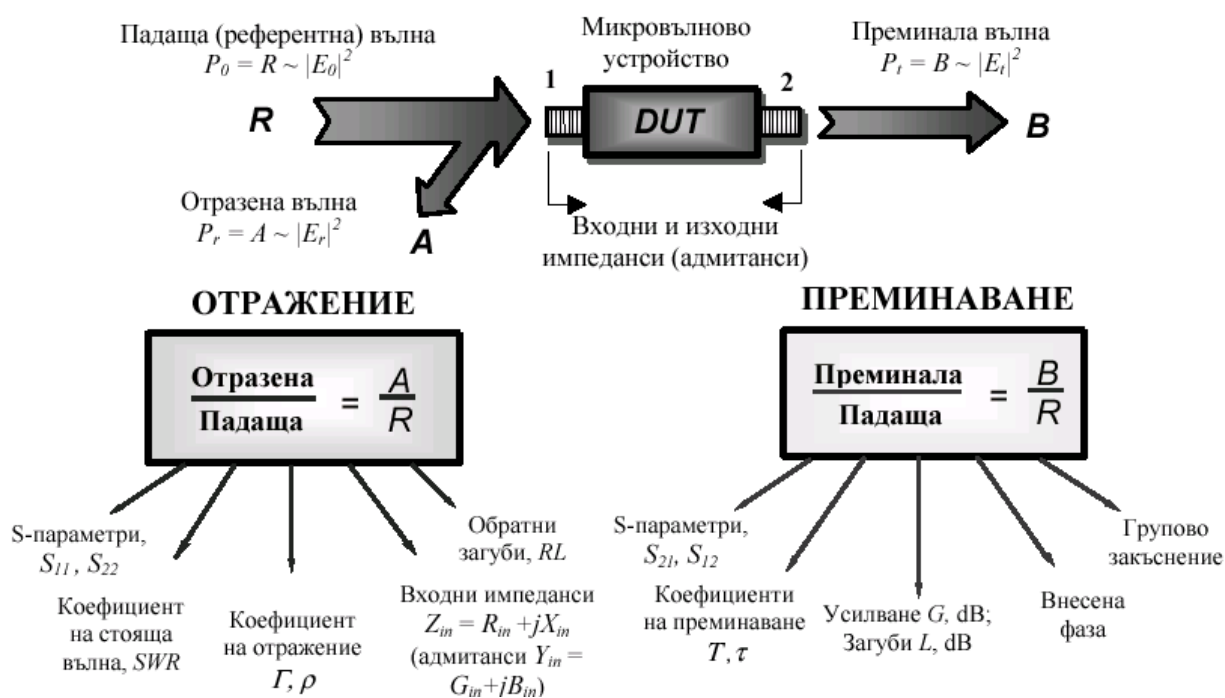


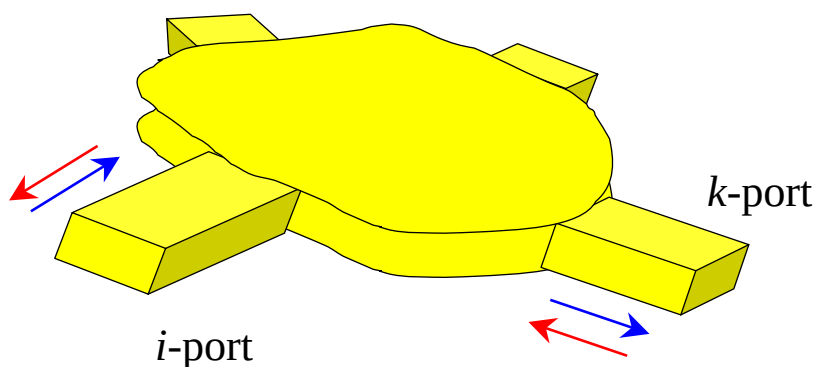
Магистърски курс "МИКРОВЪЛНОВИ ИЗМЕРВАНИЯ"

Тема 5: Измерване на S-параметри на устройства

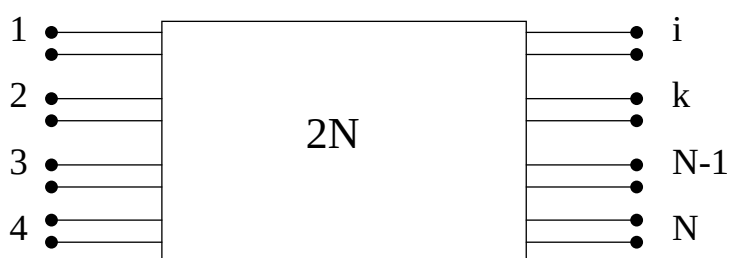
Микровълново устройство и неговите важни параметри



S-параметри на микровълнови устройства



Микровълново устройство с N входа (рамена, ports)



еквивалентно на
 $\Rightarrow 2N$ - ПОЛЮСНИК

S матрица (матрица на разсейване)

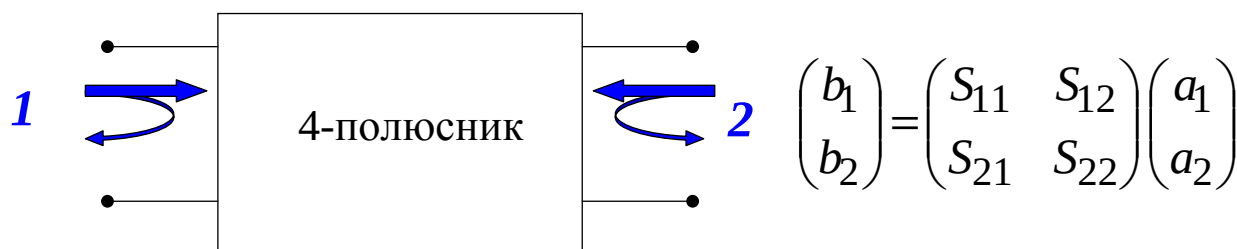
$$\hat{\mathbf{b}} = \hat{\mathbf{S}} \hat{\mathbf{a}}$$

$$b_i = S_{ik} a_k$$

$$\begin{pmatrix} b_1 \\ b_2 \\ \vdots \\ b_N \end{pmatrix} = \begin{pmatrix} S_{11} & \cdots & S_{1N} \\ \vdots & & \vdots \\ S_{N1} & \cdots & S_{NN} \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \\ \vdots \\ a_N \end{pmatrix}$$

$$\frac{1}{2}|a_i|^2 = (P_{in})_i ; \quad \frac{1}{2}|b_i|^2 = (P_r)_i$$

За 2-раменно устройство (4-полюсник):



Физичен смисъл на S параметрите на многополюсници

$$S_{ik} = |S_{ik}| e^{-j\varphi_{ik}}$$

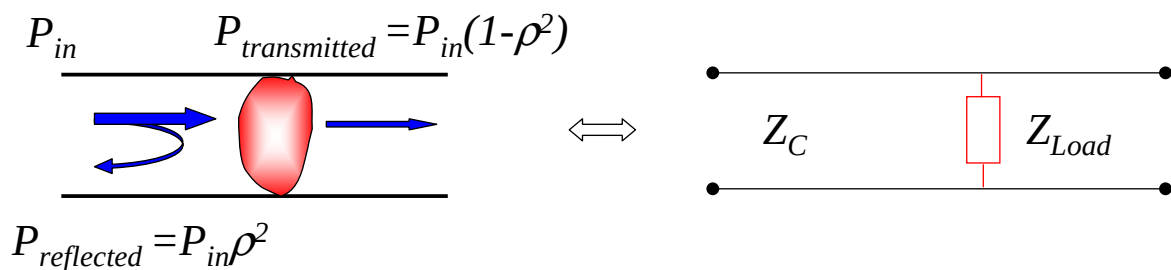
Модули: $|S_{ii}| = \frac{|b_i|}{|a_i|} = \Gamma_i$ - коефициент на отражение в i-тото рамо

$|S_{ik}| = \frac{|b_i|}{|a_k|} = T_{ik}$ - коефициент на преминаване от k-тото в i-тото рамо

Фази: $\varphi_{ik} = (\varphi_0)_{ik} + \beta_k l_k + \beta_i l_i$

- собственото фазово отместване на устройството и електрическите дължини на входното и изходното рамо до референтните равнини, където се дефинират S-параметрите

Коефициенти на отражение и стояща вълна



$$\Gamma(0) = \frac{Z_L - Z_C}{Z_L + Z_C}$$

$$|\Gamma| = \rho = \frac{SWR - 1}{SWR + 1} \in (0, 1); \quad SWR = \frac{1 + \rho}{1 - \rho} \in (1, \infty)$$

Γ - комплексен кофициент на отражение, ρ - модул на Γ

SWR - коефициент на стояща вълна;

Z_{Load} - товарен импеданс; Z_C - характеристичен импеданс

Примери:

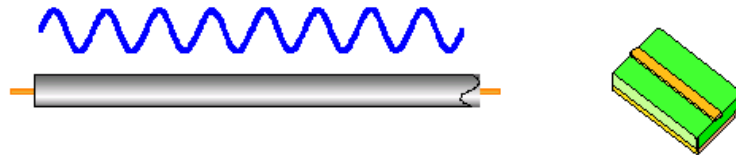
Low frequencies

- Wavelength $\gg$ wire length
- Current (I) travels down wires easily for efficient power transmission
- Voltage and current not dependent on position



High frequencies

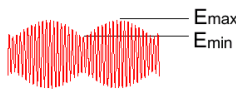
- Wavelength $\approx$ or $\ll$ wire (transmission line) length
- Need transmission-line structures for efficient power transmission
- Matching to characteristic impedance (Z_0) is very important for low reflection
- Voltage dependent on position along line



Примери:

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

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

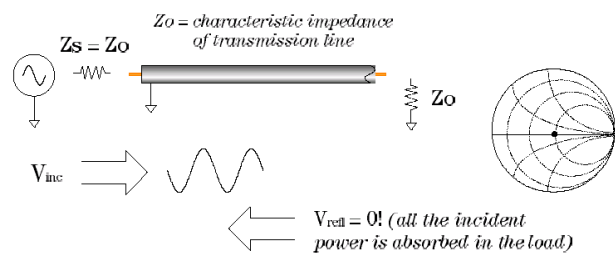


Voltage Standing Wave Ratio
 $\text{VSWR} = \frac{E_{\text{max}}}{E_{\text{min}}} = \frac{1 + \rho}{1 - \rho}$

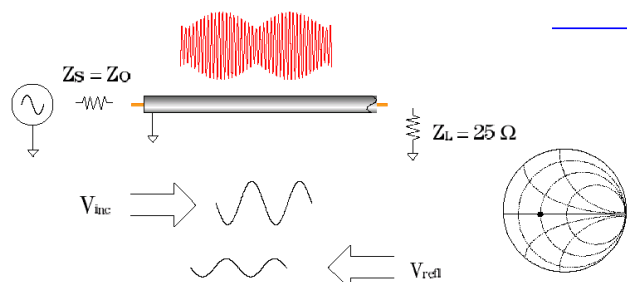
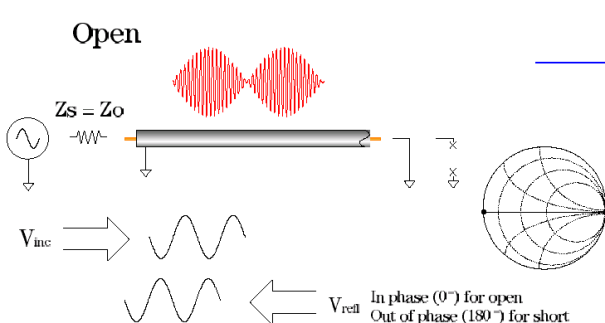
No reflection
 $(Z_L = Z_0)$

0	ρ	1
∞ dB	RL	0 dB
1	VSWR	∞

Full reflection
 $(Z_L = \text{open, short})$



Open



S параметри в dB

- Обратни загуби **RL, dB**:

$$(RL)_i = 20 \cdot \lg |S_{ii}| = 20 \cdot \lg(\rho_i) = 10 \cdot \lg \frac{(P_r)_i}{(P_{in})_i}$$

- Загуби на преминаване **L, dB**:

$$(L)_{ik} = 20 \cdot \lg |S_{ik}| = 20 \cdot \lg(T_{ik}) = 10 \cdot \lg \frac{(P_t)_i}{(P_{in})_k}$$

- Загуби от разсъгласуване **ML, dB**:

$$(ML)_{kk} = 20 \cdot \lg(1 - \rho_k^2)$$

- Внесени загуби **IL, dB**:

$$(IL)_{ik} = (L)_{ik} - (ML)_{kk} \cong (L)_{ik}$$

SWR - калкулатор

VNA Help SWR Calculator

File Match Format Help

Directivity Error Calculator

Coupler Directivity [dB]:	26	30	40	40	30	26		Min:	Max:
Reflection Coefficient:	0.35	0.40	0.45	0.45	0.40	0.35	0.414	0.378	0.452
Standing Wave Ratio:	2.0	2.2	2.4	2.6	2.8	3.0	2.414	2.216	2.651
Return Loss [dB]:	9	8	7	7	8	9	7.656	8.450	6.893
Mismatch Loss [dB]:	0.6	0.8	1.0	1.0	0.8	0.6	0.817	0.670	0.994

Mismatch Error Calculator

Source Match: Reflection Coeff.	35	0.40	0.45	0.414	Max Mismatch Error: +1.635 dB -1.375 dB
Load Match: Reflection Coeff.	35	0.40	0.45	0.414	
					Max Phase Error: +9.879° -9.879°

Voltage Ratio: 3.1623 dB: 10.000 Power Ratio: 10.000

Връзки между RL, SWR, ρ

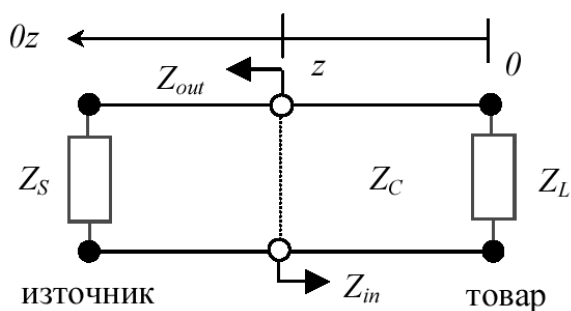
$RL, \text{ dB}$	ρ	SWR	$P_r/P_{in}, \%$	$P_t/P_{in}, \%$
-40	0.01	1.02	0.01	99.99
-20	0.1	1.21	1.0	99
-13.98	0.2	1.5	4	96
-6.02	0.5	3.0	25	75
-0.915	0.9	19.0	81	9
-0.0873	0.99	199	98	2

$$\rho = \frac{SWR - 1}{SWR + 1} \quad SWR = \frac{1 + \rho}{1 - \rho}$$

$$RL, \text{ dB} = 20 \cdot \lg \rho$$

$$P_r = P_{in} \cdot \rho^2 \quad P_t = P_{in} \cdot (1 - \rho^2)$$

Понятие за входен импеданс



• Входен (изходен) импеданс

$$Z_{in} = \frac{E(z)}{H(z)} = Z_C \frac{1 + \Gamma(z)}{1 - \Gamma(z)} = R_{in} + jX_{in}$$

$$Z_{out}(z) \cong Z_{in}^*(z)$$

характеристичен импеданс Z_C

• Товарен импеданс

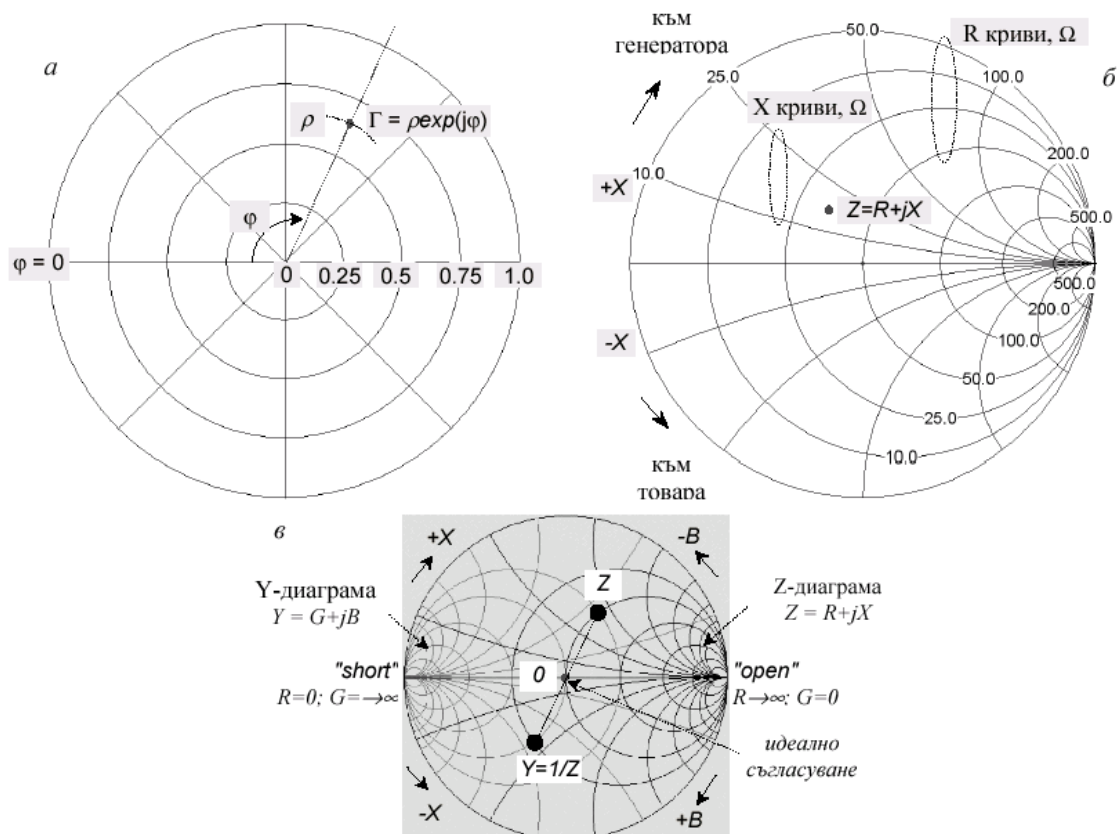
$$Z_L = Z_{in}(z=0) = Z_C \frac{1 + \Gamma(0)}{1 - \Gamma(0)} = R_L + jX_L \quad \Gamma(0) = \rho = \frac{Z_L - Z_C}{Z_L + Z_C}$$

• Известен израз за входния импеданс в дадена точка z

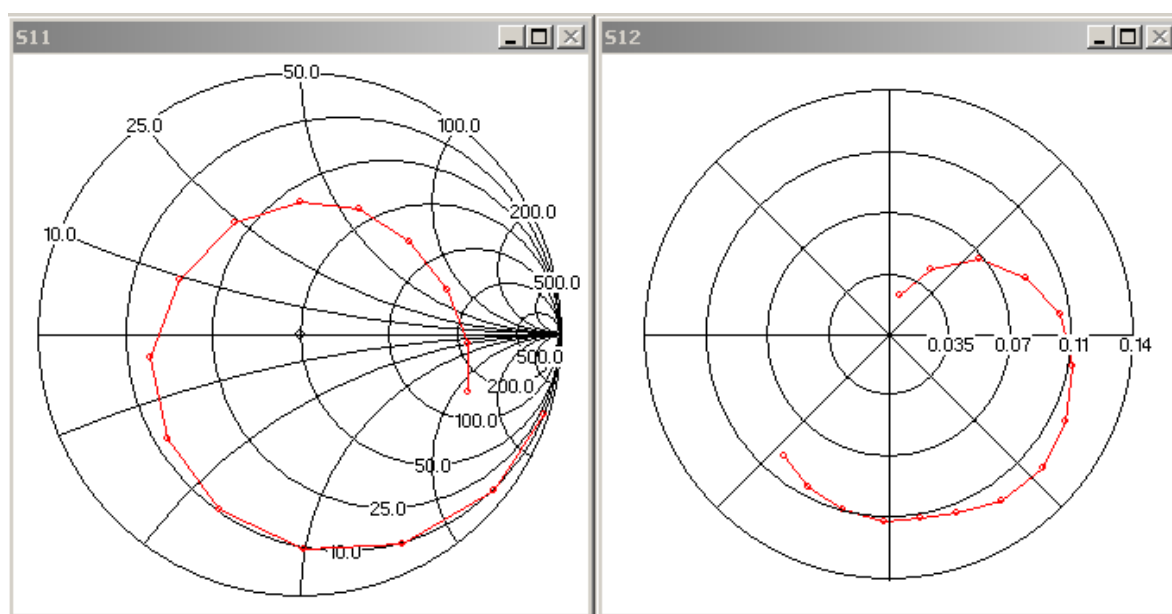
$$Z_{in} = Z_C \frac{Z_L + jZ_C \tan(\beta z)}{Z_C + Z_L \tan(\beta z)}$$

$$\beta = 2\pi/\lambda_g$$

Изобразяване на коефициент на отражение и входен импеданс. Диаграма на Смит

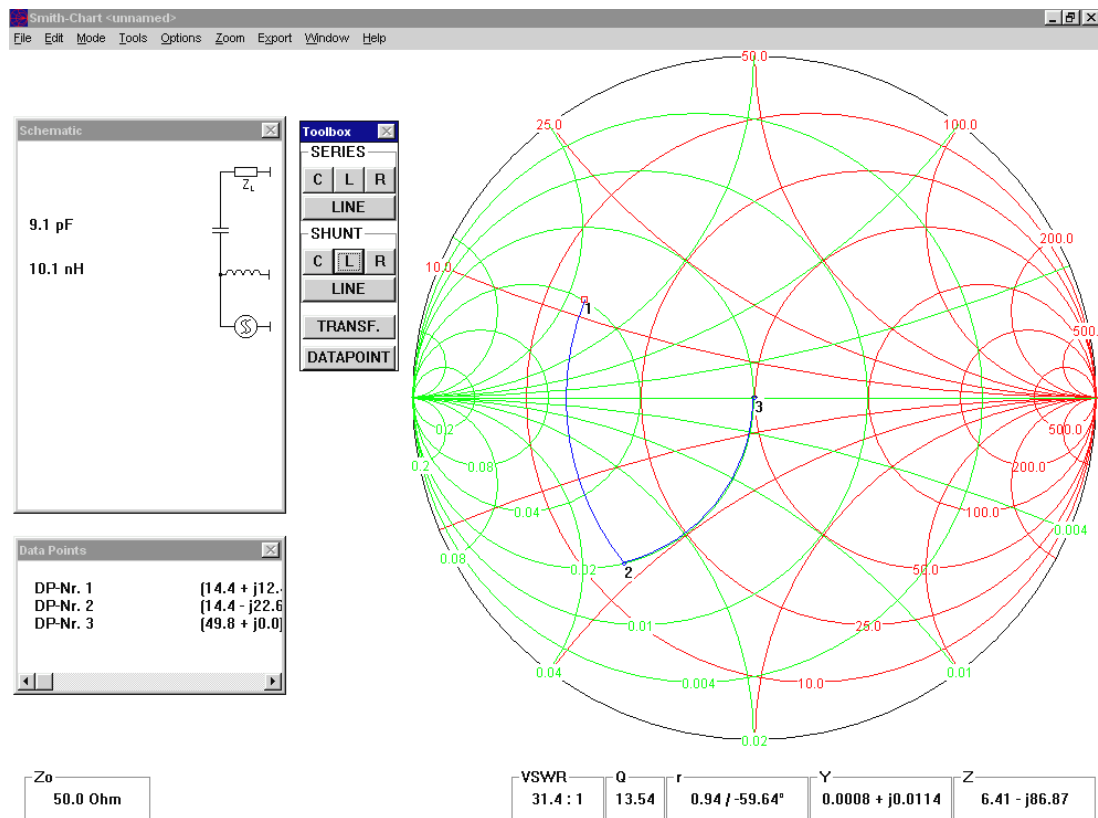


S-параметри – представяне в полярни координати



GaAs FET транзистор

Калкулатор за съгласуване на устройства



Z-матрица и Y-матрица. Връзка с S-матрица

$$\hat{\mathbf{u}} = \hat{\mathbf{Z}} \hat{\mathbf{i}}$$

$$u_i = Z_{ik} i_k$$

$$\begin{pmatrix} u_1 \\ u_2 \\ \vdots \\ u_N \end{pmatrix} = \begin{pmatrix} Z_{11} & \cdots & Z_{1N} \\ \vdots & & \vdots \\ Z_{N1} & \cdots & Z_{NN} \end{pmatrix} \begin{pmatrix} i_1 \\ i_2 \\ \vdots \\ i_N \end{pmatrix}$$

$$\hat{\mathbf{i}} = \hat{\mathbf{Y}} \hat{\mathbf{u}}$$

$$i_i = Y_{ik} u_k$$

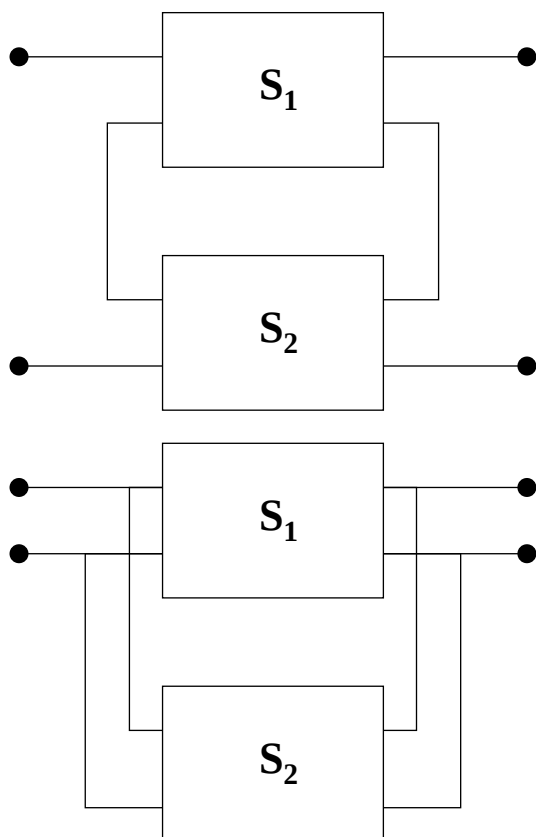
$$\hat{\mathbf{Y}} = 1 / \hat{\mathbf{Z}}$$

$$\hat{\mathbf{Z}} = (\hat{\mathbf{I}} - \hat{\mathbf{S}})^{-1} (\hat{\mathbf{I}} + \hat{\mathbf{S}})$$

$$\hat{\mathbf{Y}} = (\hat{\mathbf{I}} + \hat{\mathbf{S}})^{-1} (\hat{\mathbf{I}} - \hat{\mathbf{S}})$$

$$\begin{aligned} \hat{\mathbf{S}} &= (\hat{\mathbf{Z}} - \hat{\mathbf{I}}) (\hat{\mathbf{Z}} + \hat{\mathbf{I}})^{-1} \\ &= (\hat{\mathbf{I}} - \hat{\mathbf{Z}}) (\hat{\mathbf{I}} + \hat{\mathbf{Z}})^{-1} \end{aligned}$$

Свързване на устройства



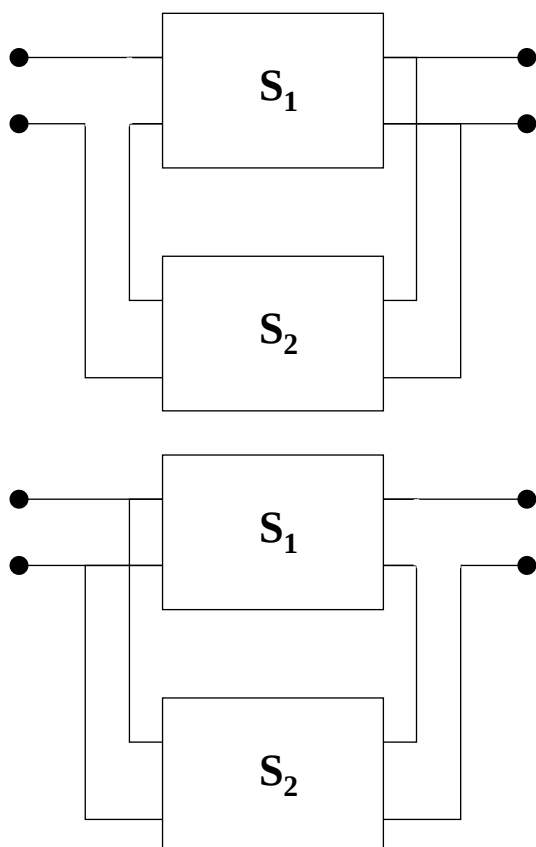
• Последователно-последователно

$$\hat{\mathbf{S}}_{ss} = \begin{bmatrix} -1 & 0 \\ 0 & -1 \end{bmatrix} \times F \left(\begin{bmatrix} -1 & 0 \\ 0 & -1 \end{bmatrix} \hat{\mathbf{S}}_1, \begin{bmatrix} -1 & 0 \\ 0 & -1 \end{bmatrix} \hat{\mathbf{S}}_2 \right)$$

• Паралелно-паралелно

$$\hat{\mathbf{S}}_{pp} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \times F \left(\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \hat{\mathbf{S}}_1, \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \hat{\mathbf{S}}_2 \right)$$

Свързване на устройства (2)



• Последователно-паралелно

$$\hat{\mathbf{S}}_{sp} = \begin{bmatrix} -1 & 0 \\ 0 & 1 \end{bmatrix} \times F \left(\begin{bmatrix} -1 & 0 \\ 0 & 1 \end{bmatrix} \hat{\mathbf{S}}_1, \begin{bmatrix} -1 & 0 \\ 0 & 1 \end{bmatrix} \hat{\mathbf{S}}_2 \right)$$

• Паралелно-последователно

$$\hat{\mathbf{S}}_{ps} = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \times F \left(\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \hat{\mathbf{S}}_1, \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \hat{\mathbf{S}}_2 \right)$$

Свързване на устройства (3)

Означения по-горе:

$$F(\hat{S}_1, \hat{S}_2) = \hat{A}^{-1} [\hat{B} + 4\hat{C}\hat{S}_2(\hat{A} - \hat{B}\hat{S}_2)^{-1}\hat{C}]$$

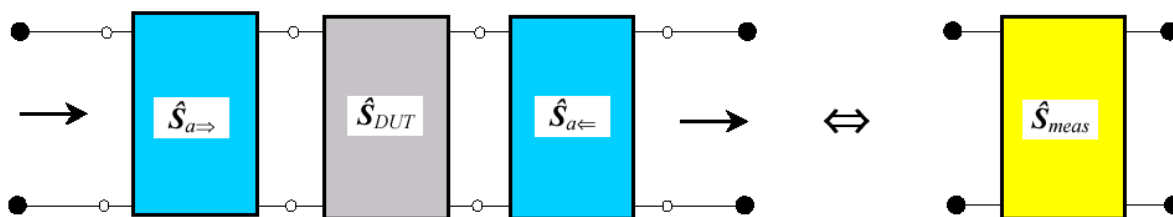
$$\hat{A} = 3\hat{I}$$

$$\hat{B} = \hat{S}_1 - \hat{I}$$

$$\hat{C} = \hat{S}_1 + \hat{I}$$

$$\hat{I} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

Каскадно свързване на устройства (при измерване)



Въвежда се T матрица:

$$\hat{T}_{meas} = \hat{T}_{a \rightarrow} \hat{T}_{DUT} \hat{T}_{a \leftarrow} \quad \rightarrow \quad \hat{T}_{DUT} = \hat{T}_{a \rightarrow}^{-1} \hat{T}_{meas} \hat{T}_{a \leftarrow}^{-1}$$

Дефиниция на S-матрица:

$$\begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix}$$

Дефиниция на T-матрица:

$$\begin{pmatrix} b_1 \\ a_1 \end{pmatrix} = \begin{pmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{pmatrix} \begin{pmatrix} a_2 \\ b_2 \end{pmatrix}$$

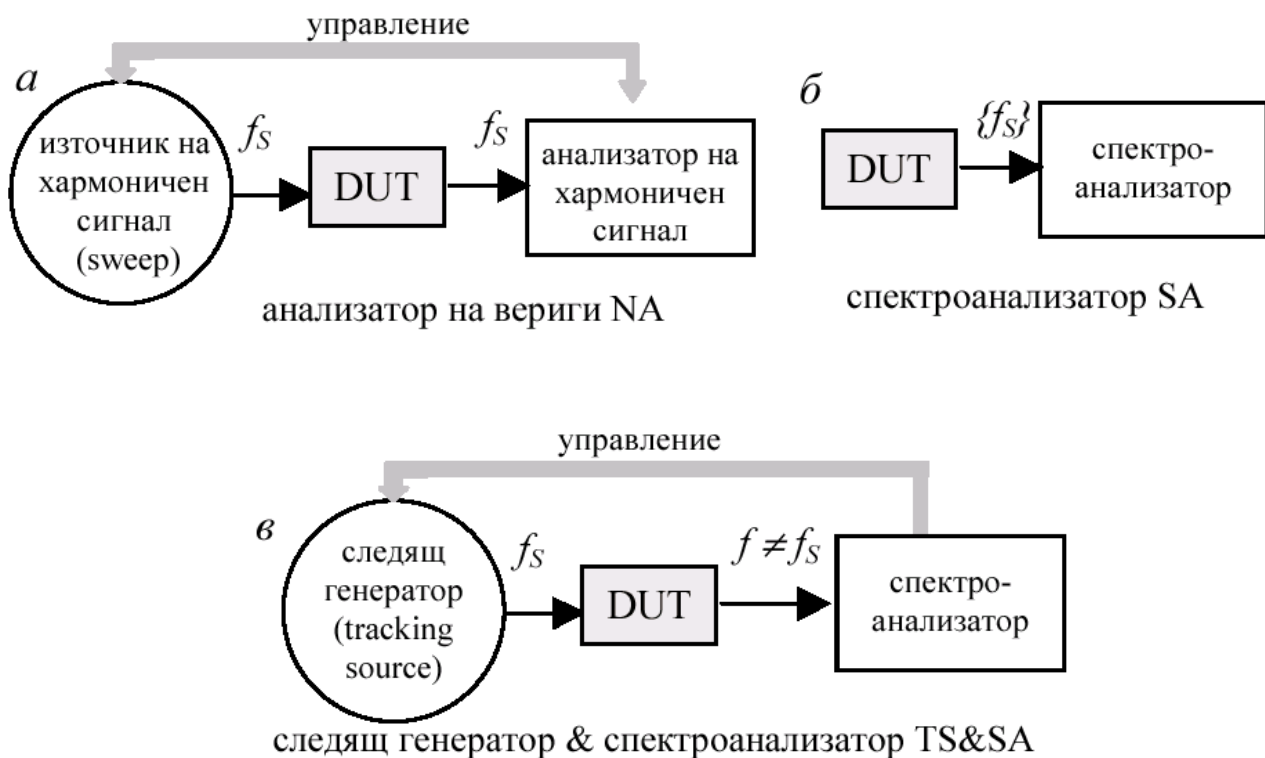
Преминане от S- към T-матрица:

$$\begin{aligned} T_{11} &= 1/S_{21} \\ T_{12} &= -S_{22}/S_{21} \\ T_{21} &= S_{11}/S_{21} \\ T_{22} &= S_{12} - S_{11}S_{22}/S_{21} \end{aligned}$$

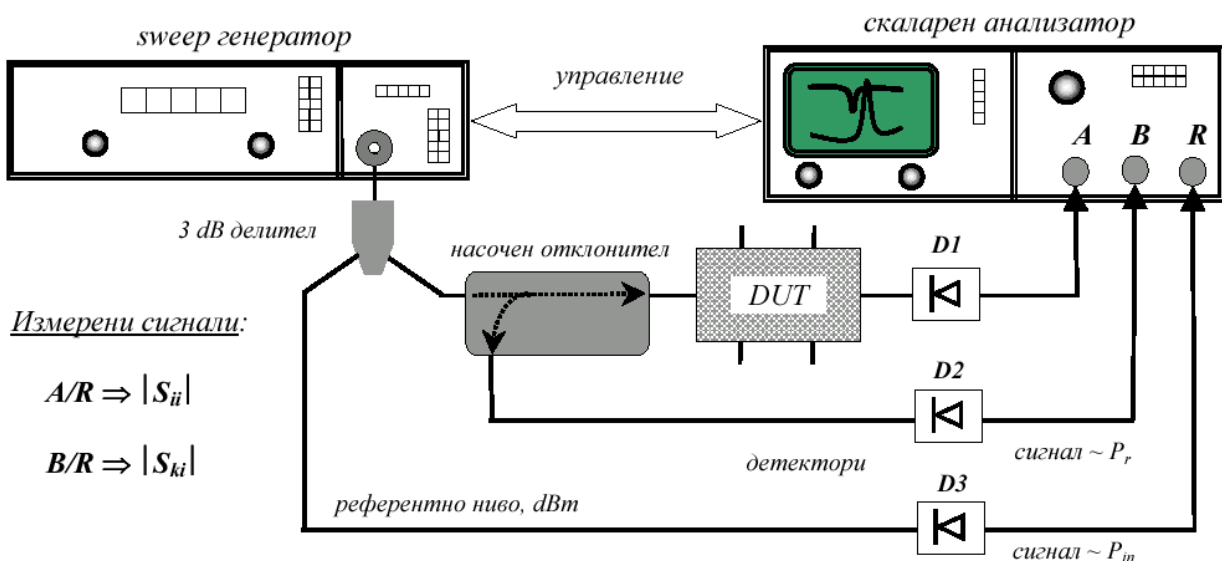
Преминане от T- към S-матрица:

$$\begin{aligned} S_{11} &= T_{21}/T_{11} \\ S_{12} &= T_{22} - T_{12}T_{21}/T_{11} \\ S_{21} &= 1/T_{11} \\ S_{22} &= -T_{12}/T_{11} \end{aligned}$$

Измерване на S параметри

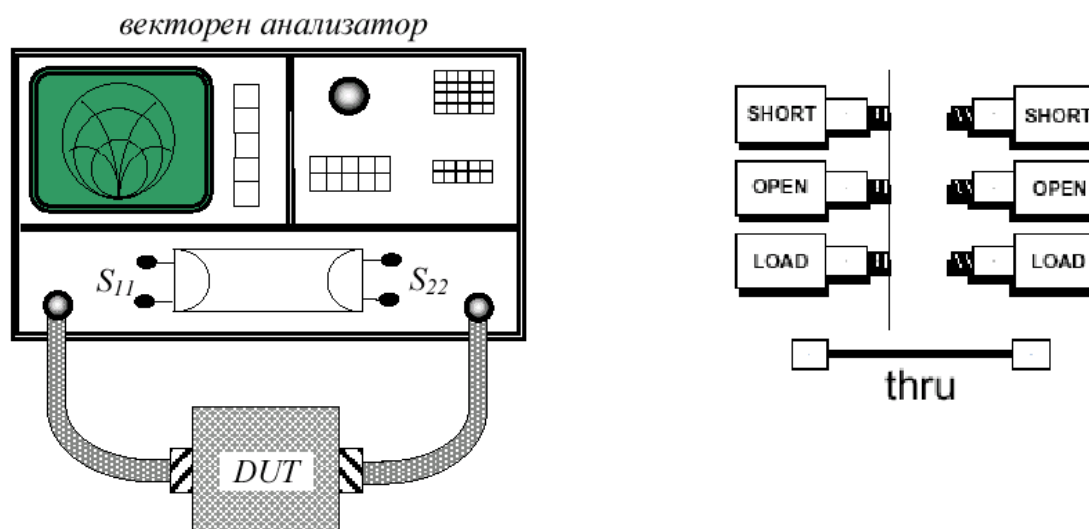


Автоматично измерване със скаларен анализатор на вериги



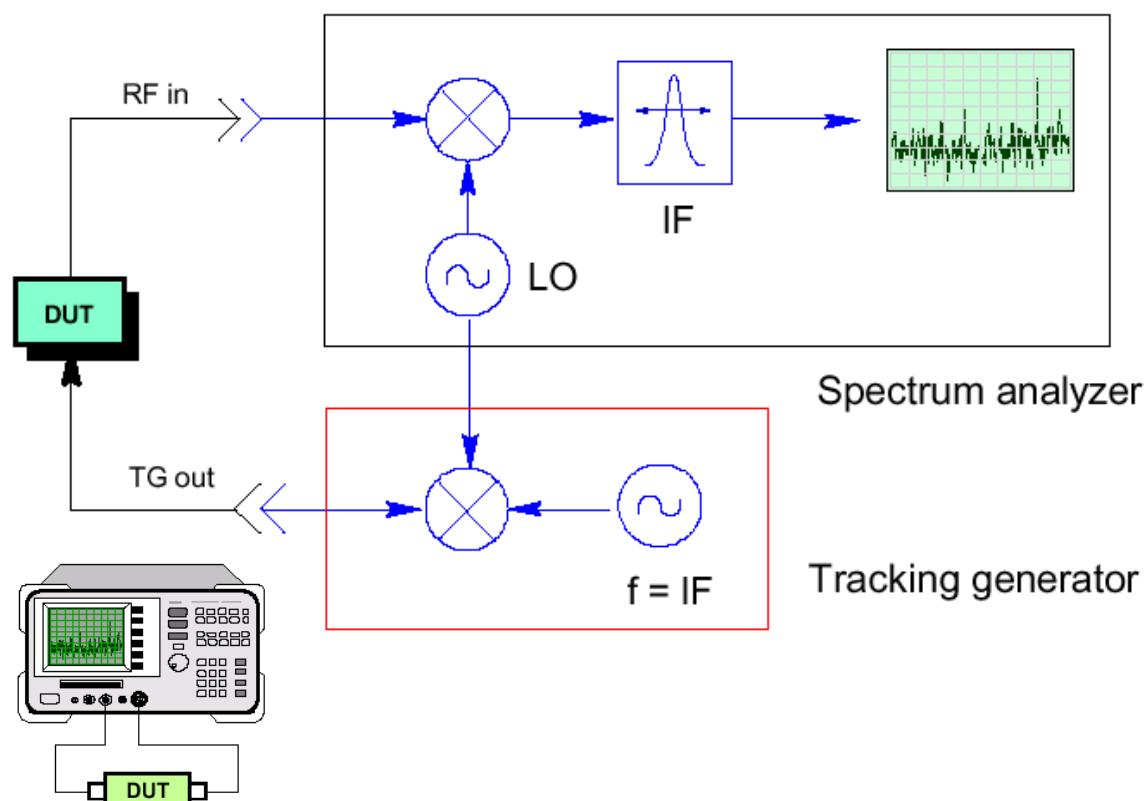
Измерва се падащата, отразена и преминала мощност (в относителни единици - отношение или в dB) и се определят само скаларните S параметри. Нуждае се от предварителна калибровка по отразен (чрез Open/Short) и преминал сигнал (чрез Thru).

Автоматично измерване с векторен анализатор на вериги



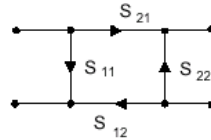
Измерва се падащата, отразена и преминала мощност и фаза и се определя пълният набор от векторни S параметри. Нуждае се от по-сложна предварителна калибровка на всяко отделно рамо и между тях (напр. SOLT калибровка - Short/Open/Load/Thru).

Други възможности за измерване

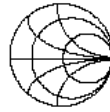


Необходимост от измерване на комплексни S параметри

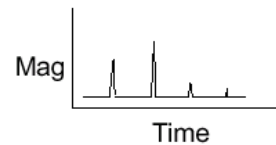
1. Complete characterization of linear networks



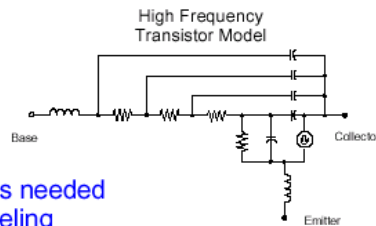
2. Complex impedance needed to design matching circuits



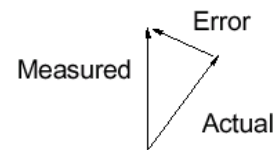
4. Time Domain Characterization



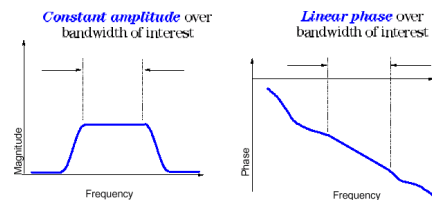
3. Complex values needed for device modeling



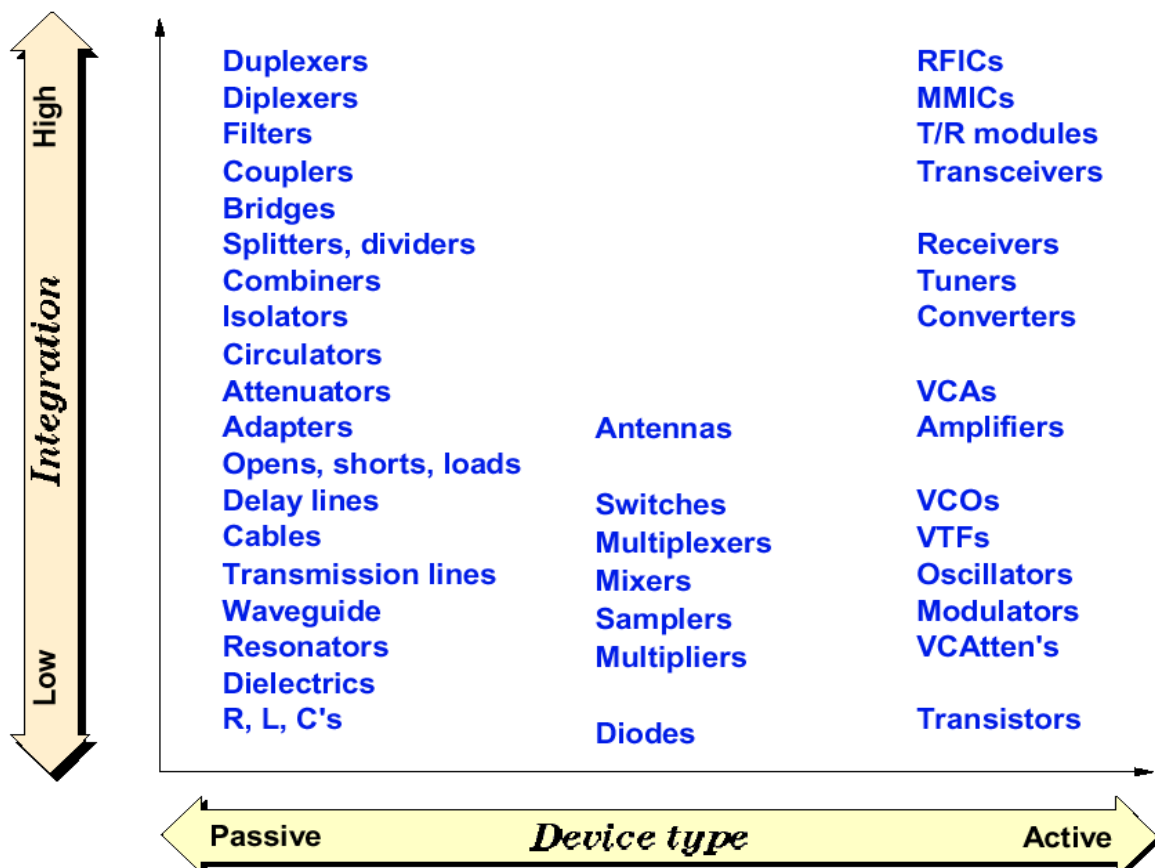
5. Vector Accuracy Enhancement



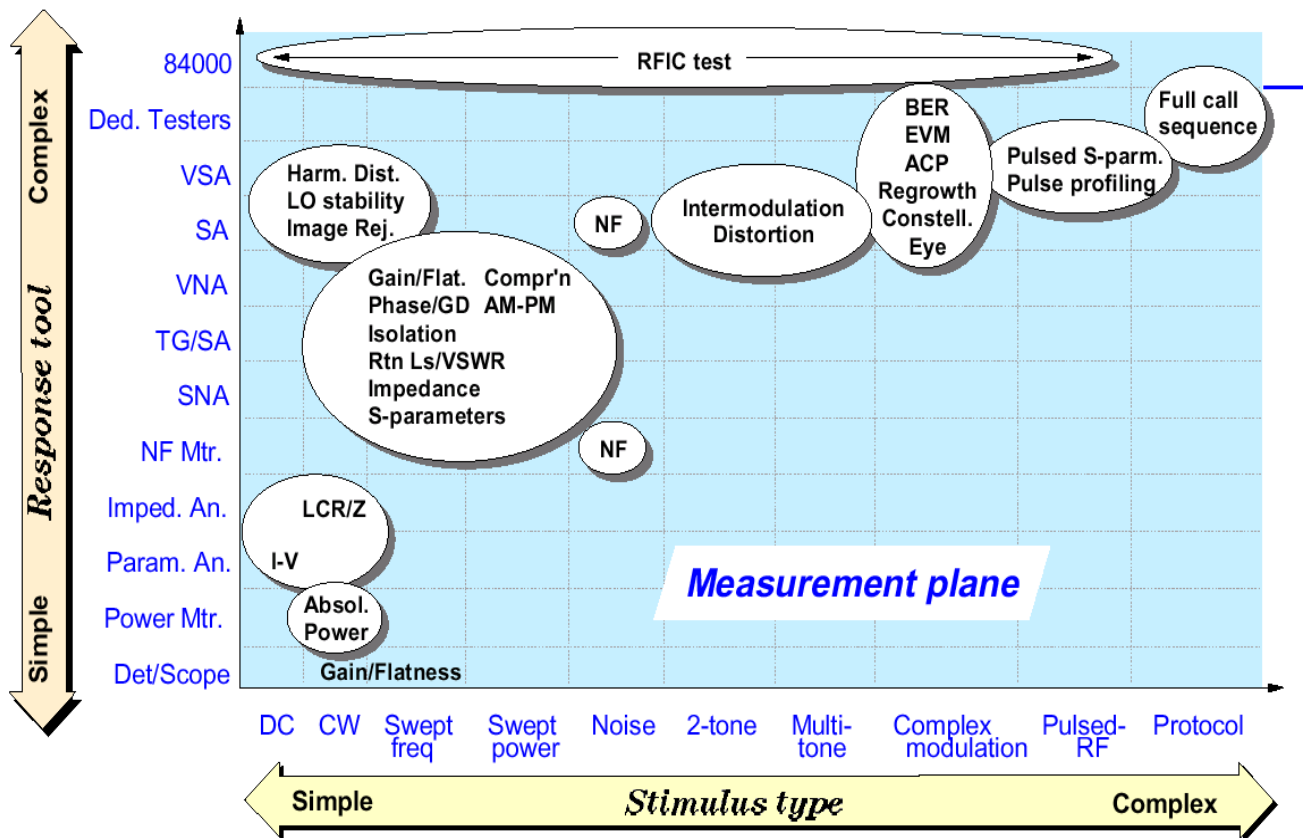
Linear Networks



Какви устройства се измерват с NA?



Какъв вид измервания се извършват с тези устройства?



Какъв вид измервания се извършват (означения)?

Response

84000	HP 84000 high-volume RFIC tester
Ded. Testers	Dedicated (usually one-box) testers
VSA	Vector signal analyzer
SA	Spectrum analyzer
VNA	Vector network analyzer
TG/SA	Tracking generator/spectrum analyzer
SNA	Scalar network analyzer
NF Mtr.	Noise-figure meter
Imped. An.	Impedance analyzer (LCR meter)
Power Mtr.	Power meter
Det./Scope	Diode detector/oscilloscope

Measurement

ACP	Adjacent channel power
AM-PM	AM to PM conversion
BER	Bit-error rate
Compr'n	Gain compression
Constell.	Constellation diagram
EVM	Error-vector magnitude
Eye	Eye diagram
GD	Group delay
Harm. Dist.	Harmonic distortion
NF	Noise figure
Regrowth	Spectral regrowth
Rtn Ls	Return loss
VSWR	Voltage standing wave ratio

По какви причини се измерват устройства?

Components often used as building blocks

- Need to verify specifications
- Examples:
 - filters to remove harmonics
 - amplifiers to boost LO power
 - mixers to convert reference signals

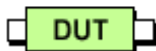
When used to pass communications signals, need to ensure distortionless transmission

- Linear networks
 - constant amplitude
 - linear phase / constant group delay
- Nonlinear networks
 - harmonics, intermodulation
 - compression
 - noise figure

When absorbing power (e.g. an antenna), need to ensure good match

Калибровки

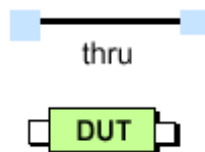
UNCORRECTED



Без калибровка:

- просто директно измерване
- на практика измерването без калибровка е некоректно (използва се само за груби оценки)
- няма корекции на характеристиките на измерителното оборудване – детектори, кабели, съединители и др.

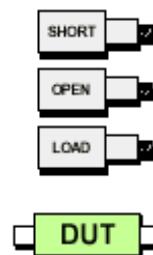
RESPONSE



Проста калибровка:

- лесна реализация
- използва се при не много точни скаларни измервания
- има само честотна корекция на отклика на измерителната система без устройството

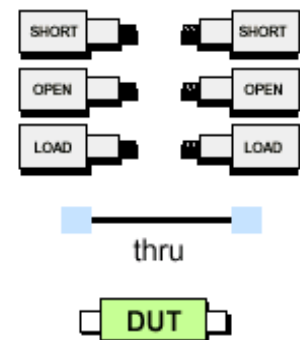
1-PORT



Калибровка за 1 рамо:

- само за измерване на отражение
- нуждае се от добре съгласуван товар
- Има корекции за: неидеална насоченост, неидеално съгласуване на източника и на измерителната равнина за отражение

FULL 2-PORT

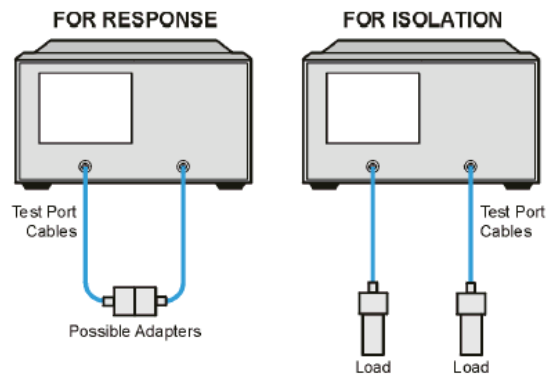
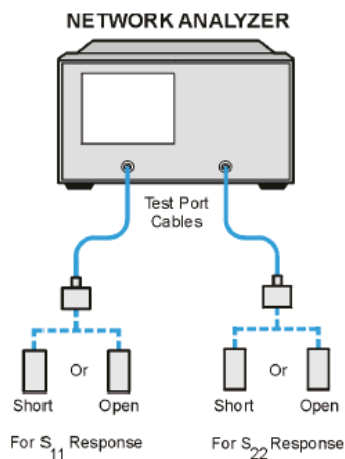


Калибровка за 2 рамена:

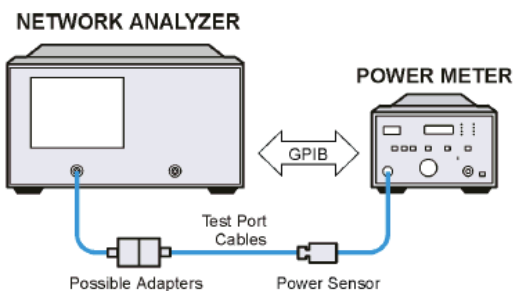
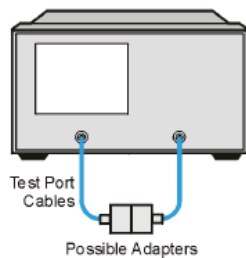
- най-висока точност
- Има корекции за: неидеални насоченост, неидеално съгласуване на източника, на измерителните равнини за отражение и преминаване, за изолация между рамената

Видове калибровки

Response

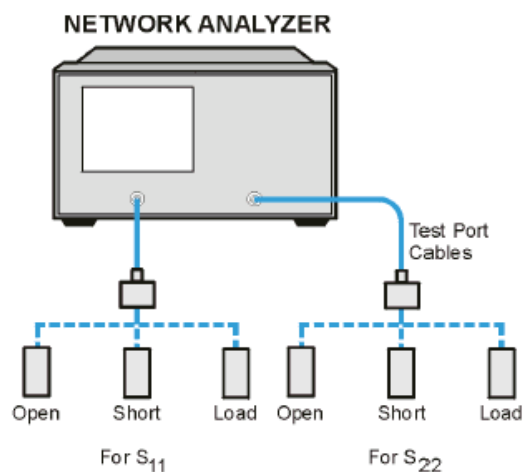


2 Ports



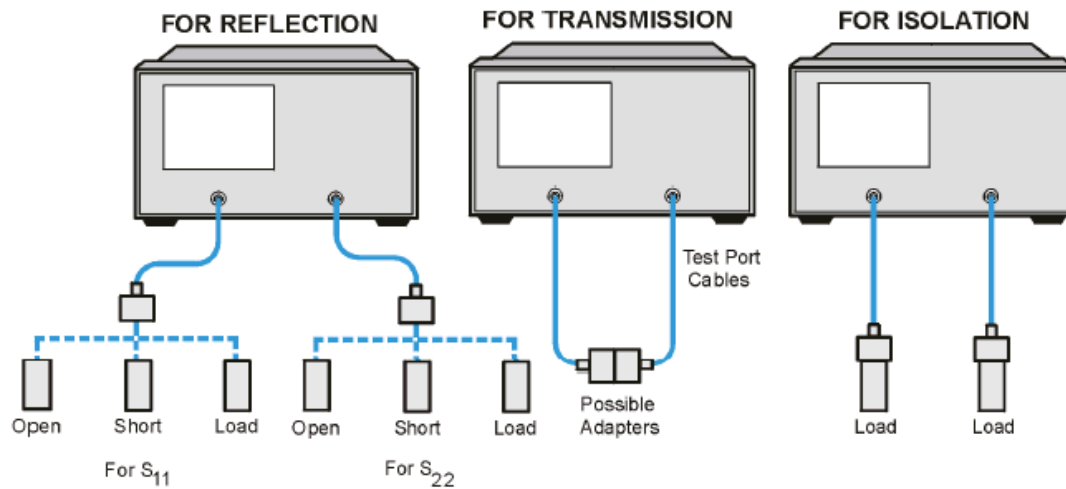
Видове калибровки (2)

One-port калибровка



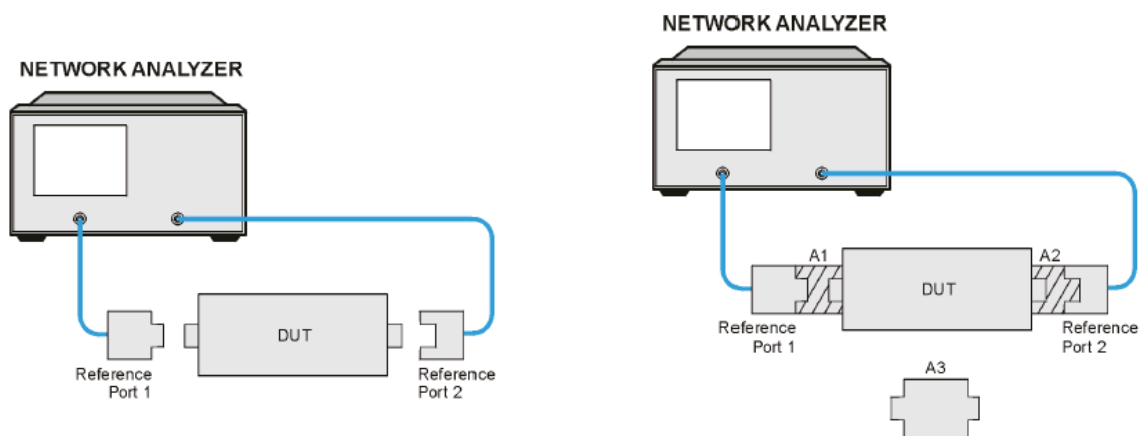
Видове калибровки (3)

Full two-port калибровка

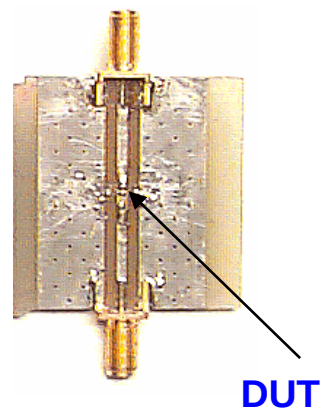
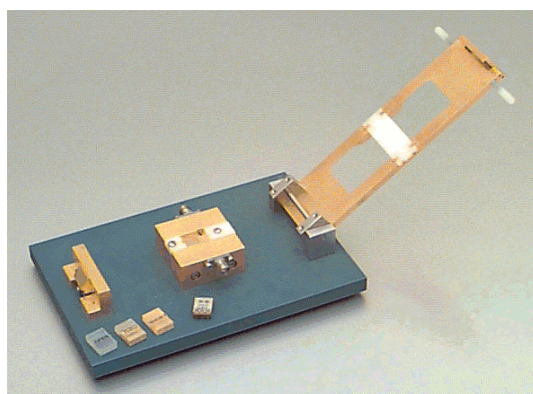
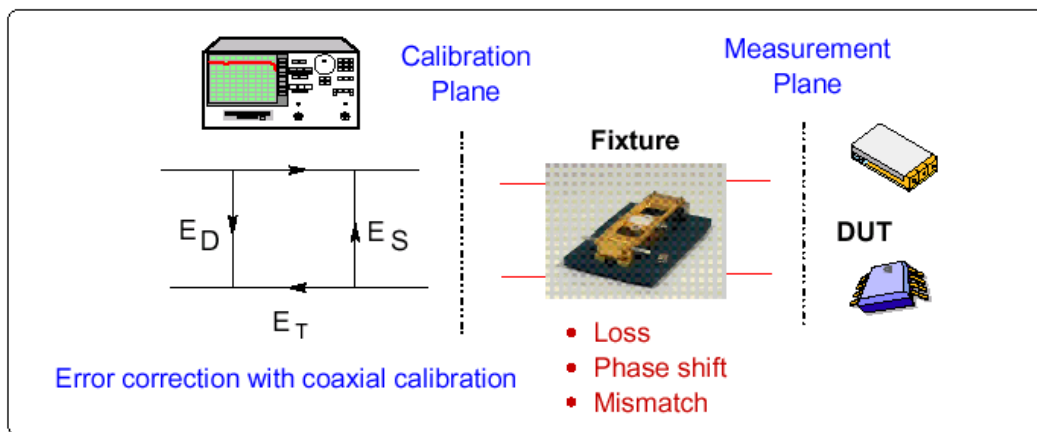


Видове калибровки (4)

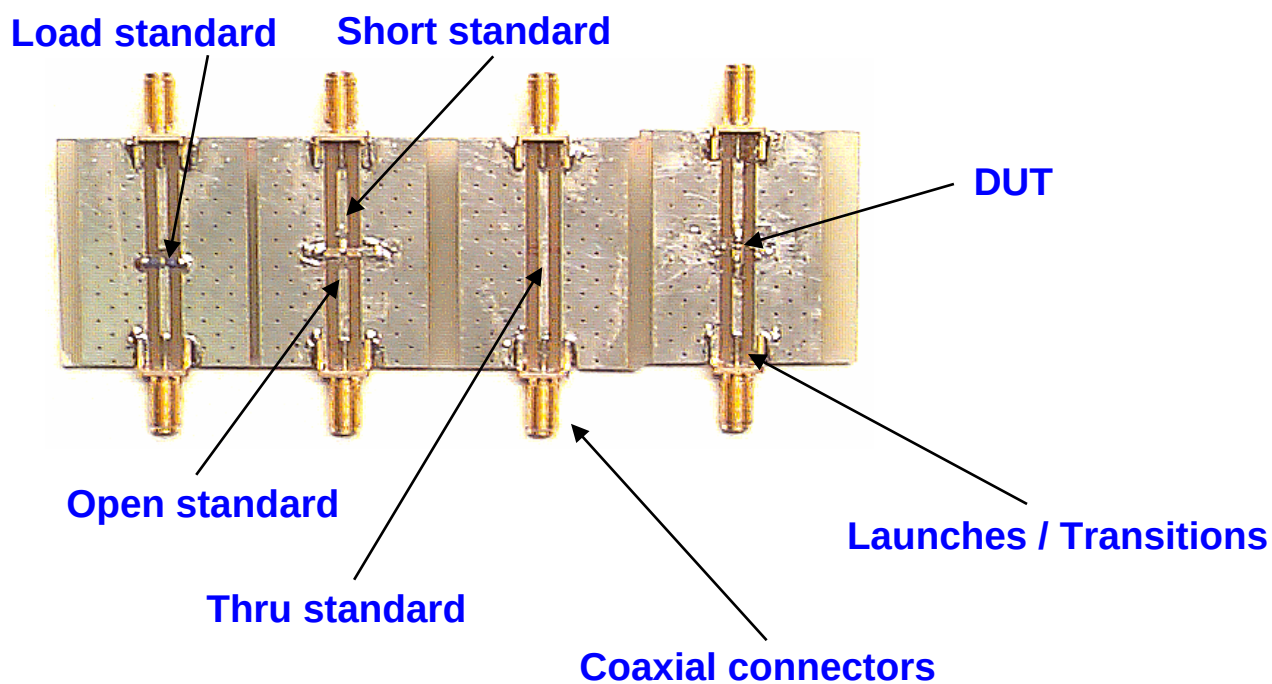
Калибровка с използване на допълнителни адаптери



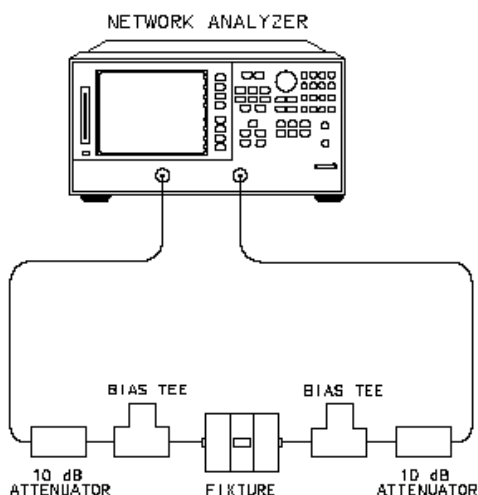
In-fixture измерване



Калибровка за in-fixture измерване (SOLT)



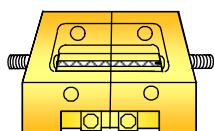
TRL калибровка (Thru-Reflect-Line)



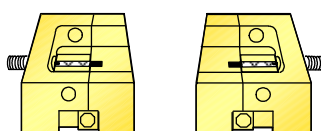
❖ **Thru:** с известно затихване и ел. дължина = 0; определя референтната измер. равнина

❖ **Open:** задава отражение = 1 и определя референтната измер. равнина за отражение

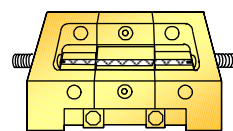
❖ **Line = Thru + $\lambda g/4$:** задава референтния импеданс на измерителната фикстура Z_0 (може и $\neq 50 \text{ Ohms}$) на мястото на Open; лентата на измерване е 8:1 от началната честота, ако внесената фаза е от 20° до 160° различна от фазата на Thru



Thru



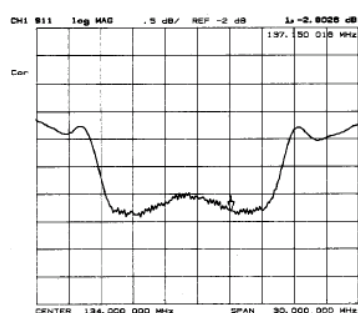
Open



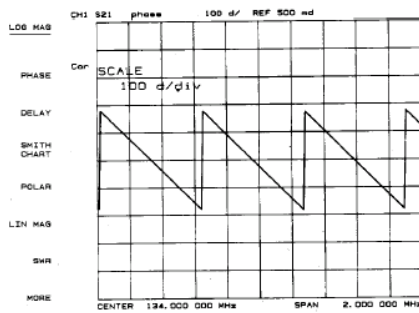
Line = Thru + $\lambda g/4$

Формати на представяне на резултатите

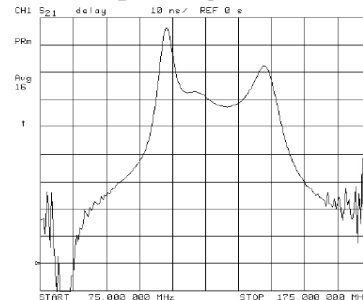
Log Magnitude Format



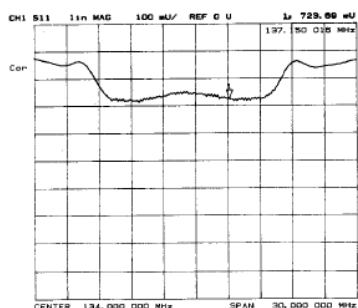
Phase Format



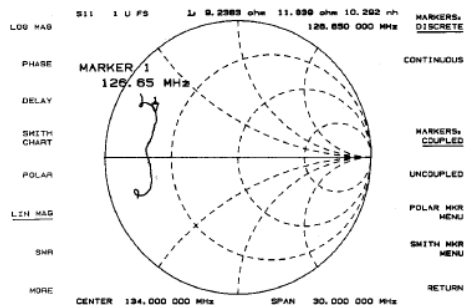
Group Delay Format



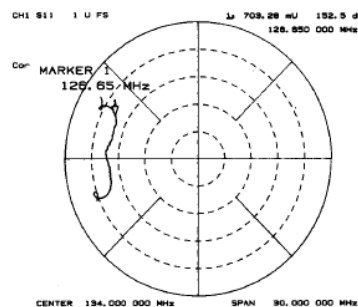
Linear Magnitude Format



Smith Chart Format

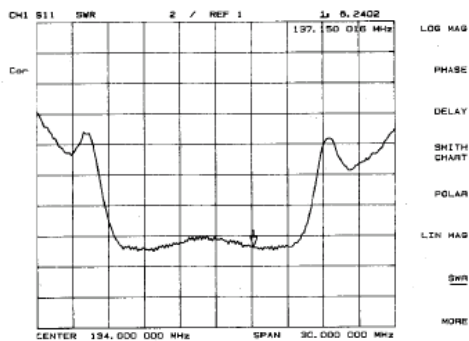


Polar Format

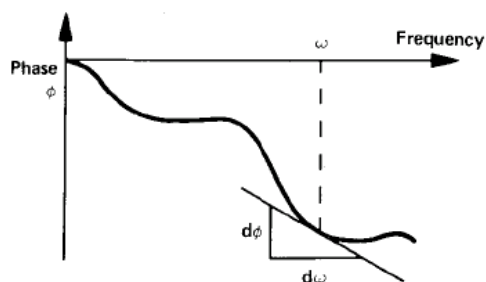


Формати на представяне на резултатите (2)

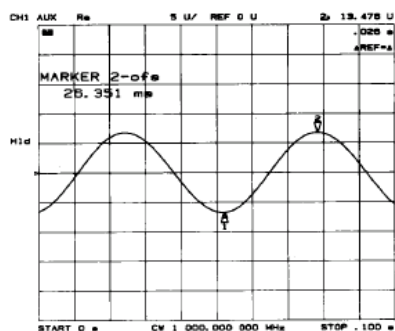
SWR Format



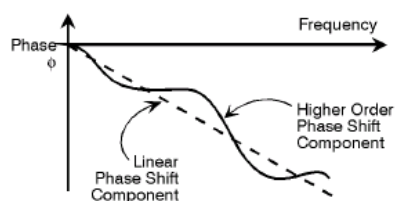
Constant Group Delay



Real Format Imaginary Format



Higher Order Phase Shift

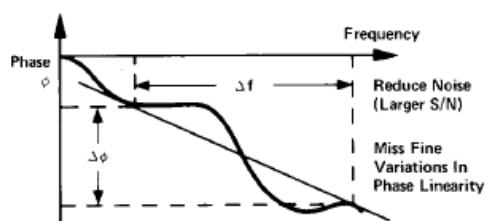
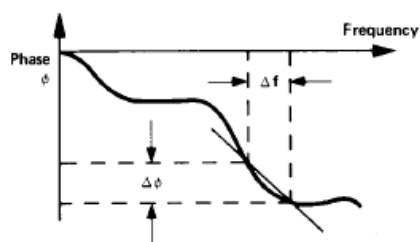


$$\text{Group Delay} = \tau_g = \frac{-d\phi}{d\omega}$$

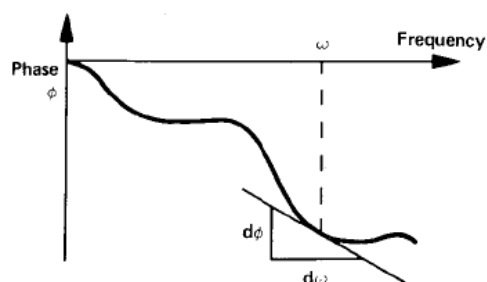
ϕ in Radians
 ω in Radians/Sec
 $= \frac{-1}{360^\circ} \cdot \frac{d\phi}{df}$
 ϕ in Degrees
 f in Hz ($\omega = 2\pi f$)

Формати на представяне на резултатите (3)

Variations in Frequency Aperture

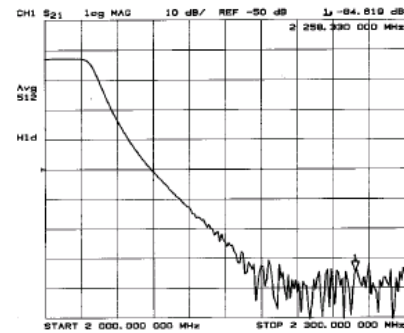
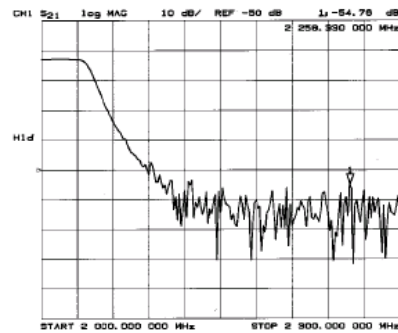


Constant Group Delay

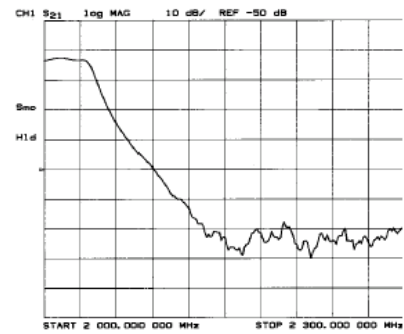
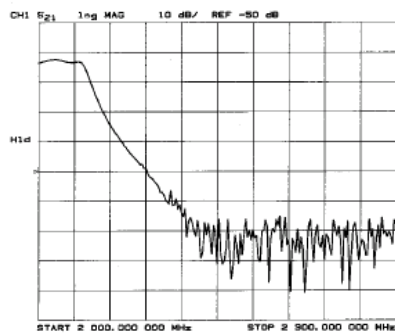


Техники на редукция на шума при измерване на S параметри

Averaging

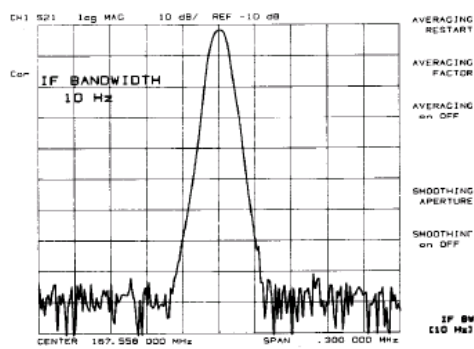
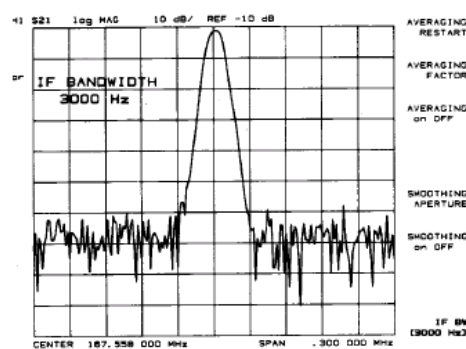


Smoothing

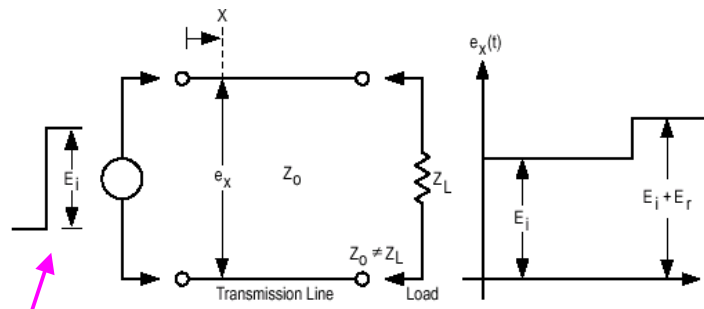


Техники на редукция на шума при измерване на S параметри

IF Bandwidth Reduction

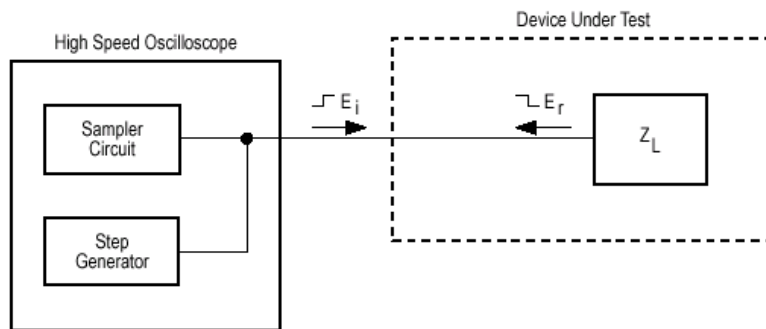


TDR рефлектومتрия

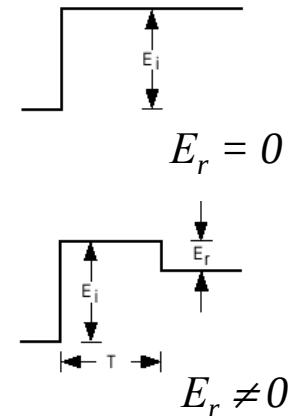


стъпаловиден сигнал

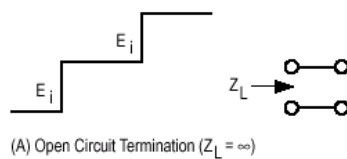
Сумарният отклик на дадена схема в дадена точка на подадения стъпаловиден сигнал зависи от типа на товара.



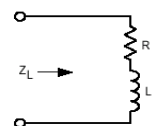
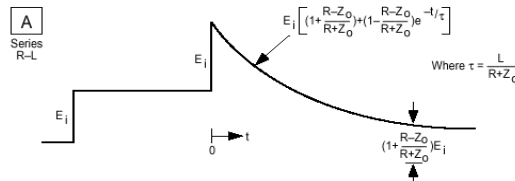
Опростена схема на TDR-рефлектومتрия



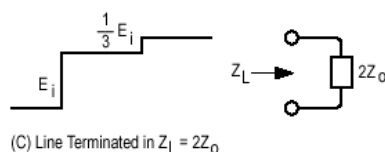
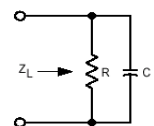
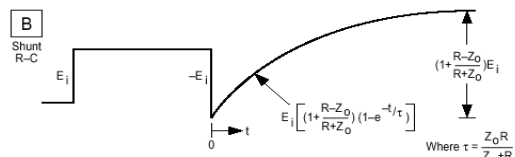
Примери за TDR отклик от различни устройства



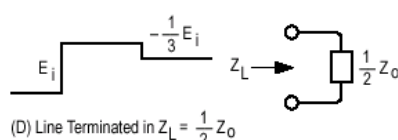
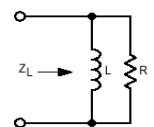
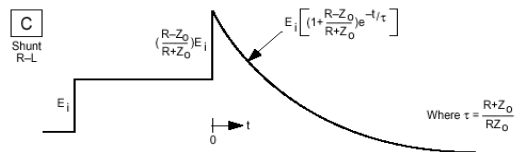
(A) Open Circuit Termination ($Z_L = \infty$)



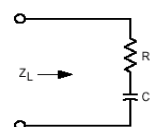
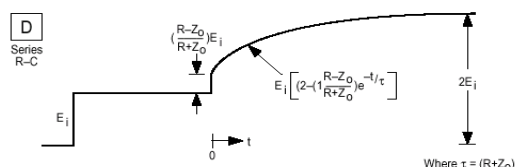
(B) Short Circuit Termination ($Z_L = 0$)



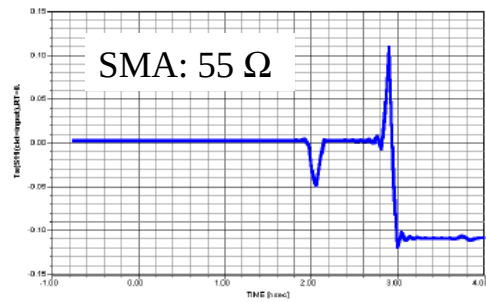
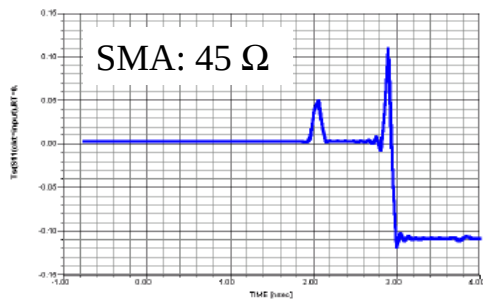
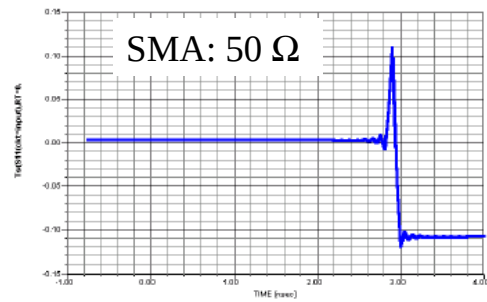
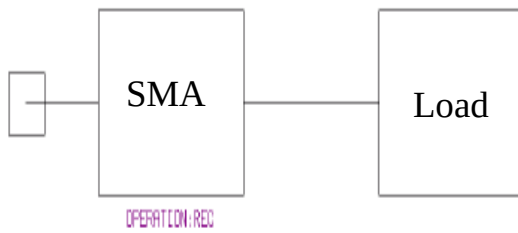
(C) Line Terminated in $Z_L = 2Z_0$



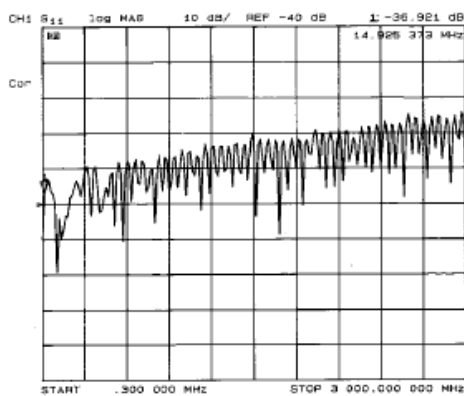
(D) Line Terminated in $Z_L = \frac{1}{2} Z_0$



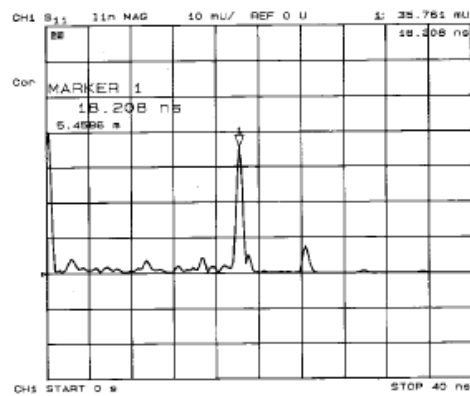
Примери за TDR отклик от съединител



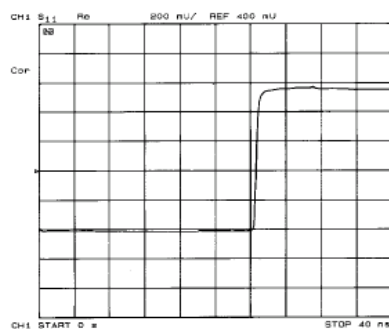
Примери за по-сложен отклик



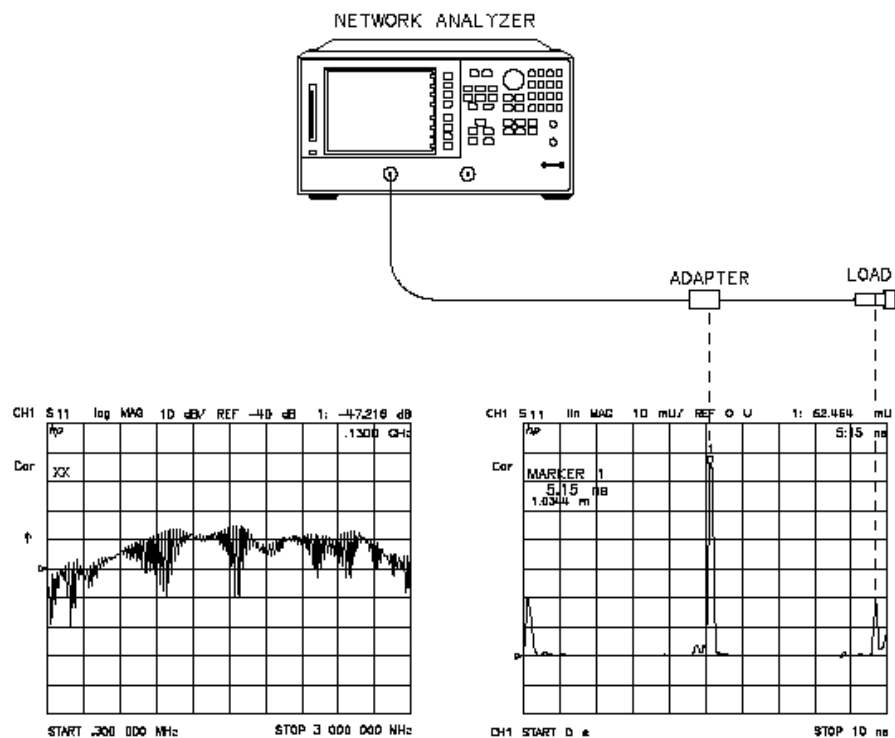
(a) Frequency Domain



(b) Time Domain Bandpass

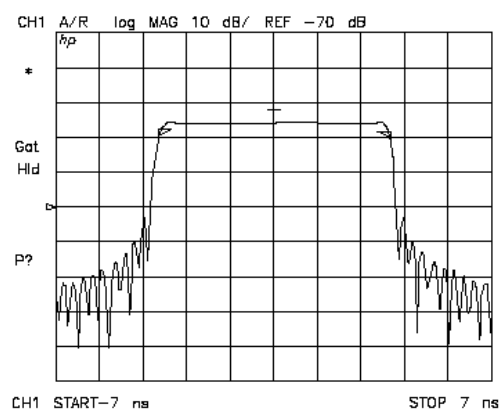


Идентификация на отклик

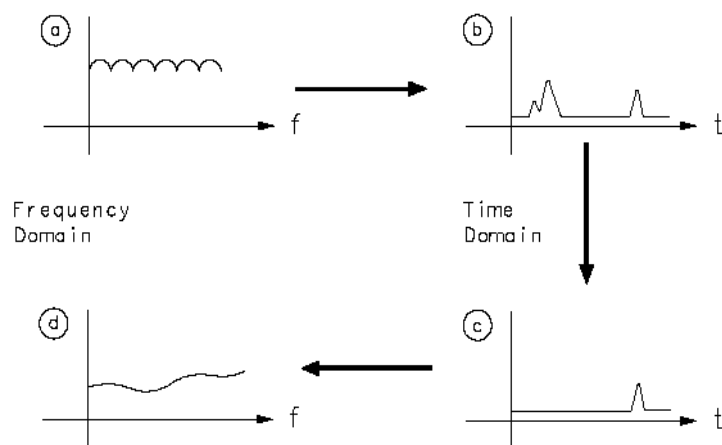


Измерване във времеви прозорец

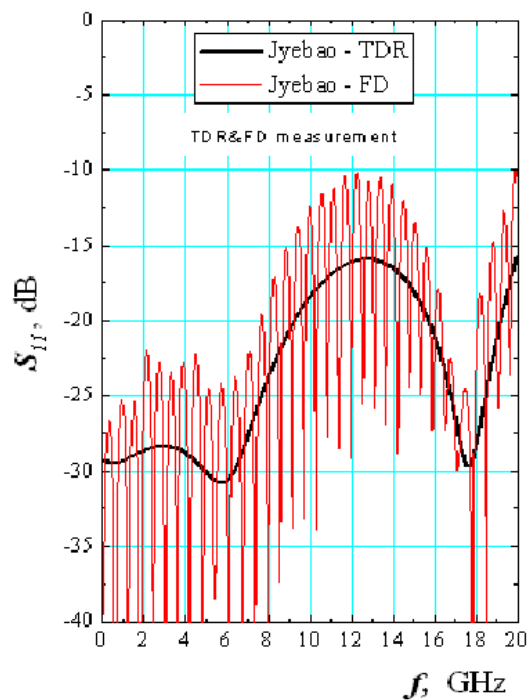
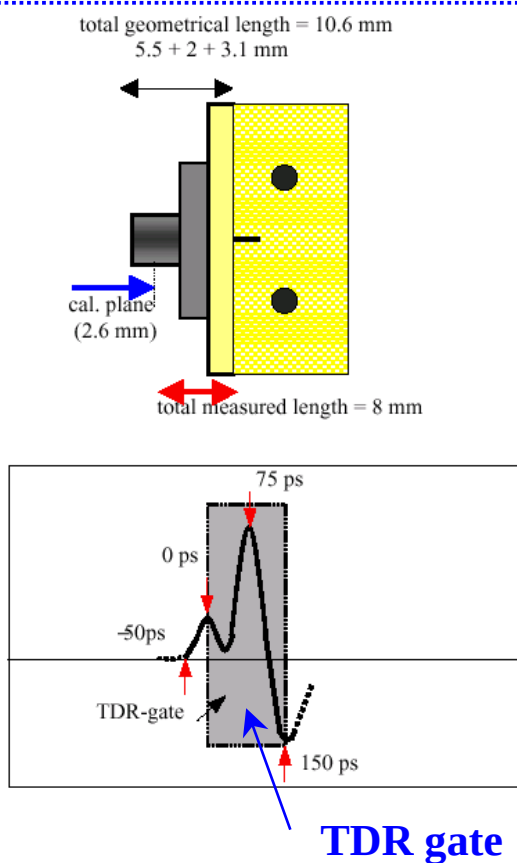
Gate Shape



Gating Operation

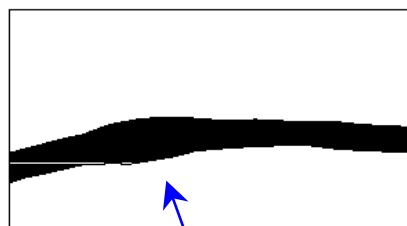
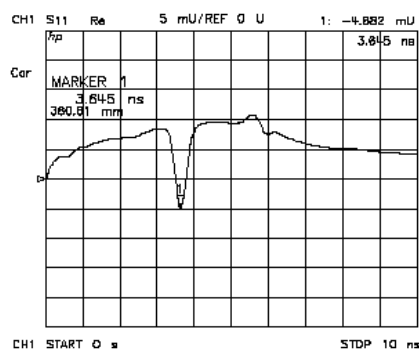


Пример за измерване на собствени RL на съединител

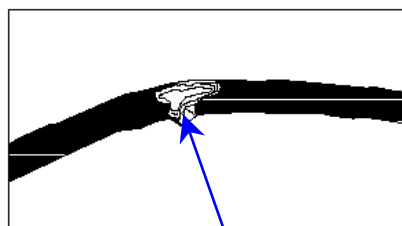
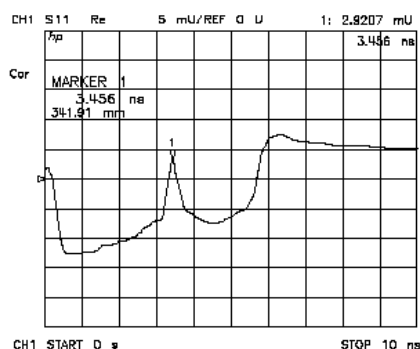


$$\tau [ps] = \frac{2d\sqrt{\epsilon_r}}{c} = \frac{d, mm}{0.0532}$$

Пример за установяване на проблеми в кабели



(a) Crimped Cable (Capacitive)



(b) Frayed Cable (Inductive)

Огънат кабел

Срязан кабел

Край на

Тема 5: