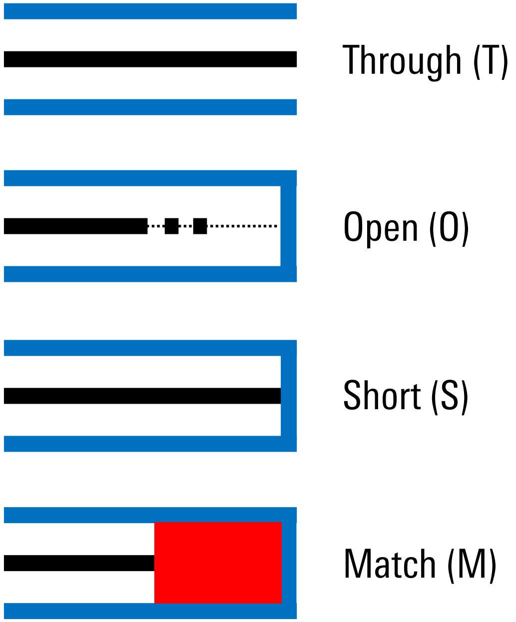


What is a calibration standard / kit?

- Calibration standards are often collected into a calibration kit
- Calibration standards are terminations or couplers with a precisely known magnitude and phase response
  - Data contained in a cal kit definition file
  - Definitions are often preloaded on instruments or can be imported (USB or similar)
- Connected and measured at the calibration / reference plane and measured during calibration

Calibration standards

- Most common calibration standards are:
  - Through (T)
  - Open (O)
  - Short (S)
  - Match (M)
- Real-world standards are not ideal
  - Especially over a wide frequency range
- Must have data describing the specific standards in use



Automatic calibration unit

- Contain calibration standards that are electronically switched during calibration
  - Controlled by the VNA (usually over USB)
- The calibration data for the internal standards is stored in the calibration unit and is automatically read by the analyzer
- Minimizes operator intervention
  - **Much** faster than manual calibration
  - Lower chance of operator error
  - Less wear on the standards

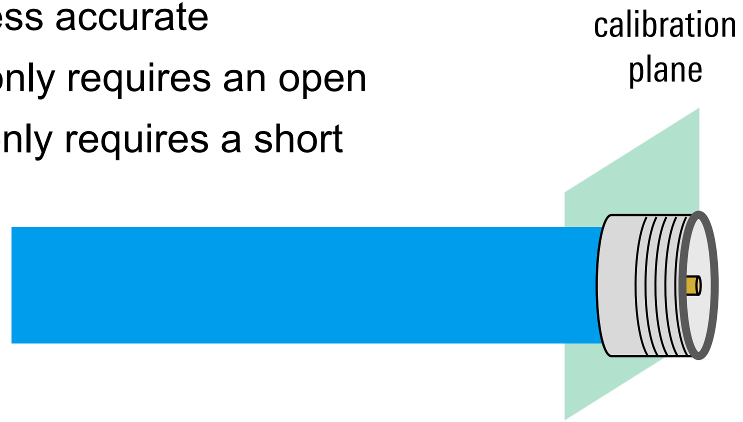
What are calibration types?

- Calibration type defines which calibration standards we use and how we connect them
- Calibration type is selected based on:
  - Number of ports
  - Direction of measurements
  - Degree of accuracy required
  - Time required
  - Available calibration standards

- Reflection Normalization
- Full One Port Calibration (OSM)
- Transmission Normalization
- One Path Two Port Calibration
- Full Two Port Calibration (TOSM)
- Full Two Port Calibration (UOSM)

One Port Calibration

- ► Used for reflection measurements
- ► Full one-port calibration (OSM)
  - – Slower, more accurate
  - – Requires an open, short, and match
- ► Normalization
  - – Faster, less accurate
  - – Open – only requires an open
  - – Short – only requires a short

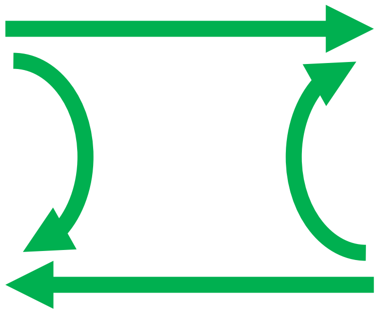


Two port calibration

- Used for transmission measurements
- Normalization
  - Requires only a through
  - Can be done in one or both directions
- One path two ports
  - Full one-port OSM + transmission normalization
- Full two port calibration
  - TOSM
  - UOSM

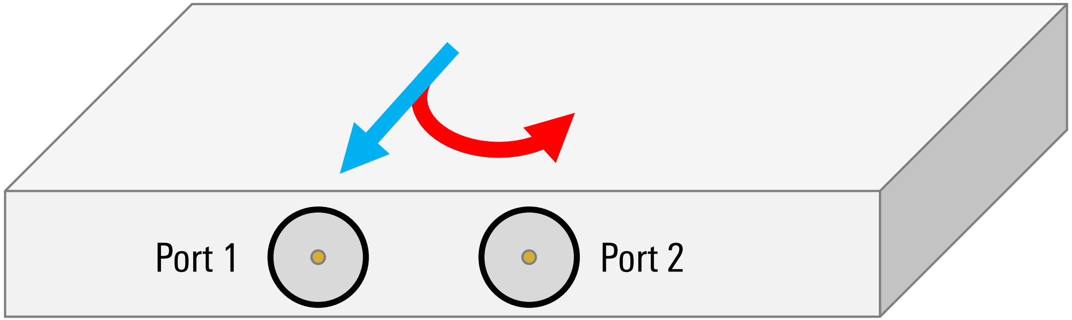
TOSM and UOSM

- TOSM: through, open, short, match
  – Most common calibration for two port measurements
- Calibrates for:
  – Reflection measurements at both ports
  – Transmission measurements in both directions
- Requires 8 sweeps
  – Three one-port standards (O, S, M) at each port
  – Through between the two ports
- UOSM replaces the through with an “Unknown”
  – Usually a generic coupler
  – Helpful when attaching different connector types



What is an isolation measurement?

- A Through calibration can be complemented by an Isolation measurement.
- Measures crosstalk between the test ports
- No physical calibration standard for isolation measurement
  - Usually the test ports are terminated with 50 Ω loads
- Not an significant source of error in most network analyzer measurements



DEMO

- ▶ Calibration
- ▶ Antenna measurements
  - – VSWR
  - – Return loss

Find out more

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