Vector Network Analyzer (VNA)

Time domain measurements

- time domain view on reflection (mostly) and transmission measurements is very useful when finding the sources of mismatch
- historically, these measurements were done using TDR oscilloscopes (usually a sampling scope combined with specialized step generator)

Time domain measurements

- today, these measurements are usually performed with a vector network analyzer (VNA)
  - frequency domain data acquired by the VNA are converted to time domain using an inverse Fourier transform
  - this mathematical approach lets the user to choose from the simulation of a step or impulse response and it is also possible to characterise band-limited (DC blocked) devices
  - some of the advantages of a VNA vs. TDR oscilloscope:
    - VNA has better dynamic range
    - VNA is less sensitive to ESD (although, it can be damaged as well)
    - VNA is widely used today for many different purposes (no need to buy another instrument)
    - …

What is a Vector Network Analyzer?

- advanced measuring instrument which can measure network parameters of electrical networks (reflections, transmissions)
  - frequency range from a few Hz up to 110 GHz (1,1 THz with external downconverters)
  - modern VNAs can be used for a broad range of measurements
- stimulus-response test system
  - generates a test signal and measures the response of a DUT
  - measures both magnitude and phase (in contrast with much less complex scalar network analyzers)
- most of the benchtop VNAs use two or four coaxial test ports for DUT connection

Measurements made with VNAs

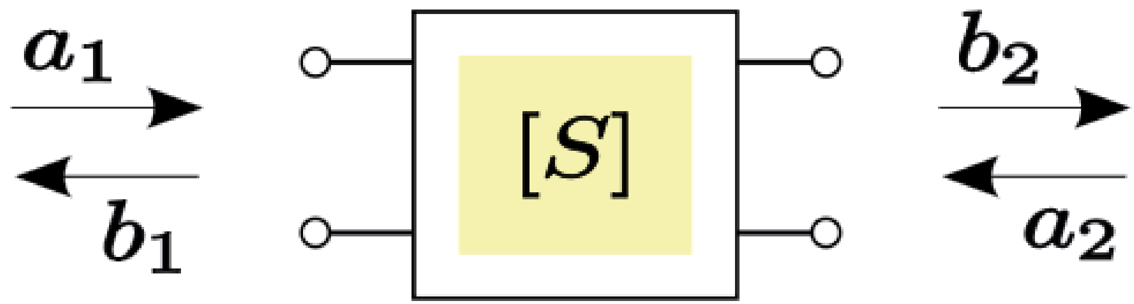
- S-parameters - transmissions, reflections (includes crosstalks)
- impedance measurements
- phase related measurements - group delay, ...
- gain compression - power sweep
- modern VNAs offer a broad range of other measurement capabilities (previously done with other measuring instruments)
  - spectrum analysis
  - noise figure measurements
  - intermodulation distortion
  - differential measurements
  - pulsed measurements
  - ...

Vector measurements

- VNAs measure both magnitude and phase of all measured quantities - complex values needed for:
  - comprehensive device modeling
  - matching circuits design
  - time-domain calculations
  - vector error corrections (corrections of mismatch effects)
  - ...
- vector data can be corrected using advanced calibration methods which results in better accuracy compared to scalar measurements (even for magnitude only)

S-parameters

- definition of S-parameters of a two-port device:



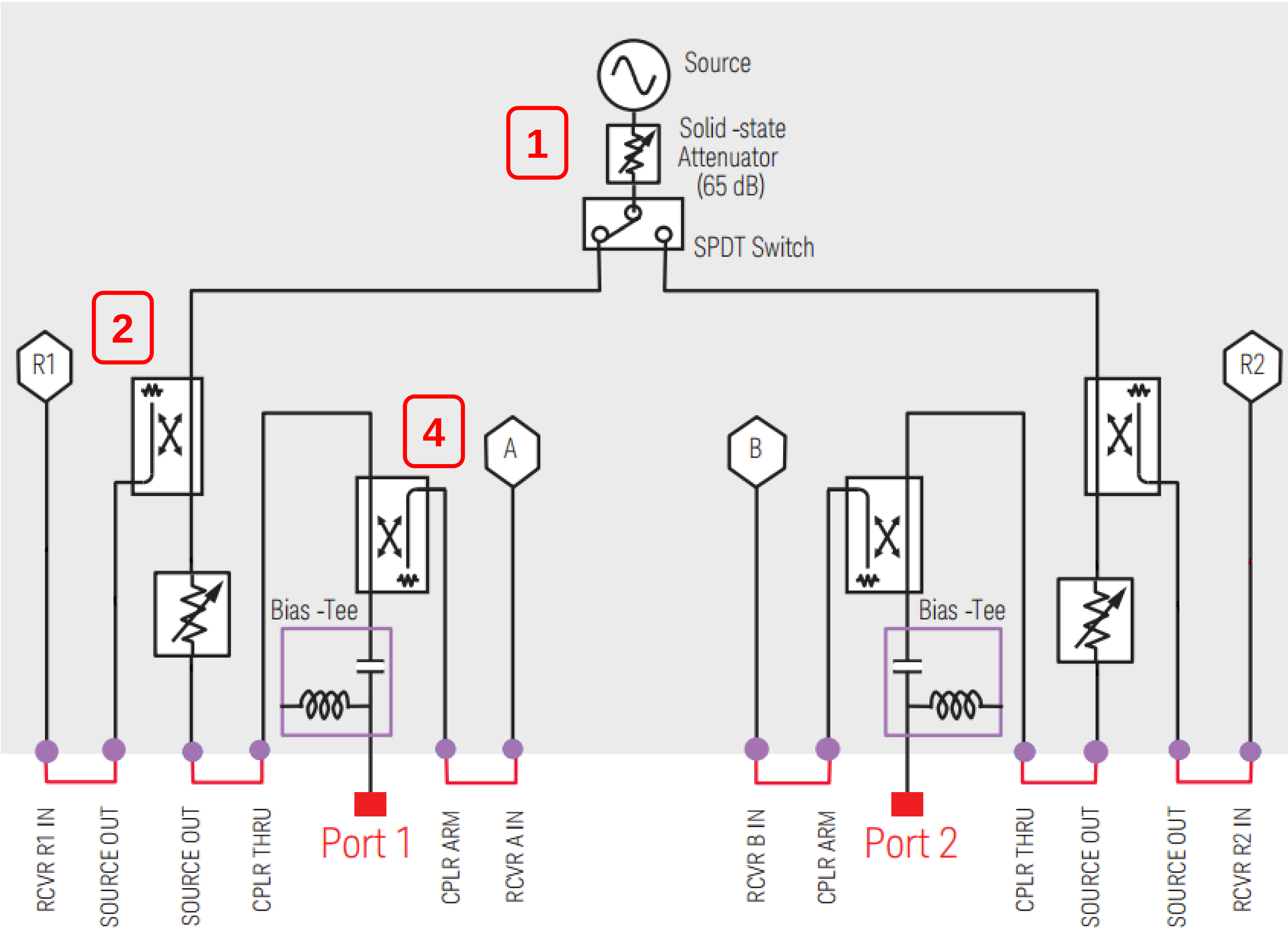
$$S_{11} = \frac{b_1}{a_1}\Big|_{a_2=0} = \Gamma_1 \qquad S_{21} = \frac{b_2}{a_1}\Big|_{a_2=0}$$

$$S_{22} = \frac{b_2}{a_2}\Big|_{a_1=0} = \Gamma_2 \qquad S_{12} = \frac{b_1}{a_2}\Big|_{a_1=0}$$

VNA hardware - basic blocks

1) source of the test signal
   - fast-tuned synthesized signal source with settable output level
   - switching between all test ports (using advanced solid-state switches)
   - modern VNAs typically contain one or two sources
2) separation of the reference signal
   - part of the signal from the source is coupled to reference receiver using a directional coupler or a power splitter
   - typically one reference receiver for each test port - R_1, R_2, ..., R_n
3) second directional coupler
   - separating signal going **back into** given test port (reflected or transmitted wave); one receiver for each test port - A, B, C, D, ...

VNA block diagram - ENA E5072A



VNA system

- VNA system typically consists of three main parts:
1) VNA base unit
    - usually three sub-units for older types; modern ones are "one-box"
    - coaxial test-ports for interfacing with DUT devices
2) test-port cables
    - very important for overall accuracy of the VNA system
    - should be high-quality, phase and amplitude stable
    - various connector types depending on VNA frequency range
3) calibration kits
    - mechanical (separate, passive standards) or ECal (automatic cal. unit)
    - also very important for accurate measurements

\+ antistatic accessories - antistatic mats, wrist straps
    - VNAs are ESD sensitive instruments and need to be handled with care

\+ other accessories - adapters, attenuators, verification standards...

Different VNA form factors

- normal bench top instrument (Keysight PNA-X)

Different VNA form factors

- handheld VNA (Keysight Fieldfox)

Different VNA form factors

- PXIe modular VNAs:

Different VNA form factors

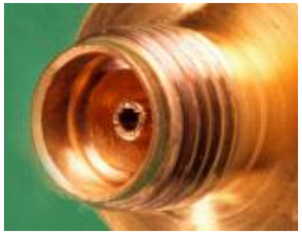
- portable USB VNA (Keysight's Streamline series)

VNA Connectors

- all of the precision coaxial connectors use air dielectric
- most of the higher-frequency precision measurement connectors are named after the inner diameter of their outer conductor
- some of the precision connectors exist in slotted and slotless version
- precision connector types:

1) 7 mm "type N" connector
   - up to 18 GHz; 50 Ω or 75 Ω
   - 12 lb-in torque; slotted or slotless versions
   - both general purpouse and metrology grade


2) 3,5 mm connector
   - up to 33 GHz; 50 Ω
   - 8 lb-in torque; slotted or slotless versions

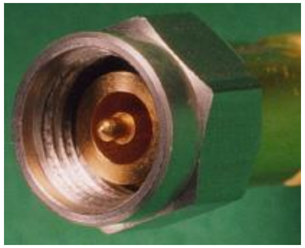
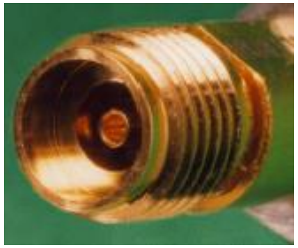
VNA Connectors

3) 2,92 mm "type K" connector
- up to 40 GHz; 50 Ω
- 5 - 8 lb-in torque; slotted only

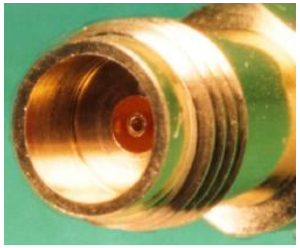
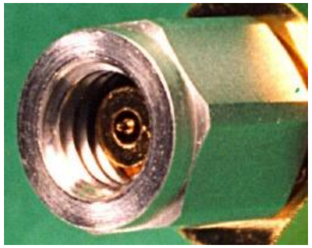
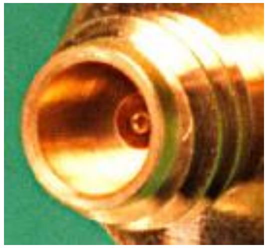
4) 2,4 mm "type Q" connector
- up to 50 GHz; 50 Ω
- 8 lb-in torque; slotted or slotless versions

5) 1,85 mm "type V" connector
- up to 65 GHz; 50 Ω
- 8 lb-in torque; slotted only

6) 1 mm connector
- up to 110 GHz; 50 Ω
- 3 lb-in torque; slotted only

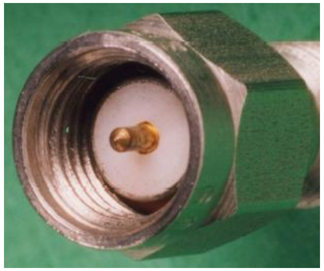


VNA Connectors

7) 7 mm precision connector "APC 7"
   - up to 18 GHz; **sexless**; 50 Ω
   - 12 lb-in torque

8) SMA connector
   - up to 26,5 GHz; sexed; 50 Ω
   - 5 lb-in torque; plastic dielectric
   - general purpouse, non-precision



- some of the connector types with identical diameters of center conductor pin and outer thread can be connected together:
  - 3,5 mm; 2,92 mm and SMA connectors
  - 2,4 mm and 1,85 mm connectors

Connector care

- precision connectors are sensitive devices with limited lifespan
  - usually hundreds to thousands of connection cycles - significantly influenced by the handling and care connectors receive by users

1) storage when not used
   - connectors should be stored in dry and clean environment always with **protective caps attached**
2) cleaning - connectors should be **cleaned regularly**
   - most important is to clean the mating surfaces of both conductors (ideally also the threads)
   - using compressed air and cotton swab with isopropanol
3) visual inspection and gauging
   - connectors should be regularly inspected for visible defects (scratches and dents on the mating surfaces, inner conductor not precisely in centre)
   - relative position of the inner and outer conductor needs to be measured using a connector gauge

Connector care

- SMA connector before and after cleaning; damaged 3.5 mm connector:

Connector care

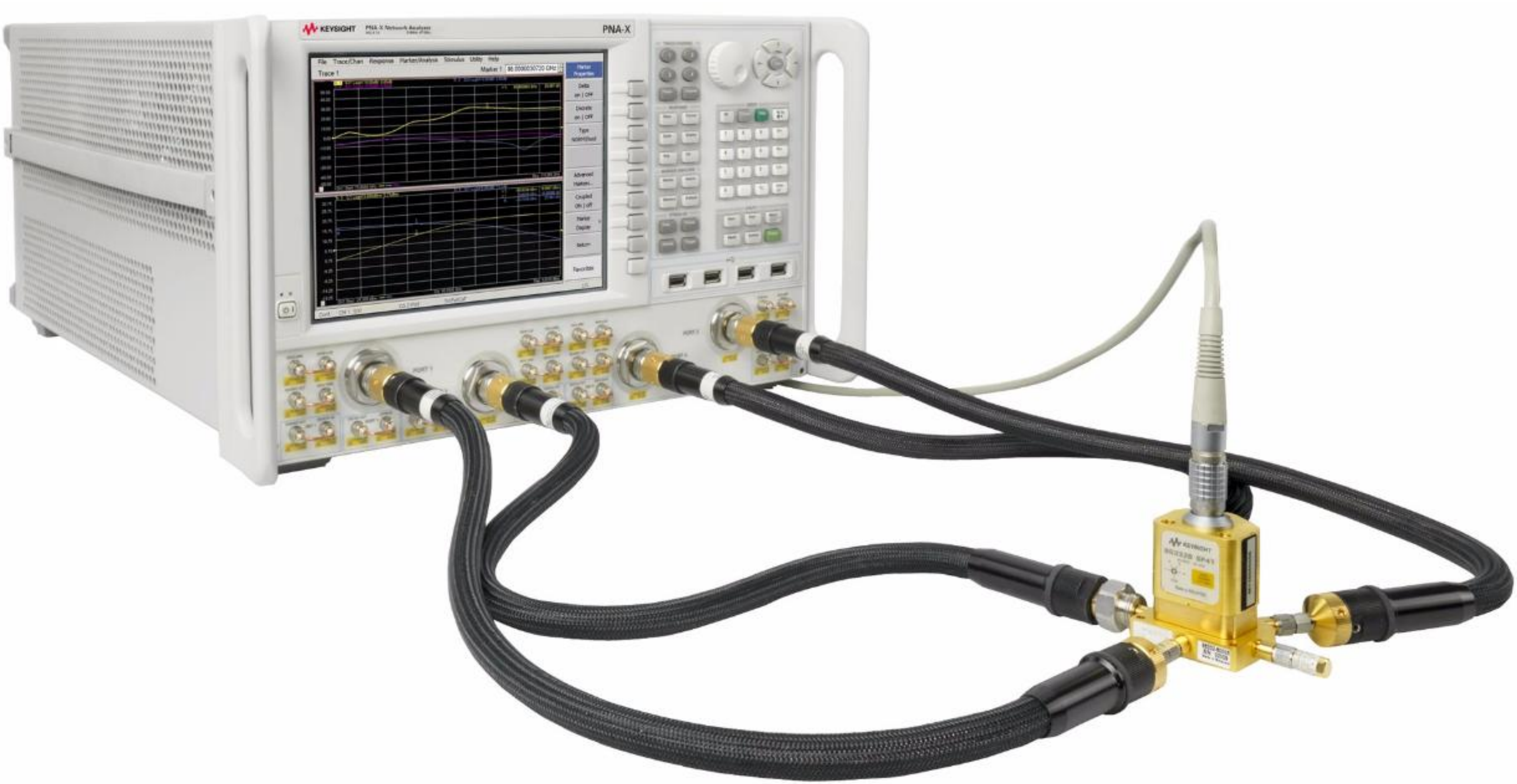
4) making a connection

- connectors should always be clean and checked before making connection
- connectors should be held in a straight line when making a connection (otherwise, the center conductor could be damaged)
- connector bodies should never be rotated against each other during tightening (only the nut of the male connector should be rotated)
- after the (reasonably) hand-tight connection is made, connectors should be finally tightened using a torque wrench (the female connector is held with a normal wrench while the torque wrench is used on the nut on the male one)
  - always use the correct torque wrench!

Test port cables

- DUTs can be connected directly to a VNAs test port (one-port DUT for reflection measurements or one of the ports of a multi-port DUT)
  - in this case an adapter (called "connector saver") placed between the test port and the DUT is strongly recommended
    (connector savers should be used in all situations when connecting some high quality or non-replaceable connector to a worse one (e.g. SMA))
- more common is to use a test port cable for every test port of the VNA
- port cables should always be as good as possible; they can cause a significant part of the measurement uncertainty
  - cables should be phase and amplitude stable with movement
  - should have high quality connectors (repeatable connection)
  - should be as flexible as possible to facilitate easy DUT connection

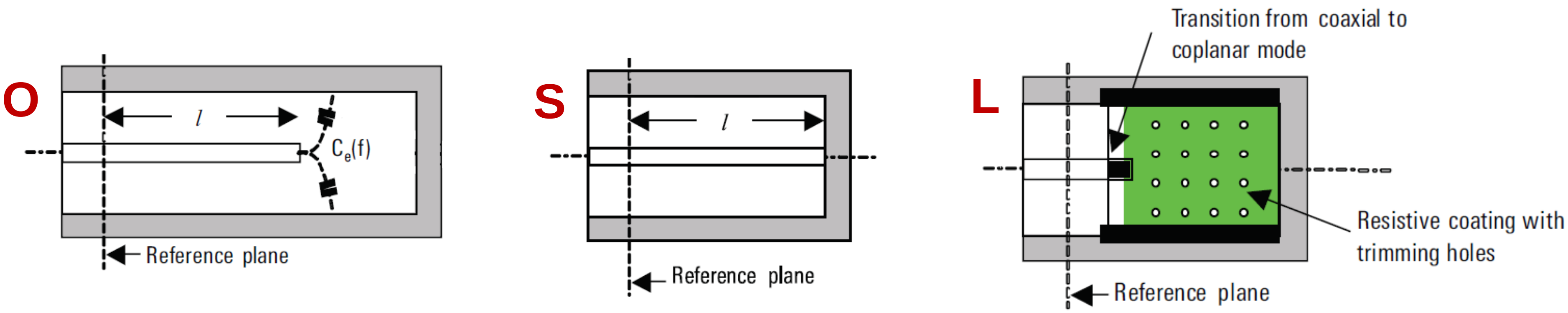
Test port cables - example



VNA Calibration

- VNA calibration is always done by measuring some known standard devices which present defined conditions to the test ports
  - characteristics of the standards are known to the analyzer - can be defined either by setting parametrs of a model describing the standard or by supplying an s-parameter file (data-based standards)
  - after the standard measurement is done, the VNA has two sets of data - how the standards "should look like" and how they appear to the uncorrected analyzer
  - from these datasets (when sufficient number of different standards was measured), the error terms of the VNA can be calculated and then applied to subsequent DUT measurements to correct the results
  - there are many different calibration techniques suitable for different situations and using different sets of standards

Calibration standards



- the simplest (and most common) OSL(T) calibration is done using these standards:
  - OPEN (O) – open end of a line; modelled as a fringe capacitance
  - SHORT (S) – shorted line; modelled as inductance
  - LOAD (L) – matched transmission line
  - THRU (T) – ideal connection of port cables – zero length, no attenuation

Calibration kits

- calibration kits provide a set of well defined standards enabling calibration of the VNA system
  - always a complete set of standards sufficient for certain calibration technique (or more techniques)
- types of calibration kits:
  - "mechanical" kits with different standard sets
    - contain separate coaxial standards like open/short/load
    - depending on the cal. method, more of these standards need to be connected to the test port one by one during the calibration
    - various versions of mechanical kits - precise/economy
  - "electronic" kits (Keysight's Ecal) - one device with USB connection to the analyzer which can switch between different internal states
    - no need to exchange calibration standards manually; single connection


Agilent
Agilent 85052C Quick Reference Air Line Connect/Disconnect Procedures
Install 7-32 GHz Air Line
Connect Port 1 to Port 2
When Disconnecting
Remove 7-32 GHz Air Line
Install 2-7 GHz Air Line
Connect Port 1 to Port 2
When Disconnecting
Remove 2-7 GHz Air Line

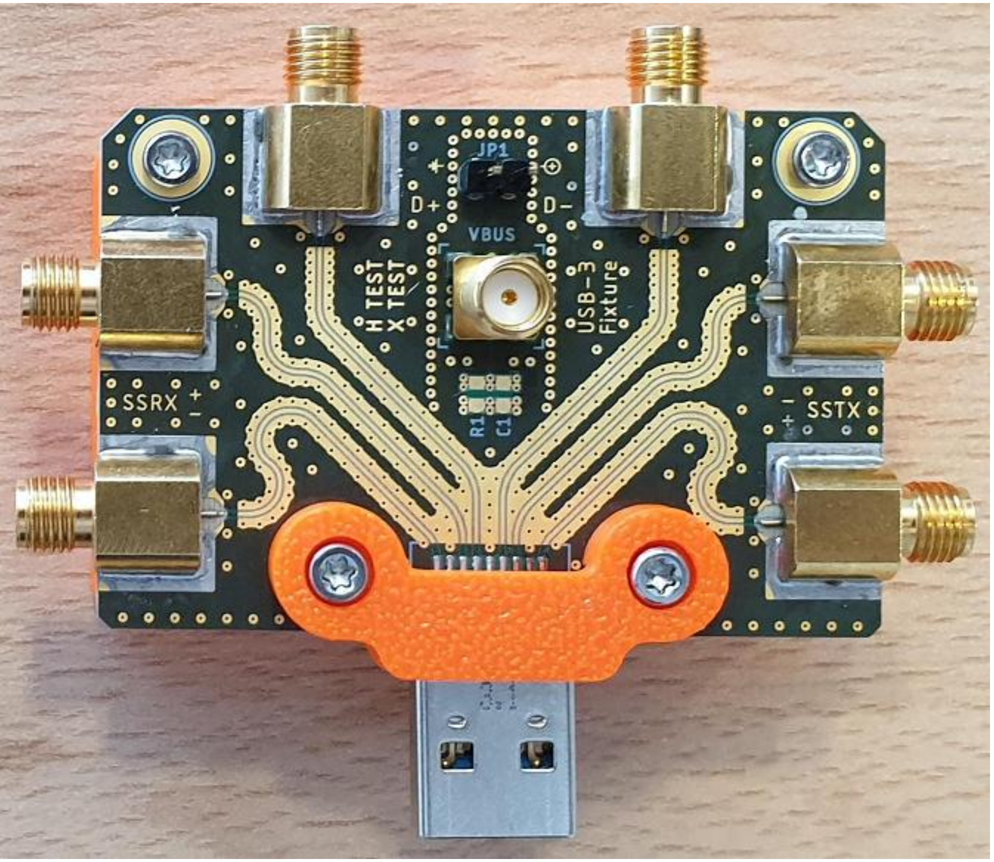
Calibration kits

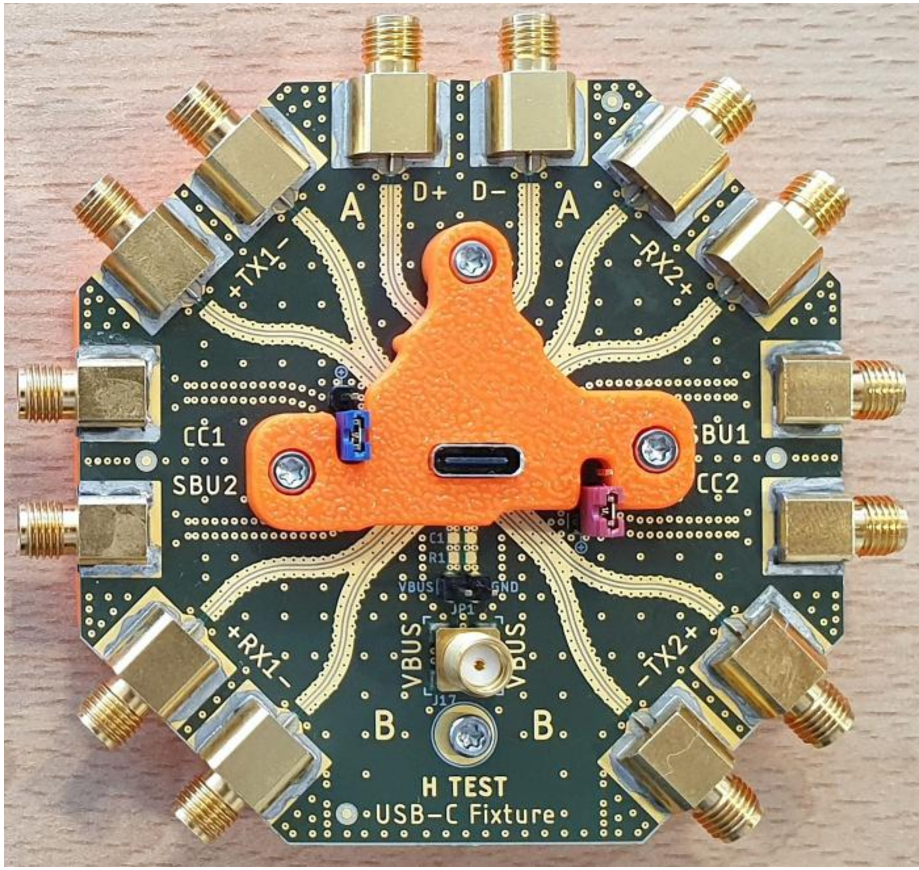
Alternative DUT connection methods

- if possible, it is always preferable to measure directly on coaxial connectors in the calibration reference plane
- sometimes, it might me necessary to use a fixture or a probe:
  - fixtures can be used for measurements on connectors for which there are no standard adapters and calibration kits
    - various automotive coaxial connectors or high speed communication connectors – USB, Ethernet, HDMI, …
    - it also serves as an adapter between single-ended and diferential lines in some cases (high speed serial buses)
  - probes can be used for connections to test points within the circuit
    - simple coaxial „pigtail“ probes (coaxial cable with stripped inner conductor) might be sufficient on lower frequencies
    - or, preferably, specialized test probes (single-ended or differential)

Alternative DUT connection methods

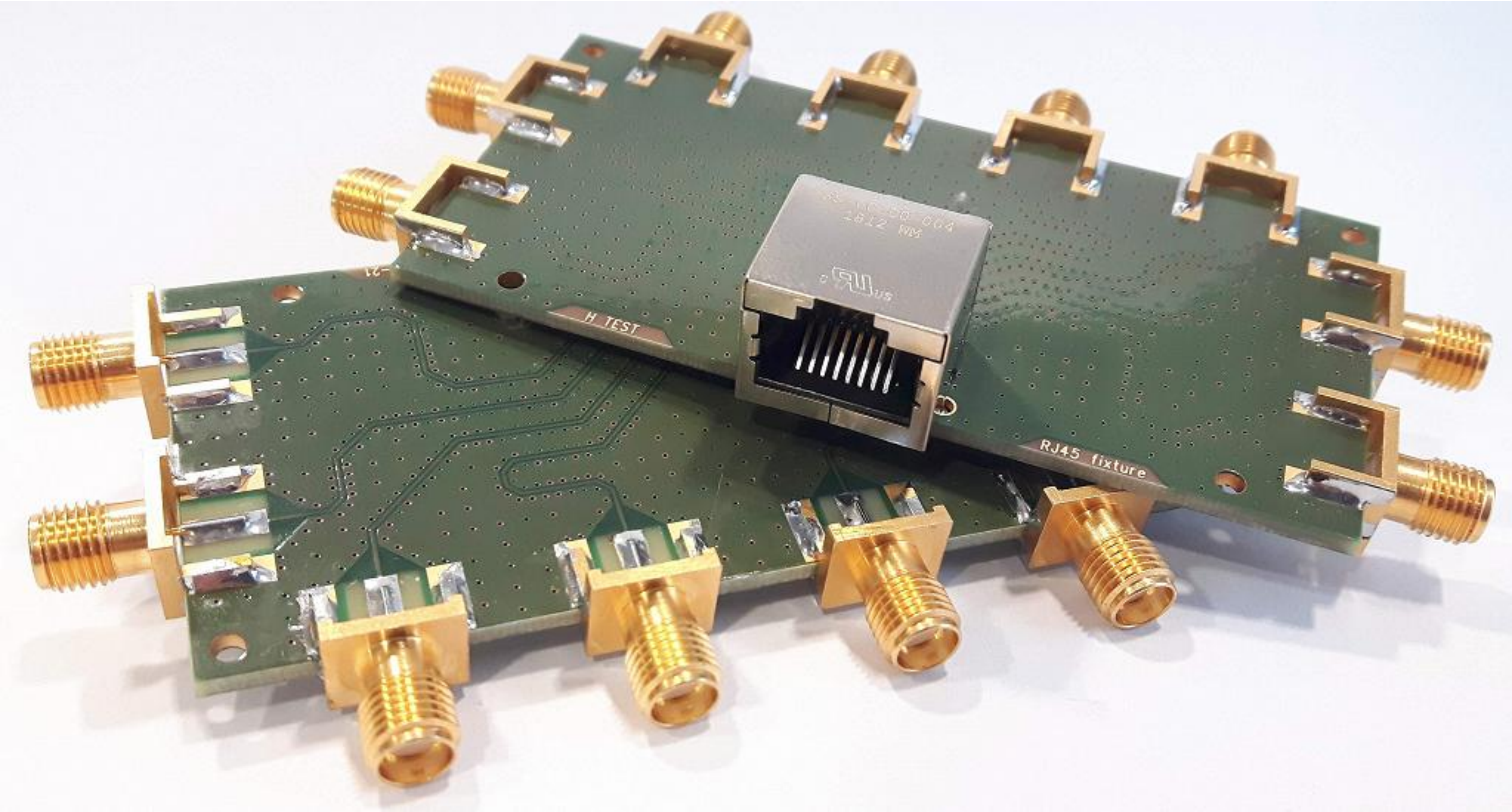
- custom measurement fixtures (USB A, USB C):





Alternative DUT connection methods

- custom measurement fixture (RJ45):



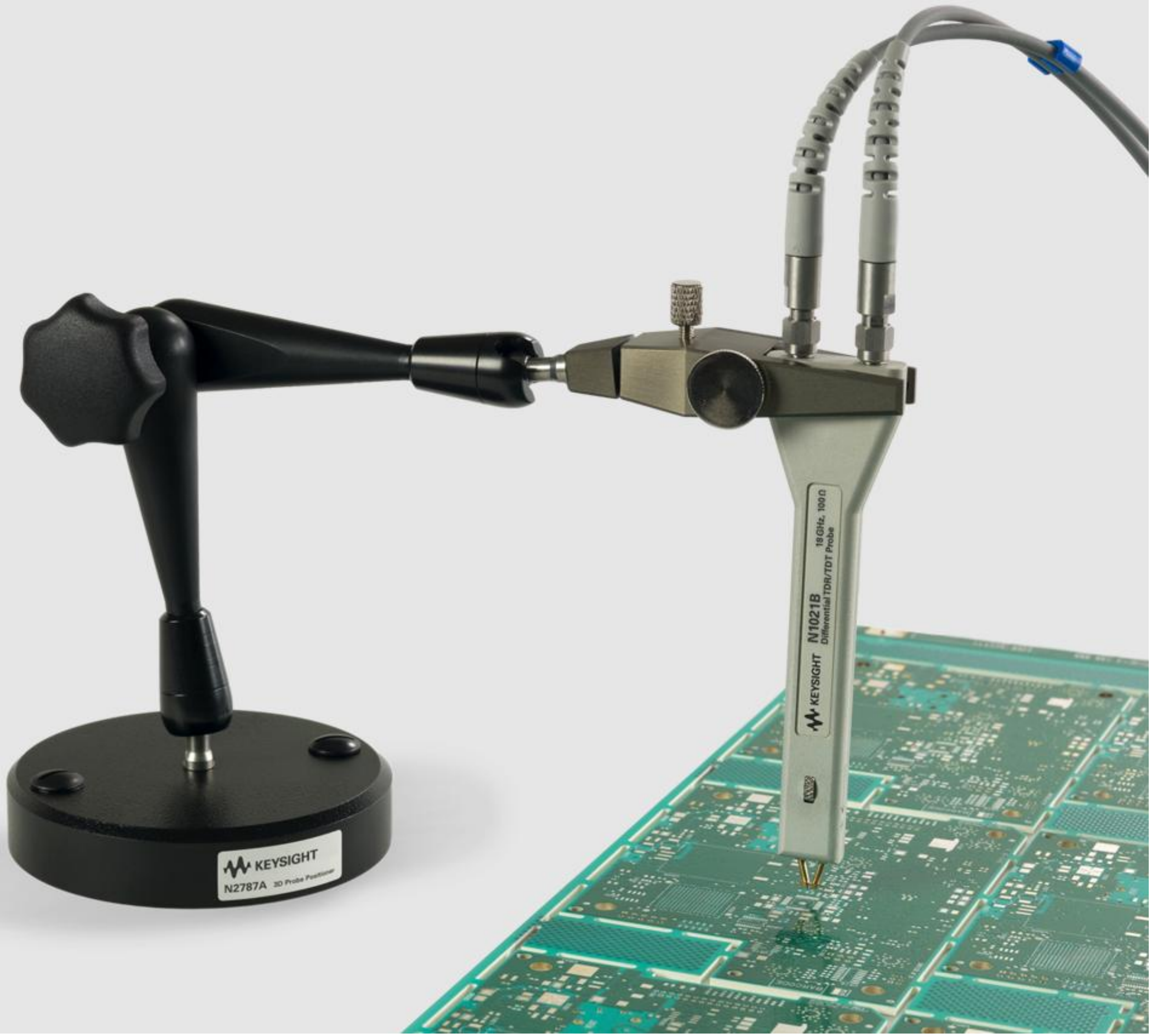
Alternative DUT connection methods

- simple „pigtail“ single-ended probe with stripped center conductor and “professional” probe from FormFactor (differential):

Alternative DUT connection methods

- Keysight N1021B differential probe:

Alternative DUT connection methods

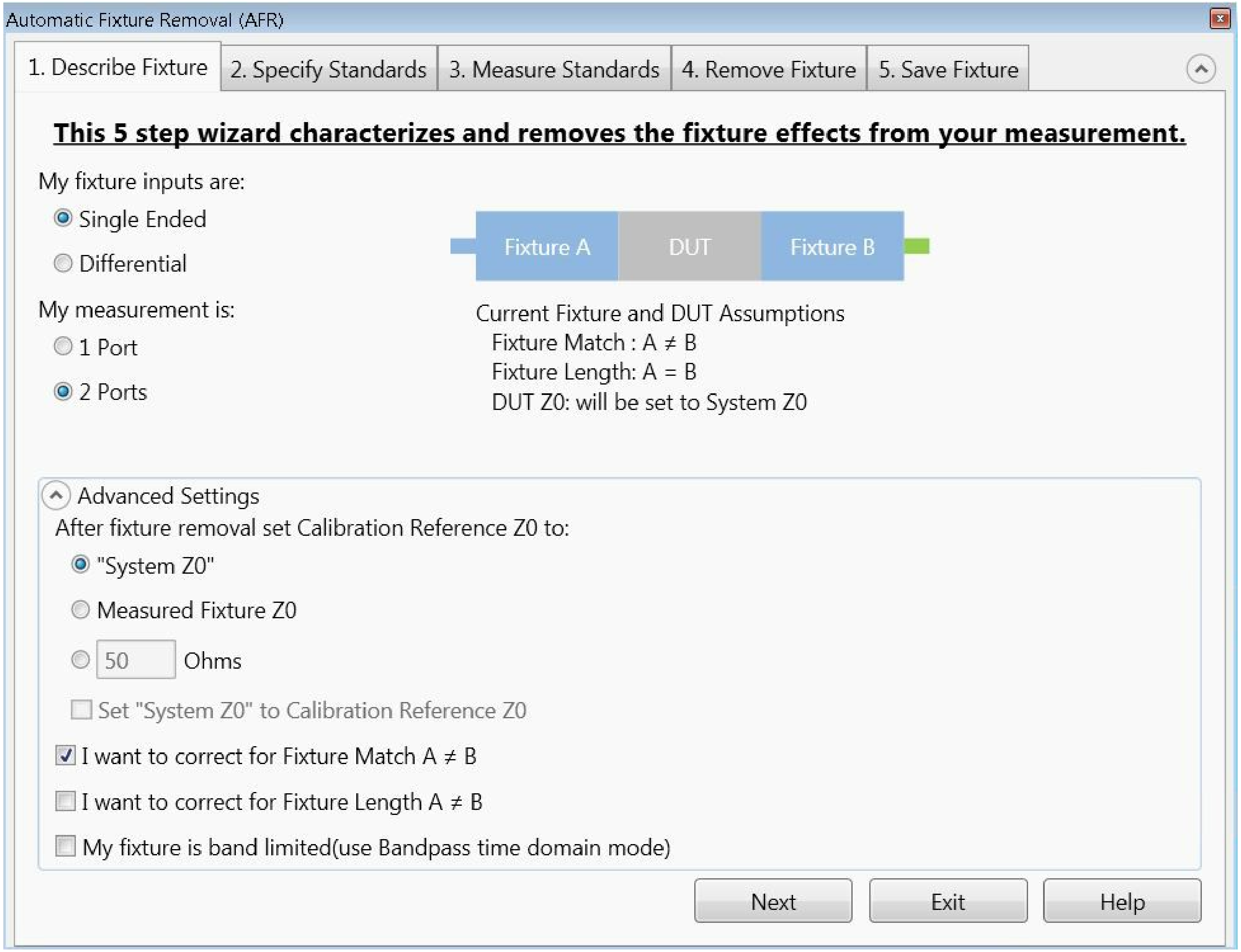


Alternative DUT connection methods

- fixtures and probes should have as good as possible intrinsic properties:
  - transmission line with defined impedance should go as far as possible (end as close as possible to the connection point)
  - the fixture/probe should be electrically short
- first step is always the standard VNA calibration on coaxial test ports
- after the calibration is done and the fixture connected to the VNA, it is necessary to correct it’s influence
  - shift the reference plane to the DUT connection point
    - „(auto) port extension“ function
  - fixture „de-embedding“ – fixture characterisation (s-parameters extraction) and mathematical removal
    - Keysight VNAs have optional „Automatic Fixture Removal“ function

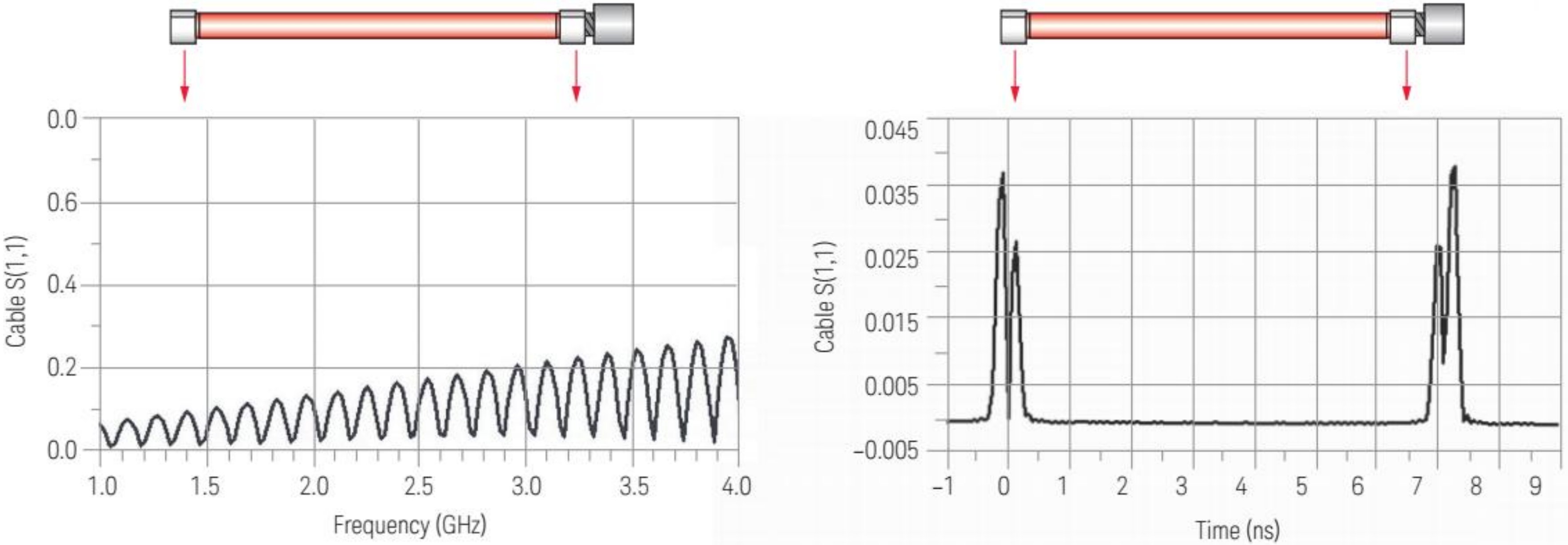
Alternative DUT connection methods

- „Automatic fixture removal“ (AFR) – settings:



Time domain measurements

- modern VNAs can use measured data (frequency domain) to calculate the DUT response in time domain (using inverse Fourier transform)
  - displays the reflection or transmission as a function of distance from the reference plane; simulation of the traditional TDR (or TDT) measurements
  - very useful for identification of the sources of mismatch observed in traditional reflection measurement



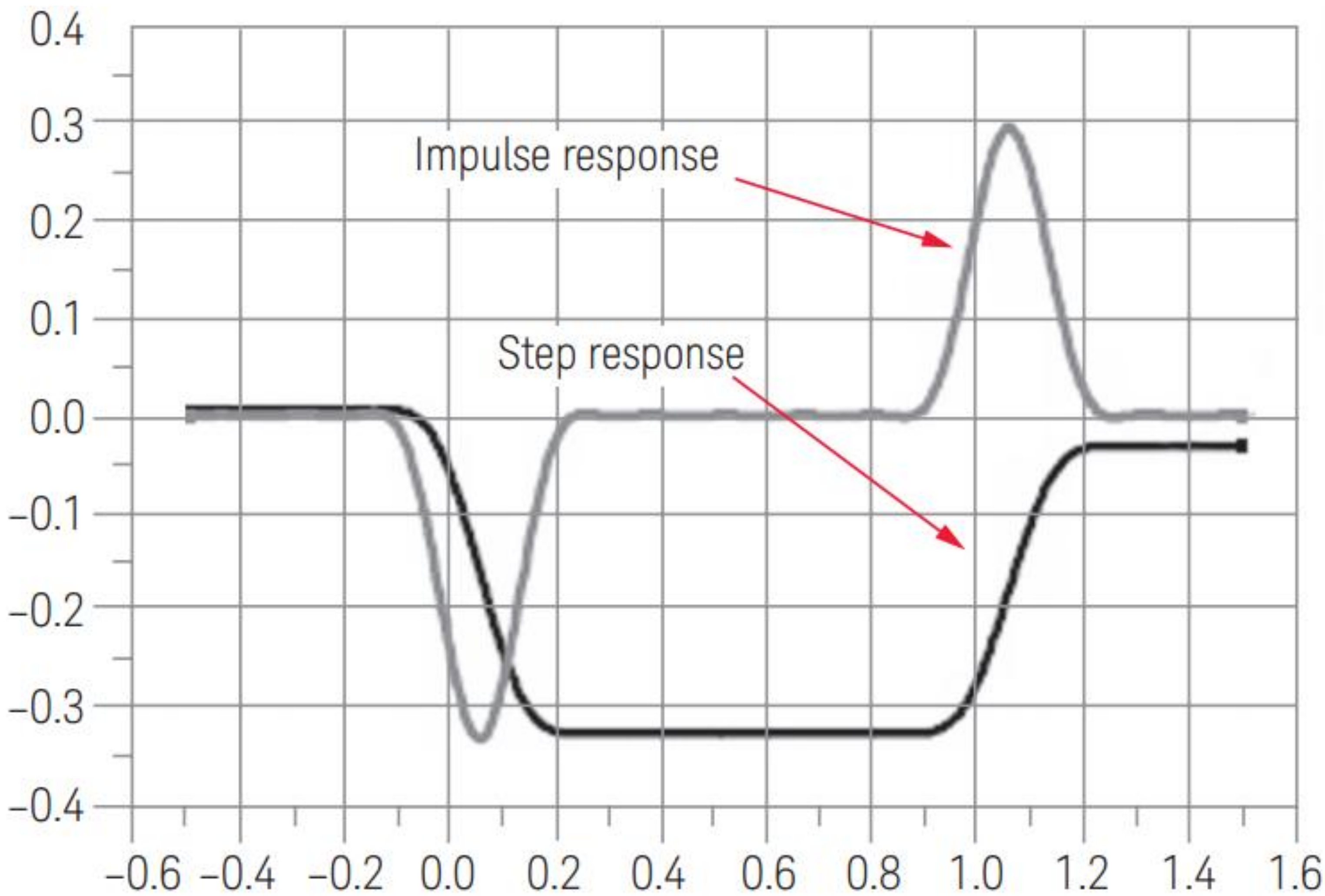
Time domain measurements

- VNA system needs to be calibrated as usual before the time domain transformation is enabled (transformation needs corrected freq. data)
  - some frequency related settings affecting the time domain transformation parametrs need to be done before the calibration
- VNA settings which affect the time domain measurement mode:

1) transformation modes
   - low-pass (impulse or step response)
     - simulates traditional TDR; generally a better choice if usable
     - usable with devices which can pass low frequencies (cables, ...)
     - twice the measurement resolution compared to the band-pass mode
     - all freq. points throughout the whole span must be multiples of start freq.
   - band pass (impulse response only)
     - most general purpouse mode; arbitrary frequency range
     - ideal for measuring band-limited devices (e.g. filters)

Element	Step response	Impulse response
Open	 Unity reflection	 Unity reflection
Short	 Unity reflection, –180 °	 Unity reflection, –180 °
Resistor $R > Z_0$	 Positive level shift	 Positive peak
Resistor $R < Z_0$	 Negative level shift	 Negative peak
Inductor	 Positive peak	 Positive then negative peaks
Capacitor	 Negative peak	 Negative then positive peaks

Time domain measurements

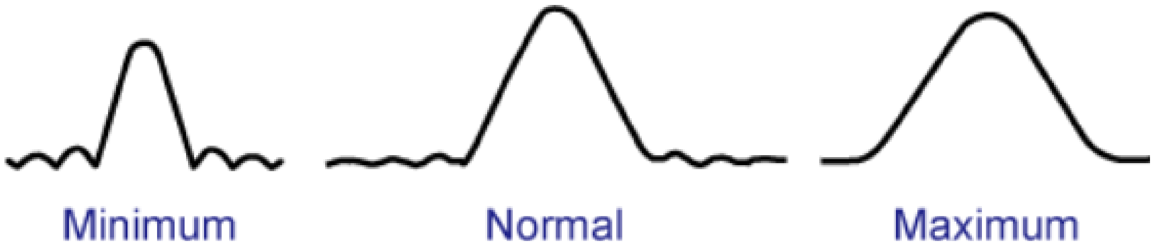


Time domain measurements

2) window function

- window function is used on the frequency domain data before the time domain conversion is done to reduce the level of parasitic side lobes
- window "width" influences the side-lobe level and time resolution
  - wider window increases the level of unwanted side lobes and decreases the minimum resolution distance (some compromise has to be found)

Window Type	Impulse Sidelobe Level (dB)	Low-pass Impulse Width (50%)	Step Sidelobe Level (dB)	Step Rise Time (10% to 90%)
Minimum	–13	0.60 / Freq Span	–21	0.45 / Freq Span
Normal	–44	0.98 / Freq Span	–60	0.99 / Freq Span
Maximum	–75	1.39 / Freq Span	–70	1.48 / Freq Span



Time domain measurements

3) frequency span (range; stop - start frequency)
   - frequency span setting influences the measurement resolution and the available (alias free) measurement range
     - wider span means better resolution and lower measurement range (when the number of frequency points is constant)
4) frequency step (span divided by number of points)
   - frequency step size influences the measurement range

- important transformation parameters:

1) measurement response resolution
   - how close two responses can be to each other to be still distinguishable (distance between discontinuities)
   - depends on time domain mode, windowing fuction, frequency span, whether it is a reflection/transmission measurement and on the relative propagation velocity

Time domain measurements

Window	Low-pass step (10% to 90%)	Low-pass impulse (50%)	Bandpass impulse
Minimum	0.45/frequency span	0.60/frequency span	1.20/frequency span
Normal	0.99/frequency span	0.98/frequency span	1.95/frequency span
Maximum	1.48/frequency span	1.39/frequency span	2.77/frequency span

time resolution calculation

$$spatial\,res.(m) = time\,res.(s) \cdot c_0 \cdot V_f$$

V_f - velocity factor

- resulting spatial resolution needs to be divided by 2 for reflection meas.

2) measurement range

- time length (or distance) which can be measured without seeing a false repetition of the response (aliasing)
  - repetitions appear periodically with increasing distance from ref. plane
  - aliasing is a consequence of discrete sampling in frequency domain
- range depends on frequency step size and relative propagation velocity

Time domain measurements

$$range(m) = \frac{1}{\Delta f} \cdot c_0 \cdot V_f$$

V_f - velocity factor

- resulting range needs to be divided by two for reflection measurements

3) level of displayed parasitic side lobes (response ripple)
   - side lobe level depends on chosen window function
   - best compromise between side lobe level and meas. resolution can be found by changing the window function while watching the response

- measurement example:
  - low-pass impulse; normal window; 2,5 GHz span; 401 points; PE cable
    - range: $400/2{,}5e9 \cdot 300e6 \cdot 0{,}66/2 \doteq 15{,}84\ m$ (for reflection meas.)
    - resolution: $0{,}98/2{,}5e9 \cdot 300e6 \cdot 0{,}66/2 \doteq 3{,}9\ cm$ (for reflection meas.)

Time domain measurements

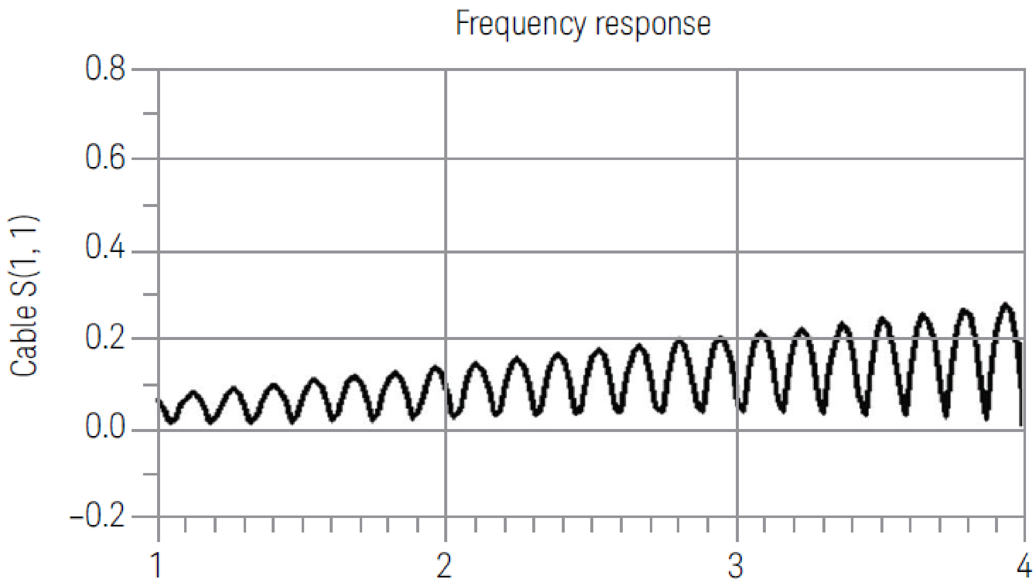
- time domain measurement resolution depending on the frequency span: (reflection measurement; "low-pass step" mode; velocity factor 0,7)

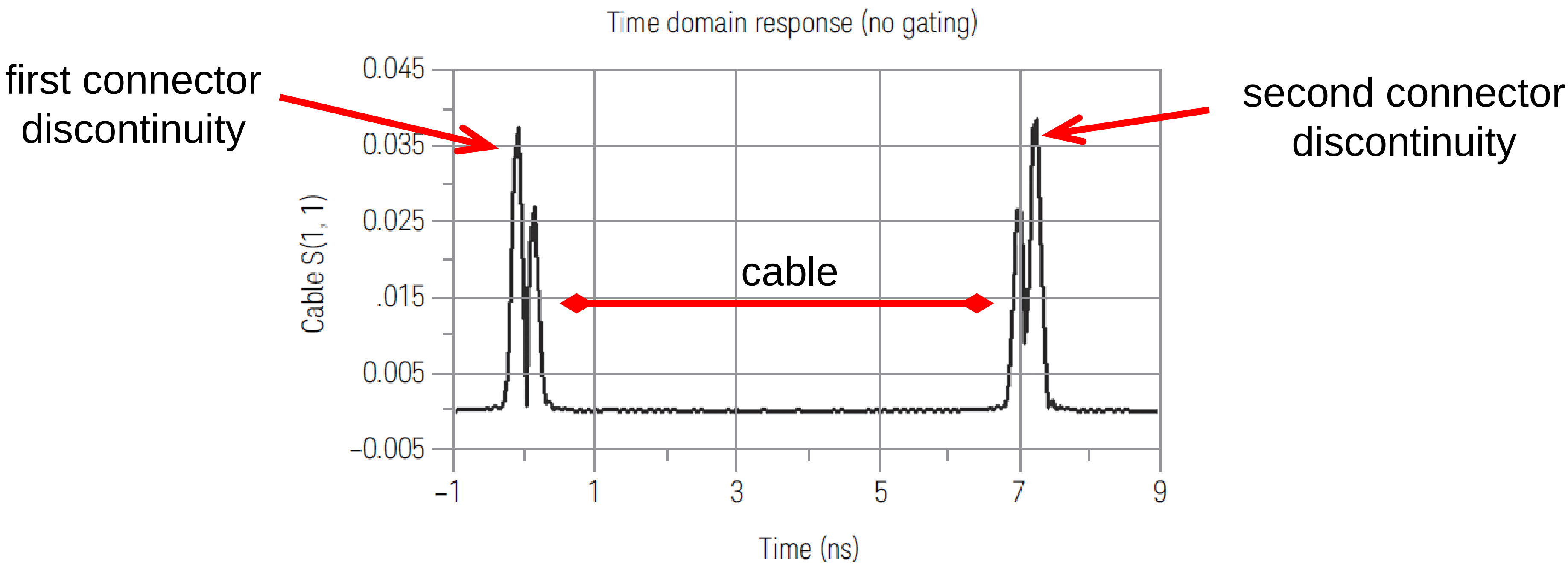
frequency span (GHz)	resolution narrow window (mm)	normal window (mm)
0.5	94.5	207.9
1.5	31.5	69.3
3	15.8	34.7
6	7.9	17.3
9	5.3	11.6
14	3.4	7.4
20	2.4	5.2
30	1.6	3.5
40	1.2	2.6
50	0.9	2.1
67	0.7	1.6

Time domain - gating

- very useful feature which enables the user to select certain time interval from the displayed TDR trace and convert that part of DUT's response back to frequency domain
  - this way it's possible to mathematically remove the influence of reflections from unwanted discontinuities
  - can be used for example to display impedance characteristics of some transmission line without the reflections on connectors
  - a window function always has to be applied on the gated interval
    - the shape of the window function influences the characteristics of the frequency domain data after the conversion
    - the result also depends on the centering of the gate interval in the original time domain trace - ideal result is obtained if the gate is right on the center of the time domain trace

Gating example

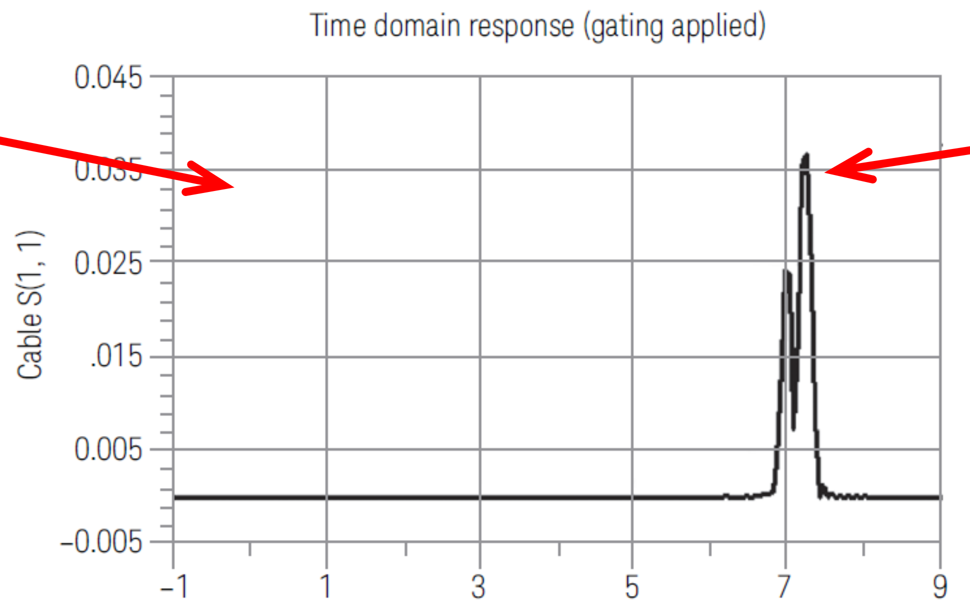


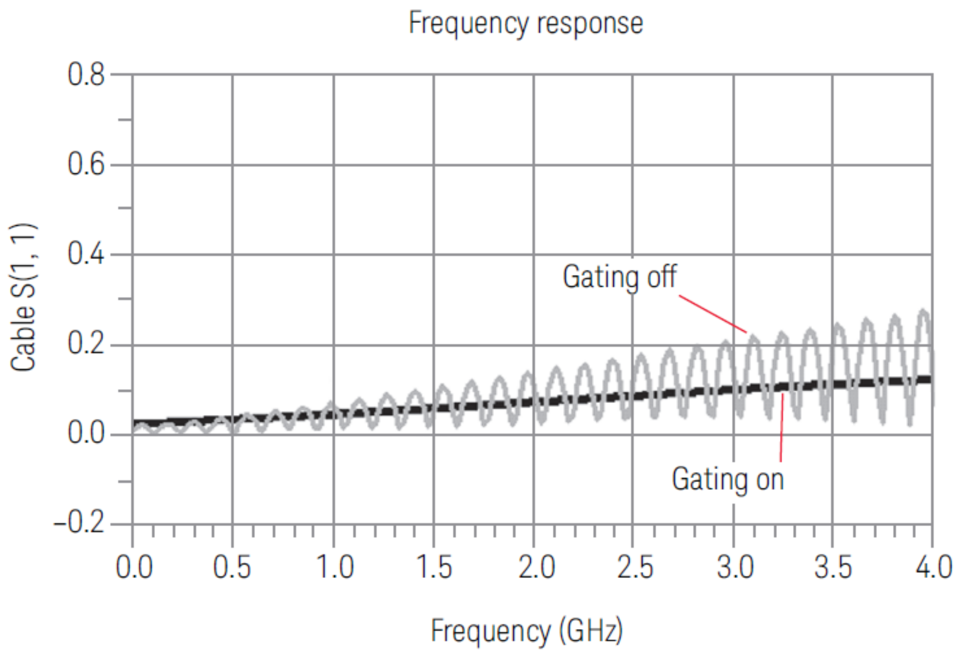


Gating example

first connector discontinuity gated out

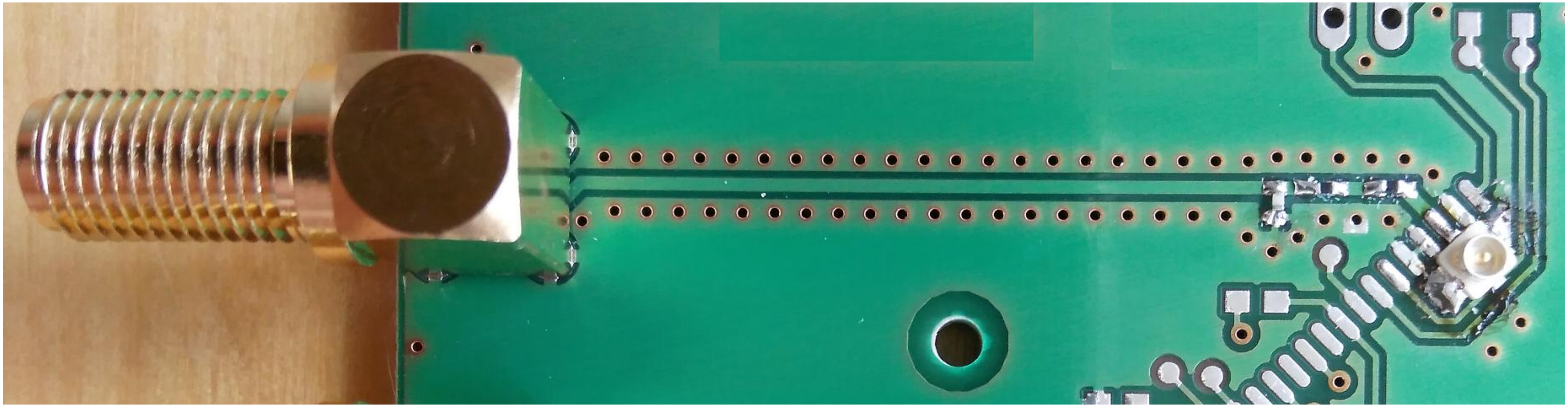
second connector discontinuity only





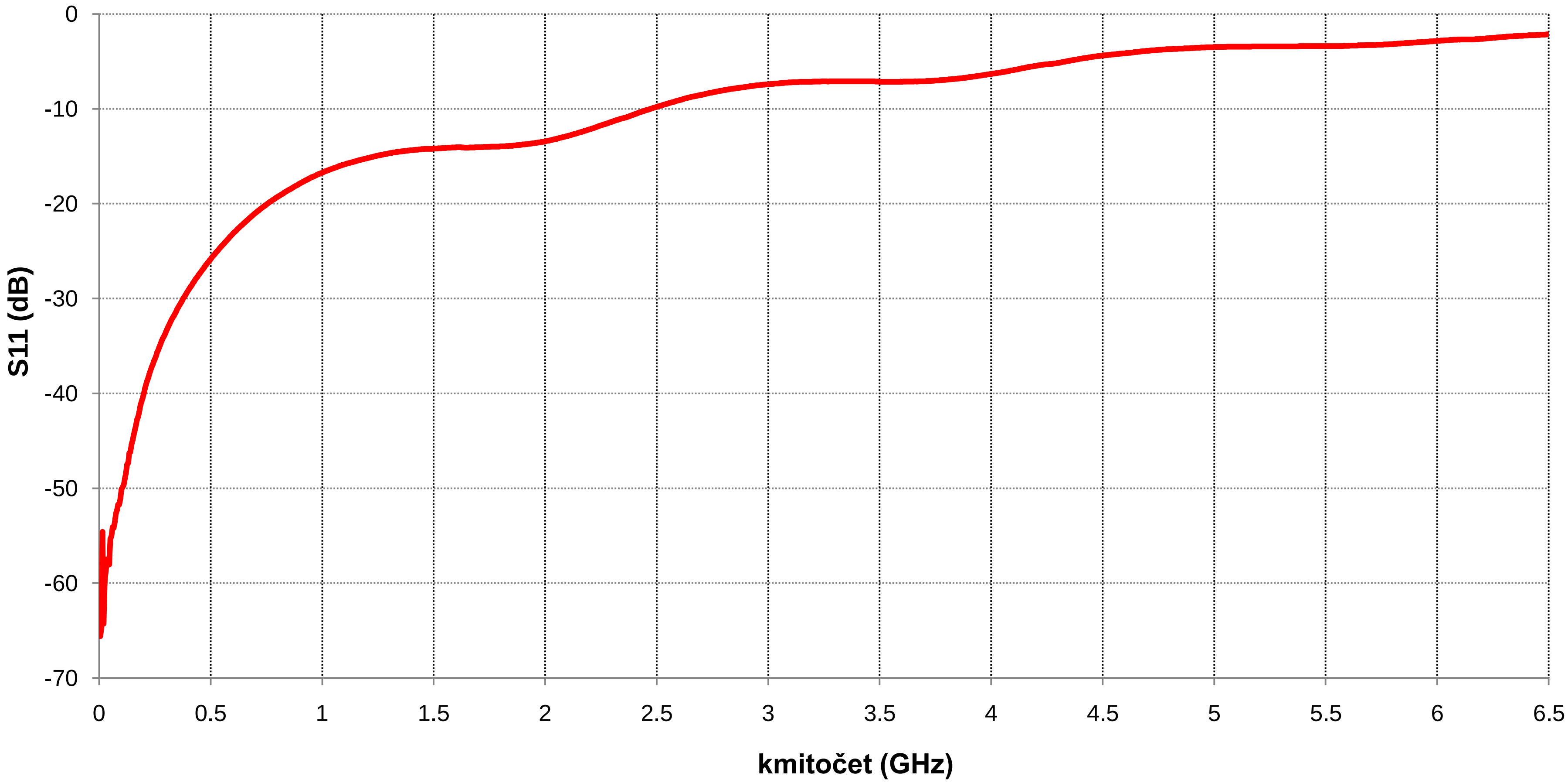
Time domain - example

- reflection measurement on a PCB trace (freq. and time domain)
  - one port measurement on a SMA connector
  - the other side of the trace was terminated with a 50 Ω SMD resistor (there is a U.FL connector instead on the following picture)
  - the time domain measurement found a major discontinuity near the 90° SMA connector



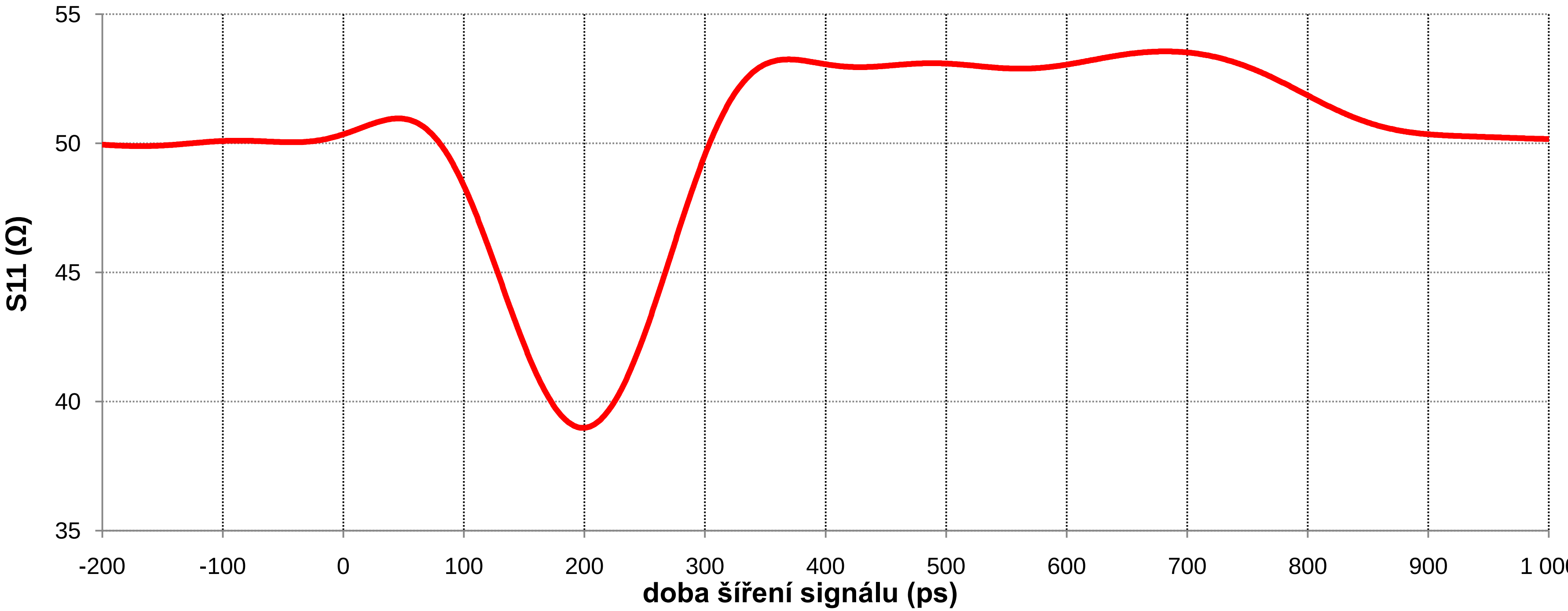
Time domain - example

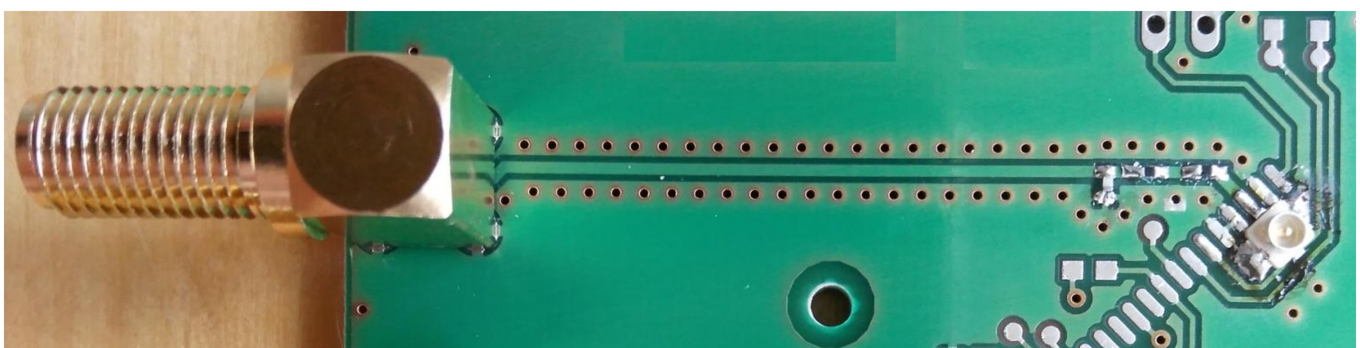
- frequency domain measurement:



Time domain - example

- time domain measurement:

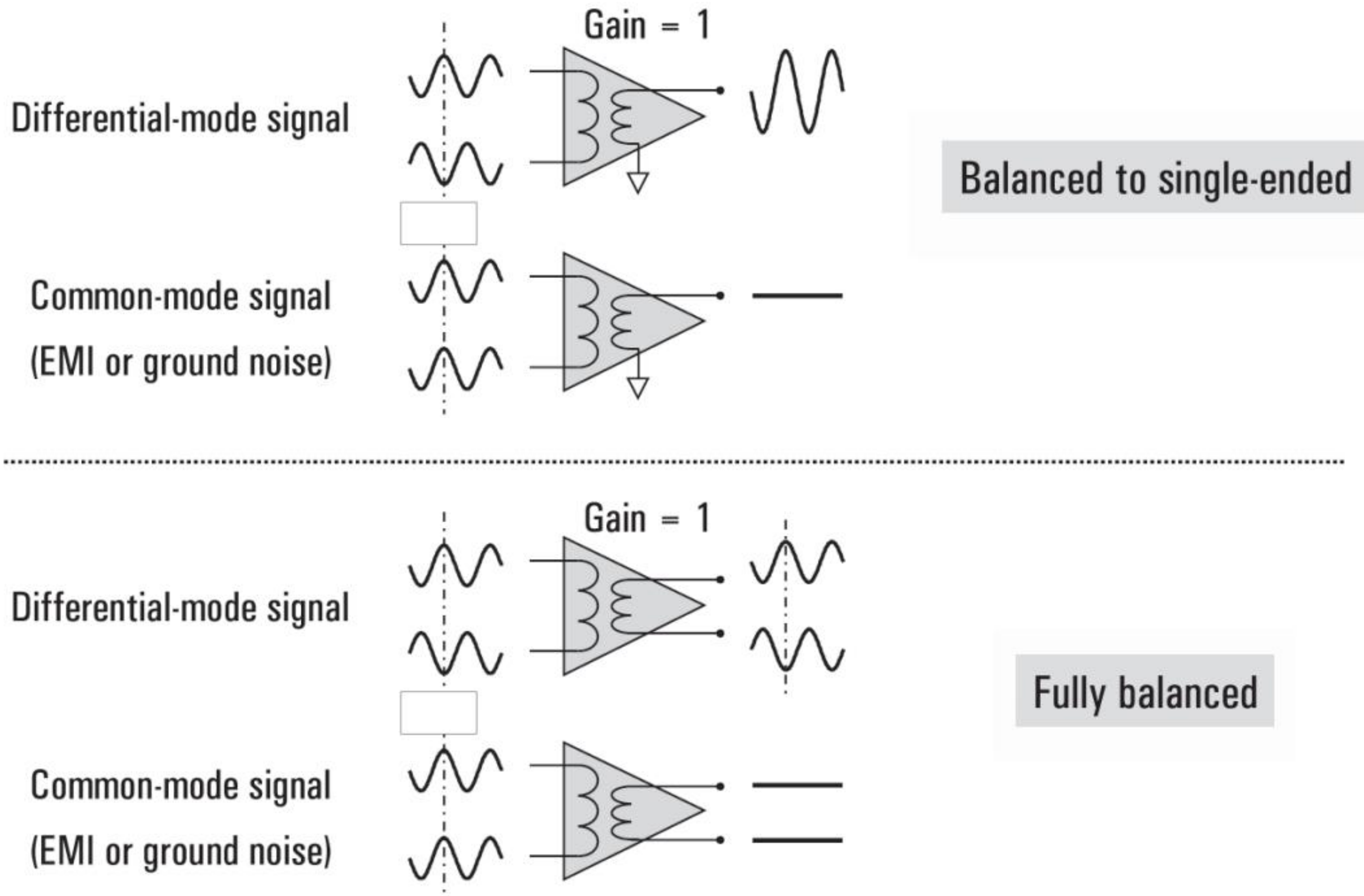




Differential measurements

- differential signal transfer has many advantages and is used more and more in modern devices
  - better immunity against external interference, lower radiation (EMI)
  - reduction of the level of second harmonics
  - lower demands on rf grounding quality
- the whole VNA system is designed as single-ended (test ports, calibration standards, ...), modern VNAs, however, can be easily configured for differential measurements
  - two physical single-ended test ports can form one logical differential port
  - calibration is done as usual (each of the single-ended test ports is calibrated separately)
  - VNA calculates differential S-parameters from the measured single-ended data

Differential measurements



Differential measurements

- "mixed-mode" S-parameters – besides the port numbers, these parametrs also identify the modes; marked as **Sabxy**
  - x, y – numbers of the logical ports
  - a, b – identify the mode (d – differential, c – common, s – single ended)
  - reflections and transmissions for differential and common modes
  - S-matrix of a 2-port differential device (bal-bal):

$$
\begin{matrix}
S_{DD11} & S_{DD12} & S_{DC11} & S_{DC12} \\
S_{DD21} & S_{DD22} & S_{DC21} & S_{DC22} \\
S_{CD11} & S_{CD12} & S_{CC11} & S_{CC12} \\
S_{CD21} & S_{CD22} & S_{CC21} & S_{CC22}
\end{matrix}
$$

Differential measurements

- normal VNAs have only one internal signal generator and therefore can not stimulate the DUT with a "true" differential signal
  - the internal source is switched between the physical ports and the differential results are calculated by merging the individual results
  - this approach can be used for DUTs operating in linear region
- some of the more advanced modern VNAs can contain two sources; their relative amplitude and phase can be precisely set
  - two sources can be used for true differential (180 ° shift) or common mode (0 °) stimulus (or anything between)
  - necessary when measuring active devices operating in non-linear region
  - Keysight's VNAs can optionally use this function (called "True Mode Stimulus"

Multiport VNAs

- modern DUTs often contain more ports than the usual four port VNA can accomodate
  - wireless rf modules for different standards or multiple bands
  - MIMO systems
  - high speed digital buses – HDMI, USB 3.1, ...
  - ...
- three ways how to get a multiport VNA system:
  - normal VNA (2 or 4 ports) + external switching matrix
  - normal VNA + external expansion test set
  - modular VNA system (based on PXIe standard) consisting of multiple separate VNA cards

Modular VNA system (true multiport)

- PXIe chassis fitted with nine VNA cards; 50 ports in total:

Modular VNA system

Summary

- modern VNAs are multipurpose instruments often used during the design of digital circuits
  - single-ended/differential lines, frequency and time domain measurements
- VNA usage requires certain level of knowledge and carefulness
  - connector care; various calibration methods; interpretation of results
- the quality of the results is affected not only by the VNA itself, but also by other elements of the measuring system
  - accessories must be chosen wisely
  - port cables, adapters, calibration kits, …