Measurements 2: Network Analysis

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- Vector network analysis
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  - Modern instrumentation
- Calibration methods
- Time domain (synthetic pulse)
- Nonlinear analysis
  - Measurement of the 1 dB compression point
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  - Harmonic measurements

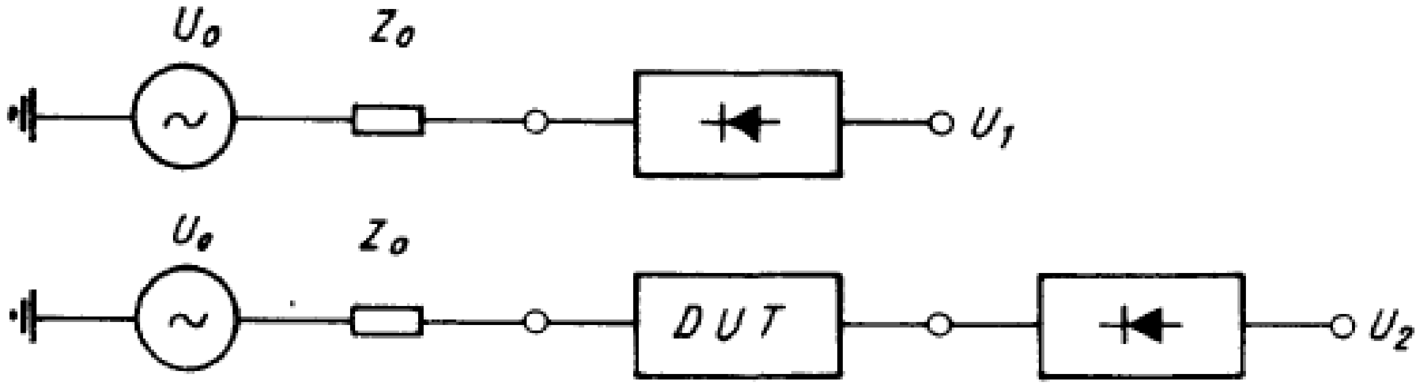
Motivation

- We want to determine the modulus and/ or modulus and phase of the reflection and transmission coefficient of a DUT
- We want to measure the complex and frequency dependent elements of the S-matrix of 1, 2, 3,4 and multi-ports
- In addition, we may be interested in nonlinear properties of our DUT (power sweep, harmonic analysis, X-parameter)
- Network analyzers meet these needs and furthermore they are also required for measurement of the beam transfer function (BTF)

Scalar network analysis

- For many measurement problems it is sufficient to know only the modulus of a complex transmission or reflection coefficient.

- A very simple measurement setup is depicted below



Scalar network analysis

- The detector may be a Schottky diode or any other RF power measuring device such as a thermo-element producing a voltage between a junction of two metals at different temperatures, or a resistor with a high temperature-coefficient (thermistor)
- The small signal response of a Schottky diode in the square law region (< - 10 dBm) delivers an output voltage (U_2) proportional to the RF power
- Often the source signal is amplitude modulated (on/off) with some low frequency e.g. 20 kHz for easier detection and suppression of DC drifts.

Scalar network analyzer

- A logarithmic amplifier often follows the diode detector to provide a reading in dB.

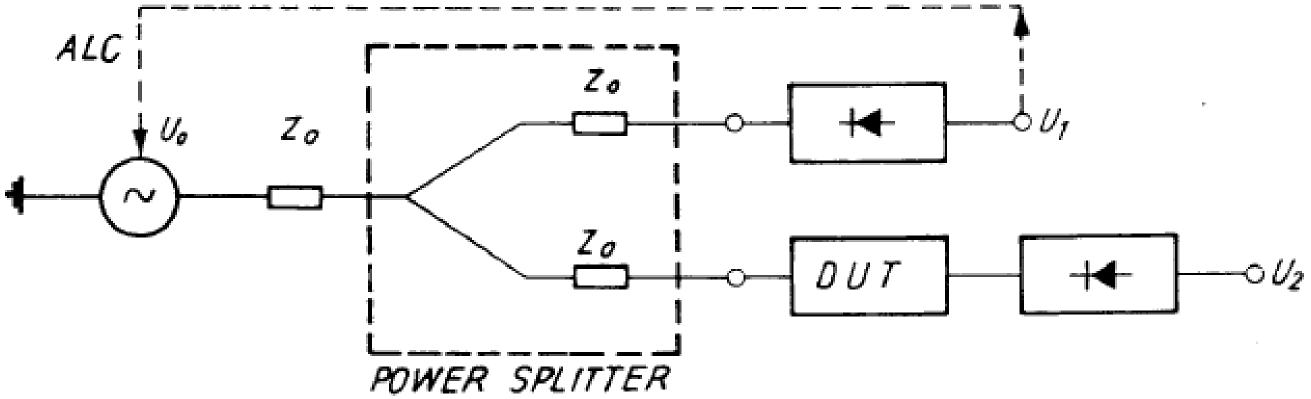
- Diode detectors may require some additional resistor networks in order to be reasonably matched to 50 Ω at the RF input side.

- As the signal strength U_0 of the RF generator is usually not constant over a wide frequency range, either **LEVELLING** (feedback loop) is needed, or some other mitigation techniques are required.

Scalar network analyzer

- A resistive power divider may provide a reference signal at any frequency and thus is very suitable for automatic level control (ALC) . The ratio U_2/U_1 cancels amplitude variations of the generator during the frequency sweep (feedback loop)

- This type of power divider (see below) which is often applied for ALC , has however an insertion loss of 6 dB

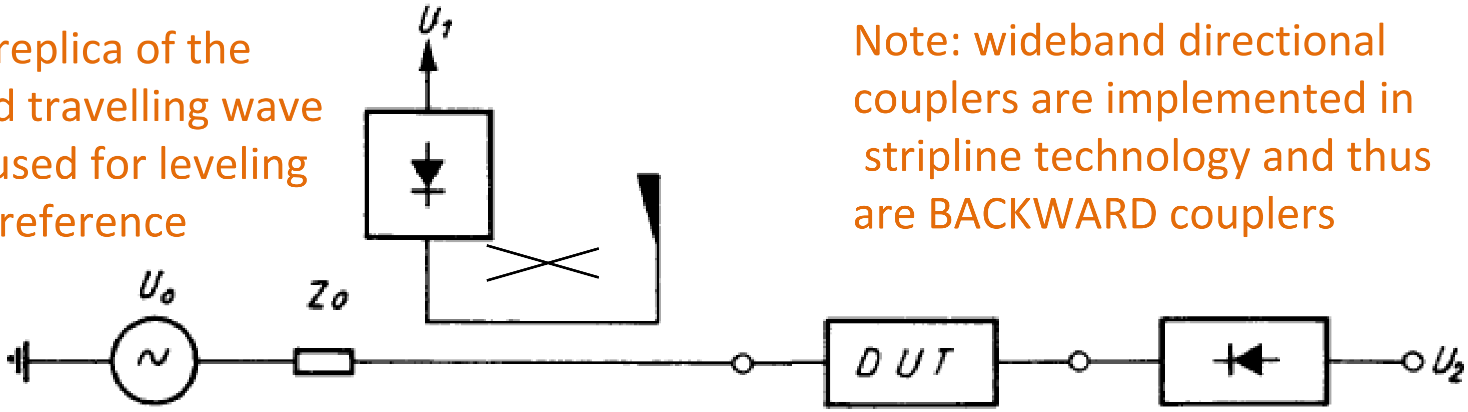


Scalar network analyzer

- Alternatively, a directional coupler (coupling e.g. -10 dB) may be used, which has an even smaller insertion loss and better directivity as compared to the resistive splitter

- But in contrast to the resistive splitter, its limited frequency range may pose a problem in certain cases

U_1 is a replica of the forward travelling wave and is used for leveling and as reference

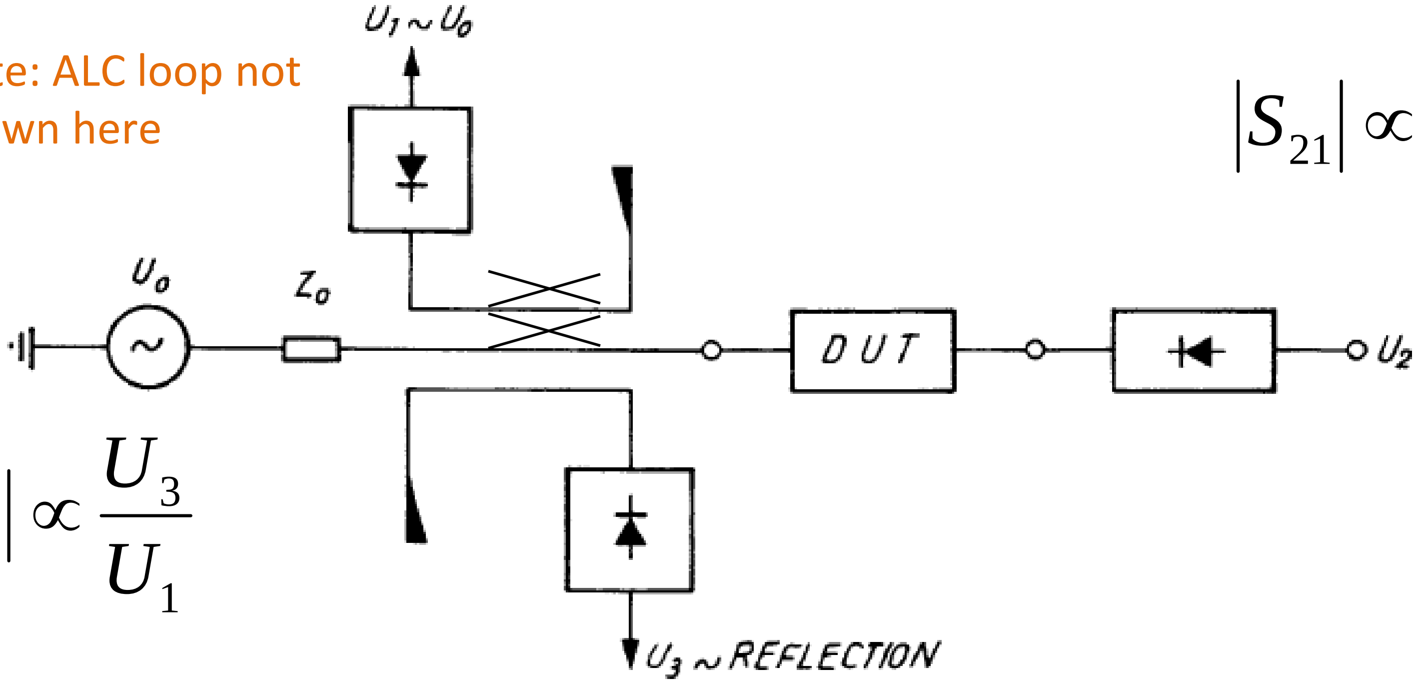


Note: wideband directional couplers are implemented in stripline technology and thus are BACKWARD couplers

Scalar network analysis

- If we want to measure simultaneously $|S_{11}|$ and $|S_{21}|$ with a scalar device, we need a dual directional coupler in order to separate the forward and reflected wave respectively

Note: ALC loop not shown here

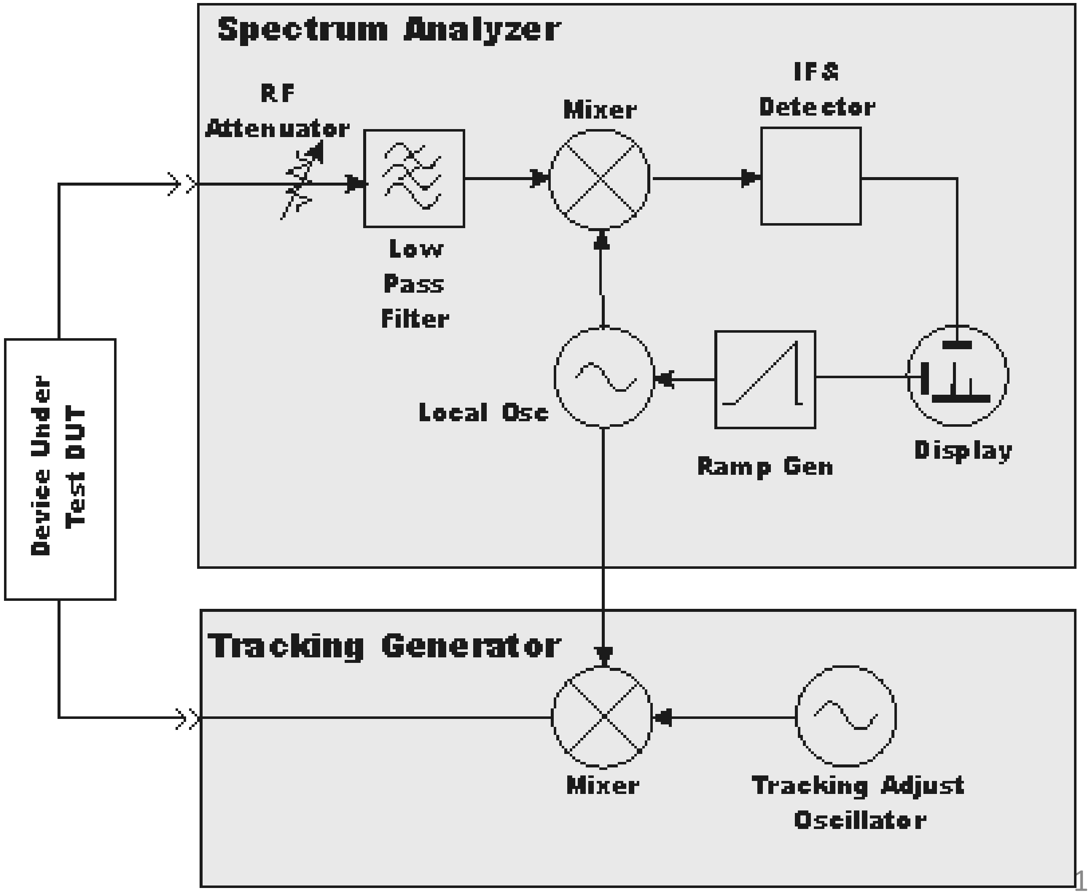


$$|S_{21}| \propto \frac{U_2}{U_1}$$

$$|S_{11}| \propto \frac{U_3}{U_1}$$

Scalar network analysis

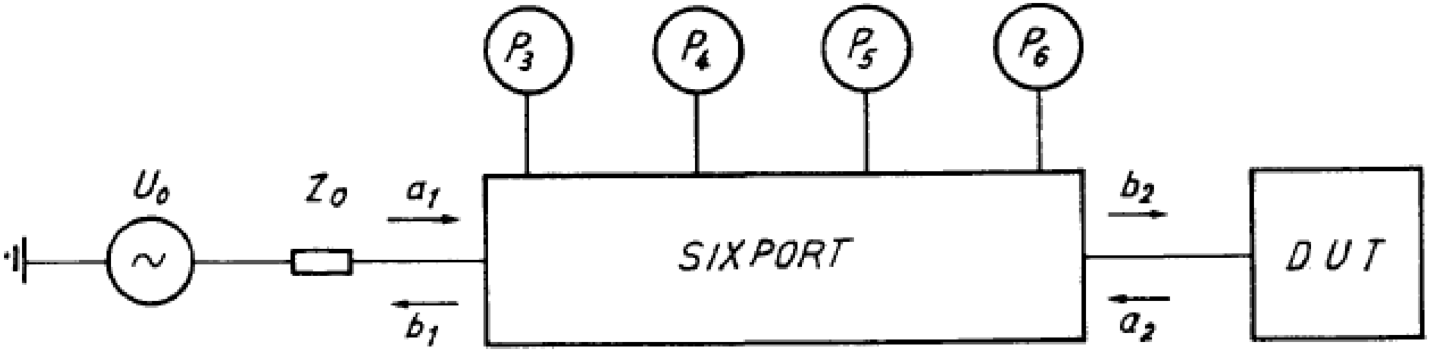
- The functionality of scalar network analysis in transmission $|S_{21}|$ can also be implemented using a **spectrum** analyzer with tracking generator:
- With a mixer based detector (superhet) we have a much higher dynamic range as compared to the direct diode detector



Six port reflectometer

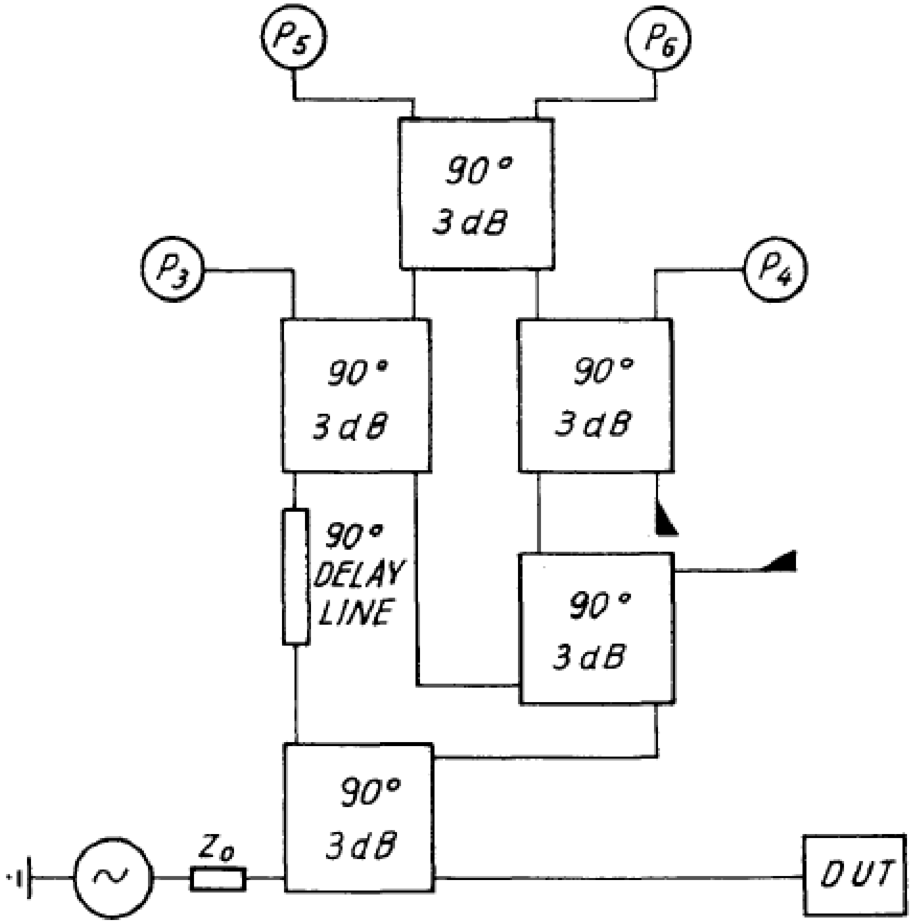
- Only with power detectors is it possible to obtain the full **vectorial** information on the reflection coefficient (4 diode detectors at ports 3..6).Its operating concept is similar to sampling the modulus of some RF signal along a RF measurement line at 4 positions

- This configuration is known as a six-port reflectometer:



Six port scalar reflectometer

- The interior of the "black box" of the previous slide is shown here
- These type of analyzer is seldom found in the average RF lab, however it is used for very high frequencies (>300GHz) where down-mixing is getting difficult and power detectors are easier available



Bridge-type methods for complex S-parameters

- Remember the relation between S-parameters and impedance of a lumped element:

$$S = \begin{pmatrix} \frac{Z}{2Z_0 + Z} & \frac{2Z_0}{2Z_0 + Z} \\ \frac{2Z_0}{2Z_0 + Z} & \frac{Z}{2Z_0 + Z} \end{pmatrix}$$

- Thus if our DUT is a single lumped element (series or shunt) we can determine the four elements of the corresponding 2-port S-matrix and vice versa

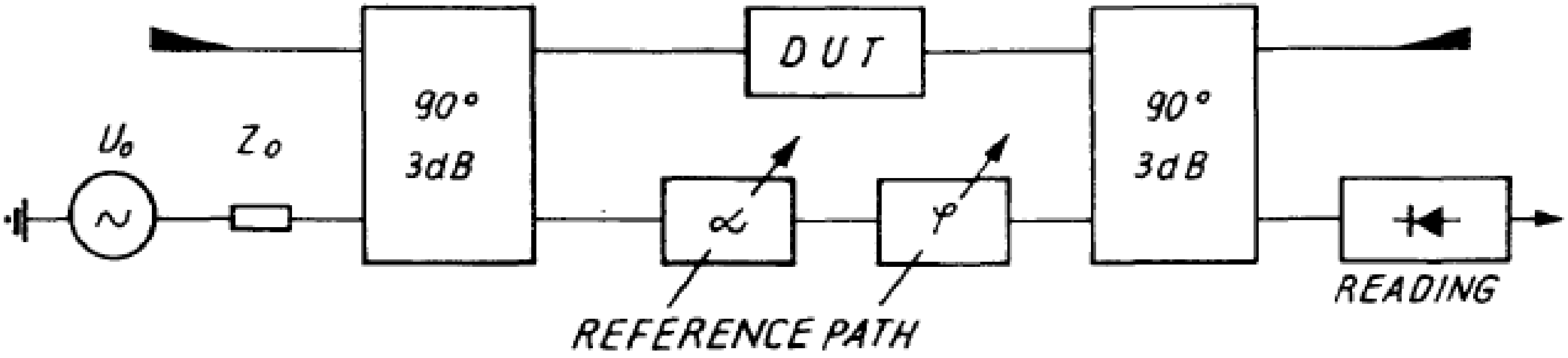
Bridge-type methods for complex S-parameters

- However, in the general case this conversion is not possible since we have no a priori information about the content of our "black box" (2-port DUT)

- In analogy to bridge measurements for impedance determination (Wheatstone bridge) there is a very similar technique for measuring S_{21} or S_{11} respectively at fixed frequency.

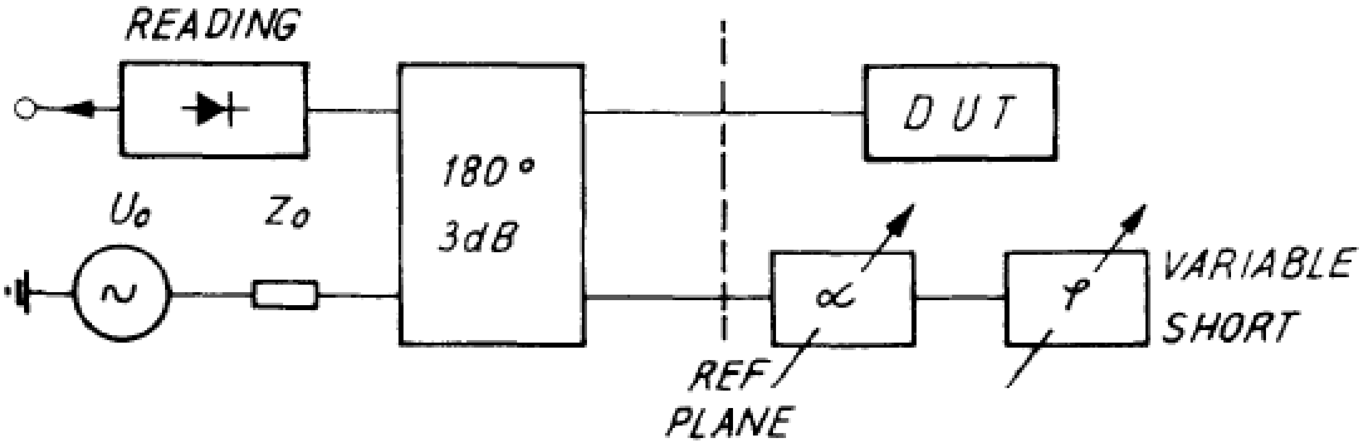
Bridge-type methods for complex S-parameters

- For the transmission measurement a calibrated attenuator and phase shifter are set such that the reading of the detector becomes minimal or zero (zero tuning). The S_{21} of the DUT then corresponds to the setting of the attenuator and the phase shifter



Bridge-type methods for complex S-parameters

- In a similar way the reflection measurement bridge measures S_{11} from a variable attenuator and a variable short:



- Certain vector volt meter based instruments use this method in an automated way for determination of S_{21} and S_{11}

Vector network analyzer

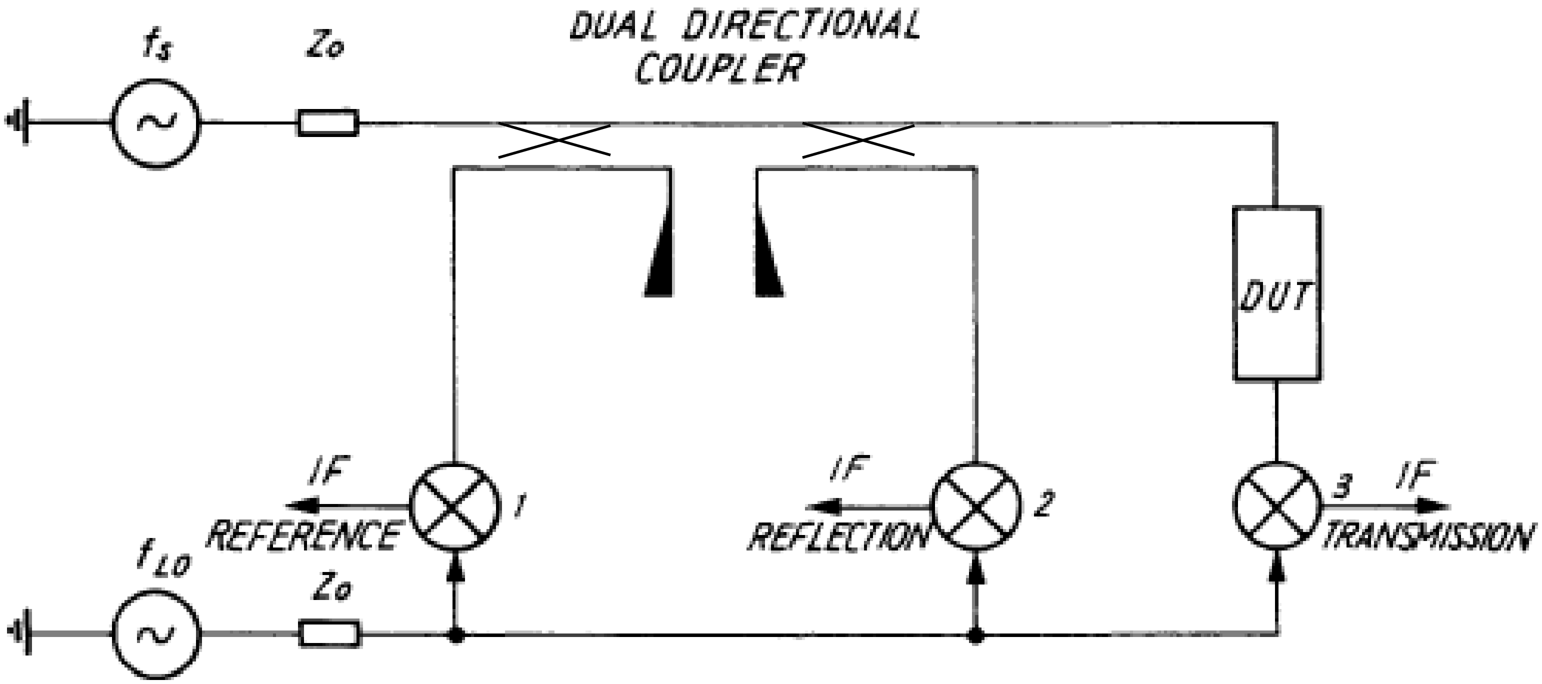
- Having discussed scalar two port measurement methods and spectrum analyzer techniques, it is just a small step to arrive at the vector network analyzer (superhet VNA)

- The VNA uses in principle two generators that are both variable in frequency but coupled via phase-locked loop circuit such that they maintain a constant difference in frequency which is exactly the intermediate frequency known from the usual superhet receiver

- This IF contains the full phase and amplitude information of the RF signal to be measured

Vector network analyzer

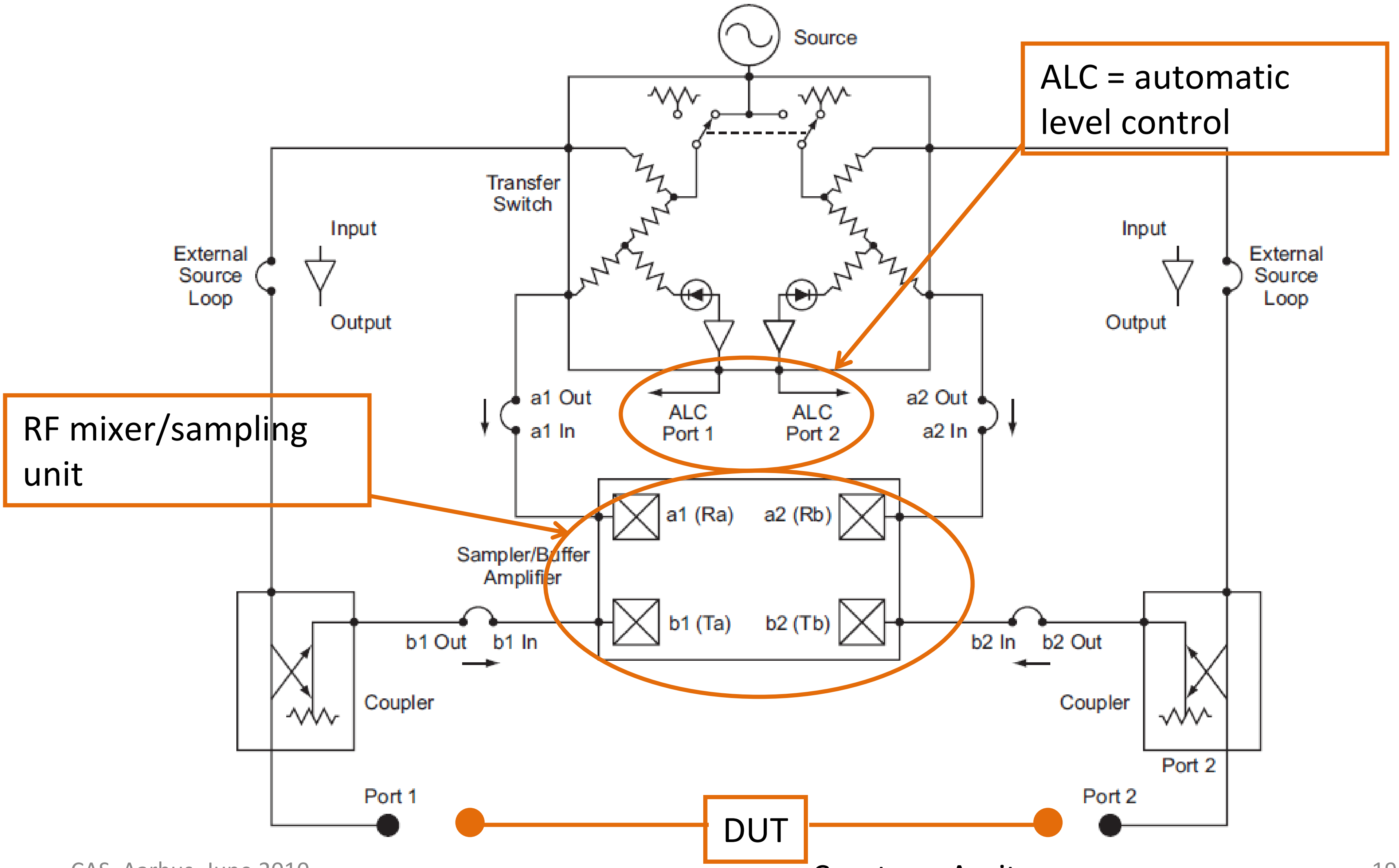
- Simplified block diagram of a vector network analyzer:



- The three mixers in the figure are characteristic of many VNA´s and are in general well matched

Vector Network Analyzer

- Block diagram of a modern 2-port VNA:



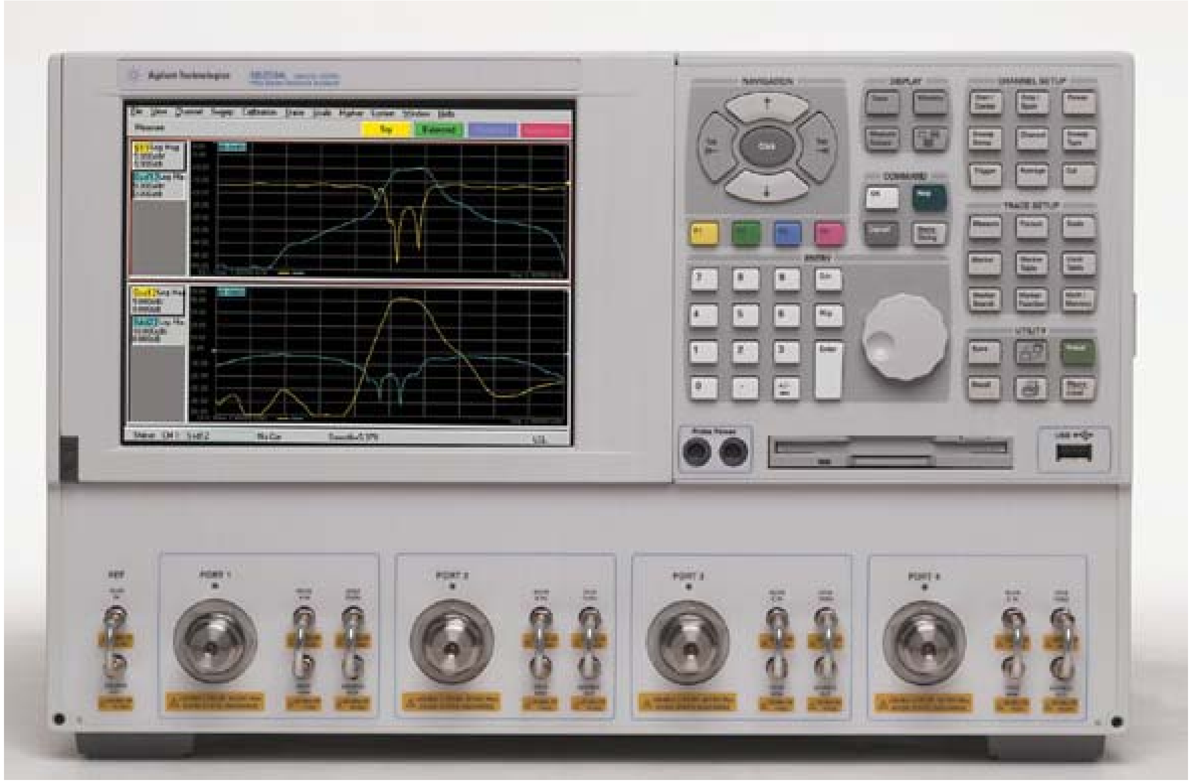
ALC = automatic level control

RF mixer/sampling unit

Courtesy: Anritsu

Vector network analyzer

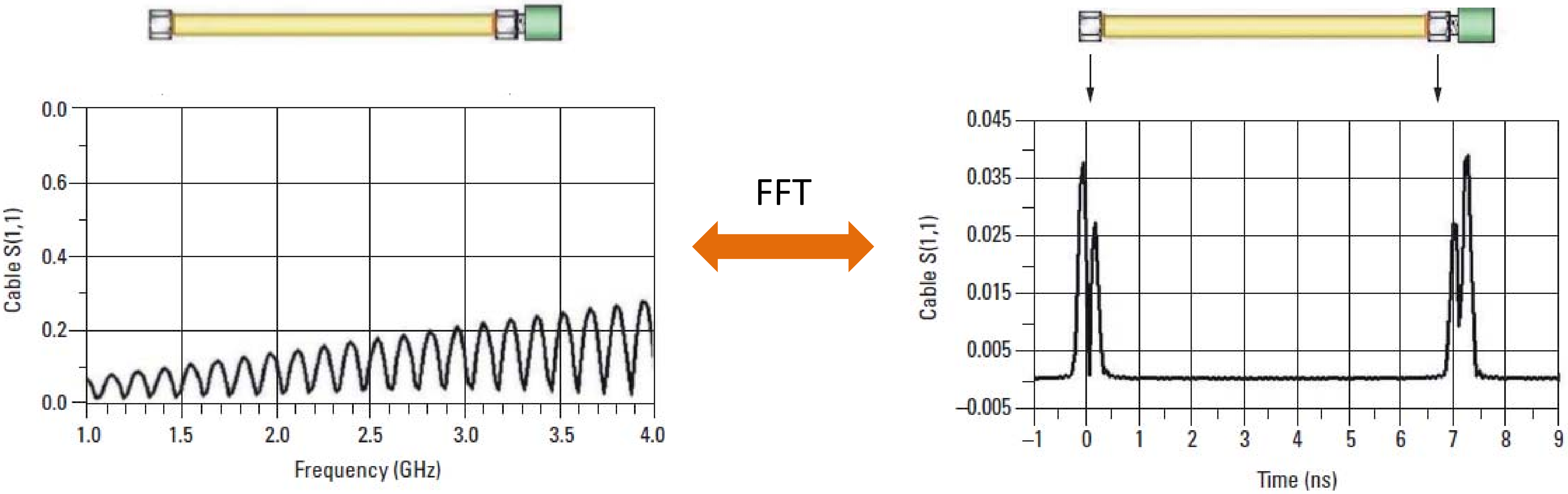
- Modern 4-port VNA:



- In principle every multiport can be analyzed with a 2-port VNA, but this is tedious and time consuming for multiports like directional couplers or circulators.

Time domain transform

- The VNA delivers complex data in the frequency domain. These data can be converted to time domain via FFT and vice versa:



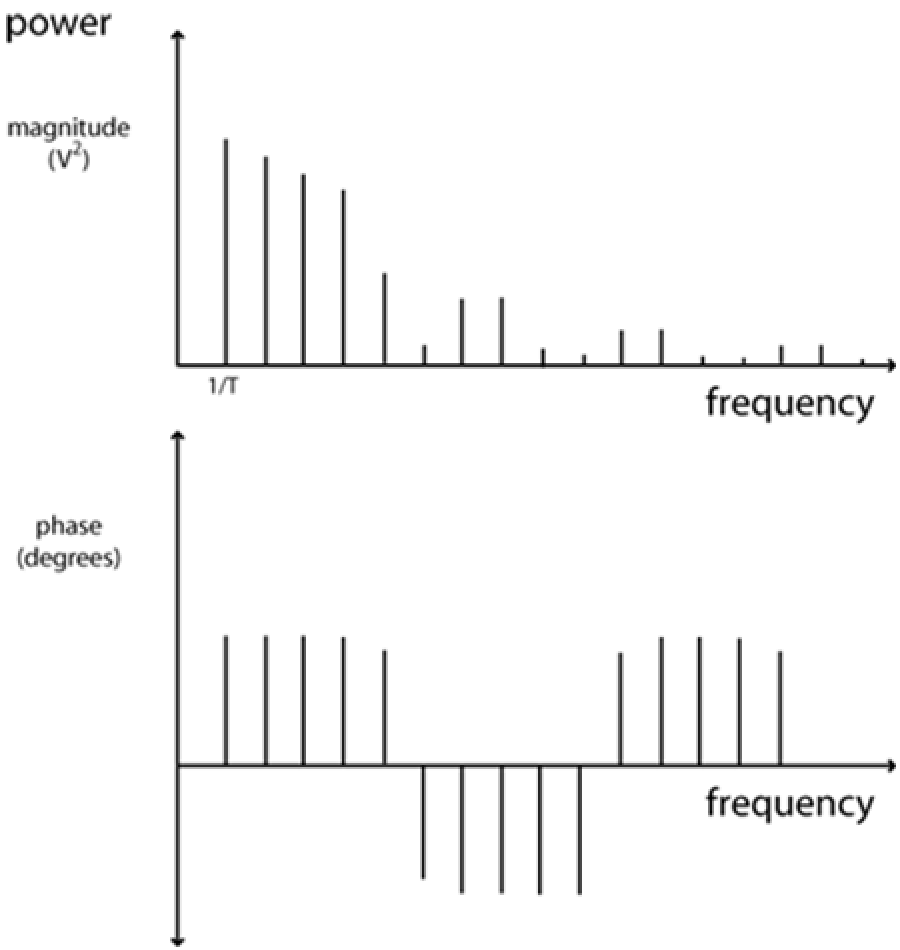
- The method is always applicable for linear and time invariant networks

Time domain

- When using the time domain option of the vector-network-analyser we have two basic modes available:
  - The "low-pass" mode and
  - The "band-pass" mode
- We will briefly discuss both of these modes in the following

Time domain: low pass mode

- The low-pass mode can only be used for equidistant sampling in the frequency domain (equidistant with respect to DC), since the Fourier Transform of a repetitive sequence of pulses has a line spectrum with equidistant spacing of the lines including the frequency zero

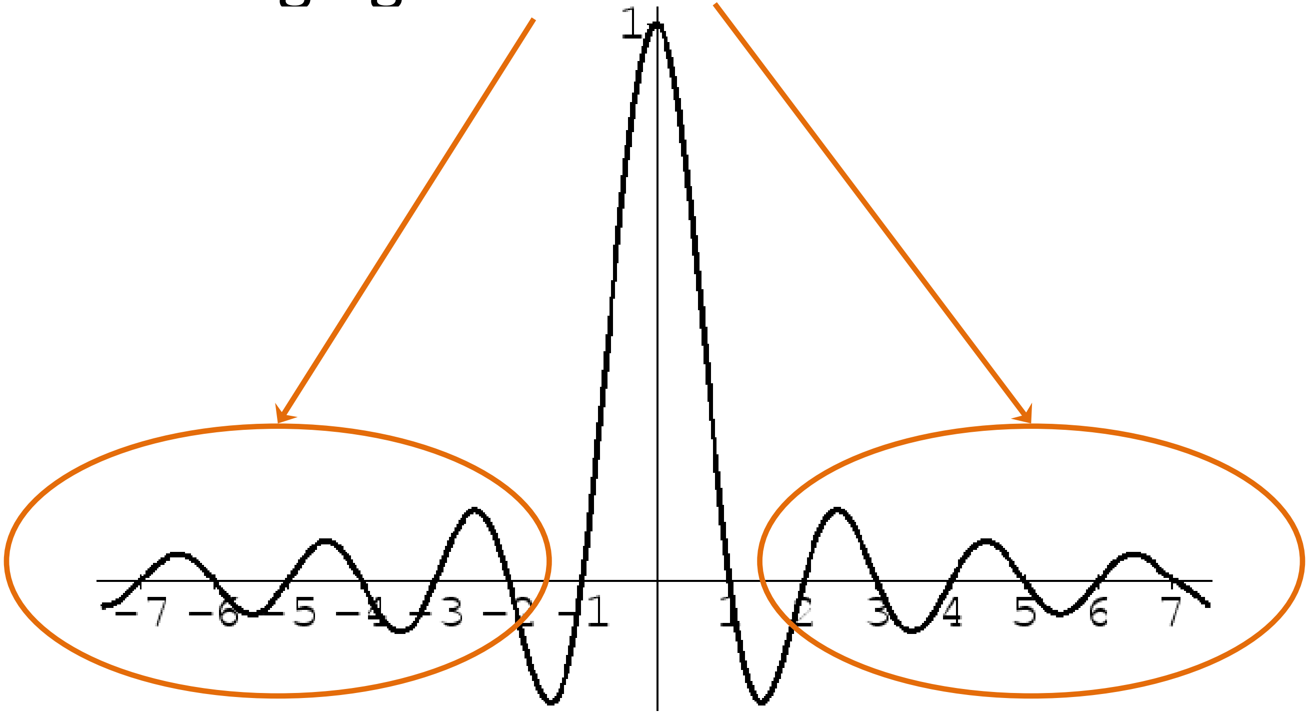


Time domain: low pass mode

- This implies that for a given frequency range and number of data points the instrument must first work out the exact frequencies for the low-pass-mode (done by using the soft-key: set frequency Low-pass).
- Once these frequencies are defined, calibration (open, short, load for S_{11} and S_{22}) can be applied. For a linear time-invariant system frequency and time domain measurements are basically completely equivalent (except for signal to noise ratio issues) and may be translated mutually via the Fourier transform.

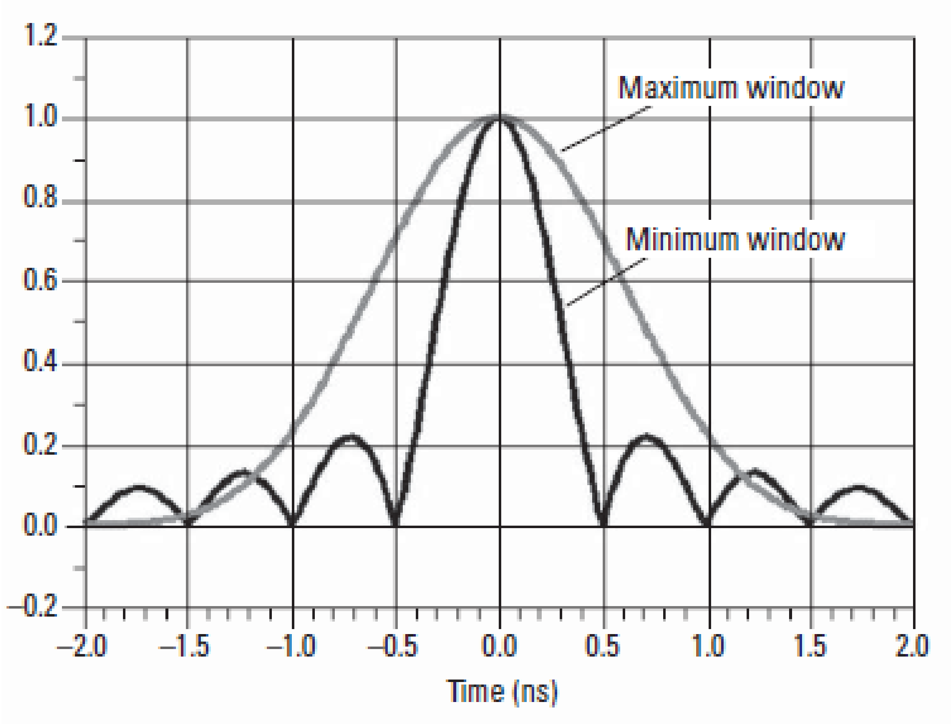
Time domain: weighting function

- Note that the Fourier transform of a spectrum with constant density over a given frequency range (rectangular spectrum) has a $\sin(t)/t_0$ characteristic in the time domain. This characteristic generates undesired ringing ="side-lobes":



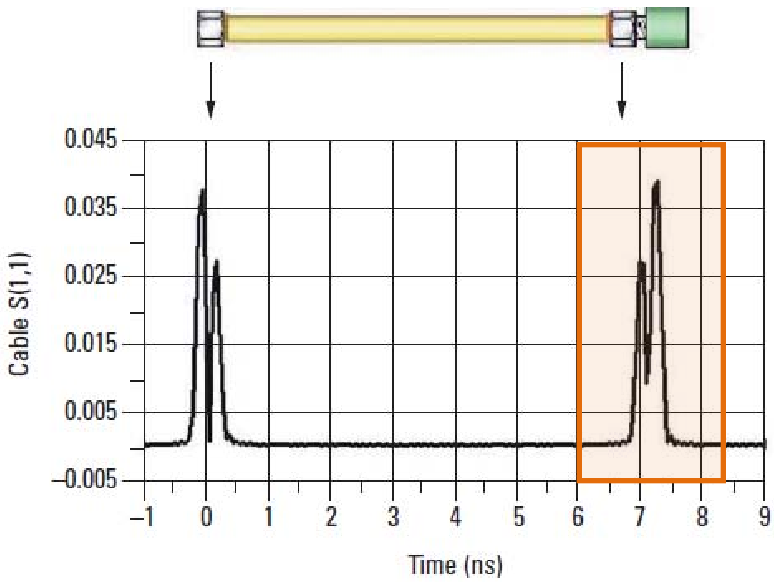
Time domain: weighting function

- Thus an (amplitude) weighting function (=window) is applied in the frequency domain before entering the FFT.
- This weighting function is typically sin^2 or Gaussian and helps to suppress strongly side-lobes in the time-domain:



Time domain: gating

- Coming back to the example shown before:



- If we are interested in the spectral content of the second peak only, we can apply a time domain gate on this pulse (=part of the signal) and return to the frequency domain applying again the FFT.

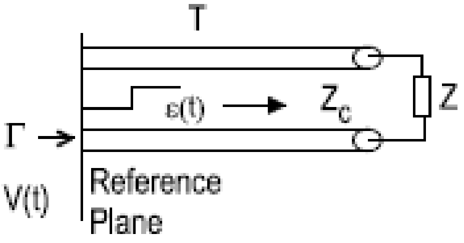
Time domain

- When using the weighting and gating functions, keep in mind that

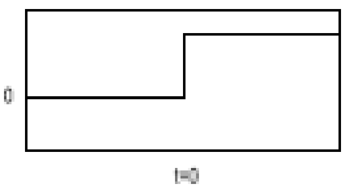
1. The application of the weighting function (window)
2. Gating is a non-linear operation and thus gating may generate artificially frequency components which were not present before gating

Time domain: S_{11} examples

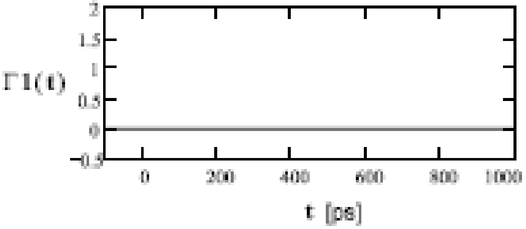
- Example of application of the synthetic pulse methode for S_{11} measurements with a



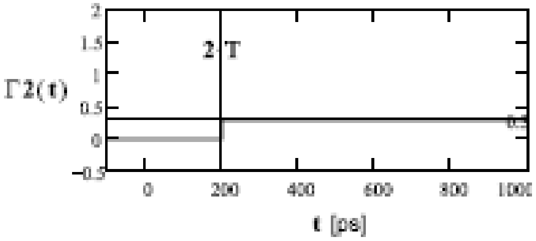
ε(t)= unity step function



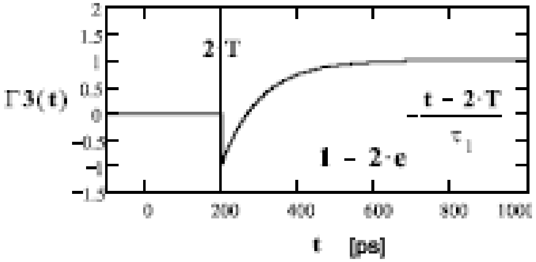
$Z = Z_c \qquad \Gamma(t) = 0$



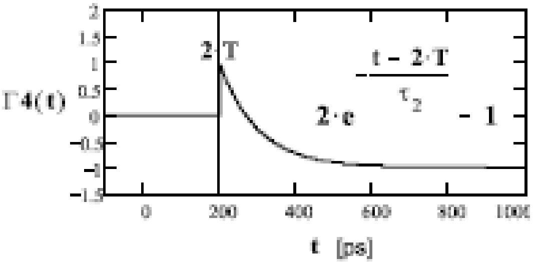
$Z = 2\cdot Z_c \qquad \Gamma = \dfrac{Z - Z_c}{Z + Z_c} = \dfrac{1}{3}$



$Z = \dfrac{1}{j\cdot\omega\cdot C} \qquad \tau_1 = Z_c\cdot C$



$Z = j\cdot\omega\cdot L \qquad \tau_2 = \dfrac{L}{Z_c}$



Within the low-pass mode we can use the pulse and step function respectively. The step function is nothing else than the integral over the pulse response.

Time domain: band pass mode

- In the band-pass mode the spectral lines (frequency domain data points) need no longer be equidistant to DC but just within the frequency range of interest.
- The corresponding time-domain response for the same bandwidth is twice as long as in the low-pass mode and we get in general complex signals in the time domain.
- These complex signals are equivalent to the I and Q signals (I = in phase and Q = quadrature) often found in complex mixer terminology.

Time domain: band pass mode

- The real part is equivalent to what one would see on a fast scope i.e. an RF signal with a Gaussian envelope.
- The meaning of the time-domain band-pass mode response in linear magnitude format is the "modulus of the complex envelope [sqrt($re^2(t)$+$imag^2(t)$)] of a carrier modulated signal".
- Note that the time domain mode can also be applied for CW excitation from the VNA but then to analyse a slowly time variant response of the DUT (up to the maximum IF bandwidth of, say 3 KHz).

Synthetic pulse/real pulse comparison

- A VNA in the time-domain low-pass step mode has a very similar range of applications as a sampling scope.
- The dynamic range of a typical sampling scope is limited to about 60 dB with a maximum input signal of 1 Volt and a noise floor around 1 mV.
- The NVA can easily go beyond 100 dB for the same maximum level of the input signal of about +10 dBm.

Synthetic pulse/real pulse comparison

- Both instruments are using basically the same kind of detector, either a balanced mixer (4 diodes) or the sampling head (2 or 4 diodes), but the essential difference is the noise floor and the average power arriving at the receiver.

- In the case of the VNA we have a CW signal with bandwidth of a few Hz and thus can obtain with appropriate filtering a very good signal to noise ratio since the thermal noise floor is a –174 dBm/Hz.

Synthetic pulse/real pulse comparison

- For the sampling scope we get a short pulse with a rather low repetition rate (typically around 100 kHz) and all the energy is spread over the full frequency range (typically 20 to 50 GHz bandwidth).
- With this low average power (around a micro-Watt) the spectral density is orders of magnitude lower than in the case of the VNA and this finally makes the large difference in dynamic range (even without gain switching).
- Also the VNA permits in the band-pass mode to tailor a wide range of band-limited RF-pulses, which would be very tedious with a sampling scope.

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Calibration

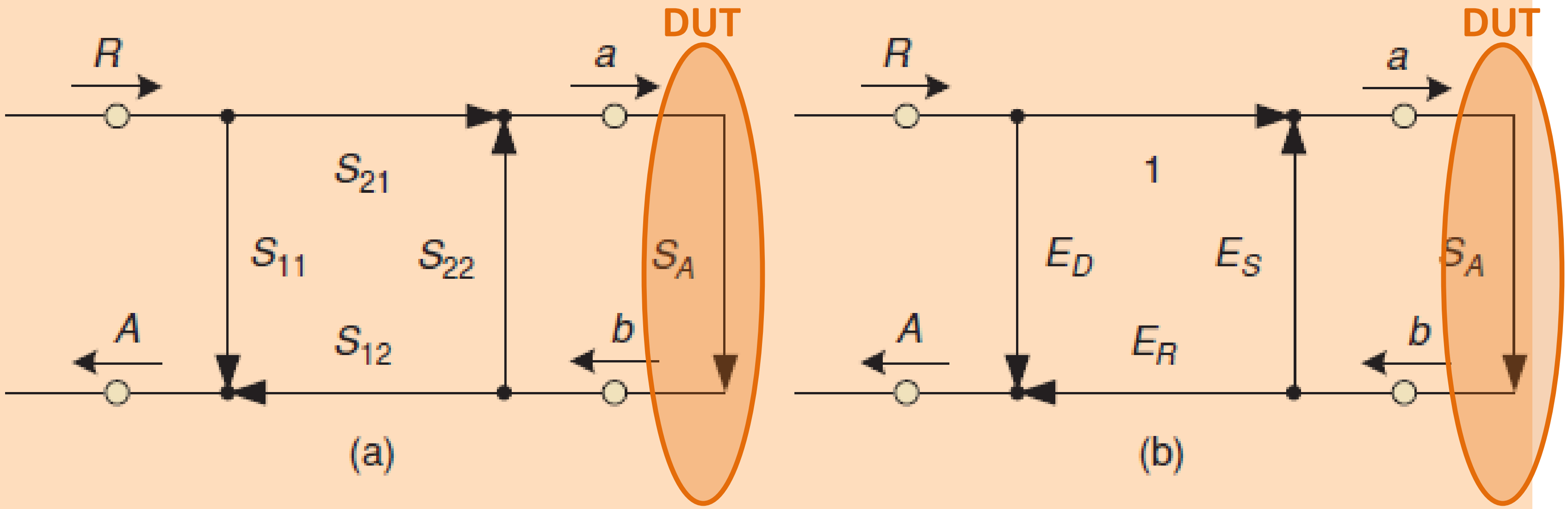
- Even a modern VNA is not perfect. There are residual errors from
  - Source mismatch
  - Finite directivity of the internal directional couplers
  - Unavoidable losses in the connecting cables from the VNA to the DUT
- All these three error terms are in general complex and frequency dependent
- These three error terms can be represented by an S-matrix error model with three independent parameters ($S_{21} = S_{12}$)

Calibration

- Although they cannot be eliminated, their degrading effect on the precision of the measurement can be mitigated by a “calibration procedure”
- This is done e.g. for an S_{11} measurement by connecting three calibration standards (open, short load) at the end of the test cables
- These calibration standards (calibration kit) themselves are electrically very good, but not perfect either. However, their frequency dependent electromagnetic properties are well defined, precisely known and saved in the electronic memory of the VNA.

Calibration

- An example for three term error correction:



The relationship between the actual S_A and the measured S_M=A/R S-parameter of the DUT is given by

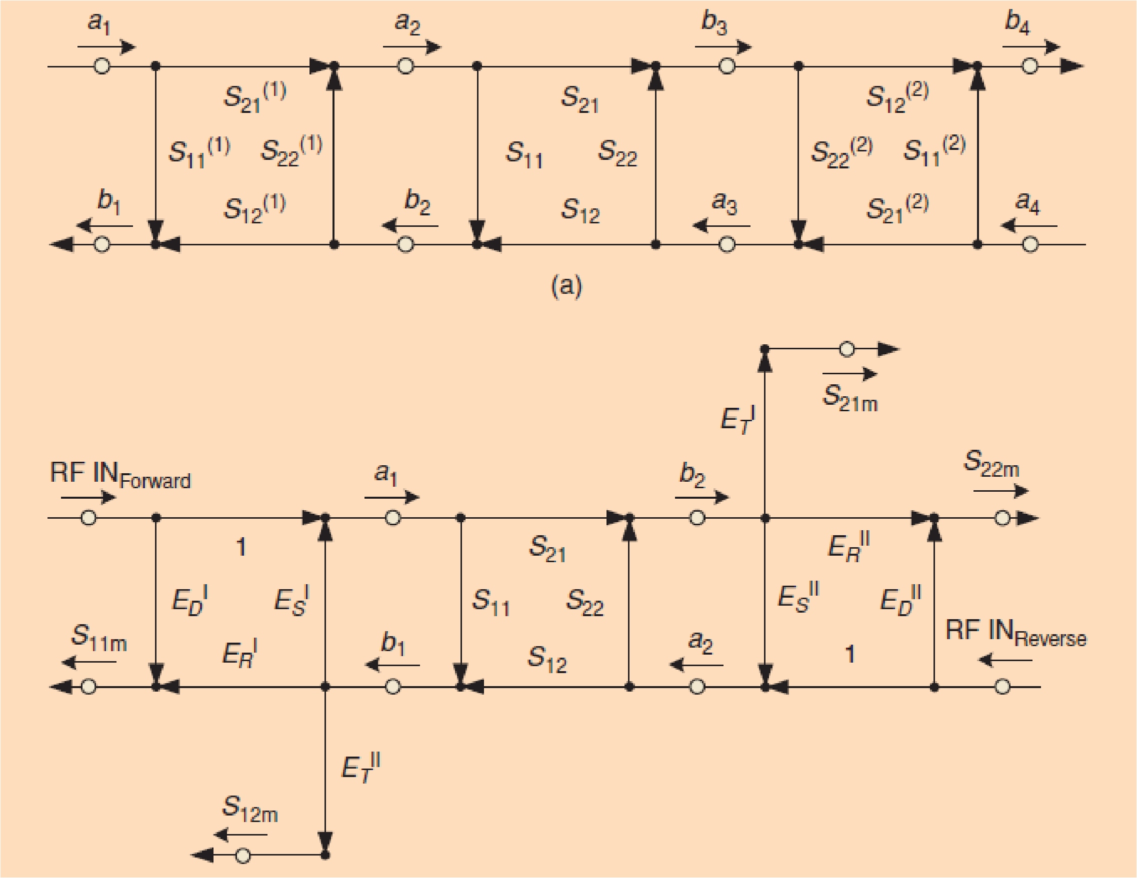
$$S_{11A} = \frac{S_{11M} - E_D}{E_S\,(S_{11M} - E_D) + E_R}$$

E_D=directivity
E_S=source match
E_R=cable losses + match

Courtesy: A. Rumiantsev, N. Ridler, VNA callibration, IEEE microwave magazine, June 2008

Calibration

- For a full 2-port calibration we need eight calibration measurements in order to satisfy the requirements for an eight term error model:



Courtesy: A. Rumiantsev, N. Ridler, VNA callibration, IEEE microwave magazine, June 2008

Calibration

- The manual connection and de-connection of the calibration standards already for a full 2-port calibration is time consuming and can be boring
- The situation is even worse when doing a full 4-port calibration (32 (!) connections and de-connections of standards)
- For this reason, the electronic calibration kit has been invented and became very popular
- In this case, each port is connected via cable to the electronic calibration box
- With this method, a full 4-port calibration takes less than a minute

Calibration

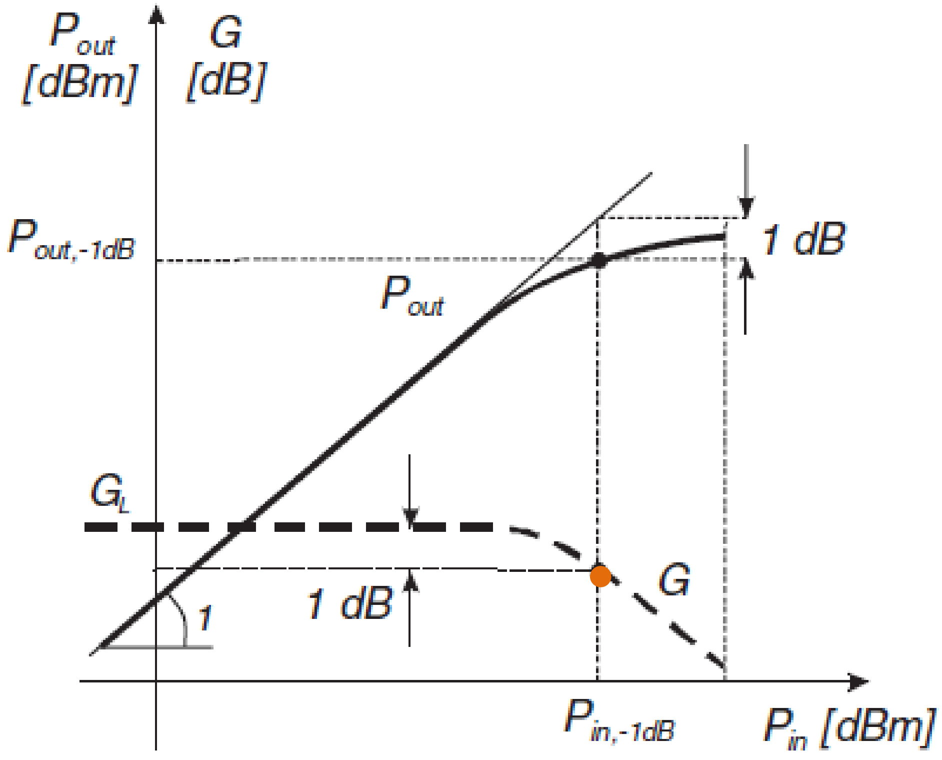
- And it looks like this...

Mechanical cal-kit

Electronic cal-kit

Nonlinear analysis

- Power sweep for finding the 1dB compression point of an amplifier:
- At a fixed frequency the generator power is linearly increased over a defined range
- The 1dB compression point is then defined as the reduction of small signal gain by 1 dB

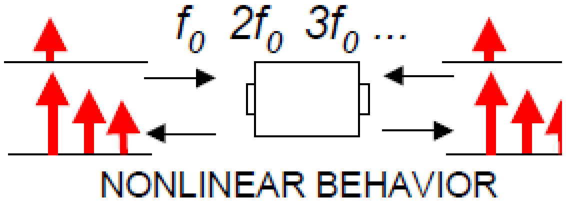


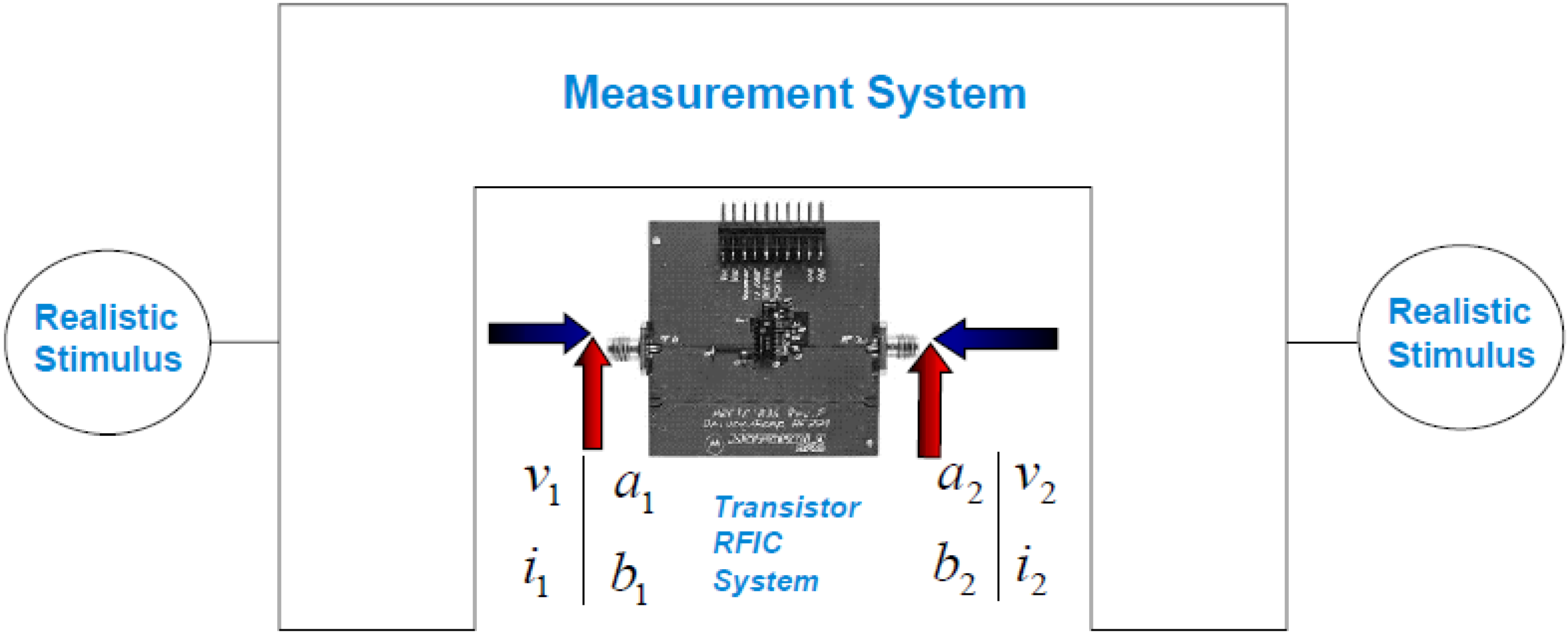
Nonlinear analysis

- The classical S-parameters are defined for linear and time invariant networks only
- X-parameters® represent a new category of nonlinear network parameters for high-frequency design.
- They characterize the amplitudes and relative phase of harmonics generated by components under large input power levels at all ports.
- Correctly characterize impedance mismatches and frequency mixing behavior to allow accurate simulation of cascaded nonlinear X-parameter blocks, such as amplifiers and mixers.

Further information: J. Verspecht ,Large-Signal Network Analysis,*IEEE Microwave Magazine* **6** (4): 82–92. 2009.

A Large-Signal Network Analyzer





- **Representation Domain**
  - Frequency (f)
  - Time (t)
  - Freq - time (envelope)

- **Physical Quantity Sets**
  - Travelling Waves (A, B)
  - Voltage/Current (V, I)

- **Analysis**

$$g\left(v_1, v_2, i_1, i_2, t \mid f\right)$$

$$h\left(v_1, v_2, i_1, i_2, t \mid f\right)$$

Characterization

Summary

- Network analyzer technology has gone through an impressive evolution over the last 40 years
- The availability of cheap computer power has permitted sophisticated controls and calibration functions
- Vector network analyzers are nowadays available up to 300 GHz (with external frequency converter units)
- Scalar network analyzers can reach about 1 THz
- For lower frequencies scalar network analyzers are a lower cost and moderate performance alternative to VNA's
- Often Spectrum- and VNA-functions are combined in a single unit