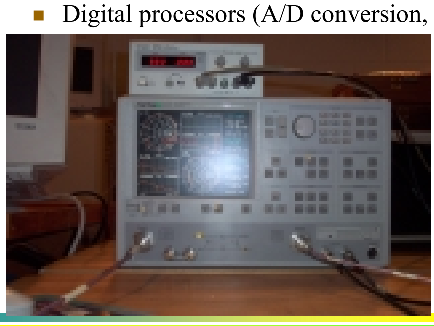
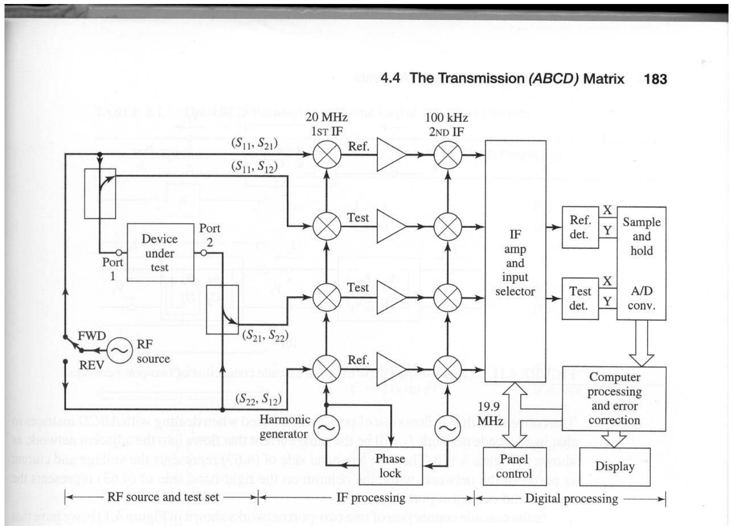
RF/Microwave Circuits I

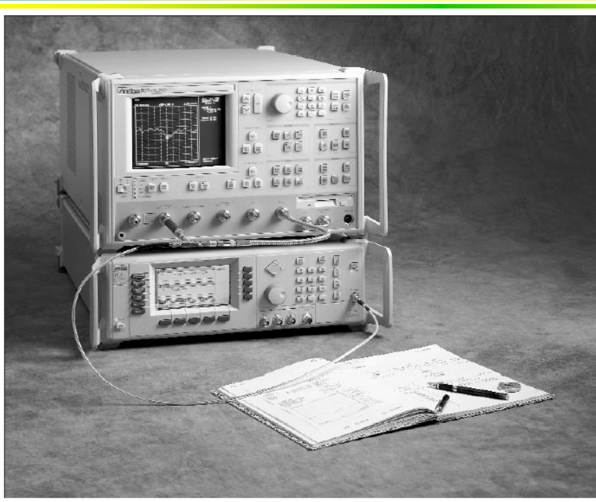
VNA Calibration
Fall 2007

VNA & Calibration

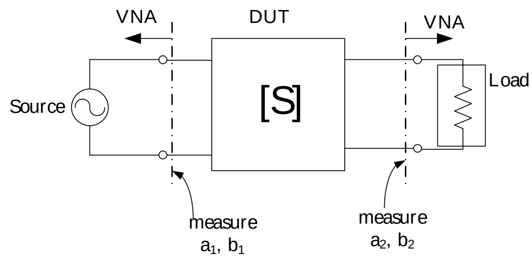
- Vector Network Analyzer → Measures amplitude and phase of
  - Reference, reflected, and transmitted signal to find [S]
- Basic Components of VNA
  - Synthesized swept signal RF source
  - Test set (signal routing from/to source, DUT, and internal IF circuitry)
  - IF circuitry (down convert RF to IF, e.g., 100KHz) (page 183, 3rd edition)
  - Digital processors (A/D conversion, amp & phase measurements, etc)





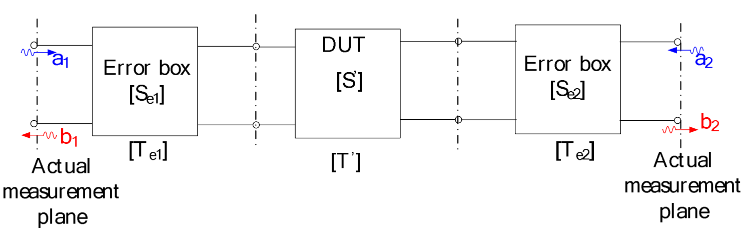


From Anritsu



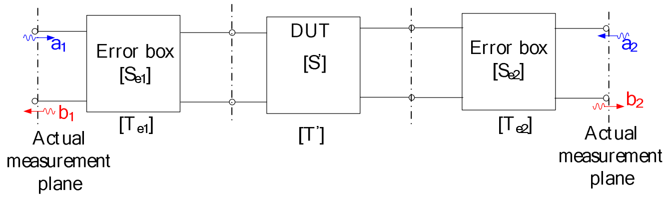
- In reality, there is much hardware within VNA that affects a_1, b_1, etc
- Measurements are determined after IF and digital processing
- ∴ To determine [S] of the DUT, we need information about signals at DUT ports → have to calibrate/remove all VNA effects

- First step: Determine how to represent these complex VNA effects. This is "error modeling"



- [S] → scattering matrix
- [T] → transmission matrix (e.g., [ABCD])
- Error box – networks that include internal VNA effects (couplers, switches, IF and DSP circuits, etc) and possibly external cables etc
  - different "error models" have different "error boxes"

- Second Step: Determine values for error box parameters (i.e., [S_{e1}], [S_{e2}] or [T_{e1}], [T_{e2}]).
  - Determining the error box parameters is called "calibration"



$$[T_m] = [T_{e1}][T^{'}][T_{e2}]$$

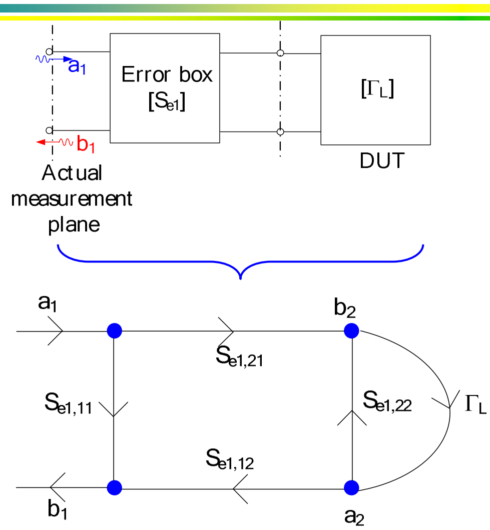
This what we measure (or raw-measured data)

Error corrected or "calibrated data"

$$[T^{'}] = [T_{e1}]^{-1}[T_m][T_{e2}]^{-1}$$

Determined when calibration is performed

A SIMPLE 1-PORT MEASUREMENT



$$S_{11}^{'} = S_{11,e1} + \frac{S_{21,e1}\Gamma_L S_{12,e1}}{1 - S_{22,e1}\Gamma_L}$$

Goal: Find $[S_{e1}]$ (i.e., "calibrate" the system)

- You can select different Γ_L (cal stds) and measure S_{11}

- How?

(i) choose $\Gamma_L = 0$ (use match load)

then $S_{11}' = S_{e1,11}$

$$S_{11}' = S_{11,e1} + \frac{S_{21,e1}\Gamma_L S_{12,e1}}{1 - S_{22,e1}\Gamma_L}$$

(ii)

$$\left(1 - \Gamma_L S_{e1,22}\right)\left(S_{11}' - S_{e1,11}\right) = \left(S_{e1,21}\right)\left(\Gamma_L\right)\left(S_{e1,12}\right)$$

$$U_1 \bullet K = U_2$$

U = unknown

K= known

1-port calibration (cont'd)

(iii)

choose 2 more known Γ_L's (e.g., Γ_L = 1 (*open*) and -1 (*short*))

$\Rightarrow$ find U_1 and U_2 (2 equations and 2 unknowns)

(iv)

once U_1 is known, find $S_{e1,22}$

(v)

also know $\left(S_{e1,21} \cdot S_{e1,12}\right) \Rightarrow$ you only need to know the product

Now that you know $[S_{e1}]$

$$\Gamma_L = \frac{\left(S_{11}' - S_{e1,11}\right)}{\left(S_{e1,21} - S_{e1,12}\right) + S_{e1,22}\left(S_{11}' - S_{e1,11}\right)}$$

Commonly Used Calibration Methods

1. OSL (can be used only for 1-port calibration)
   - Open, Short, Load
2. OSLT (2-port calibration)
   - Open, Short, Load, Thru
     - Thru is a section of matched transmission line
3. LRM
   - Thru Line, Reflect, Matched load
     - Reflect can be open or short
4. TRL
   - Thru line, Reflect, delay Line

Commonly Used Calibration Methods

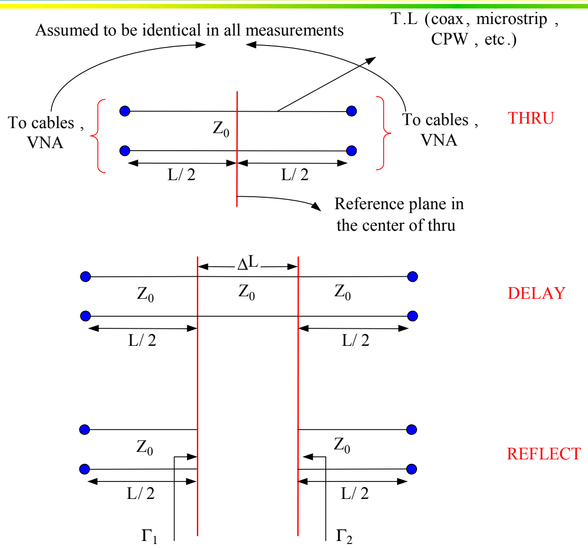
- For many calibration methods, precise knowledge of the standards (e.g., the Γ for the short) must be known
  - It won't be exactly -1!

TRL Calibration

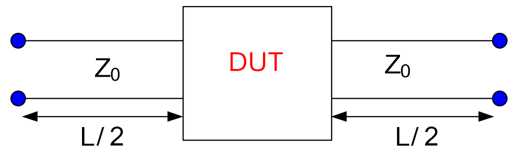
- Used for planar circuits (e.g., microstrip) this is the most accurate approach, especially at mm-wave frequencies
- Does not require perfect (or well known) matched loads, opens, or sorts (other methods do require) ⇒ TRL is known as "self-calibrating"

- **How to construct TRL calibration lines for measuring a DUT…**

TRL Calibration



TO MEASURE DUT



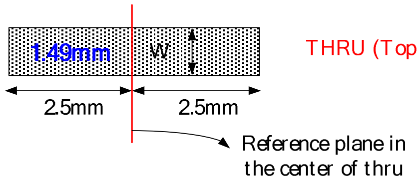
DESIGN RULES

- Z_0 must be identical for all standards and DUT
- Theoretically, any $L > 0$ is acceptable
- Ideally, $\Delta L = 90°$ at center frequency
  - Calibration is typically valid from f_1 to f_2, when
  - f_1 when $\Delta L = 20°$
  - f_2 when $\Delta L = 160°$
- Reflect standards do not have to be perfect opens or shorts, but Γ_1 has to be identical to Γ_2
- Z_0 does not have to be 50Ω, but its value does serve as the reference impedance for the calculated [S] matrix

DESIGN TRL STD's FROM 1-6GHz AND MEASURE A CHIP CAPACITOR

- We need to know the following:
  - Capacitor size, substrate properties on which capacitor will be mounted/measured, what kind of TL (microstrip, CPW, etc)
  - Frequency range
- Capacitor dimensions from the manufacturer data sheet is
  - 2mm × 1.2mm
  - Given that the substrate is 31-mil FR-4 (ε_r=4.27)
- Choose a value of "L", this is the length of "thru". There is no equation for choosing L
  - Let's say L=5mm

CALCULATIONS



THRU (Top View)

Use equation 3.197 to calculate W that will give Z_0=50Ω

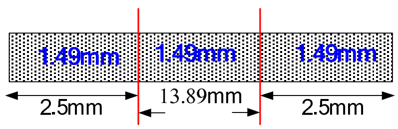
W from 3.197 is 1.49mm

We want the length ΔL = 90° at 3GHz (center frequency)

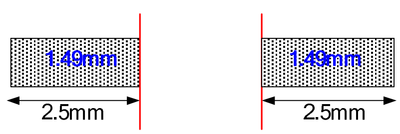
$$\lambda = \frac{V_{ph}}{f} = \frac{c}{\sqrt{\varepsilon_{eff}}\, f}$$

Use 3.195 for calculating ε_{eff}

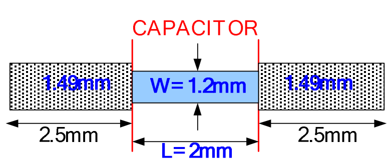
ΔL= 13.89mm



DELAY

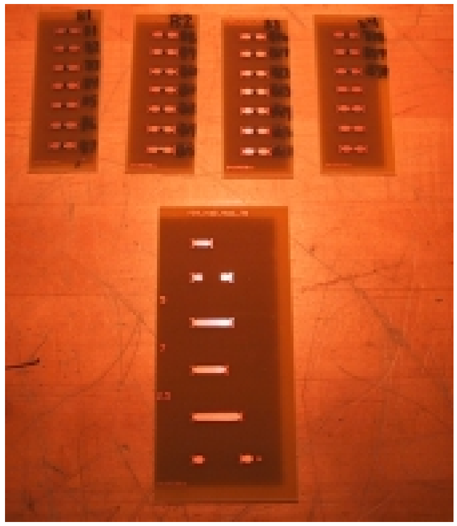


REFLECT



DUT

TRL Standards and Test Fixtures



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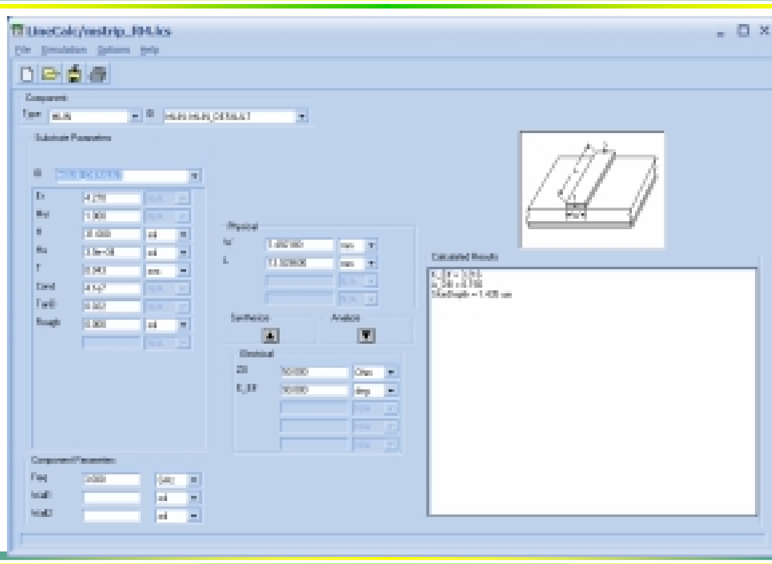
LineCalc



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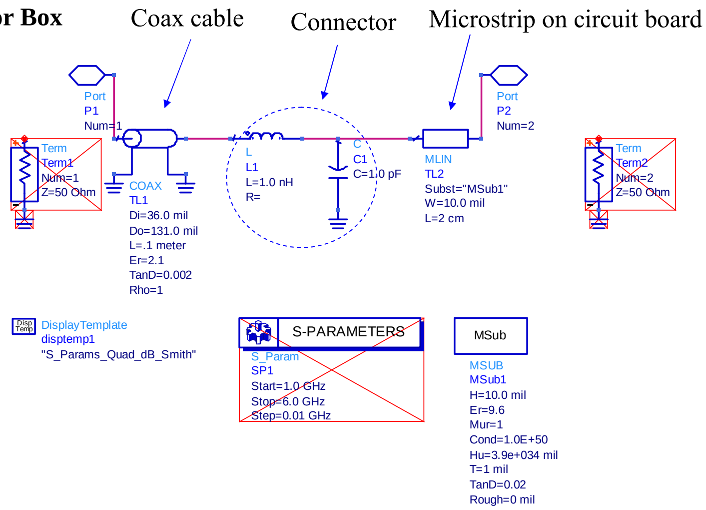
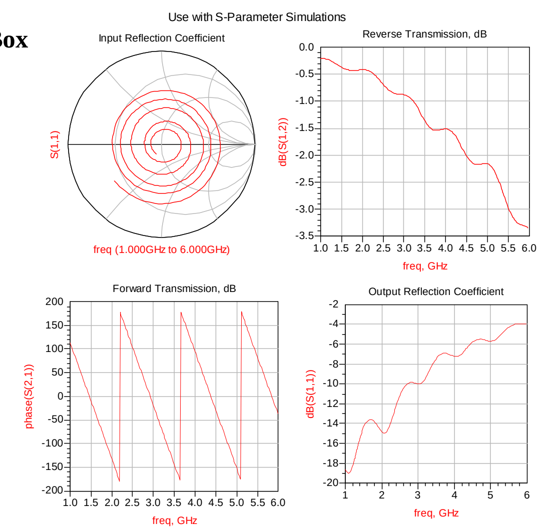
De-Embedding Example

Hypothetical Error Box

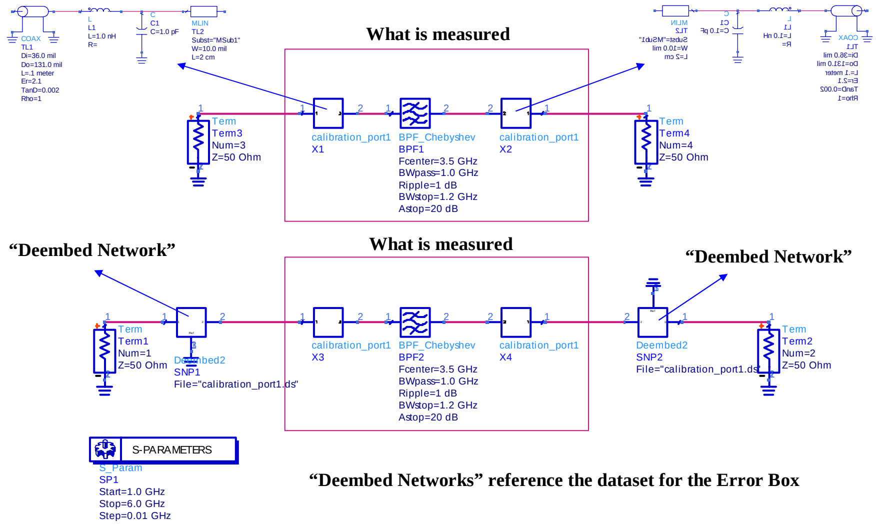


De-Embedding Example

S-parameters for the Error Box



De-Embedding Example



"Deembed Networks" reference the dataset for the Error Box

De-Embedding Example

BLUE – Measured Data

RED – Deembedded Data