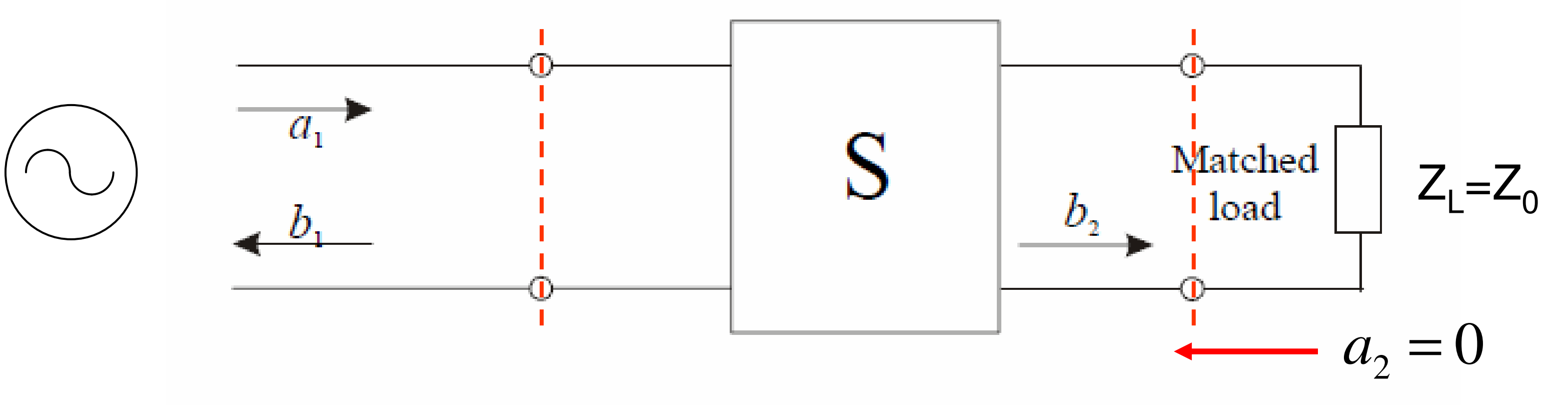
Analizador de Redes Vectorial (VNA)

Medidas Electrónicas 2

Profesor: Ing. Alejandro Henze

Determinación de los parámetros S: S_{11} y S_{21}



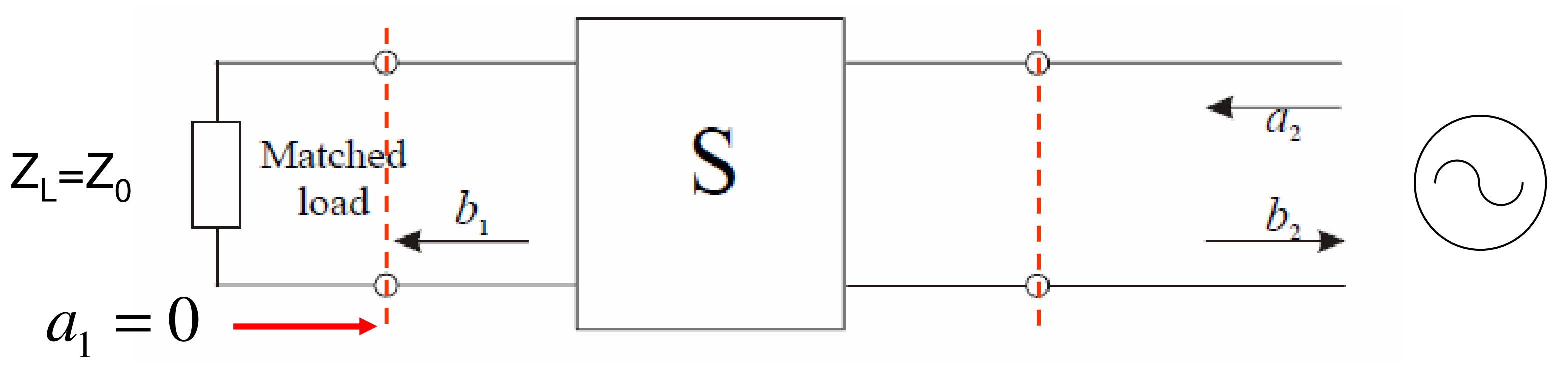
Parámetros Forward

$$S_{11} = \left.\frac{b_1}{a_1}\right|_{a_2=0}$$

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

$$S_{21} = \left.\frac{b_2}{a_1}\right|_{a_2=0}$$

Determinación de los parámetros S: S_{22} y S_{12}



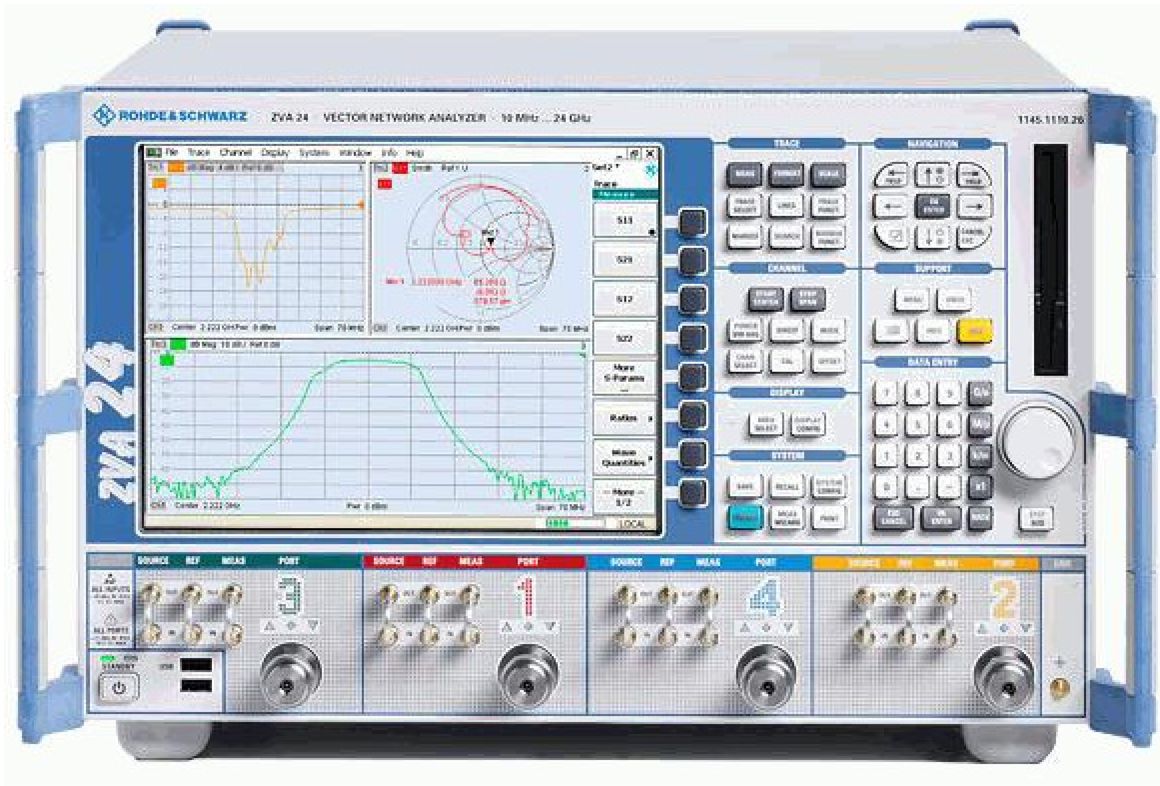
Parámetros Reverse

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

$$S_{22} = \left.\frac{b_2}{a_2}\right|_{a_1=0}$$

$$S_{12} = \left.\frac{b_1}{a_2}\right|_{a_1=0}$$

Analizador de Redes Vectorial (VNA)



VNA con cables de medición

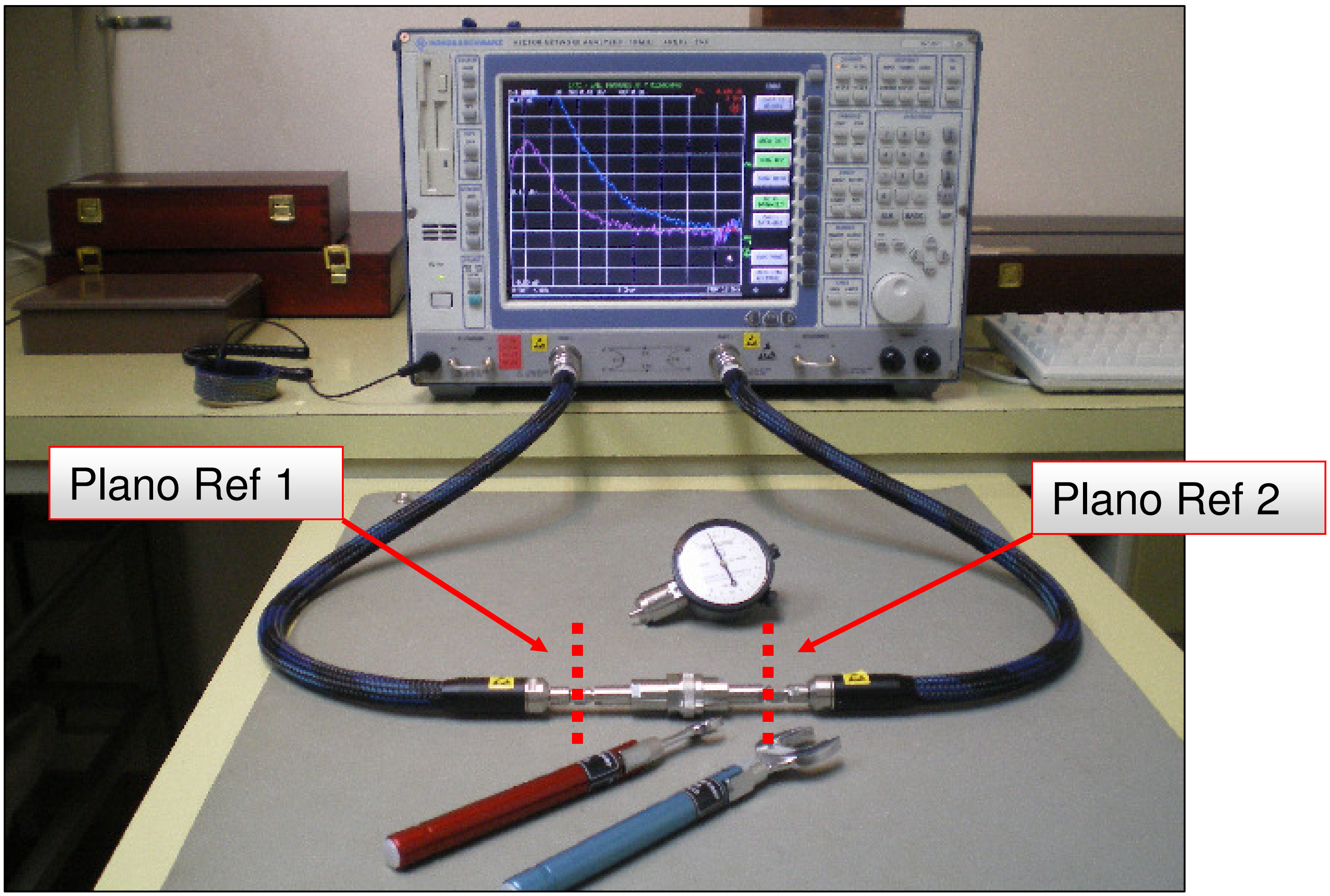


Diagrama en Bloques Básico

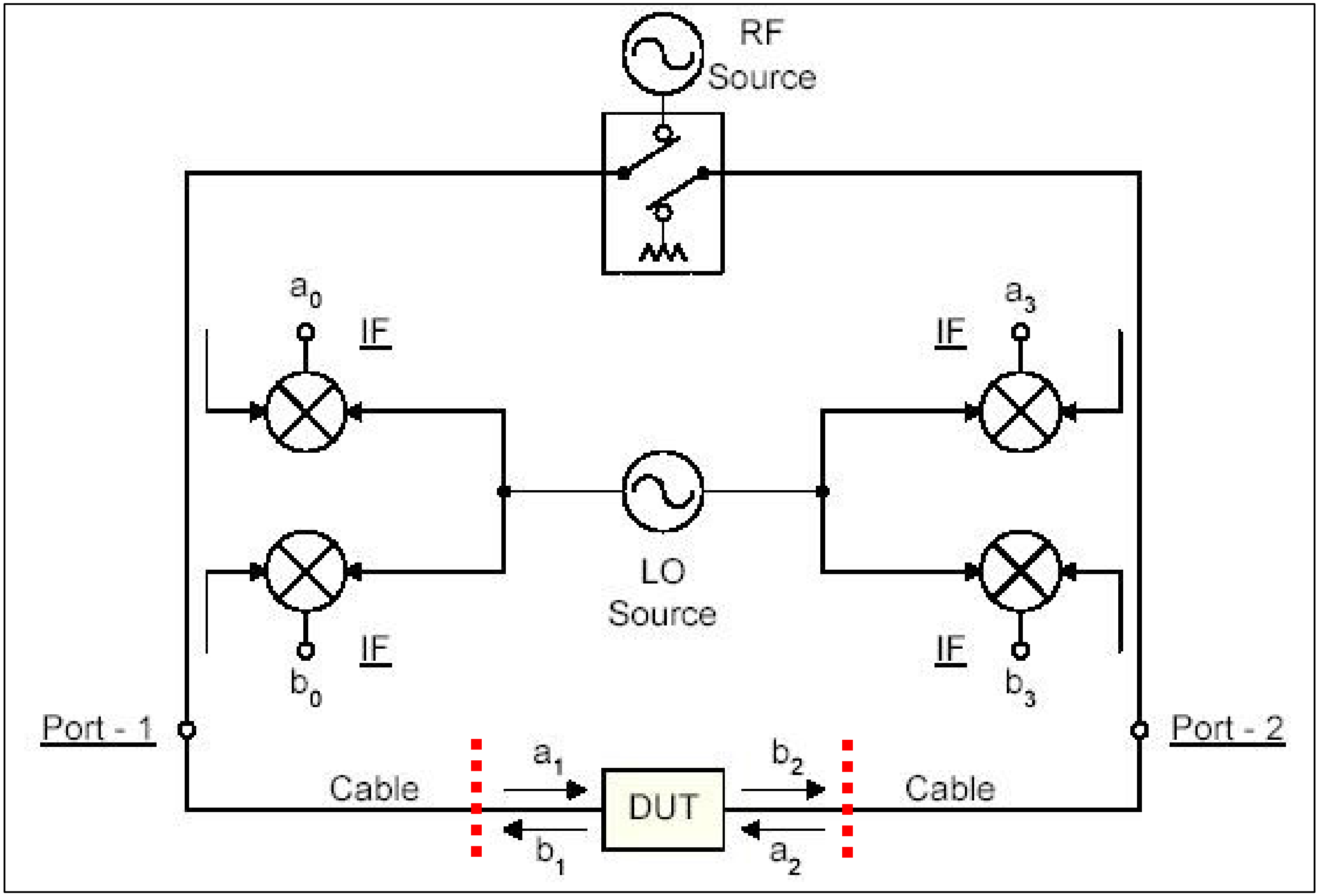


Diagrama en Bloques Básico

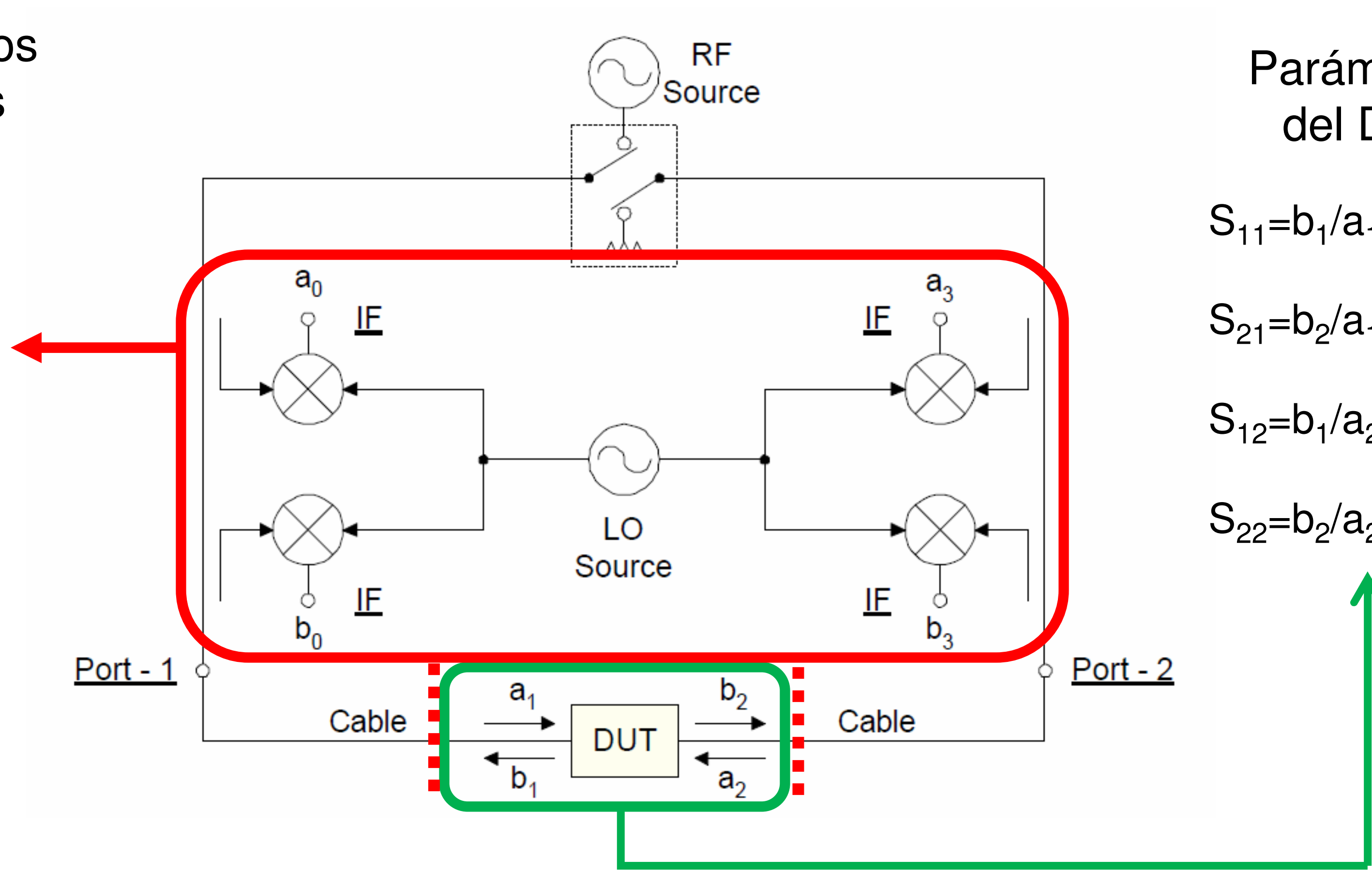
Parámetros medidos

$S_{11M}=b_0/a_0$

$S_{21M}=b_3/a_0$

$S_{12M}=b_0/a_3$

$S_{22M}=b_3/a_3$



Parámetros del DUT

$S_{11}=b_1/a_1\ (a_2=0)$

$S_{21}=b_2/a_1\ (a_2=0)$

$S_{12}=b_1/a_2\ (a_1=0)$

$S_{22}=b_2/a_2\ (a_1=0)$

Determinación de los parámetros S

Parámetros medidos

$S_{11M}=b_0/a_0$

$S_{21M}=b_3/a_0$

$S_{12M}=b_0/a_3$

$S_{22M}=b_3/a_3$

$\boxed{\text{Algoritmo de corrección}}$

Errores Sistemáticos del Sistema

Calibración VNA

Parámetros del DUT

$S_{11}=b_1/a_1$ $(a_2=0)$

$S_{21}=b_2/a_1$ $(a_2=0)$

$S_{12}=b_1/a_2$ $(a_1=0)$

$S_{22}=b_2/a_2$ $(a_1=0)$

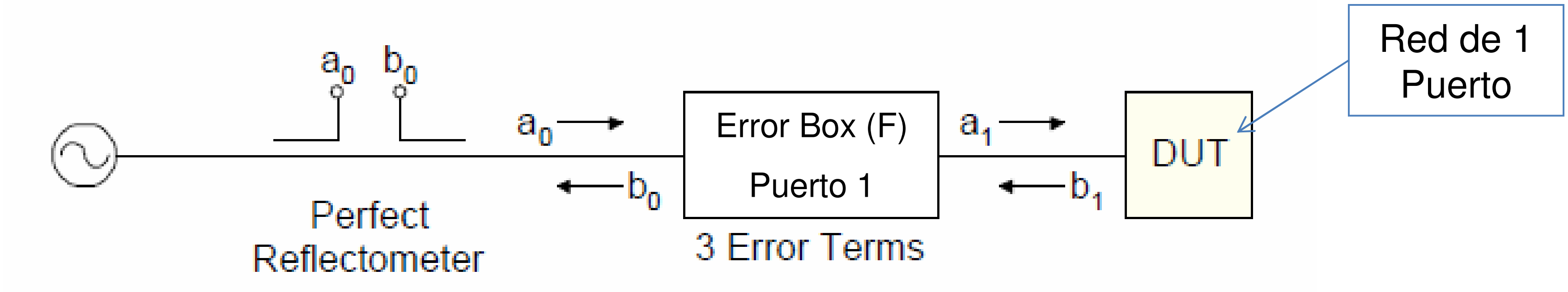
Calibración a 1 Puerto

Modelo de 3 Términos de Error

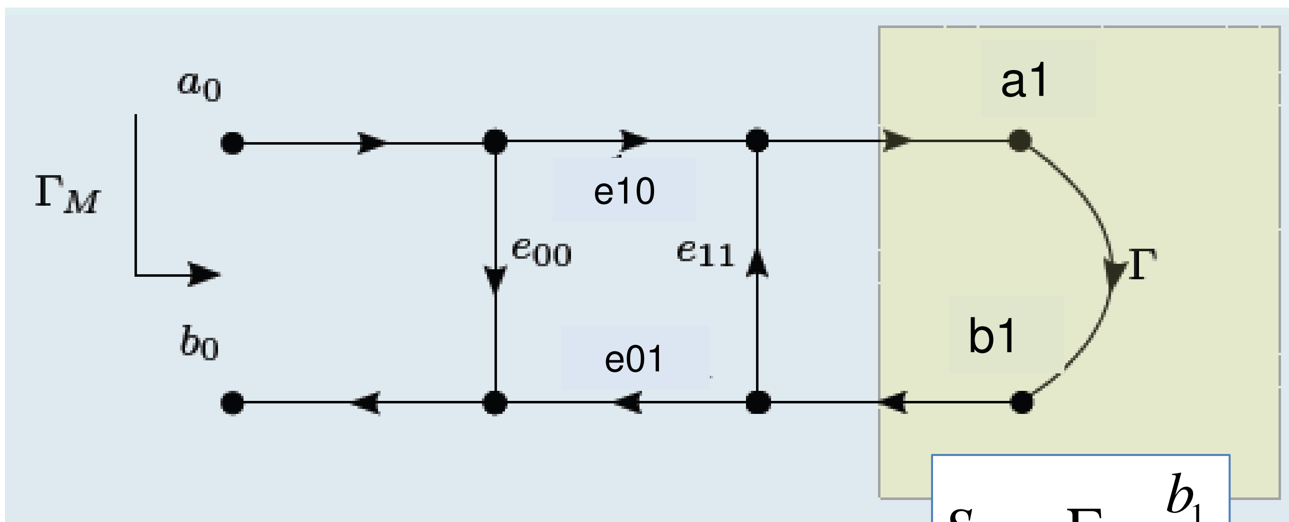
Métodos de Calibración: OSM

Método	Standards de calibración necesarios	Términos de error	Conexiones mínimas
OSM	Open-Short-Match	3	3
TOSM (SOLT)	Through-Open-Short-Match	12	8
TOM	Through-Open-Match	7	6
TRM	Through-Reflect-Match	7	6
TSD	Through-Short-Delay	7	6
TRL/TRL*	Through-Reflect-Line	7	6
LRL	Line-Reflect-Line	7	6
TNA	Through-Network-Attenuator	7	6
TOM-X	Through-Open-Match-Xtalk	15	10
LRM	Line-Reflect-Match	7	6
LRA	Line-Reflect-Attenuator	7	6
UOSM	Unknown Through-Open-Short-Match	7	8
GRL	Gated-Reflect-Line		
Multiline TRL	Multiline Through-Reflect-Line		

Modelo de 4 Términos de Errores

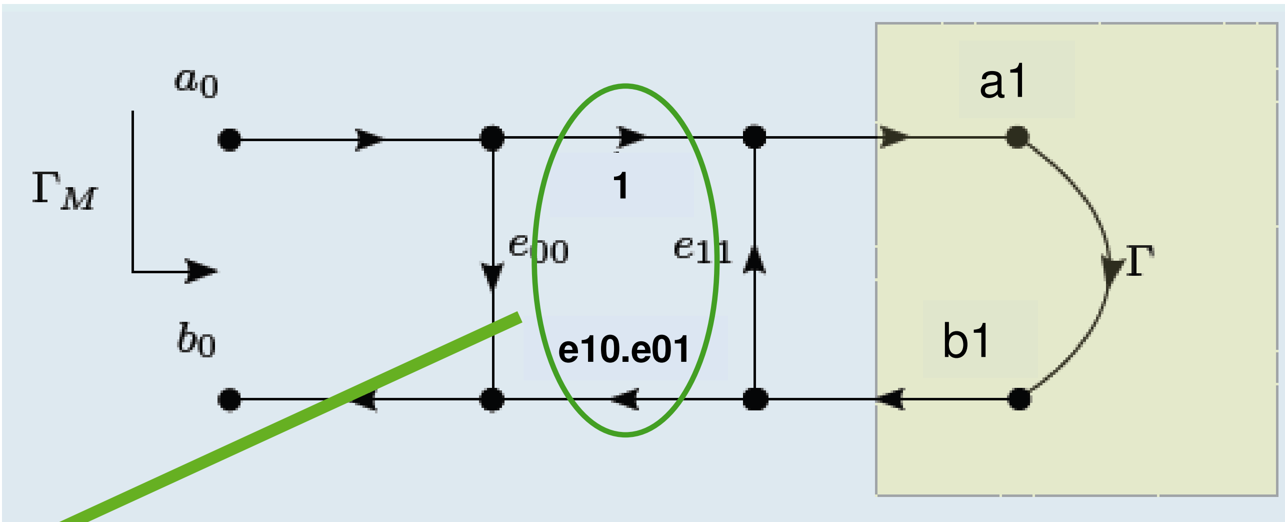


$$S_{11M} = \Gamma_M = \frac{b_0}{a_0}$$



$$S_{11} = \Gamma = \frac{b_1}{a_1}$$

Modelo de 3 Términos de Errores

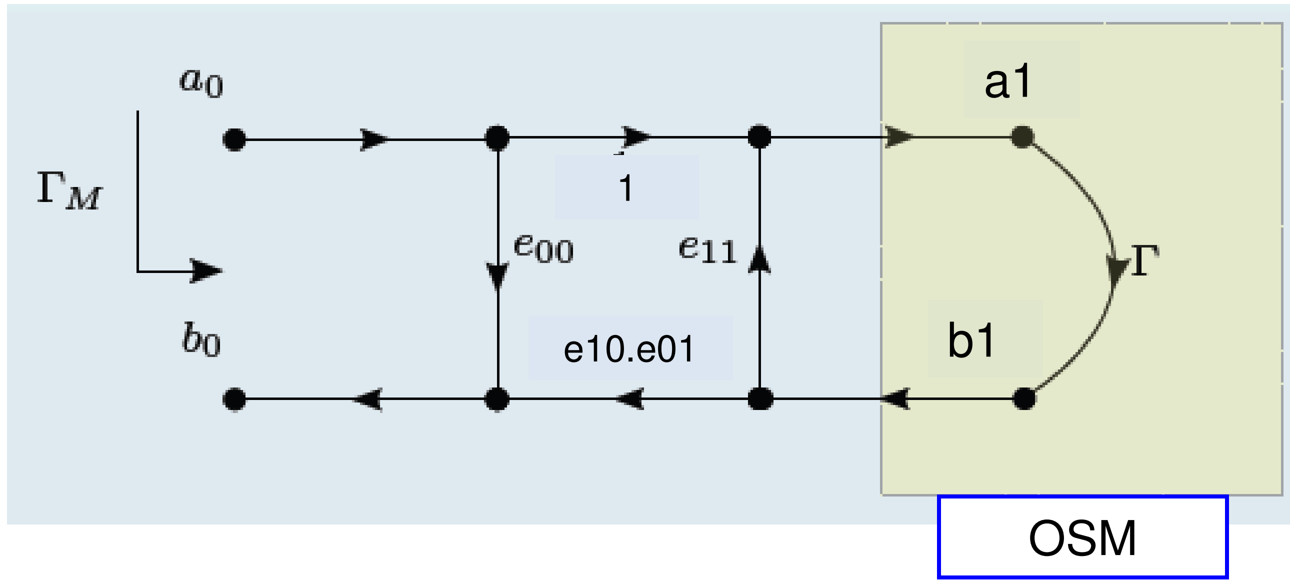


Aplico Mason

$$\Gamma_M = e_{00} + \frac{e_{10}.e_{01}.\Gamma}{(1 - e_{11}.\Gamma)} = \frac{e_{00} - \Gamma(e_{00}.e_{11} - e_{10}.e_{01})}{(1 - e_{11}.\Gamma)} = \frac{e_{00} - \Gamma.\Delta e}{(1 - e_{11}.\Gamma)}$$

Regla de Kuhn

Calibración OSM



$$\Gamma_M = \frac{e_{00} - \Gamma.\Delta e}{(1 - e_{11}.\Gamma)}$$

- e_{00}: directividad
- e_{11}: *source match*
- $\Delta_e = e_{00}e_{11} - e_{10}e_{01}$, siendo $e_{10}e_{01}$ el error de *tracking*

Cálculo de los 3 Términos de Error

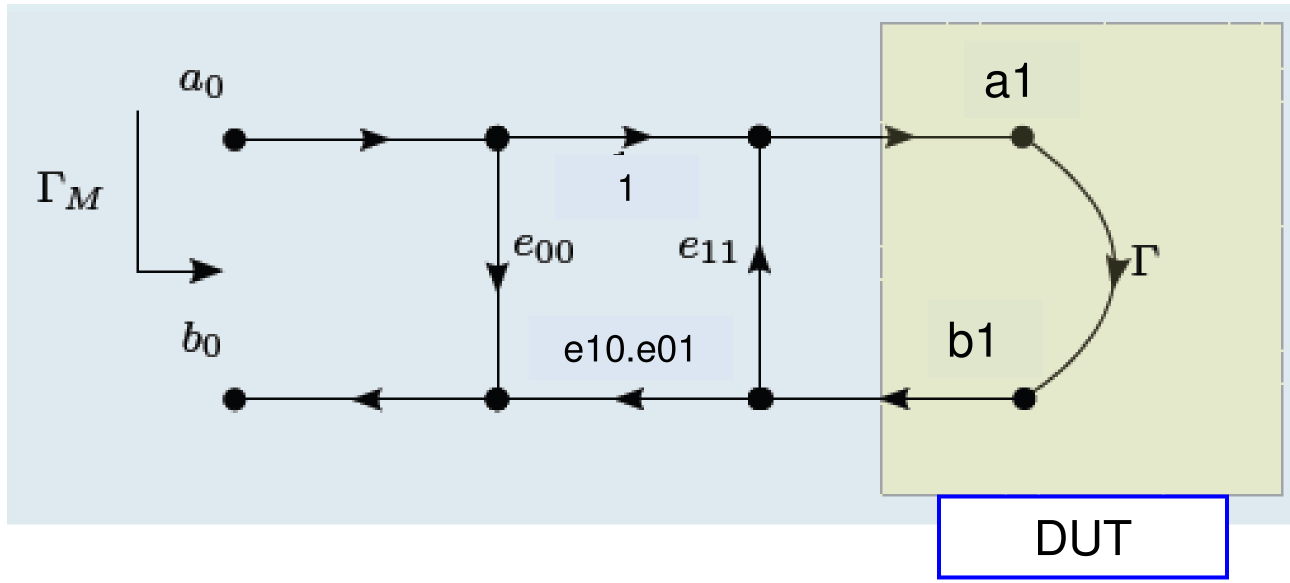
$$\Gamma_M = \frac{e_{00} - \Gamma.\Delta e}{(1 - e_{11}.\Gamma)}$$

$$e_{00} + \Gamma\Gamma_M e_{11} - \Gamma\Delta_e = \Gamma_M$$

$$\begin{bmatrix} 1 & \Gamma_1\Gamma_{M1} & -\Gamma_1 \\ 1 & \Gamma_2\Gamma_{M2} & -\Gamma_2 \\ 1 & \Gamma_3\Gamma_{M3} & -\Gamma_3 \end{bmatrix} \begin{bmatrix} e_{00} \\ e_{11} \\ \Delta_e \end{bmatrix} = \begin{bmatrix} \Gamma_{M1} \\ \Gamma_{M2} \\ \Gamma_{M3} \end{bmatrix} \begin{array}{l} \text{Match} \\ \text{Open} \\ \text{Short} \end{array}$$

Condición	Parámetro	Modelo utilizado	Observaciones
Match	Γ_1	$Z_L = 50\ \Omega$	Utilización de sliding-load para altas frecs.
Open	Γ_2	$Z_L = 1/j\omega C_T$	$C_T = C_0 + C_1 f + C_2 f^2 + C_3 f^3$
Short	Γ_3	$Z_L = j\omega L_T$	$L_T = L_0 + L_1 f + L_2 f^2 + L_3 f^3$

Medición DUT



$$\Gamma_M = \frac{e_{00} - \Gamma.\Delta e}{(1 - e_{11}.\Gamma)}$$

Despejo Γ

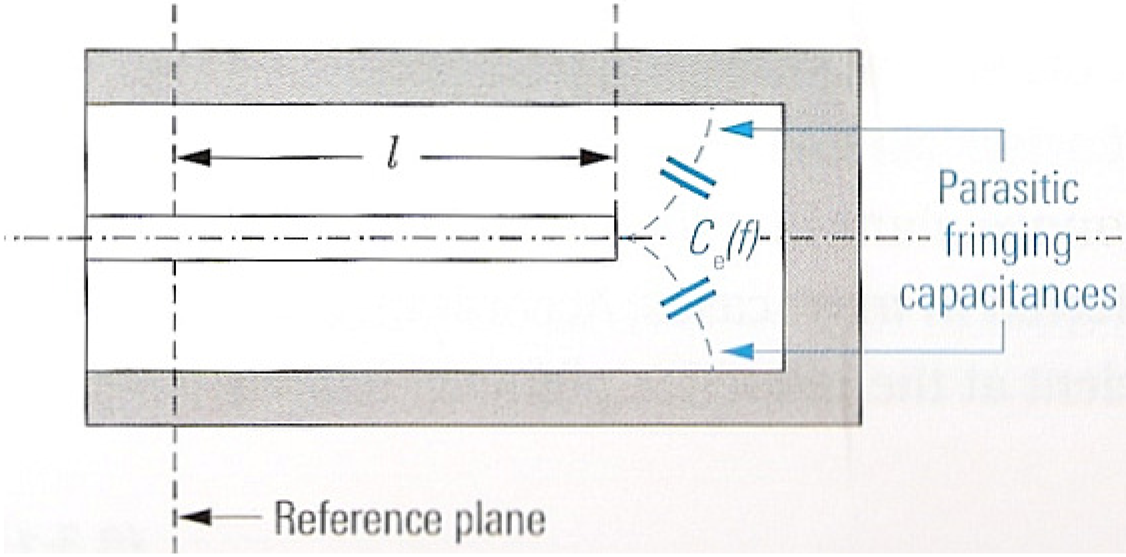
$$\Gamma = \frac{\Gamma_M - e_{00}}{(\Gamma_M.e_{11} - \Delta e)}$$

Algoritmo de corrección

OPEN (Circuito Abierto)

$$\Gamma_{open} = \frac{Z_{open} - Z_0}{Z_{open} + Z_0} e^{-2\gamma l}$$

$$Z_{open} = \frac{1}{j\omega C(f)}$$



$$C(f) = C_0 + C_1 f + C_2 f^2 + C_3 f^3$$

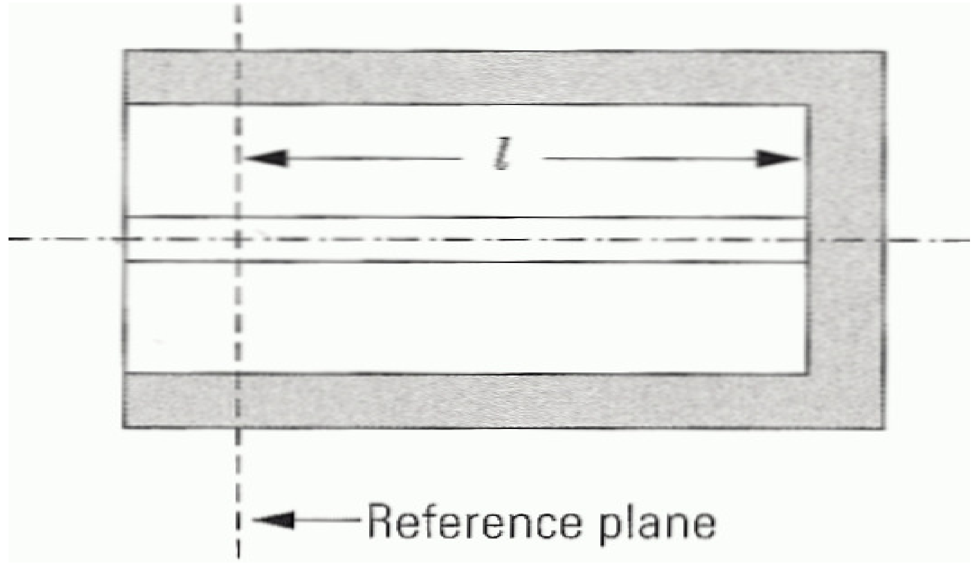
Offset length	Phase uncertainty		Polynomial coefficients for the fringing capacitance			
	0 to 8 GHz	8 to 26.5 GHz	C_0	C_1	C_2	C_3
5.00 mm	≤0.5°	≤2.5°	13.6348 fF	−0.2164 fF/GHz	0.0189 fF/GHz^2	−0.00028 fF/GHz^3

Especificación típica

SHORT (Corto Circuito)

$$\Gamma_{short} = \frac{Z_{short} - Z_0}{Z_{short} + Z_0} e^{-2\gamma l}$$

$$Z_{short} = j\omega L(f)$$

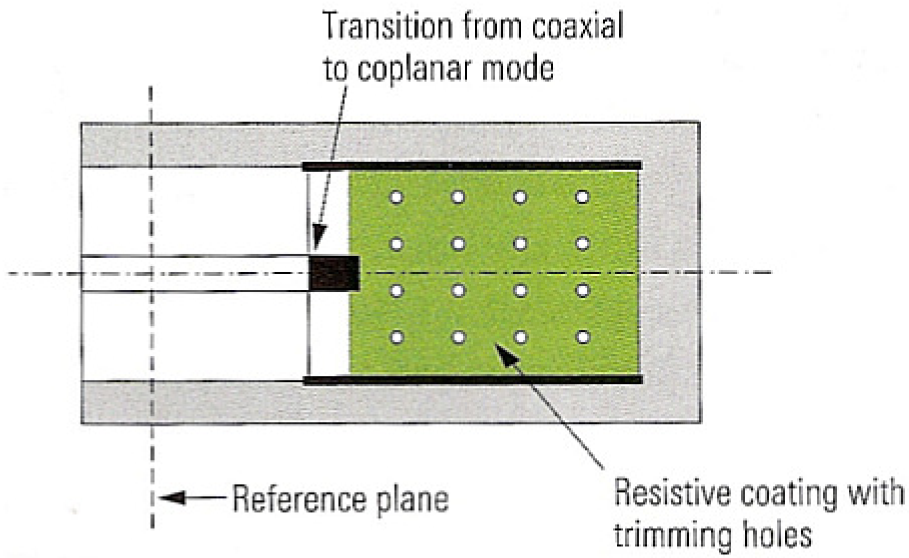


$$L(f) = L_0 + L_1 f + L_2 f^2 + L_3 f^3$$

Offset length	Phase uncertainty		Polynomial coefficients for the inductance			
	0 to 8 GHz	8 to 26.5 GHz	L_0	L_1	L_2	L_3
5.00 mm	≤0.5°	≤2.0°	0 pH	0 pH/GHz	0 pH/GHz^2	0 pH/GHz^3

Especificación típica

MATCH (Carga Adaptada)



DC resistance	Return loss		Max. power
	0 to 4 GHz	4 to 26.5 GHz	
50 Ω ± 0.5 Ω	≥40 dB	≥30 dB	0.5 W (27 dBm)

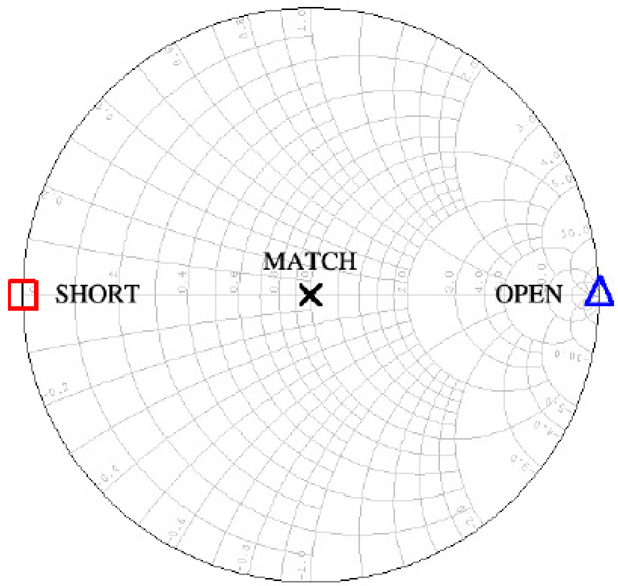
Especificación típica para un open

- Es una impedancia con gran BW, cuyo valor se corresponde a la Zo del sistema
- En la figura se ve una implementación cuyo conductor central termina en un sustrato con revestimiento resistivo, el cual es agujereado mediante un laser para ajusta de manera optima el valor .
- Con esta técnica pueden lograrse pérdidas de retorno del orden de 45dB (hasta 4GHz)
- Inicialmente se consideraba $\Gamma = 0$ en el modelo de calibración. En la actualidad los VNA permiten incluir las propiedades no-ideales del match

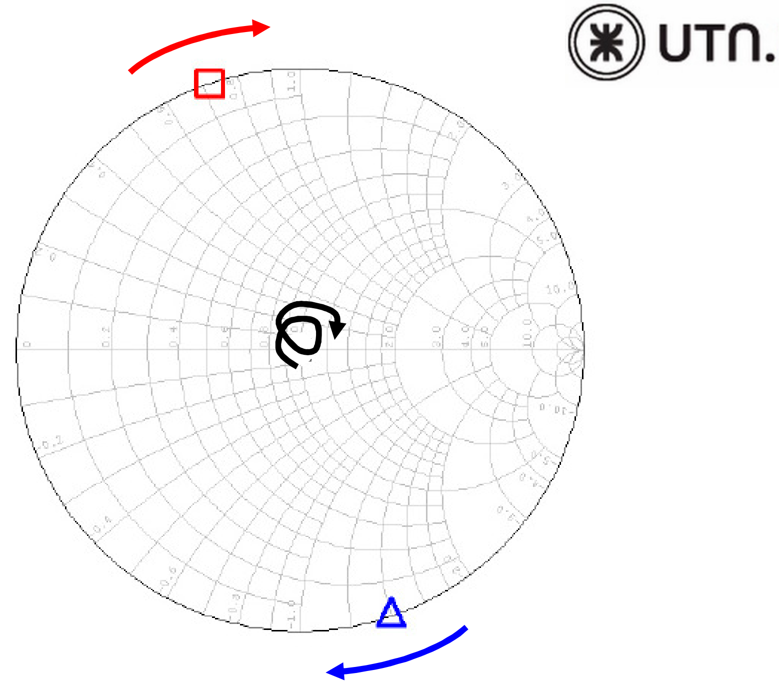
Kit de Calibración OSM

OSM conector N(f)

OSM conector N(m)



Frec < 2 GHz



Frec > 2 GHz

OPEN => $\Gamma 2 \approx 1$

SHORT => $\Gamma 3 \approx -1$

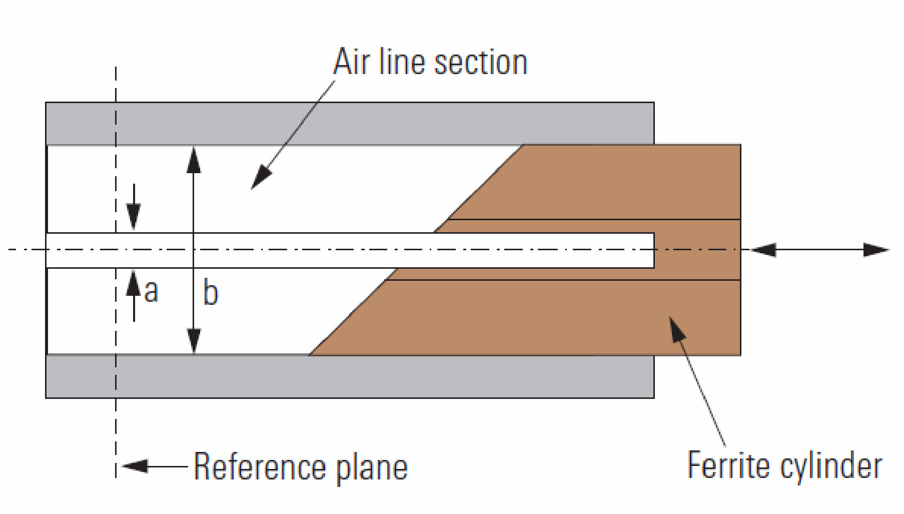
MATCH => $\Gamma 1 \approx 0$

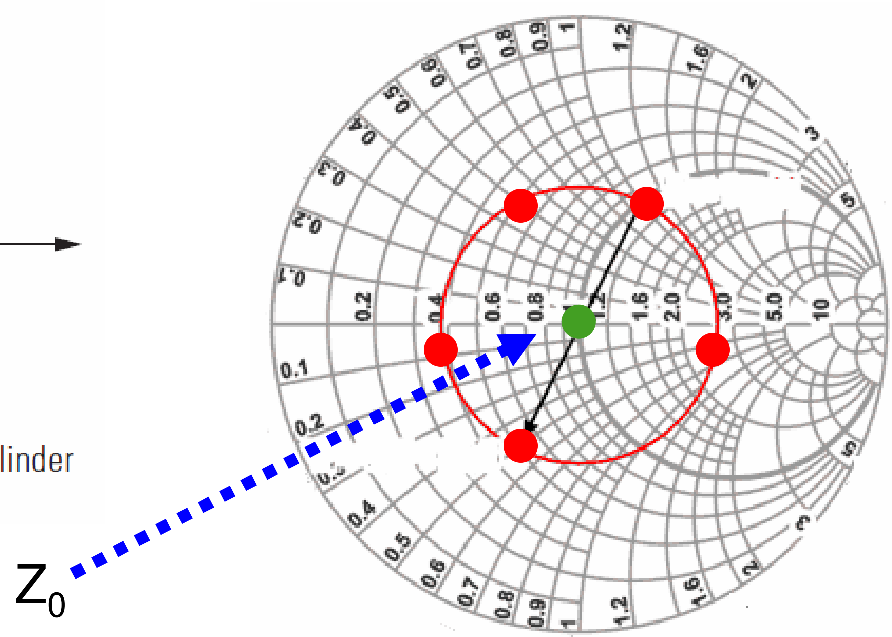
OPEN => $\Gamma 2 = \dfrac{1 - j2\pi f Z_0 C_e(f)}{1 + j2\pi f Z_0 C_e(f)} e^{-j4\pi l/\lambda}$

SHORT => $\Gamma 3 = \dfrac{j2\pi f L_e(f) - Z_0}{j2\pi f L_e(f) + Z_0} e^{-j4\pi l/\lambda}$

~~MATCH~~ → SLIDING LOAD

Sliding Loads





Calibración a 2 Puertos

Métodos Full 2-Port:

- TOSM
- TRL

Métodos incompletos

Métodos de Calibración: TOSM (SOLT)

Método	Standards de calibración necesarios	Términos de error	Conexiones mínimas
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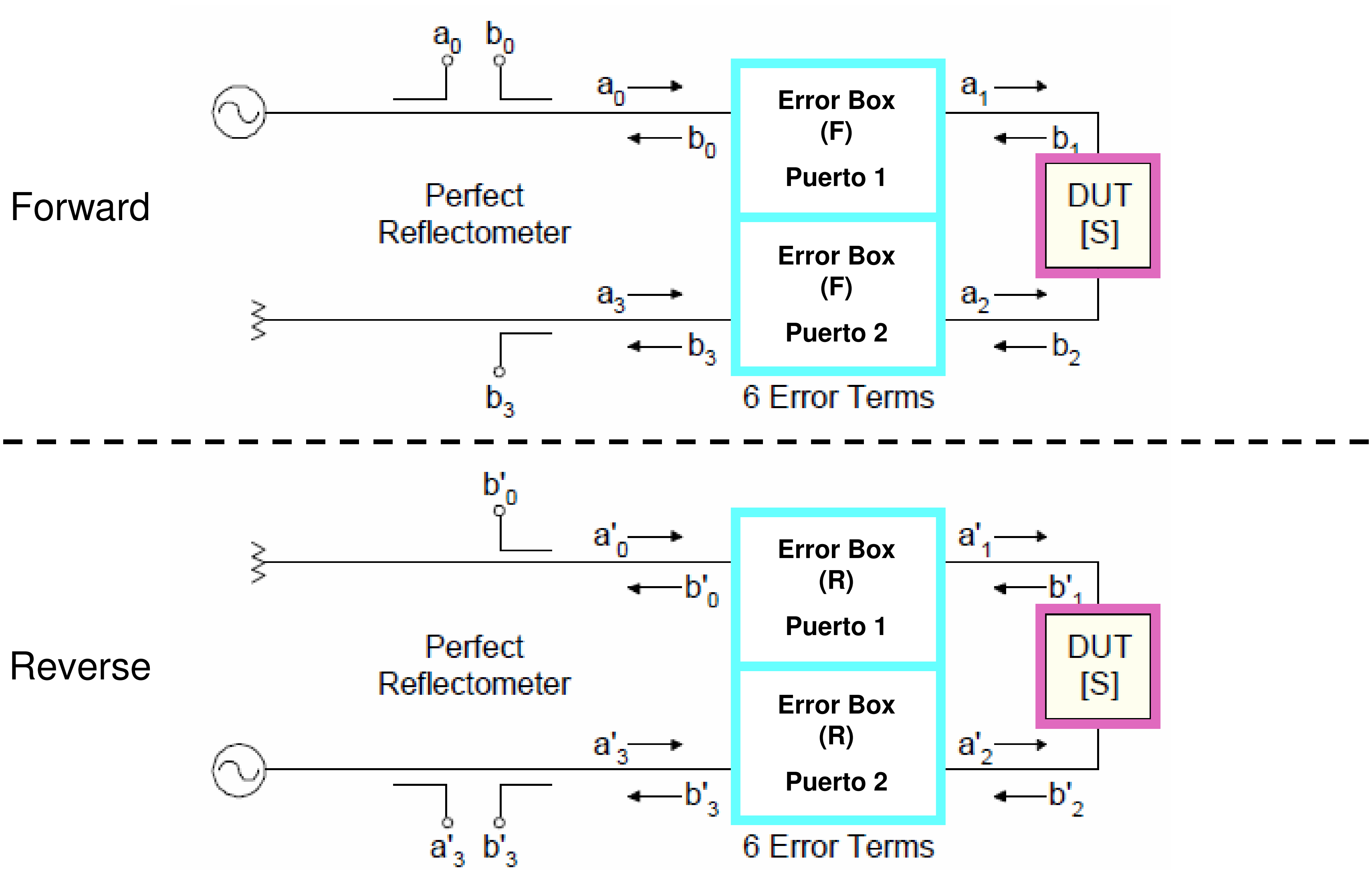
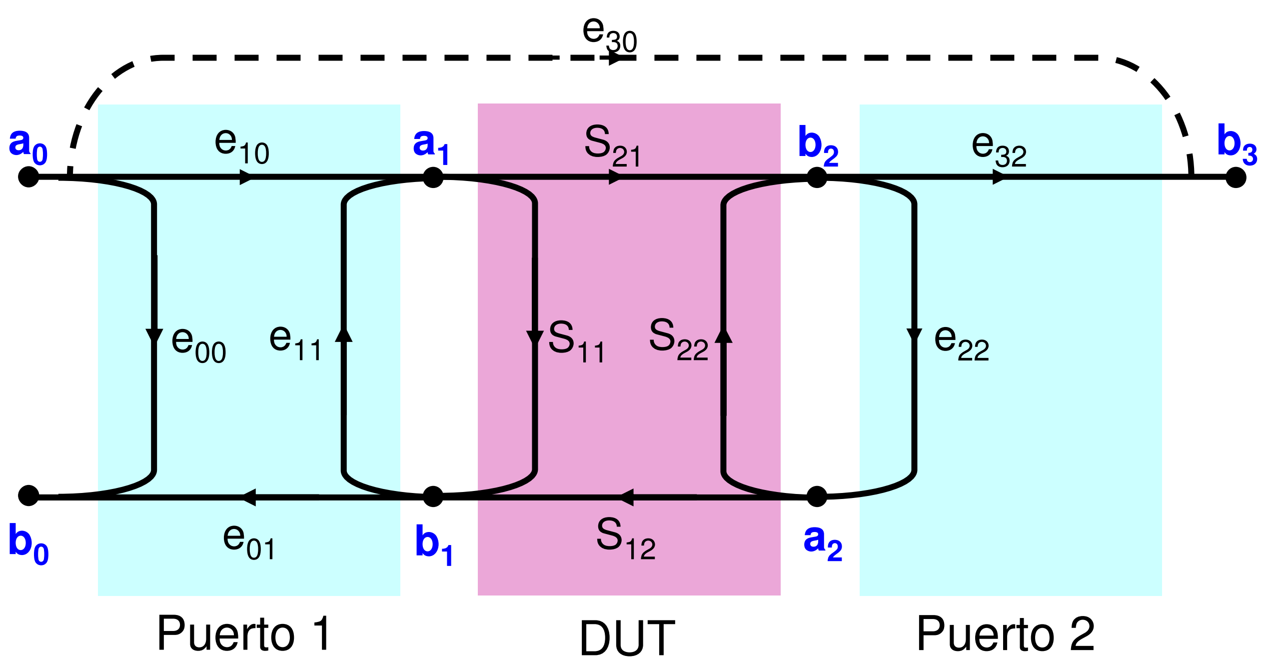
Multiline TRL	Multiline Through-Reflect-Line		

Modelo de 12 Términos de Error



Método de Calibración: TOSM

Modelo de Corrección Forward (S_{11} y S_{21})



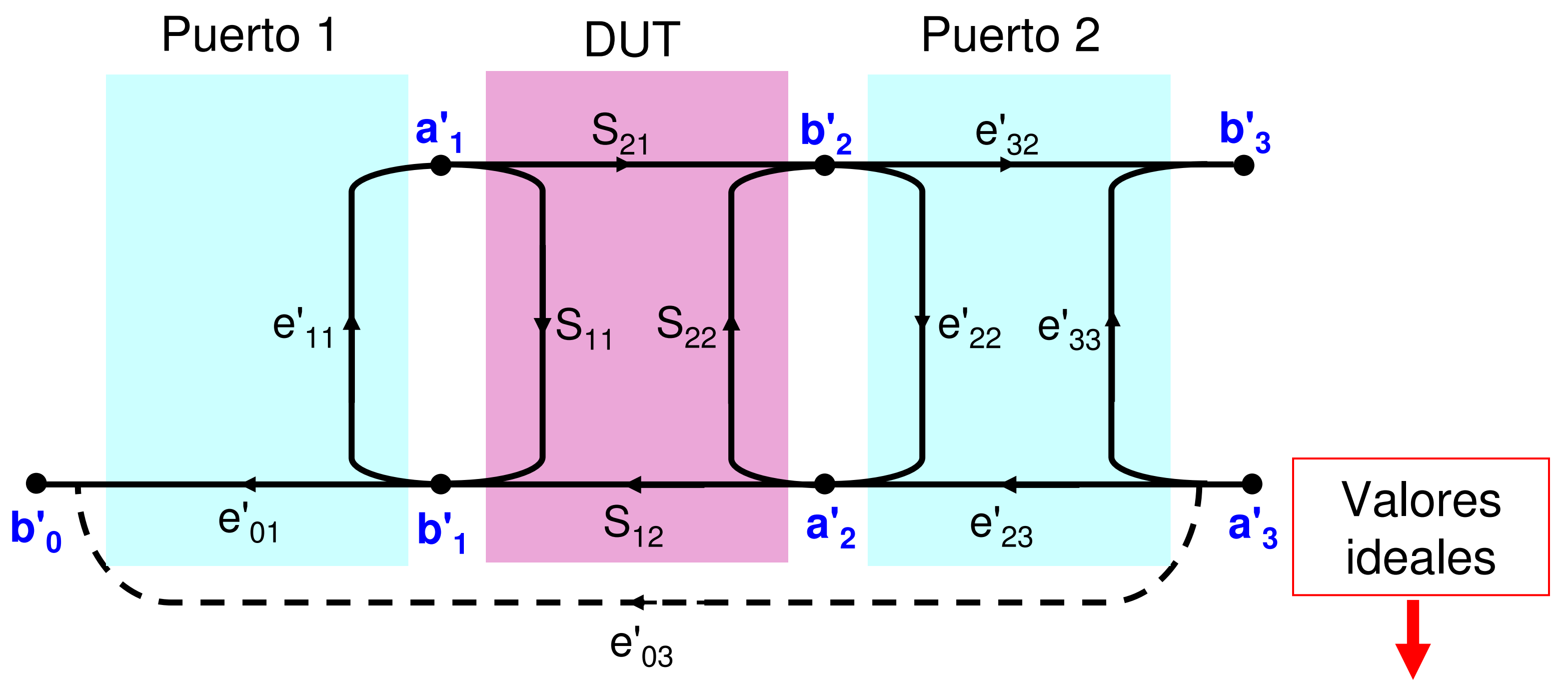
Valores ideales

Términos de Error

Directividad (F)	e00	=	0
Source Match del Puerto 1	e11	=	0
Tracking de Reflexión (F)	e10.e01	=	1
Tracking de Transmisión (F)	e10.e32	=	1
Crosstalk entre puertos (F)	e30	=	0
Load Match del Puerto 2	e22	=	0

Método de Calibración: TOSM

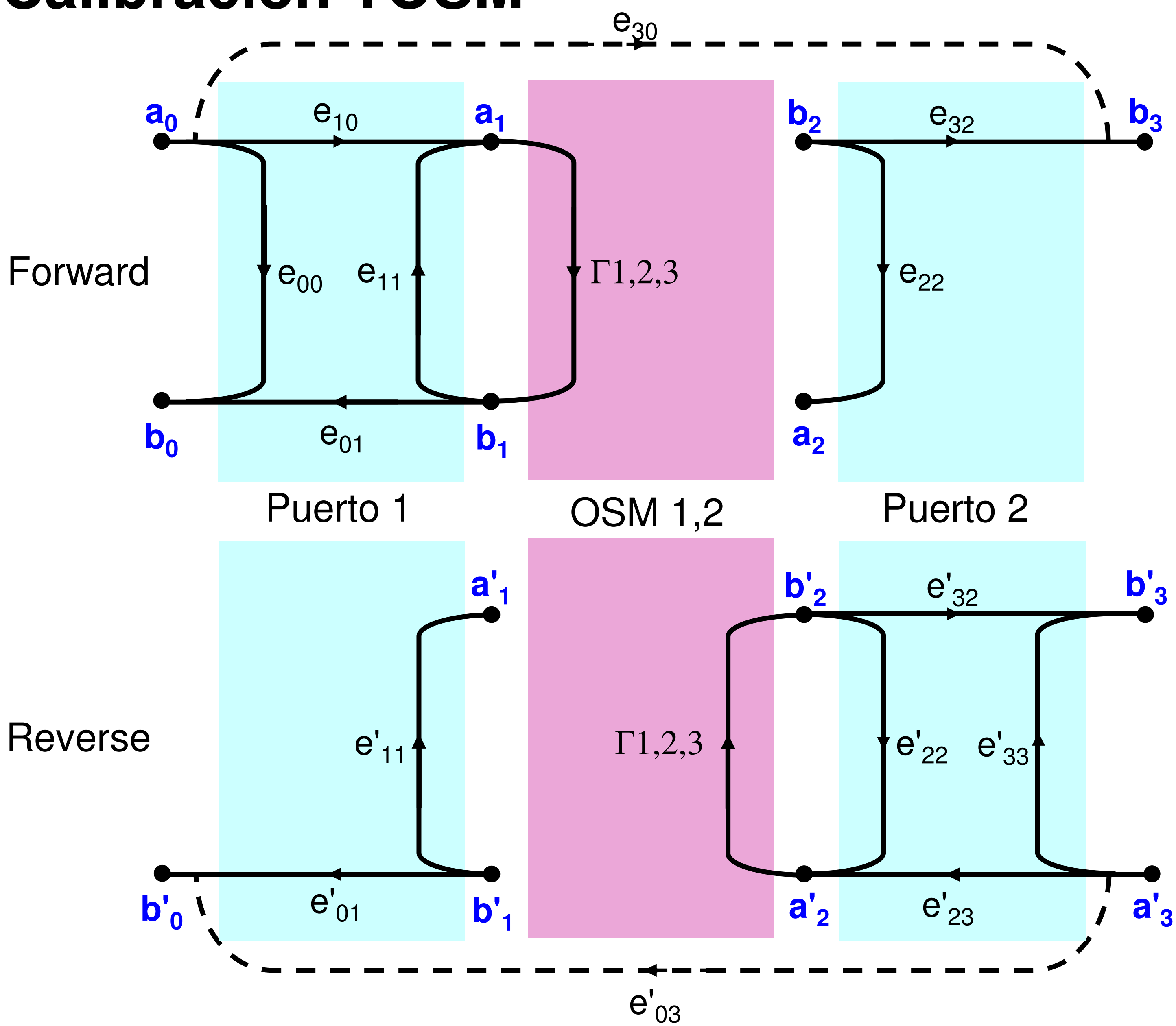
Modelo de Corrección Reverse (S_{22} y S_{12})



Términos de Error

Directividad (R)	e‘33	= 0
Source Match del Puerto 2	e‘22	= 0
Tracking de Reflexión (R)	e’23.e‘32	= 1
Tracking de Transmisión (R)	e’01.e‘23	= 1
Crosstalk entre puertos (R)	e'03	= 0
Load Match del Puerto 1	e‘11	= 0

Calibración TOSM



e00

e11

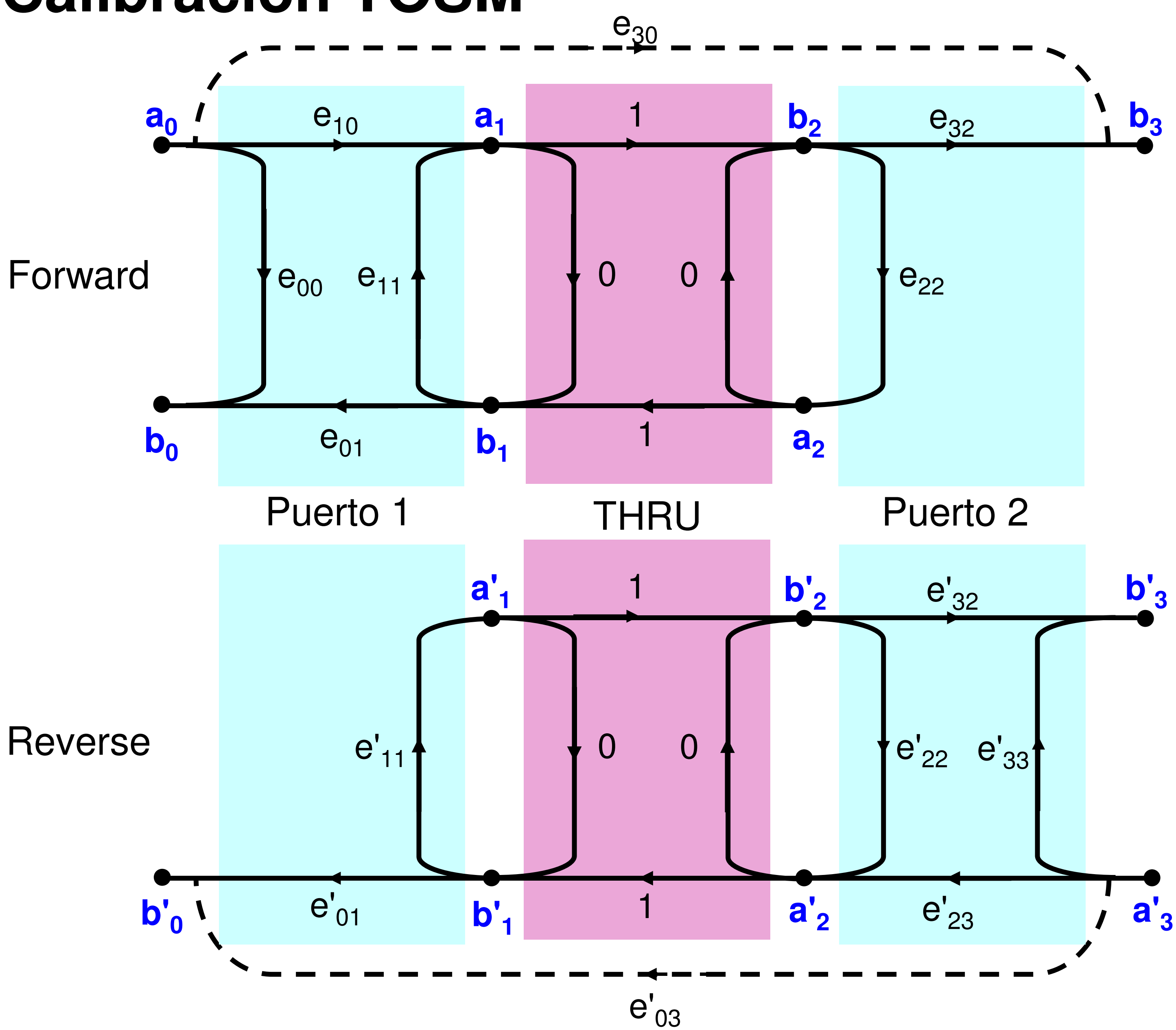
e10.e01

e'33

e'22

e'23.e'32

Calibración TOSM



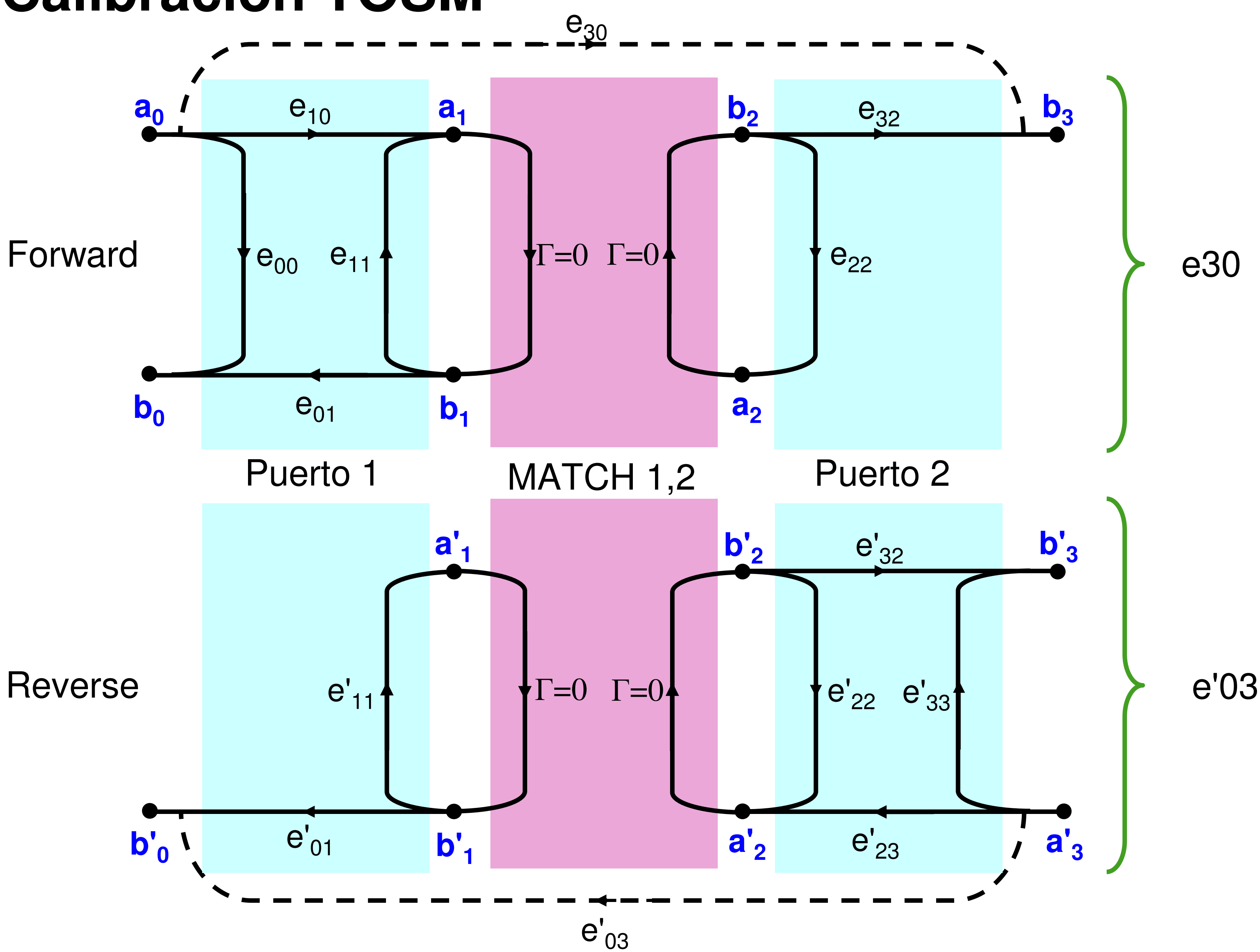
e22

e10.e32

e’11

e’01.e‘23

Calibración TOSM



Cálculo de los Términos de Error (Forward)

Calibración Puerto 1 (OSM):

$$e_{00} = S_{11M}(match)$$

$$e_{11} = \frac{S_{11M}(open) + S_{11M}(short) - 2 \cdot e_{00}}{S_{11M}(open) - S_{11M}(short)}$$

$$e_{10}e_{01} = \frac{-2 \cdot (S_{11M}(open) - e_{00}) \cdot (S_{11M}(short) - e_{00})}{S_{11M}(open) - S_{11M}(short)}$$

Crosstalk entre Puertos (Match):

$$e_{30} = S_{21M}(match_{1,2})$$

Calibración entre Puertos (Thru):

$$e_{22} = \frac{S_{11M}(Thru) - e_{00}}{S_{11M}(Thru) \cdot e_{11} - (e_{00}.e_{11} - e_{10}e_{01})}$$

$$e_{10}e_{32} = \left(S_{21M}(Thru) - e_{30}\right) \cdot \left(1 - e_{11}.e_{22}\right)$$

Referencias utilizadas:

$\Gamma_{OPEN} = 1$
$\Gamma_{SHORT} = -1$
$\Gamma_{MATCH} = 0$

$$S_{THRU} = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$$

Cálculo de los Términos de Error (Reverse)

Calibración Puerto 2 (OSM):

$$e'_{33} = S_{22M}\left(match_2\right)$$

$$e'_{11} = \frac{S_{22M}(open_2) + S_{22M}(short_2) - 2 \cdot e'_{33}}{S_{22M}(open_2) - S_{22M}(short_2)}$$

$$e'_{23}e'_{32} = \frac{-2 \cdot \left[S_{22M}(open_2) - e'_{33}\right] \cdot \left[S_{22M}(short_2) - e'_{33}\right]}{S_{22M}(open_2) - S_{22M}(short_2)}$$

Crosstalk entre Puertos (Match):

$$e'_{03} = S_{12M}\left(match_{1,2}\right)$$

Calibración entre Puertos (Thru):

$$e'_{11} = \frac{S_{22M}(Thru) - e'_{33}}{S_{22M}(Thru) - \Delta e'}$$

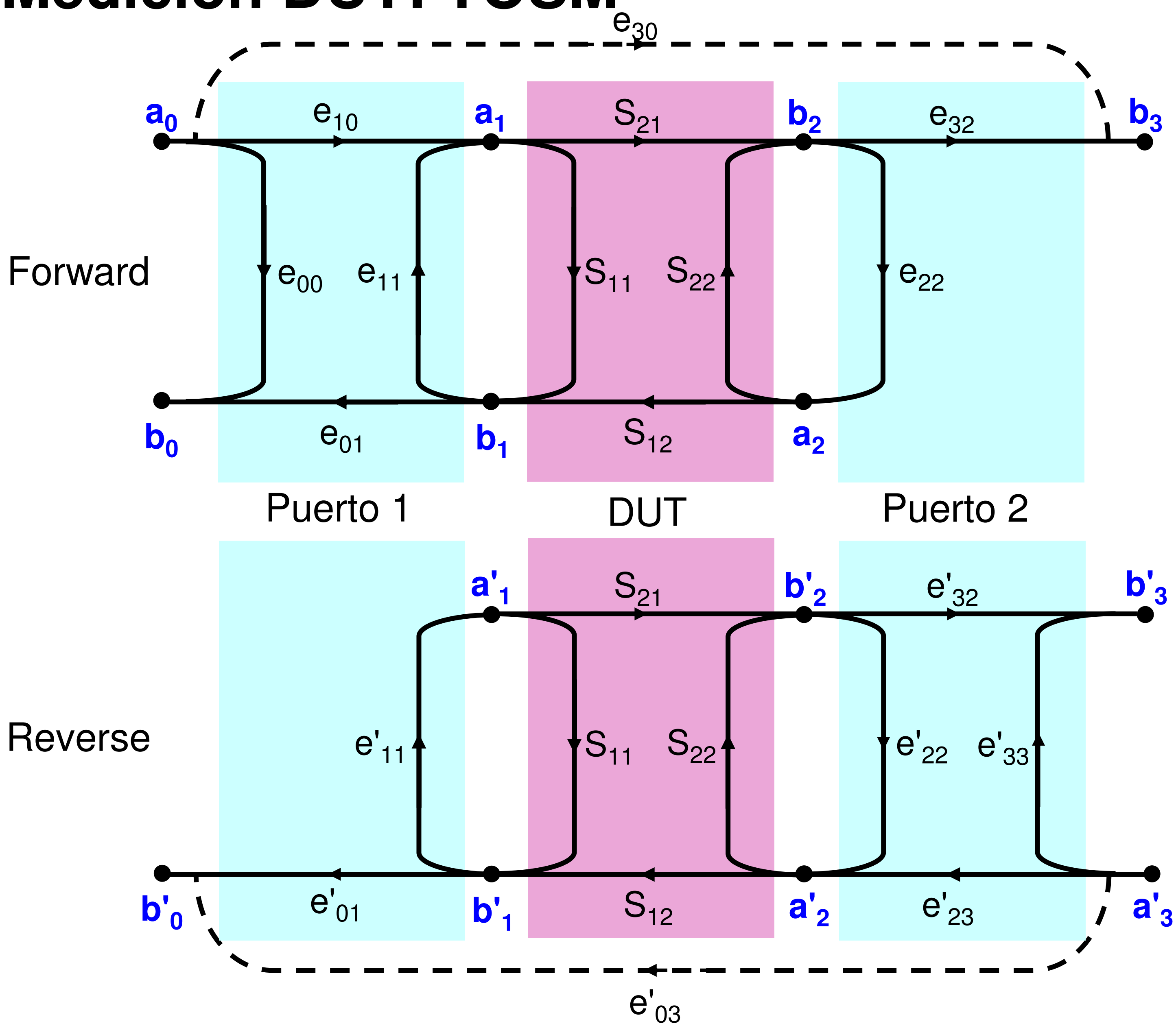
$$e'_{23}e'_{32} = \left[S_{12M}(Thru) - e'_{03}\right] \cdot (1 - e'_{33}e'_{11})$$

Referencias utilizadas:

$\Gamma_{OPEN} = 1$
$\Gamma_{SHORT} = -1$
$\Gamma_{MATCH} = 0$

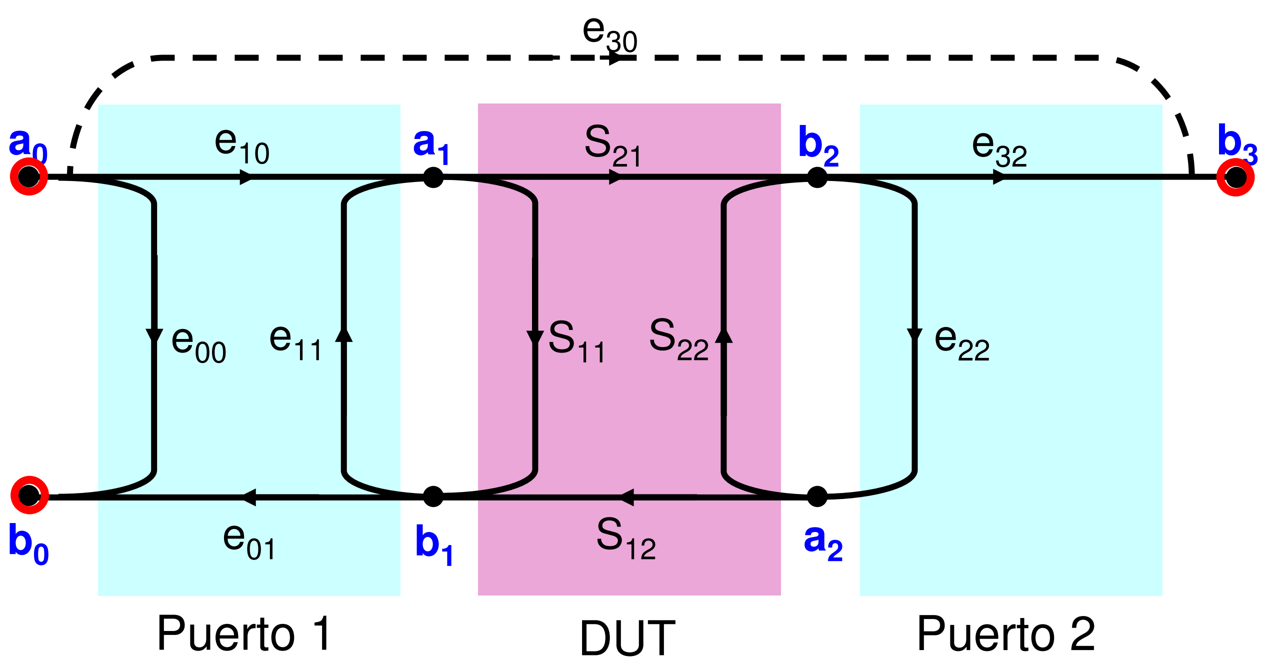
$$S_{THRU} = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$$

Medición DUT: TOSM



Método de Calibración: TOSM

Modelo de Corrección Forward (S_{11} y S_{21})



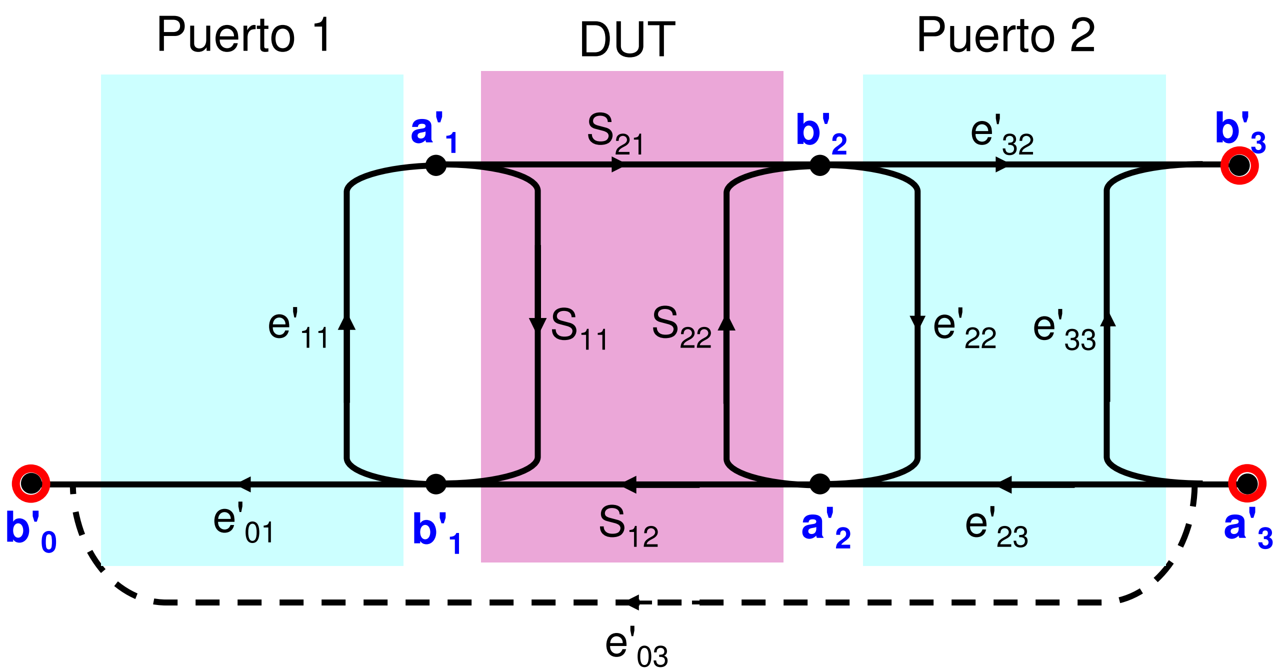
$$S_{11M} = \frac{b_0}{a_0} = e_{00} + \frac{e_{10}e_{01} \cdot (S_{11} - e_{22}\Delta_S)}{1 - e_{11}S_{11} - e_{22}S_{22} + e_{11}e_{22}\Delta_S}$$

$$S_{21M} = \frac{b_3}{a_0} = e_{30} + \frac{e_{10}e_{32} \cdot S_{21}}{1 - e_{11}S_{11} - e_{22}S_{22} + e_{11}e_{22}\Delta_S}$$

$$\Delta_S = S_{11}S_{22} - S_{12}S_{21}$$

Método de Calibración: TOSM

Modelo de Corrección Reverse (S_{22} y S_{12})



$$S_{22M} = \frac{b'_3}{a'_3} = e'_{33} + \frac{e'_{23}\, e'_{32} \cdot \left(S_{22} - e'_{11}\, \Delta_S\right)}{1 - e'_{11}\, S_{11} - e'_{22}\, S_{22} + e'_{11}\, e'_{22}\, \Delta_S}$$

$$\Delta_S = S_{11}S_{22} - S_{12}S_{21}$$

$$S_{12M} = \frac{b'_0}{a'_3} = e'_{03} + \frac{e'_{23}\, e'_{01} \cdot S_{12}}{1 - e'_{11}\, S_{11} - e'_{22}\, S_{22} + e'_{11}\, e'_{22}\, \Delta_S}$$

Algoritmos de Corrección: TOSM

$$S_{11} = \frac{N_{11} \cdot (1 + N_{22} \cdot e'_{22}) - e_{22} \cdot N_{21} \cdot N_{12}}{D}$$

$$S_{21} = \frac{N_{21} \cdot [1 + N_{22} \cdot (e'_{22} - e_{22})]}{D}$$

$$S_{22} = \frac{N_{22} \cdot (1 + N_{11} \cdot e_{11}) - e'_{11} \cdot N_{21} \cdot N_{12}}{D}$$

$$S_{12} = \frac{N_{12} \cdot [1 + N_{11} \cdot (e_{11} - e'_{11})]}{D}$$

$$N_{11} = \frac{S_{11M} - e_{00}}{e_{10} e_{01}}$$

$$N_{12} = \frac{S_{12M} - e'_{03}}{e'_{23} e'_{01}}$$

$$N_{21} = \frac{S_{21M} - e_{30}}{e_{10} e_{32}}$$

$$N_{22} = \frac{S_{22M} - e'_{33}}{e'_{23} e'_{32}}$$

$$D = (1 + N_{11} \cdot e_{11}) \cdot (1 + N_{22} \cdot e'_{22}) - N_{21} \cdot N_{12} \cdot e_{22} \cdot e'_{11}$$

4 Parámetros S del DUT $\left\{ \begin{array}{l} \text{12 términos de error (6 F y 6 R)} \\ \text{4 Parámetros S medidos del DUT} \end{array} \right.$

Kit de Calibración mecánico TOSM – Conector N

Kit de Calibración Electrónico

Cálculo Incertidumbres: S_{11} a 1 Puerto

$$S_{11} = \frac{S_{11CORR} - e_{00RES}}{e_{01}e_{10RES} + e_{11RES}\left(S_{11CORR} - e_{00RES}\right)}$$

$$u(S_{11}) = \left|\frac{\partial S_{11}}{\partial e_{00}}\right|.u(e_{00}) + \left|\frac{\partial S_{11}}{\partial e_{11}}\right|.u(e_{11}) + \left|\frac{\partial S_{11}}{\partial e_{10}e_{01}}\right|.u(e_{10}e_{01})$$

$$u(S_{11}) = \left|-1\right|.u(e_{00}) + \left|-S_{11}{}^{2}\right|.u(e_{11}) + \left|-S_{11}\right|.u(e_{10}e_{01})$$

$$U(|S_{11}|) = E_D + \left|S_{11}{}^{2}\right|.E_S + \left|S_{11}\right|.(1 - E_{RT})$$

$$U\left(\phi S_{11}\right) = arcsen\left[\frac{U\left(|S_{11}|\right)}{|S_{11}|}\right]$$

Cálculo Incertidumbres: S_{11} a 2 Puertos

$$S_{11} = \frac{N_{11} \cdot (1 + N_{22} \cdot e'_{22}) - e_{22} \cdot N_{21} \cdot N_{12}}{D}$$

$$D = (1 + N_{11} \cdot e_{11}) \cdot (1 + N_{22} \cdot e'_{22}) - N_{21} \cdot N_{12} \cdot e_{22} \cdot e'_{11}$$

$$N_{11} = \frac{S_{11M} - e_{00}}{e_{10} e_{01}} \qquad N_{12} = \frac{S_{12M} - e'_{03}}{e'_{23} e'_{01}}$$

$$N_{21} = \frac{S_{21M} - e_{30}}{e_{10} e_{32}} \qquad N_{22} = \frac{S_{22M} - e'_{33}}{e'_{23} e'_{32}}$$

$$u(S_{11}) = \left|\frac{\partial S_{11}}{\partial e_{00}}\right| .u(e_{00}) + \left|\frac{\partial S_{11}}{\partial e_{11}}\right| .u(e_{11}) + \left|\frac{\partial S_{11}}{\partial e_{22}}\right| .u(e_{22}) + \left|\frac{\partial S_{11}}{\partial e_{10} e_{01}}\right| .u(e_{10} e_{01})$$

$$u(S_{11}) = |-1| .u(e_{00}) + \left|-S_{11}{}^{2}\right| .u(e_{11}) + |-S_{11}| .u(e_{10} e_{01}) + |-S_{21}.S_{12}| .u(e_{22})$$

$$U(|S_{11}|) = E_D + \left|S_{11}{}^{2}\right| .E_S + |S_{11}| .(1 - E_{RT}) + |S_{21}.S_{12}| .E_L$$

$$U(\phi S_{11}) = arcsen\left[\frac{U(|S_{11}|)}{|S_{11}|}\right]$$

Cálculo Incertidumbres: S_{21} a 2 Puertos

$$S_{21} = \frac{N_{21} \cdot [1 + N_{22} \cdot (e'_{22} - e_{22})]}{D}$$

$$D = (1 + N_{11} \cdot e_{11}) \cdot (1 + N_{22} \cdot e'_{22}) - N_{21} \cdot N_{12} \cdot e_{22} \cdot e'_{11}$$

$$N_{11} = \frac{S_{11M} - e_{00}}{e_{10}e_{01}} \qquad N_{12} = \frac{S_{12M} - e'_{03}}{e'_{23}e'_{01}}$$

$$N_{21} = \frac{S_{21M} - e_{30}}{e_{10}e_{32}} \qquad N_{22} = \frac{S_{22M} - e'_{33}}{e'_{23}e'_{32}}$$

$$u(S_{21}) = \left|\frac{\partial S_{21}}{\partial e_{30}}\right| .u(e_{30}) + \left|\frac{\partial S_{21}}{\partial e_{11}}\right| .u(e_{11}) + \left|\frac{\partial S_{21}}{\partial e_{22}}\right| .u(e_{22}) + \left|\frac{\partial S_{21}}{\partial e_{10}e_{32}}\right| .u(e_{10}e_{32})$$

$$u(S_{21}) = |-1| .u(e_{30}) + |-S_{11}.S_{21}| .u(e_{11}) + |-S_{21}.S_{22}| .u(e_{22}) + |-S_{21}| .u(e_{10}e_{32})$$

$$\frac{U(|S_{21}|)}{|S_{21}|} = \frac{E_X}{|S_{21}|} + |S_{11}|.E_S + |S_{22}|.E_L + (1 - E_{TT})$$

$$U(\phi S_{21}) = arcsen\left[\frac{U(|S_{21}|)}{|S_{21}|}\right]$$

Errores Residuales TOSM

System data	Raw system data	Effective system data
Reflection tracking	≤2 dB	≤0.04 dB
Directivity	≥29 dB	≥46 dB
Source match	≥22 dB	≥39 dB
Transmission tracking	≤2 dB	≤0,06 dB
Isolation	≥130 dB	≥130 dB
Load match	≥22 dB	≥44 dB

Directividad	$\|e00\| \leq 0,035$	$E_D \leq 0,005$
Source Match	$\|e11\| \leq 0,079$	$E_S \leq 0,011$
Tracking de Reflexión	$\|e10e01\| \geq 0,794$	$1-E_{RT} \leq 0,005$
Tracking de Transmisión	$\|e10e32\| \geq 0,794$	$1-E_{TT} \leq 0,007$
Crosstalk	$\|e30\| \leq 0,0000003$	$E_X \leq 0,0000003$
Load Match	$\|e22\| \leq 0,079$	$E_L \leq 0,006$

Métodos derivados del TOSM

Completo

TOSM

Incompleto

Normalización

1-Path 2-Port

1-Port + Normalización

Enhanced-Response

VNA – S Parameter

VNA – T/R

Métodos derivados del TOSM

Completo

TOSM

Incompleto

Normalización

1-Port + Normalización

Enhanced-Response

1-Path 2-Port

Ventajas

•Incertidumbres bajas (mide los 12 términos de error del modelo).

Desventajas

•Requiere 8 pasos de calibración.
•SIEMPRE debe medir los 4 parámetros S.

Métodos derivados del TOSM

Completo

TOSM

Incompleto

Normalización

1-Port +
Normalización

Enhanced-
Response

1-Path 2-Port

Ventajas

- Requieren entre 1 y 4 pasos de calibración (más rápido y simple).
- Miden 1 o 2 parámetros S (Forward o Reverse)

Desventajas

- Incertidumbres mas altas (miden **SOLO ALGUNO** de los 12 términos de error del modelo).

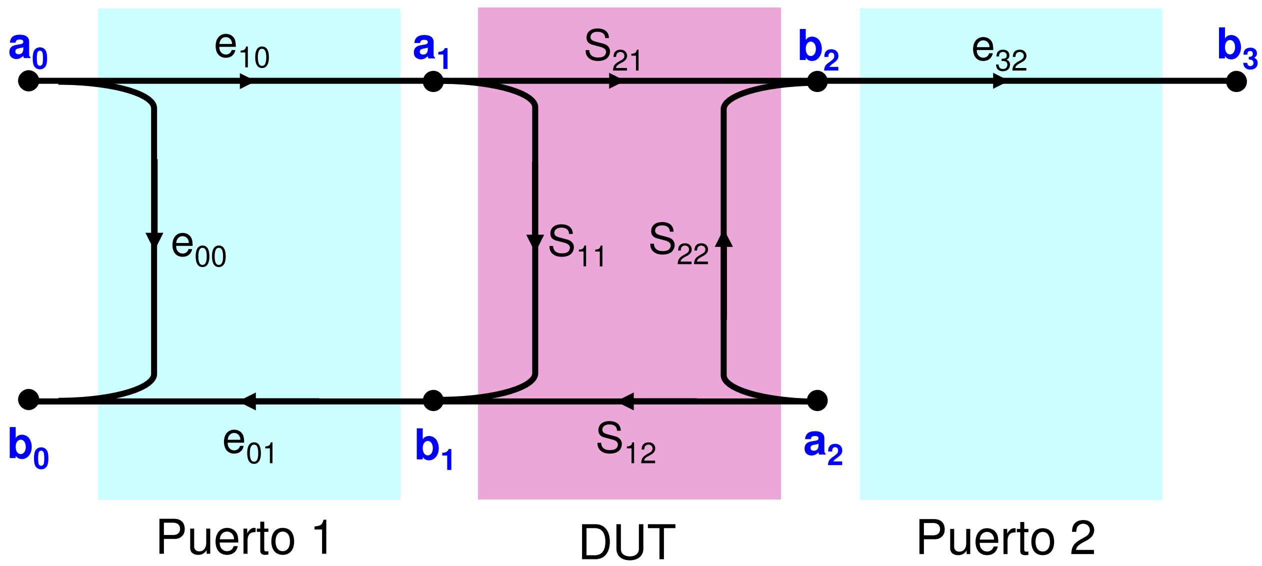
Método de Calibración : INCOMPLETO

- Normalización
- 1-Port + Normalización
- Enhanced-Response
- 1-Path 2-Port

- **Casos derivados del método TOSM.**
- **Calculan entre 1 y 5 términos de error.**
- **Algunos términos de error son calculados parcialmente.**
- **Introducen ERRORES SISTEMÁTICOS en la corrección de los parámetros S del DUT.**

Método de Calibración: Normalización

Modelo de Corrección Forward (S_{21})

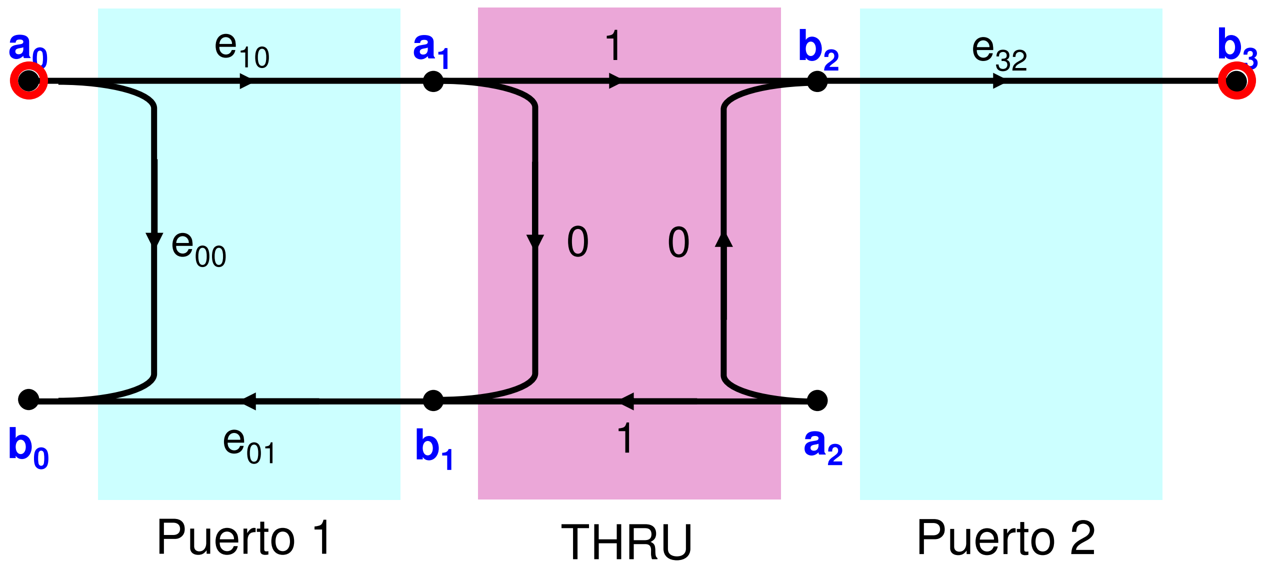


Términos de Error

Directividad (F)	e00	
Source Match del Puerto 1	e11	= 0
Tracking de Reflexión (F)	e10e01	
Tracking de Transmisión (F)	**e10e32**	
Crosstalk entre puertos (F)	e30	= 0
Load Match del Puerto 2	e22	= 0

Método de Calibración: Normalización

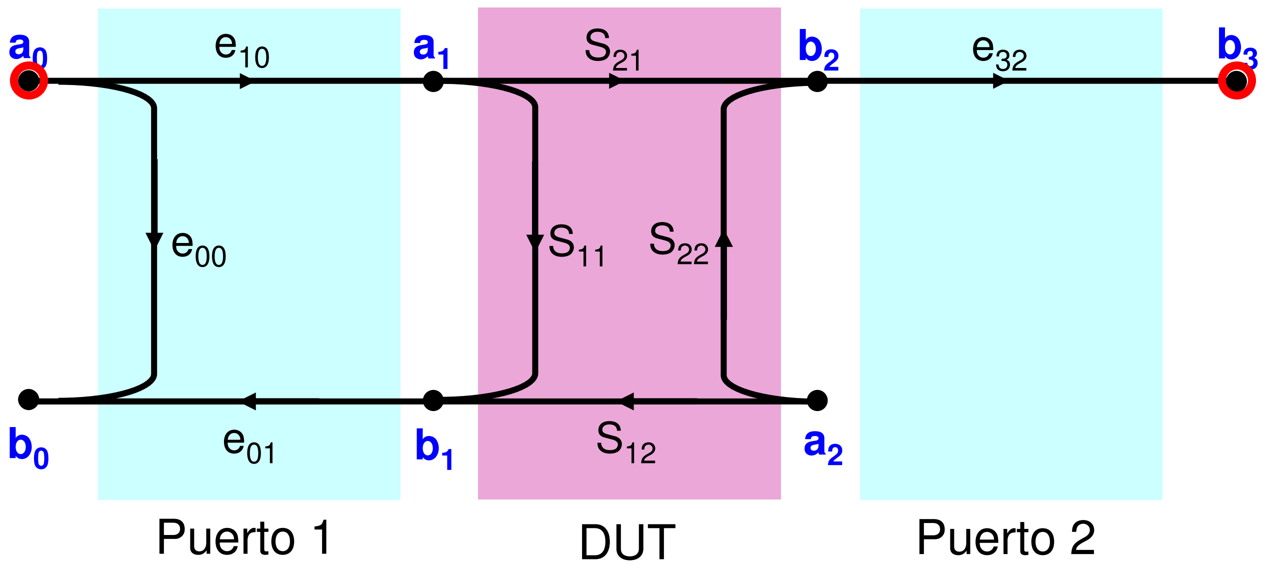
Calibración: Cálculo de $e_{10.}\ e_{32}$



$$S_{21M} = \frac{b_3}{a_0} = e_{10}e_{32} \quad => \quad e_{10}e_{32} = S_{21M}$$

Método de Calibración: Normalización

Medición DUT: S_{21}



$$S_{21M} = \frac{b_3}{a_0} = S_{21}.e_{10}e_{32} \quad => \quad S_{21} = \frac{S_{21M}}{e_{10}e_{32}}$$

Algoritmos de Corrección: Normalización

$$S_{21} = \frac{S_{21M}(DUT)}{e_{10}e_{32}}$$

S_{21} del DUT

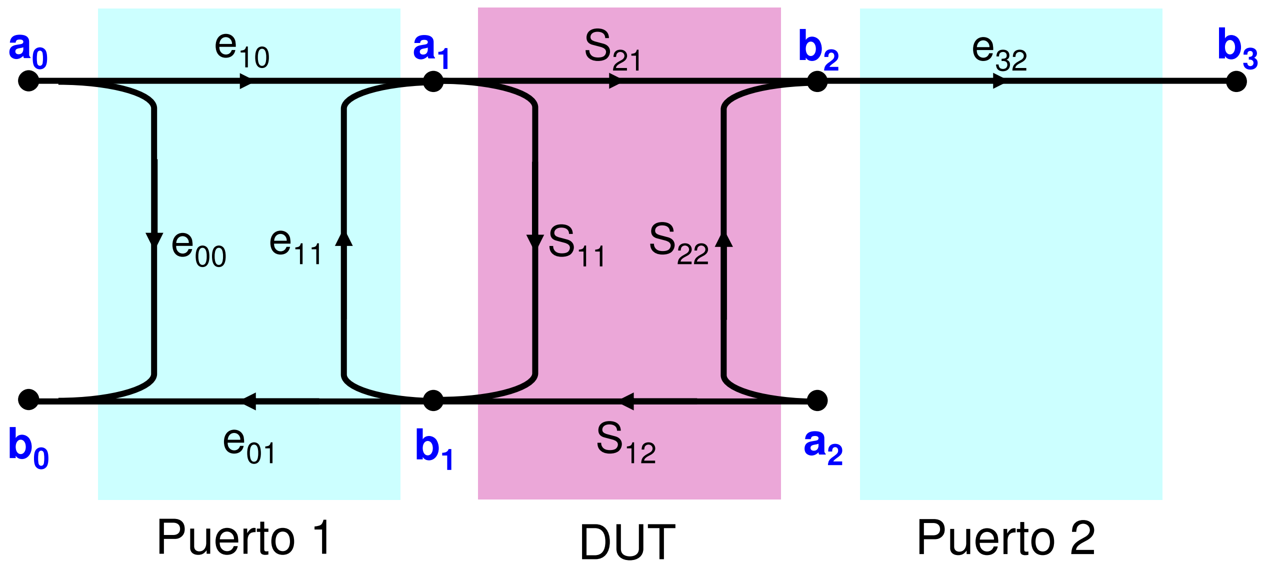
- 1 término de error ($e_{10}e_{32}$).
- S_{21} medido del DUT.

Error sistemático de S_{21}

- Tracking de Transmisión **parcialmente** calculado.
- Considerar nulos e_{30}, e_{11} y e_{22}.

Método de Calibración: 1-Port+N

Modelo de Corrección Forward (S_{11} y S_{21})

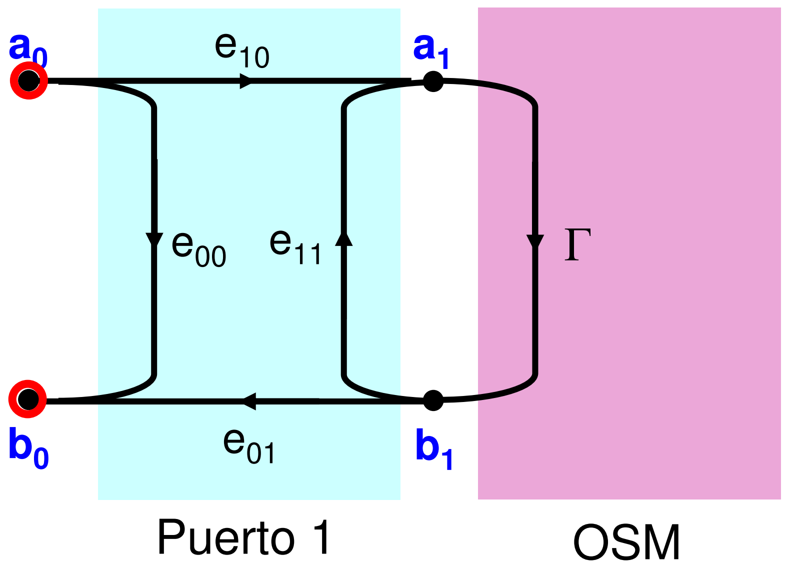


Términos de Error

Directividad (F)	e00	
Source Match del Puerto 1	e11	
Tracking de Reflexión (F)	e10e01	
Tracking de Transmisión (F)	e10e32	
Crosstalk entre puertos (F)	e30	= 0
Load Match del Puerto 2	e22	= 0

Método de Calibración: 1-Port+N

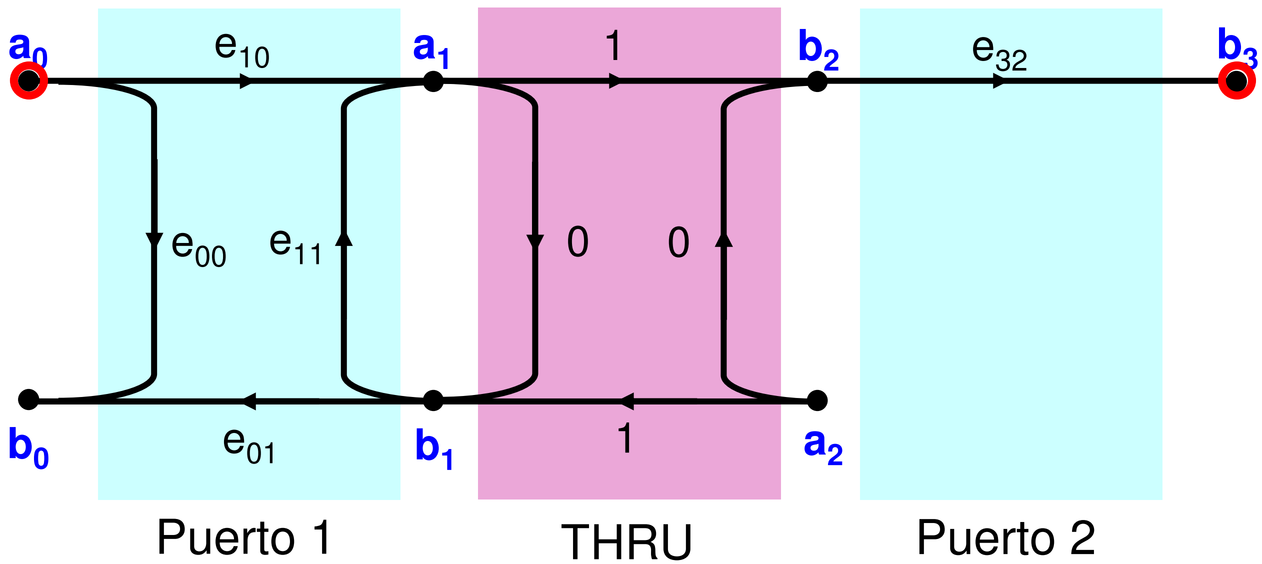
Calibración: Cálculo de e_{00}, e_{11} y $e_{10}.e_{01}$



Símil OSM

Método de Calibración: 1-Port+N

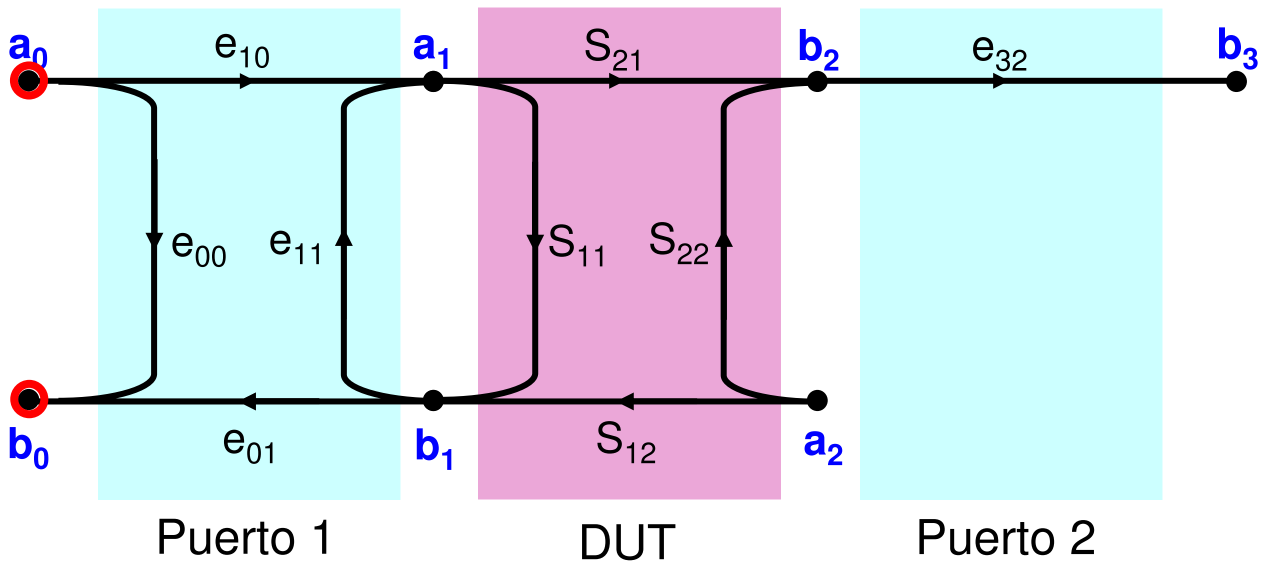
Calibración: Cálculo de $e_{10}.e_{32}$



$$S_{21M} = \frac{b_3}{a_0} = e_{10}e_{32} \quad \Rightarrow \quad e_{10}e_{32} = S_{21M}$$

Método de Calibración: 1-Port+N

Medición DUT: S_{11}

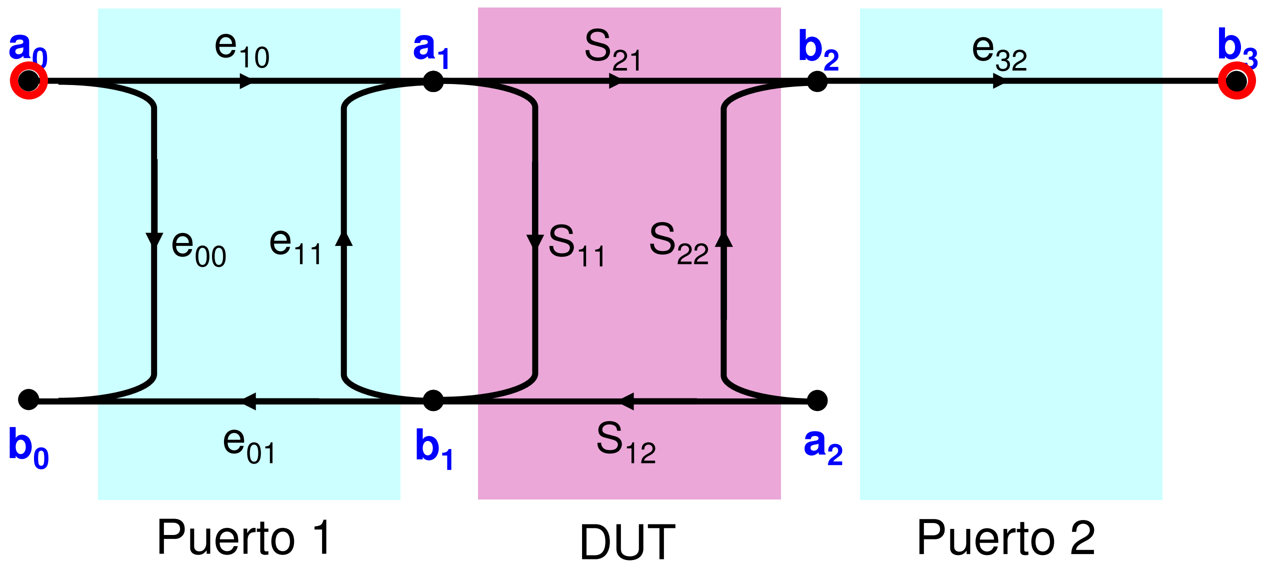


$$S_{11M} = \frac{b_0}{a_0} = e_{00} + \frac{e_{10}e_{01} \cdot S_{11}}{1 - e_{11}S_{11}} \quad \Rightarrow \quad S_{11} = \frac{S_{11M} - e_{00}}{S_{11M} \cdot e_{11} - \Delta e}$$

Idem S_{11} a 1 Puerto

Método de Calibración: 1-Port+N

Medición DUT: S_{21}



$$S_{21M} = \frac{b_3}{a_0} = S_{21}.e_{10}e_{32} \quad => \quad S_{21} = \frac{S_{21M}}{e_{10}e_{32}}$$

Algoritmos de Corrección: 1-PORT+N

$$S_{11} = \frac{S_{11M}(DUT) - e_{00}}{S_{11M}(DUT) \cdot e_{11} - \Delta e}$$

$$S_{21} = \frac{S_{21M}(DUT)}{e_{10}e_{32}}$$

S_{11} del DUT

- 3 términos de error.
- S_{11} medido del DUT.

S_{21} del DUT

- 1 término de error ($e_{10}e_{32}$).
- S_{21} medido del DUT.

Error sistemático de S_{11}

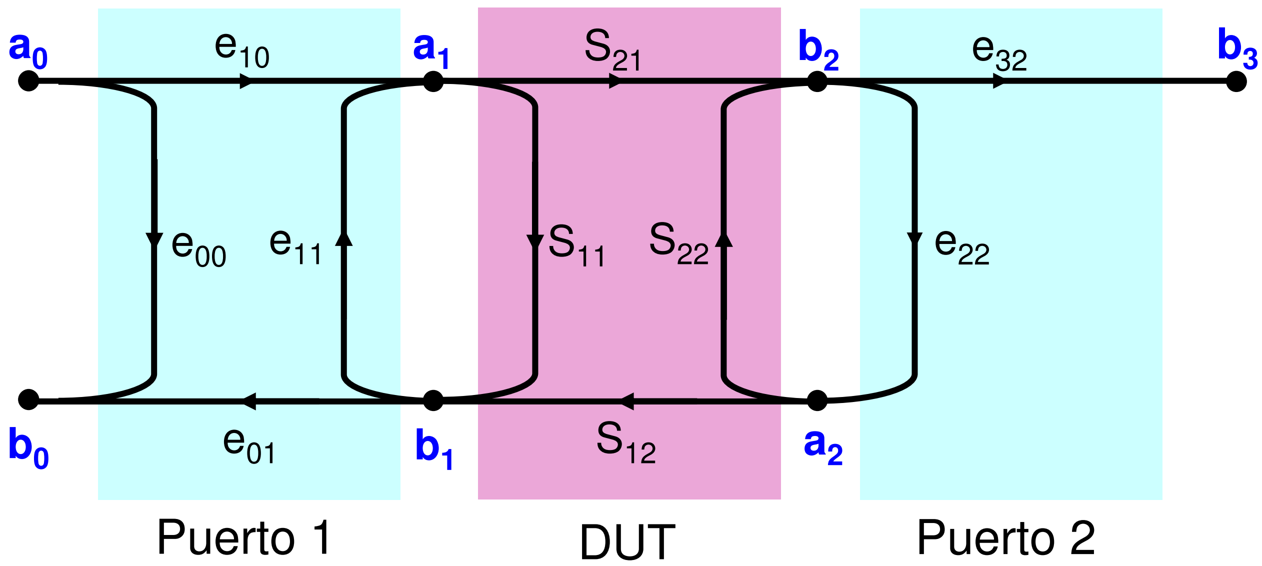
- Considera nulo e_{22}.
- Considera nulos todos los errores Reverse.

Error sistemático de S_{21}

- Tracking de Transmisión **parcialmente** calculado.
- Considerar nulos e_{30}, e_{11}, e_{22} y todos los errores Reverse.

Método de Calibración: Enhanced-Response

Modelo de Corrección Forward (S_{11} y S_{21})

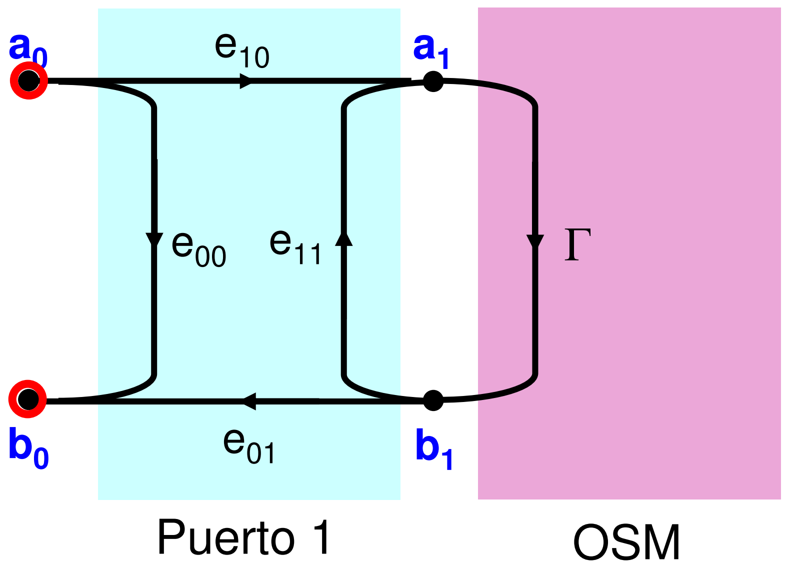


Términos de Error

Directividad (F)	e00	
Source Match del Puerto 1	e11	
Tracking de Reflexión (F)	e10e01	
Tracking de Transmisión (F)	e10e32	
Crosstalk entre puertos (F)	e30	= 0
Load Match del Puerto 2	**e22**	

Método de Calibración: Enhanced-Response

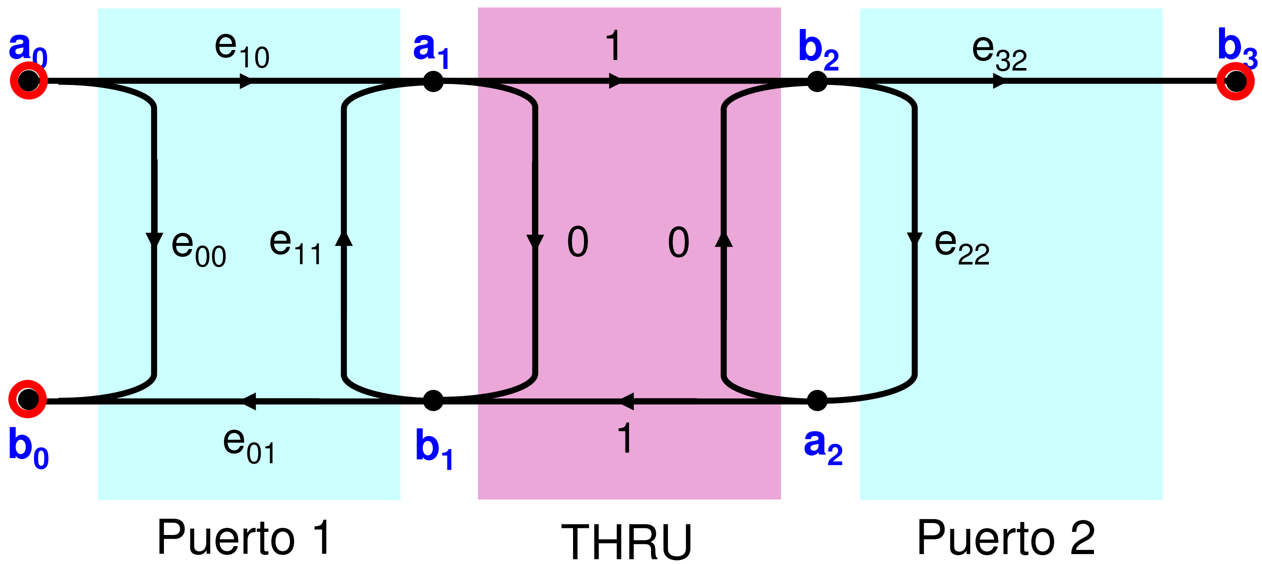
Calibración: Cálculo de e_{00}, e_{11} y $e_{10}.e_{01}$



Símil OSM

Método de Calibración: Enhanced-Response

Calibración: Cálculo de e_{22} y $e_{10.}e_{32}$

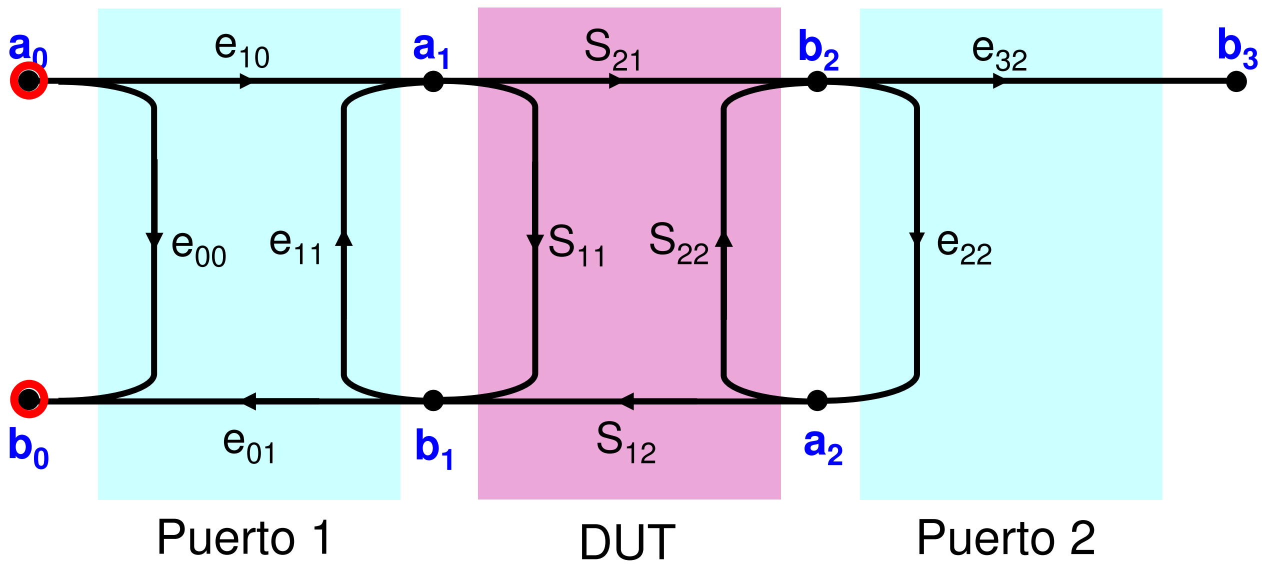


$$S_{11M} = \frac{b_0}{a_0} = e_{00} + \frac{e_{10}e_{01} \cdot \left(S_{11} - e_{22}\Delta_S\right)}{1 - e_{11}S_{11} - e_{22}S_{22} + e_{11}e_{22}\Delta_S} \quad \Rightarrow \quad e_{22} = \frac{S_{11M} - e_{00}}{S_{11M} \cdot e_{11} - \Delta e}$$

$$S_{21M} = \frac{b_3}{a_0} = \frac{e_{10}e_{32} \cdot S_{21}}{1 - e_{11}S_{11} - e_{22}S_{22} + e_{11}e_{22}\Delta_S} \quad \Rightarrow \quad e_{10}e_{32} = S_{21M} \cdot (1 - e_{11}e_{22})$$

Método de Calibración: Enhanced-Response

Medición DUT: S_{11}

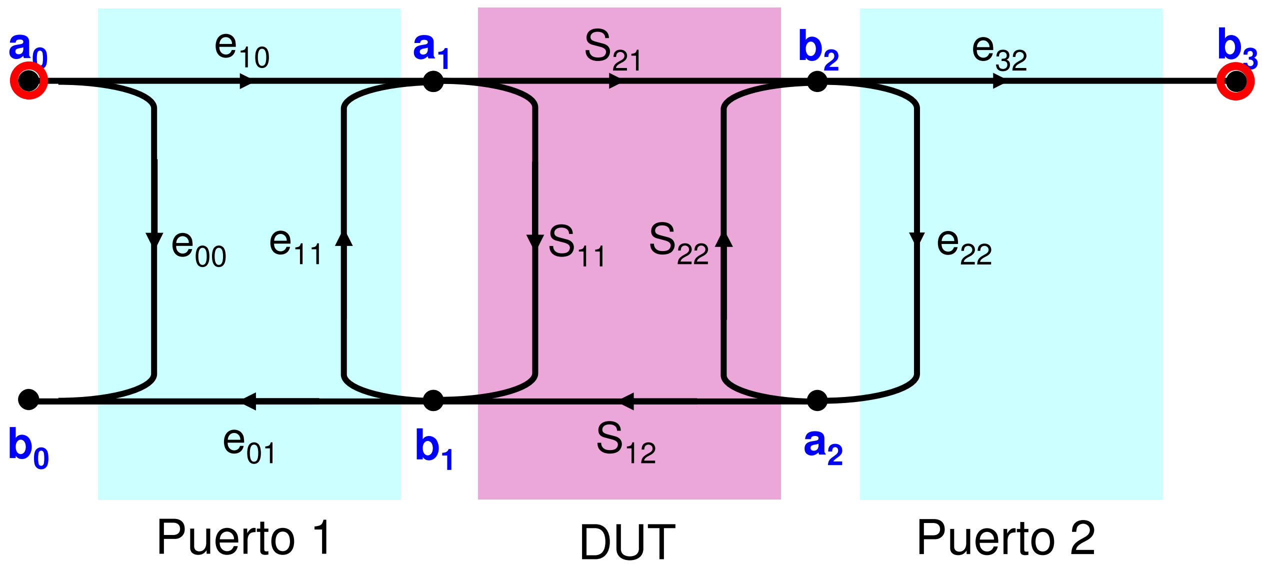


$$S_{11\mathrm{M}} = \frac{b_0}{a_0} = e_{00} + \frac{e_{10}e_{01}\cdot\left(S_{11} - e_{22}\Delta_S\right)}{1 - e_{11}S_{11} - e_{22}S_{22} + e_{11}e_{22}\Delta_S} \quad \Rightarrow \quad S_{11} = \frac{S_{11\mathrm{M}} - e_{00}}{S_{11\mathrm{M}}\cdot e_{11} - \Delta e}$$

$\boxed{\text{Idem } S_{11} \text{ a 1 Puerto}}$

Método de Calibración: Enhanced-Response

Medición DUT: S_{21}



$$S_{21M} = \frac{b_3}{a_0} = \frac{e_{10}e_{32}\cdot S_{21}}{1 - e_{11}S_{11} - e_{22}S_{22} + e_{11}e_{22}\Delta_S} \quad => \quad S_{21} = \frac{S_{21M}}{e_{10}e_{32}}\cdot\left[\frac{e_{01}e_{10}}{e_{11}S_{11M} - \Delta e}\right]$$

Algoritmo de Corrección: Enhanced-Response

$$S_{11} = \frac{S_{11M}(DUT) - e_{00}}{S_{11M}(DUT) \cdot e_{11} - \Delta e} \qquad S_{21} = \frac{S_{21M}(DUT)}{e_{10}e_{32}} \cdot \left[\frac{e_{01}e_{10}}{e_{11}S_{11M}(DUT) - \Delta e} \right]$$

S_{11} del DUT

- 3 términos de error.
- S_{11} medido del DUT.

S_{21} del DUT

- 4 términos de error.
- S_{21} medido del DUT.

Error sistemático de S_{11}

- Considera nulos todos los errores Reverse.

Error sistemático de S_{21}

- Considera nulos e_{30} y todos los errores Reverse.

Método de Calibración: 1-Path 2-Port

Calibración

Cálculo de los Términos de Error (Forward)

Ídem método Enhanced-Response

Medición

Aplicación Algoritmos de Corrección al DUT

Ídem método TOSM

Considera e_{xy}(Forward) = e_{xy}(Reverse)

1ra medición:

S_{11} corregido = S_{11} DUT

S_{21} corregido = S_{21} DUT

Se gira el DUT

2da medición:

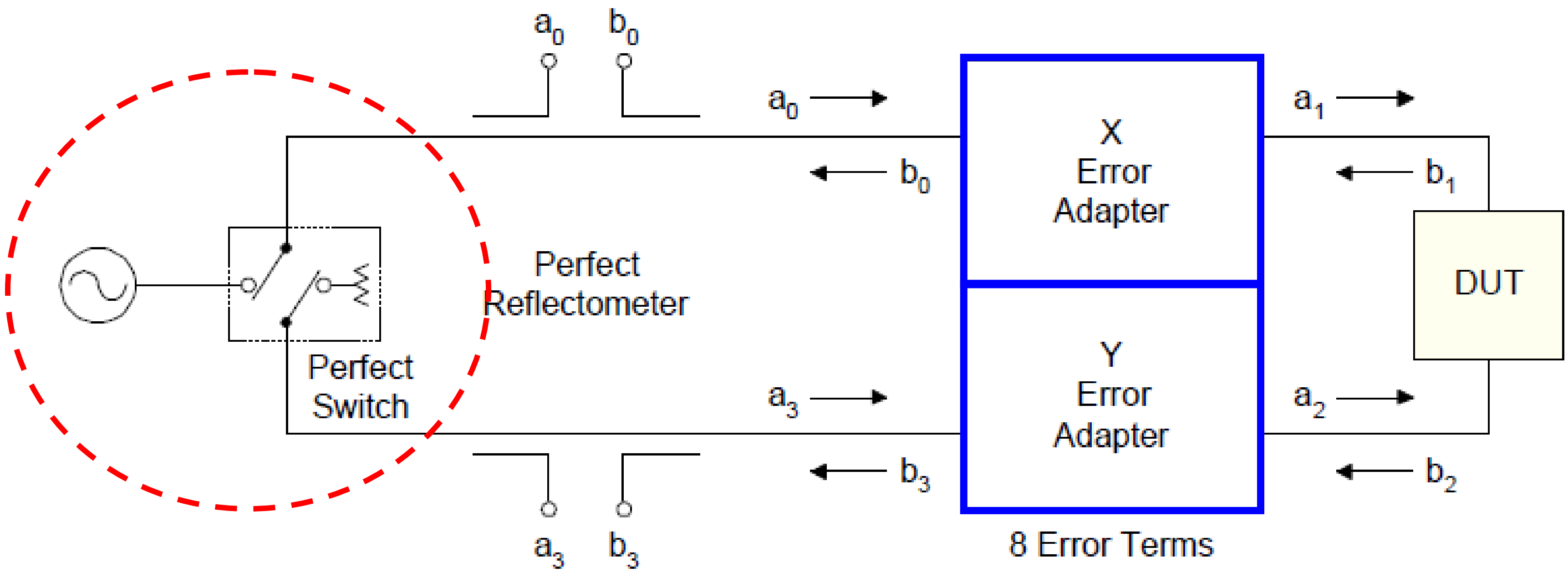
S_{11} corregido = S_{22} DUT

S_{21} corregido = S_{12} DUT

Métodos de Calibración: TRL

Método	Standards de calibración necesarios	Términos de error	Conexiones mínimas
OSM	Open-Short-Match	3	3
TOSM (SOLT)	Through-Open-Short-Match	12	8
TOM	Through-Open-Match	7	6
TRM	Through-Reflect-Match	7	6
TSD	Through-Short-Delay	7	6
TRL/TRL*	Through-Reflect-Line	7	6
LRL	Line-Reflect-Line	7	6
TNA	Through-Network-Attenuator	7	6
TOM-X	Through-Open-Match-Xtalk	15	10
LRM	Line-Reflect-Match	7	6
LRA	Line-Reflect-Attenuator	7	6
UOSM	Unknown Through-Open-Short-Match	7	8
GRL	Gated-Reflect-Line		
Multiline TRL	Multiline Through-Reflect-Line		

Modelo de 8 Términos de Error

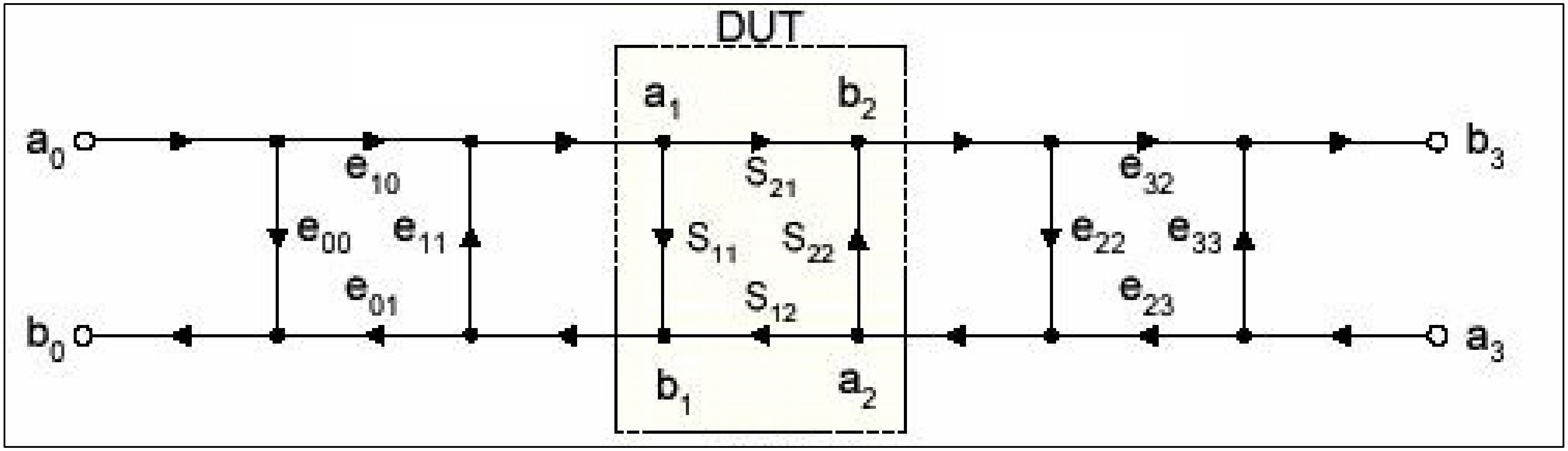


El algoritmo de corrección asume:

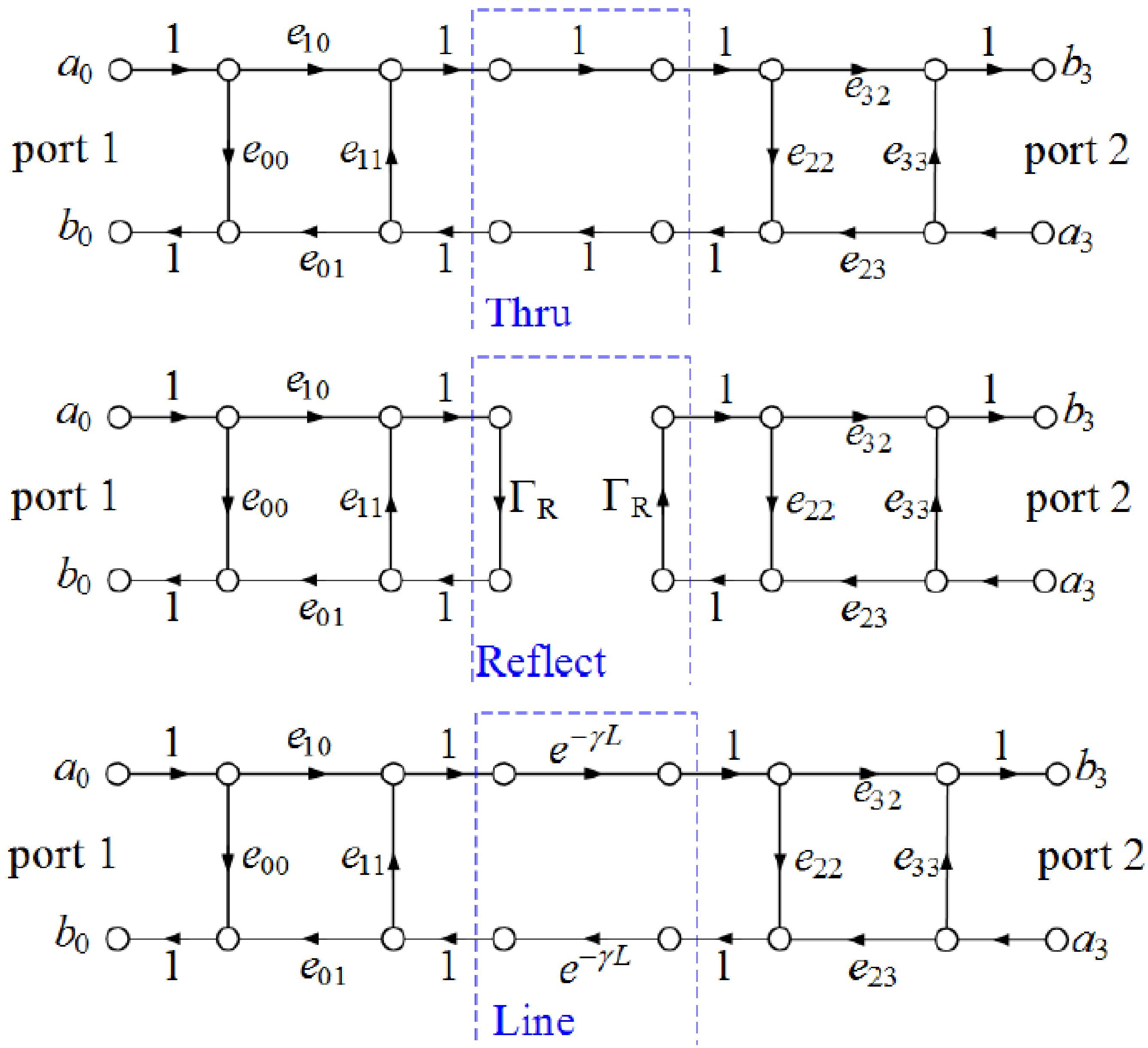
- Comportamiento del switch perfecto.

Modelo de 8 Términos de Error

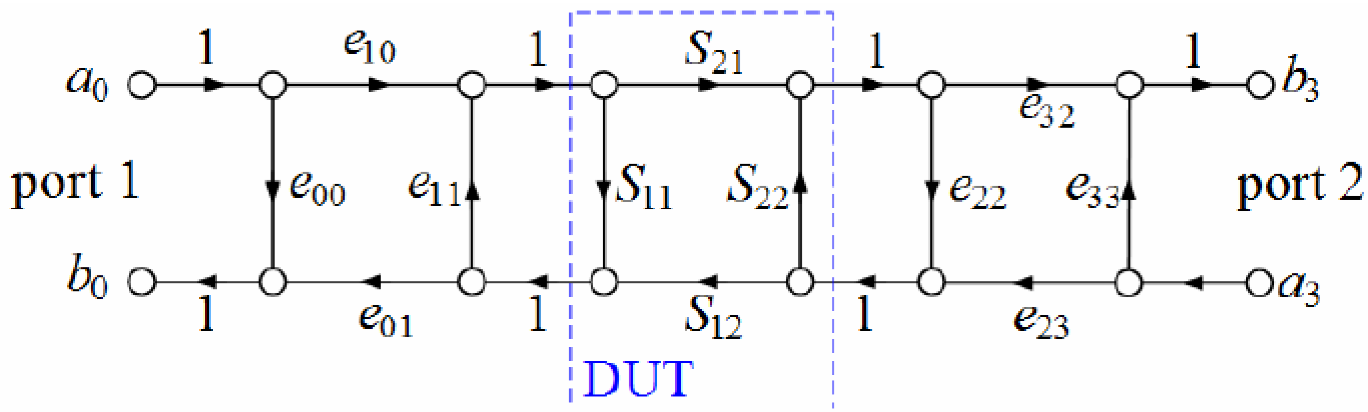
Diagrama de flujo de señal



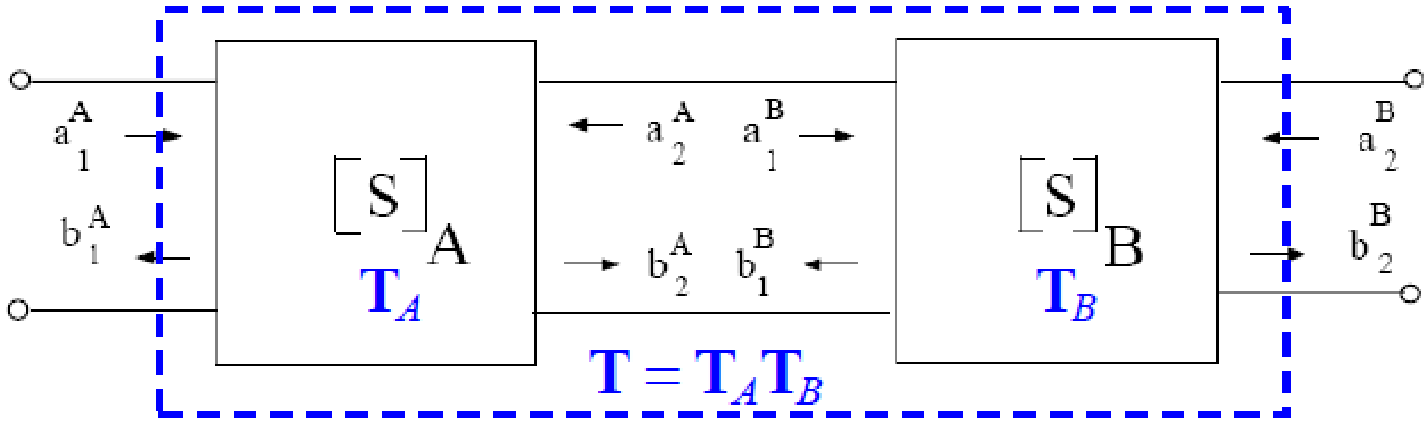
Calibración TRL



Medición DUT



Matriz Transferencia T



$$\begin{bmatrix} a_1{}^A \\ b_1{}^A \end{bmatrix} = \begin{bmatrix} T_{11}{}^A & T_{12}{}^A \\ T_{21}{}^A & T_{22}{}^A \end{bmatrix} \cdot \begin{bmatrix} b_2{}^A \\ a_2{}^A \end{bmatrix}$$

1 CUADRIPOLO

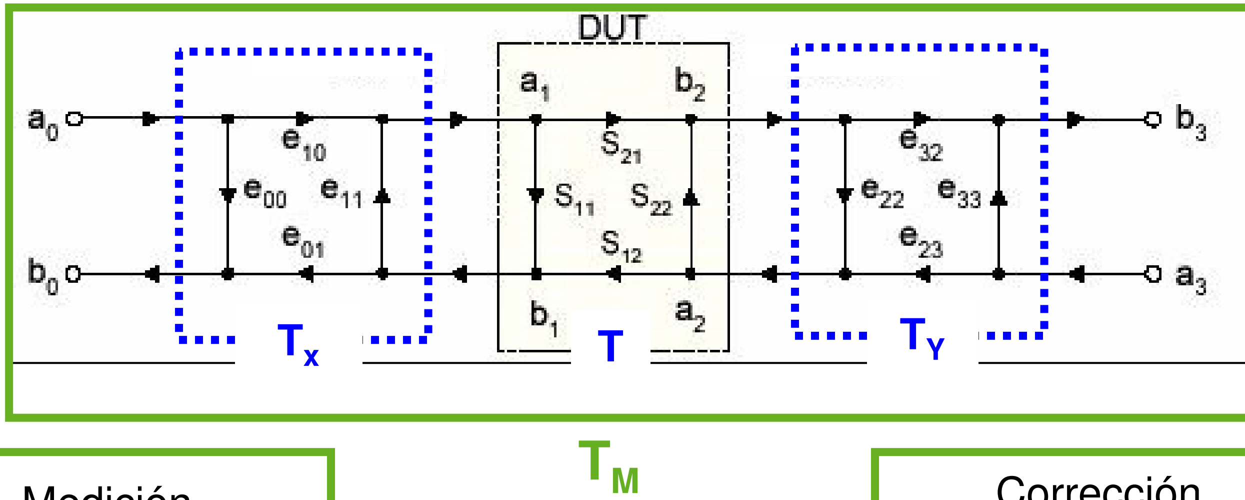
$$\begin{bmatrix} a_1{}^A \\ b_1{}^A \end{bmatrix} = \begin{bmatrix} T_{11}{}^A & T_{12}{}^A \\ T_{21}{}^A & T_{22}{}^A \end{bmatrix} \cdot \begin{bmatrix} T_{11}{}^B & T_{12}{}^B \\ T_{21}{}^B & T_{22}{}^B \end{bmatrix} \cdot \begin{bmatrix} b_2{}^B \\ a_2{}^B \end{bmatrix}$$

2 CUADRIPOLOS EN CASCADA

Pasaje de Parámetros S a T:

$$\begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} = S_{21}^{-1} \begin{bmatrix} -\Delta_S & S_{11} \\ -S_{22} & 1 \end{bmatrix}, \quad \Delta_S = S_{11}S_{22} - S_{12}S_{21}$$

Corrección Matricial en TRL



Medición

$$\mathbf{T_M = T_X T\, T_Y}$$

Corrección

$$\mathbf{T = T_X^{-1} T_M\, T_Y^{-1}}$$

$$\mathbf{T} = \frac{1}{S_{21}}\begin{bmatrix} -\Delta_S & S_{11} \\ -S_{22} & 1 \end{bmatrix}$$

$$\Delta_S = S_{11}S_{22} - S_{12}S_{21}$$

$$\mathbf{T_X} = \frac{1}{e_{10}}\begin{bmatrix} -\Delta_X & e_{00} \\ -e_{11} & 1 \end{bmatrix}$$

$$\Delta_X = e_{00}e_{11} - e_{10}e_{01}$$

$$\mathbf{T_M} = \frac{1}{S_{21M}}\begin{bmatrix} -\Delta_M & S_{11M} \\ -S_{22M} & 1 \end{bmatrix}$$

$$\Delta_M = S_{11M}S_{22M} - S_{12M}S_{21M}$$

$$\mathbf{T_Y} = \frac{1}{e_{32}}\begin{bmatrix} -\Delta_Y & e_{22} \\ -e_{33} & 1 \end{bmatrix}$$

$$\Delta_Y = e_{22}e_{33} - e_{32}e_{23}$$

Corrección Matricial en TRL simplificado

7 Términos de Error

$$\mathbf{T_M} = \frac{1}{(e_{10}e_{32})}\begin{bmatrix} -\Delta_X & e_{00} \\ -e_{11} & 1 \end{bmatrix} \mathbf{T} \begin{bmatrix} -\Delta_Y & e_{22} \\ -e_{33} & 1 \end{bmatrix} = \frac{1}{(e_{10}e_{32})}\mathbf{ATB}$$

$$\Rightarrow \mathbf{T} = (e_{10}e_{32})\mathbf{A}^{-1}\mathbf{T_M}\mathbf{B}^{-1}$$

<u>Calibración:</u>

$$T_{M1} = T_X . T_{THRU} . T_Y$$

$$T_{M2} = T_X . T_{REFLECT} . T_Y$$

$$T_{M3} = T_X . T_{LINE} . T_Y$$

calcula $\Rightarrow$

T_X Matriz T Error Box Puerto 1

T_Y Matriz T Error Box Puerto 2

<u>Medición DUT:</u>

$$T_M = T_X . T_{DUT} . T_Y \Rightarrow T_{DUT} \Rightarrow S_{DUT}$$

Ventajas TRL vs TOSM

En TRL: 3 STD x 4 mediciones = 12 ecuaciones

En TRL: 7 términos de error

Hay 5 parámetros de las referencias que no necesitan saberse

	No es necesario conocer		Debe conocerse
Thru:		=>	4 parámetros S
Reflect:	Valor de reflexión	=>	$\Gamma_{REFL1}=\Gamma_{REFL2}$
Line:	2 de sus parámetros (L y δ)	=>	S_{11} y S_{22}
			7 datos conocidos

Line (TRL) está mejor definida que MATCH (TOSM).

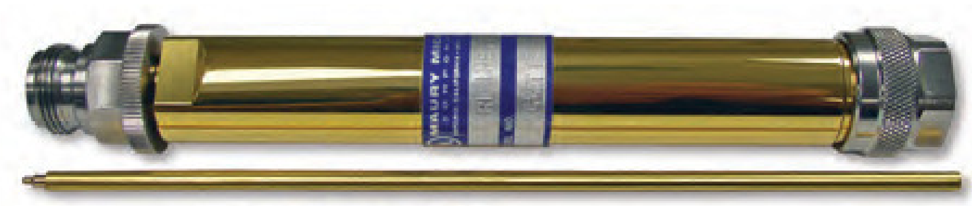
Kit de Calibración TRL

UTN.BA

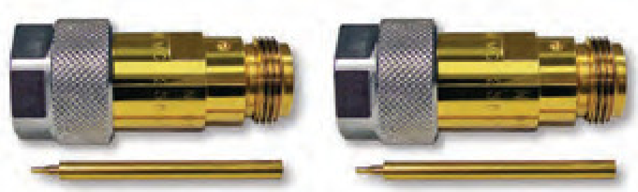
Thru

Reflect

(Open – Short)



Line1 (15 cm)

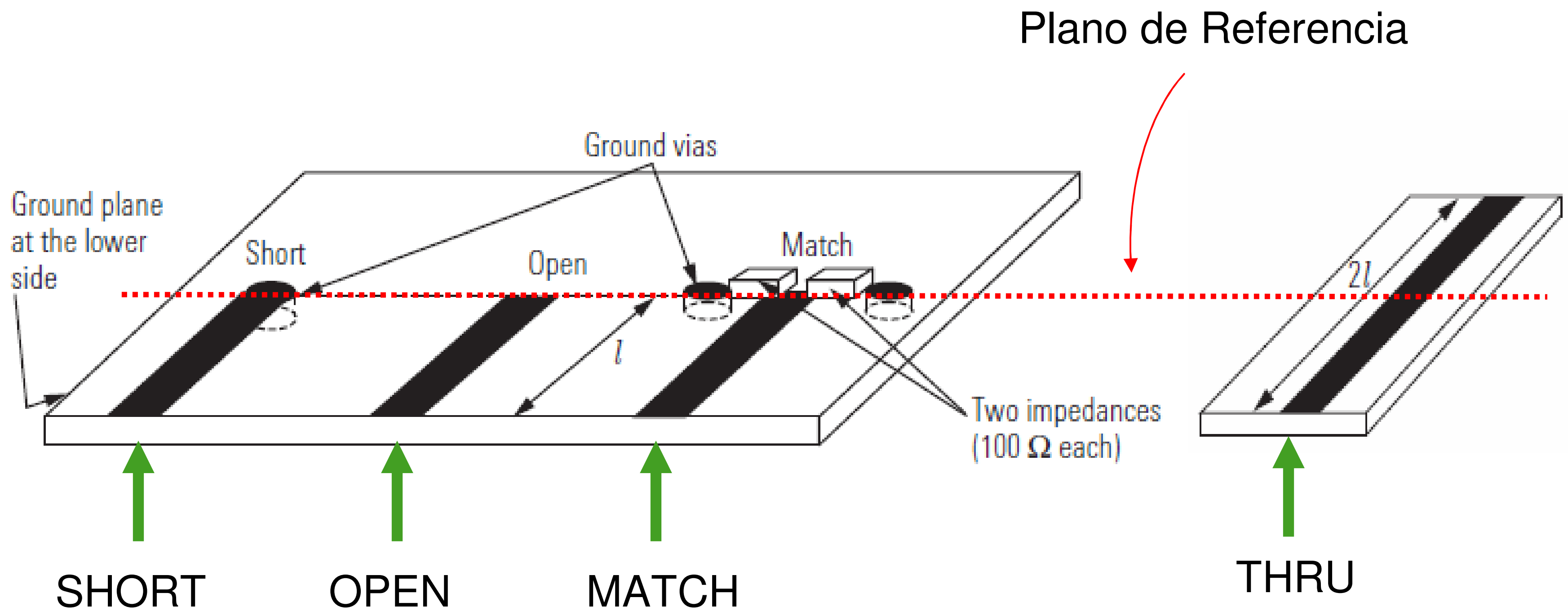


Line 2 (3,82 cm)

Line 3: (3,12 cm)

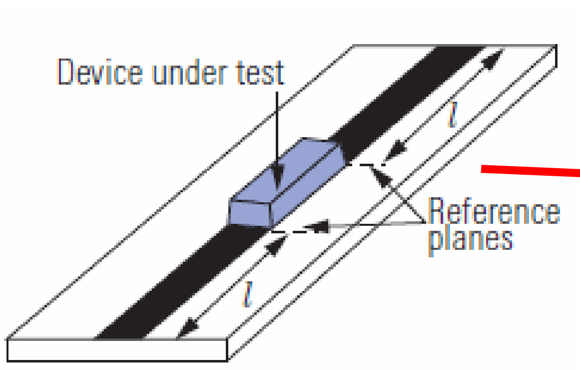
Medición de parámetros S en Sistemas Microstrip

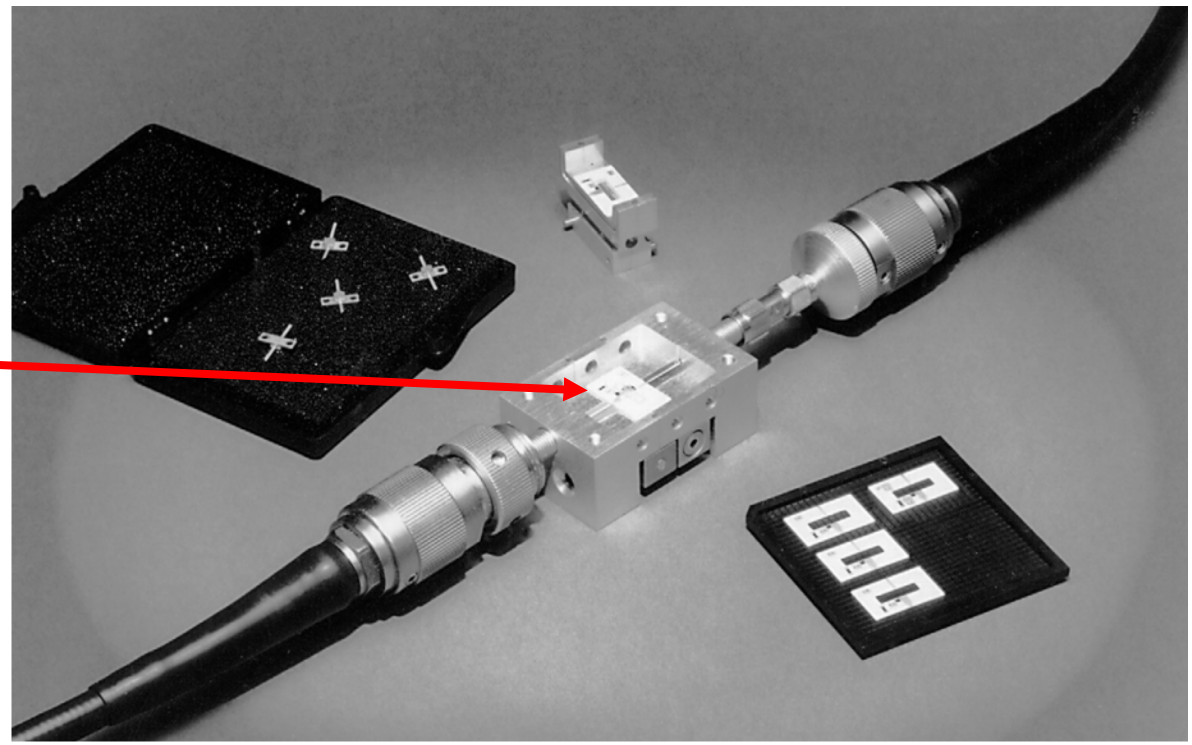
Calibración:



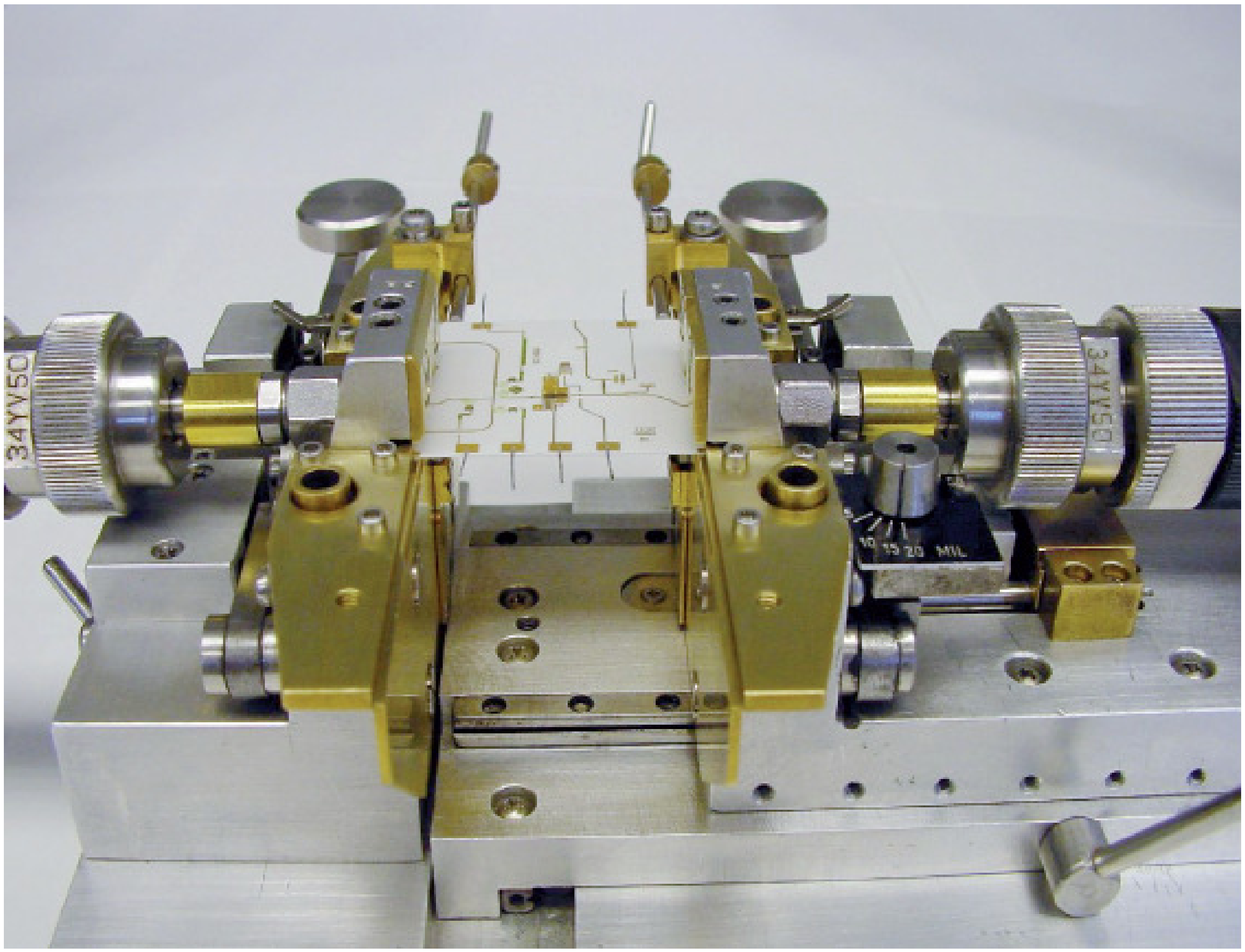
Medición de parámetros S en Sistemas Microstrip

Medición DUT:

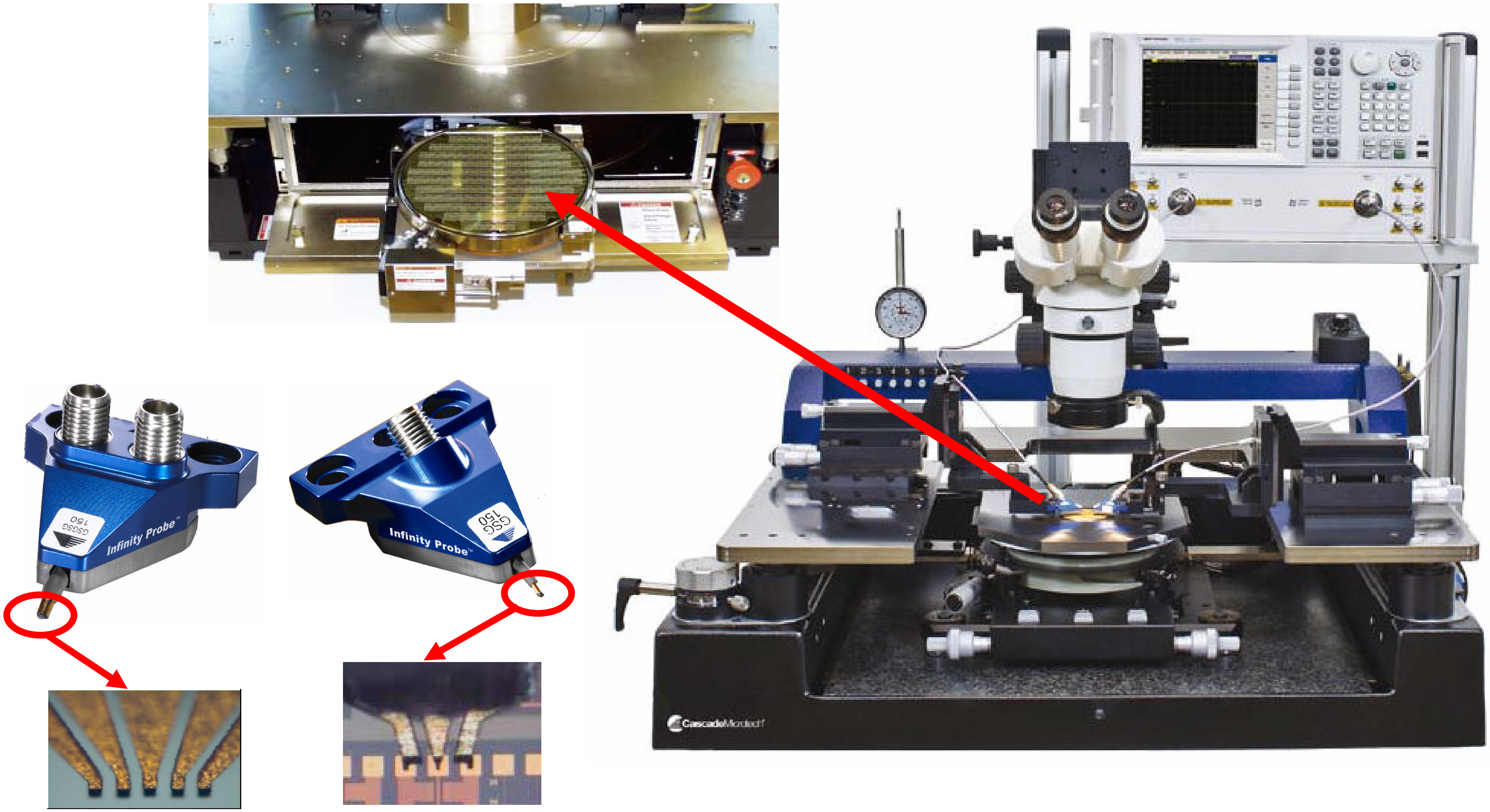




Test Fixture para sustratos en RF



Medición de Parámetros S: On-Wafer

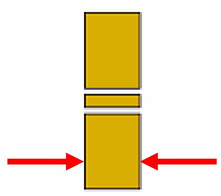


GSGSG GSG

Pitch 150 µm

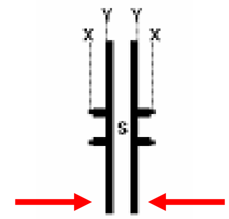
Kit de Calibración

Sustrato Coplanar de Referencia



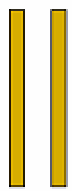
200 µm

THRU

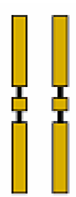


150 µm

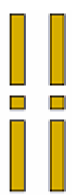
Marcas de alineación



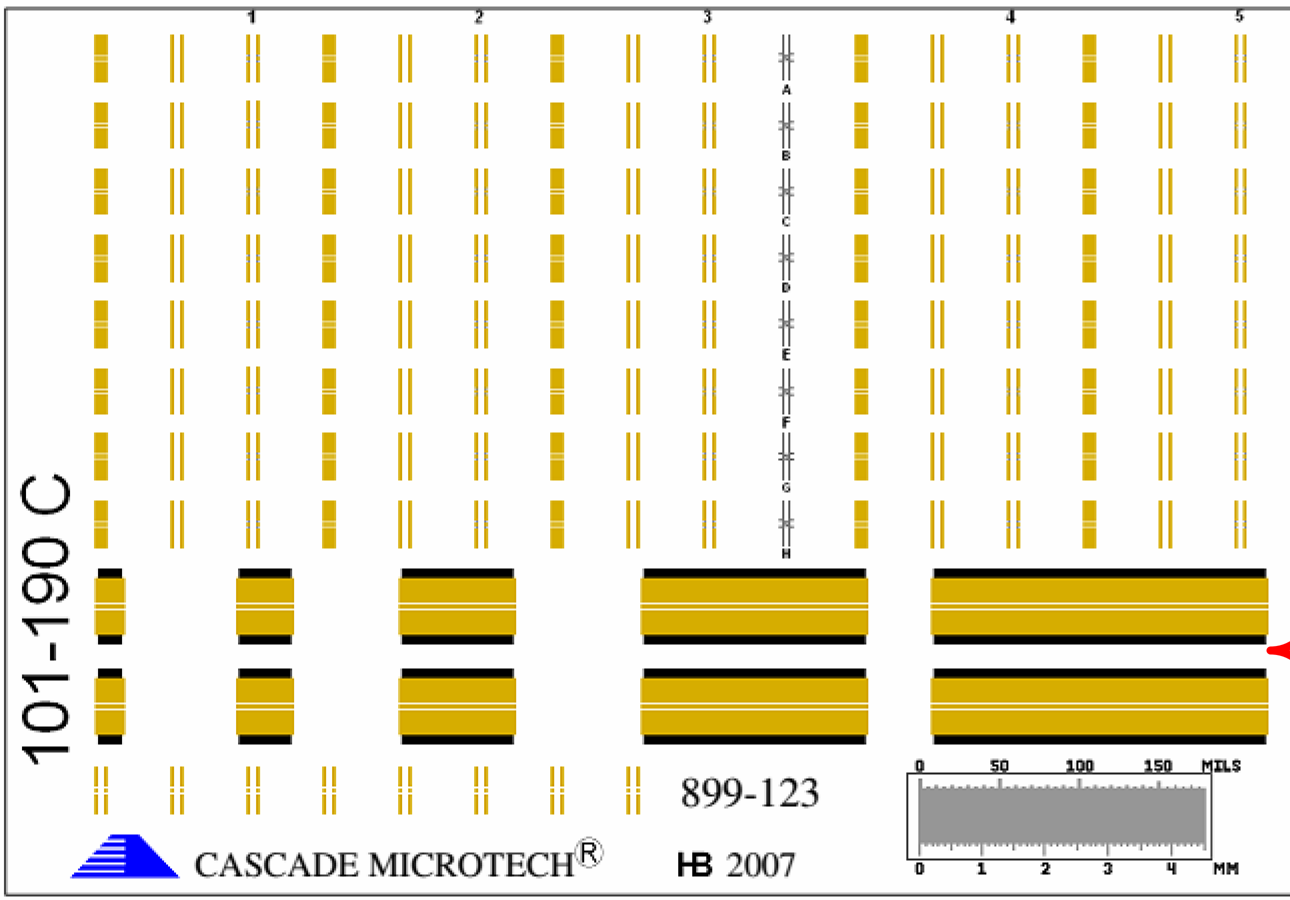
SHORT



MATCH



OPEN



LINEA

450 µm

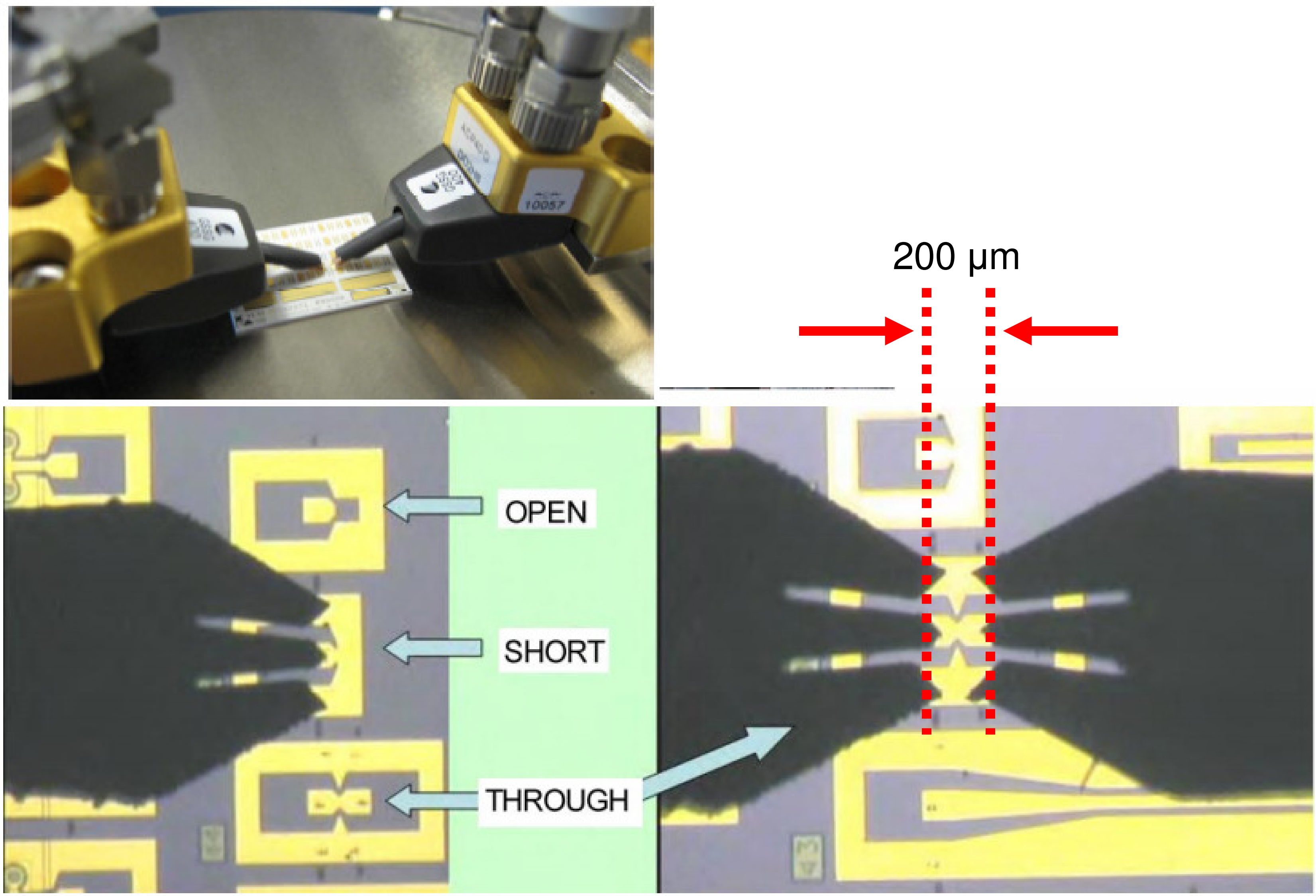
900 µm

1800 µm

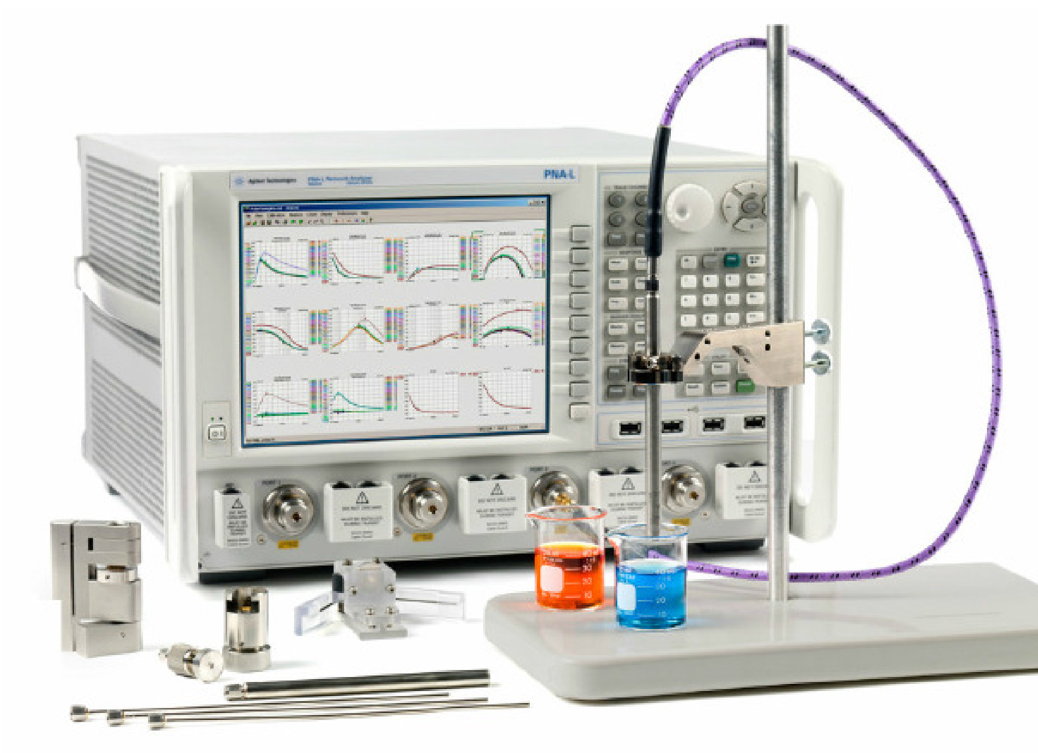
3500 µm

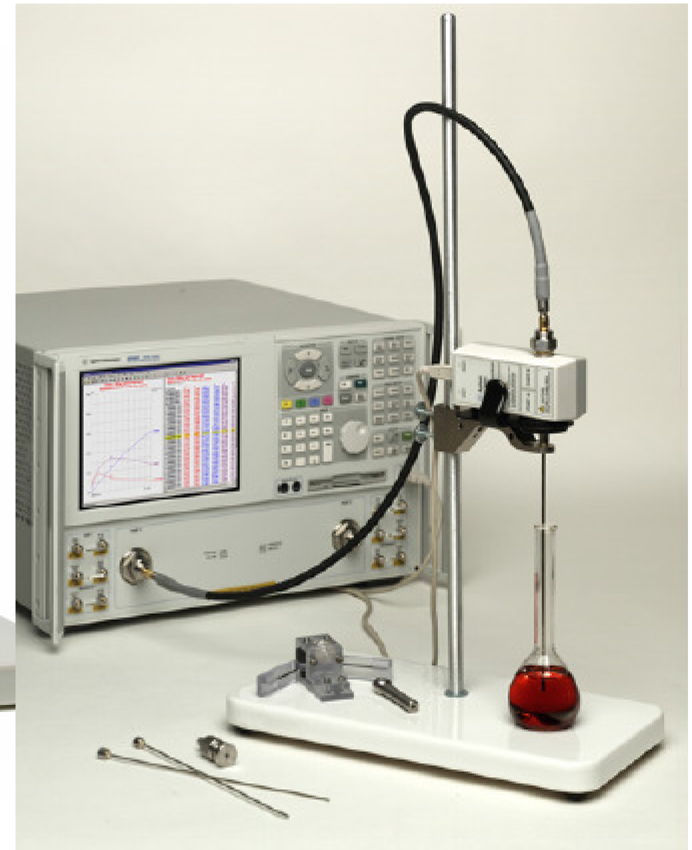
5250 µm

Calibración de probes coplanares GSG



Otras Aplicaciones: Materiales y líquidos





- Permitividad Compleja $\varepsilon_r = \varepsilon_r' + j\varepsilon_r''$
- Permeabilidad Compleja $\mu_r = \mu_r' + j\mu_r''$
- Tangente δ
- Conductividad