PBL (Project-Based Learning)

I. PBL Basics

1.1 Why PBL?

- Develop team work skills
- Develop problem-solving skills
- Develop effective communication skills
- Collaborative work experience: Learn from peer-to-peer interaction and imitation

1.2 PBL Procedures

❑ Steps in PBL

1. Problem Definition

2. Understand the Basics: theory, concept

3. Design: coding, algorithm, device, test fixture

4. Experiment: measurement, code execution, simulation

5. Write a Project Report: project report

❑ Writing a Project Report

Title: Transmission Line Theory Applied to Material Constants Measurements

Author(s): Gildong Hong and Soonhee Kim

Summary: summarize the project report

1. Introduction: project purpose, project execution steps

2. Theory: figure, equations

3. Experiment: codes, code execution

4. Conclusion: summarize the findings from the project

II. PBL Topic 1: Material Constants Measurements

2.1 Basics of RF Material Constants Measurements

❑ Material Constants

- Dielectric materials: permittivity (유전율)

$\varepsilon = \varepsilon' - j\varepsilon''$ (complex permittivity)

$\varepsilon = \varepsilon_0 \varepsilon_r (1 - j\tan\delta_e)$

$\varepsilon_0 = 8.854 \times 10^{-12}$ F/m (permittivity of vacuum)

ε_r : relative permittivity

$\tan\delta_e$: dielectric loss tangent

- Magnetic materials: permeability (투자율)

$\mu = \mu' - j\mu''$ (complex permeability)

$\mu = \mu_0 \mu_r (1 - j\tan\delta_m)$

$\mu_0 = 4\pi \times 10^{-7}$ H/m (permeability of vacuum)

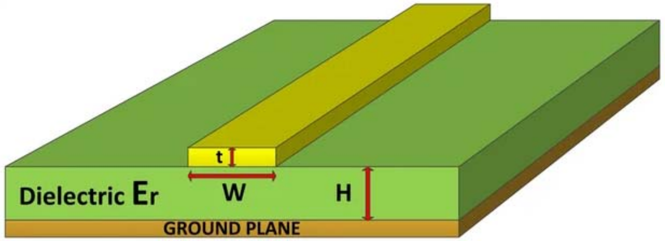
μ_r : relative permeability

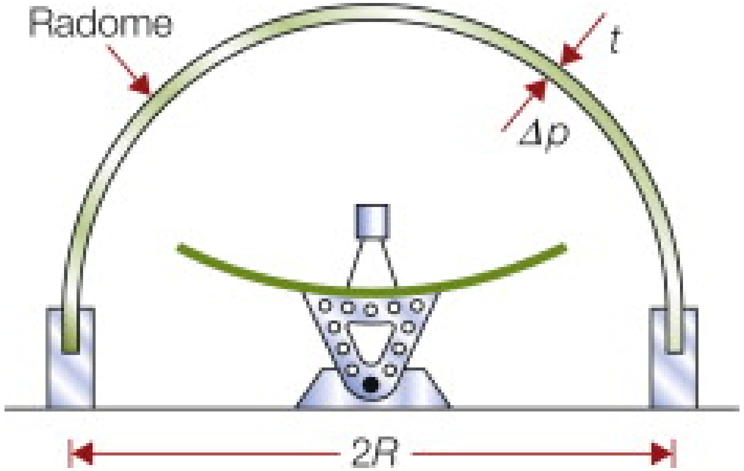
$\tan\delta_m$: magnetic loss tangent

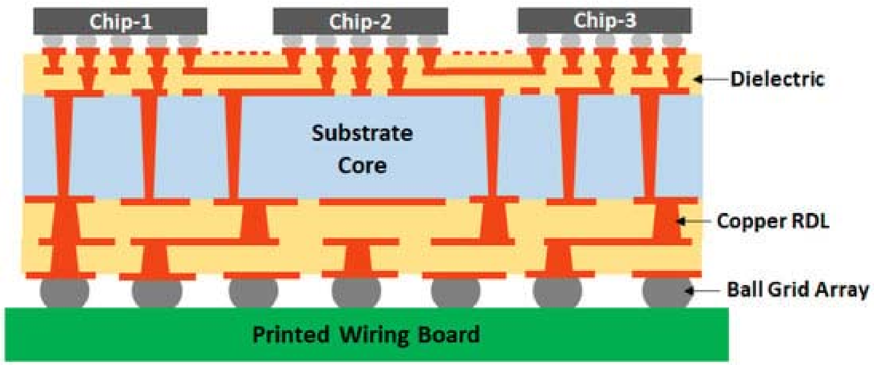
2.1 Basics of RF Material Constants Measurements

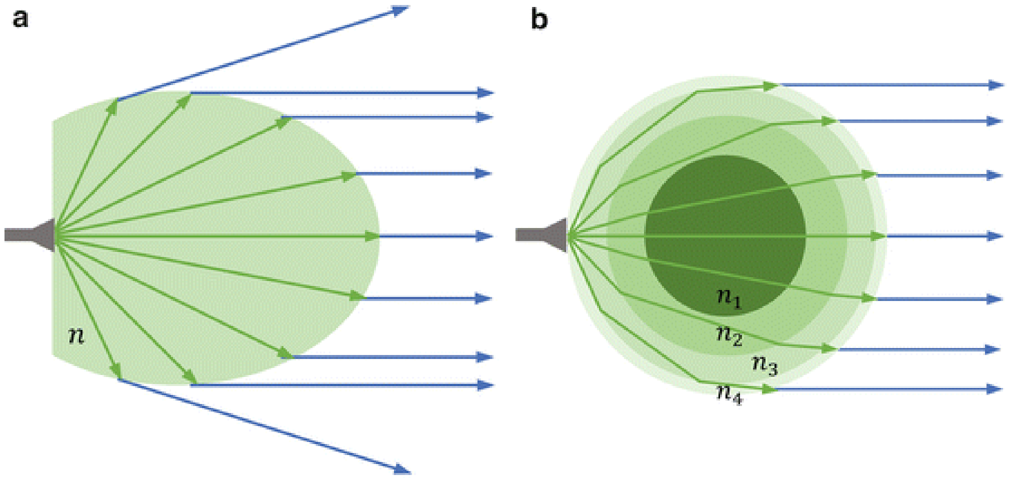
❑ Why Do You Need to Measure Material Constants

- Printed circuit board (PCB) design
- Radome design
- Lens antenna design
- Inductor design
- Semiconductor packaging









2.1 Basics of RF Material Constants Measurements

- Example: Ferrite composite, permittivity & permeability, 7-14 GHz, 2016 Int Conf Radar Antenna Electron. Telecomm.

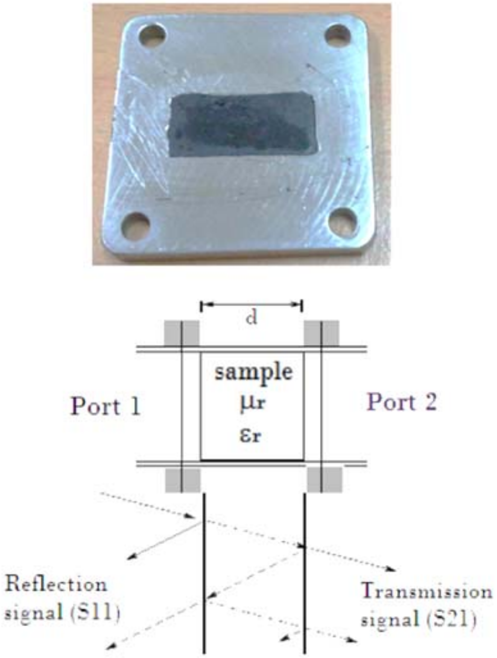


Fig. 1. Sample holder and transmission line methods for hexagonal ferrite

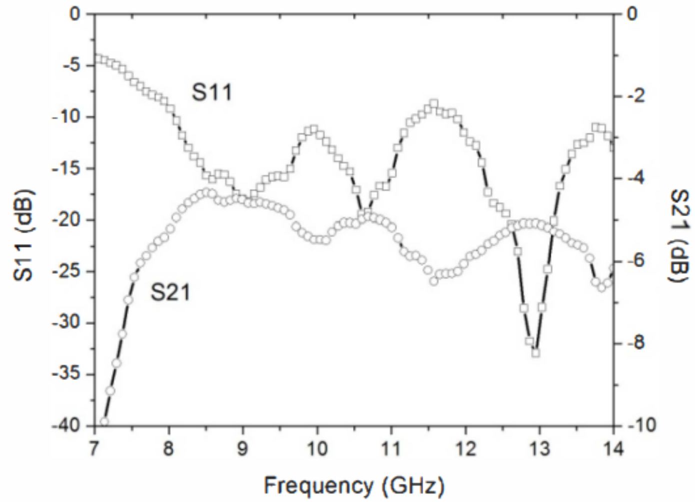


Fig. 2. Results of measurement of the S-parameter of hexagonal ferrite.

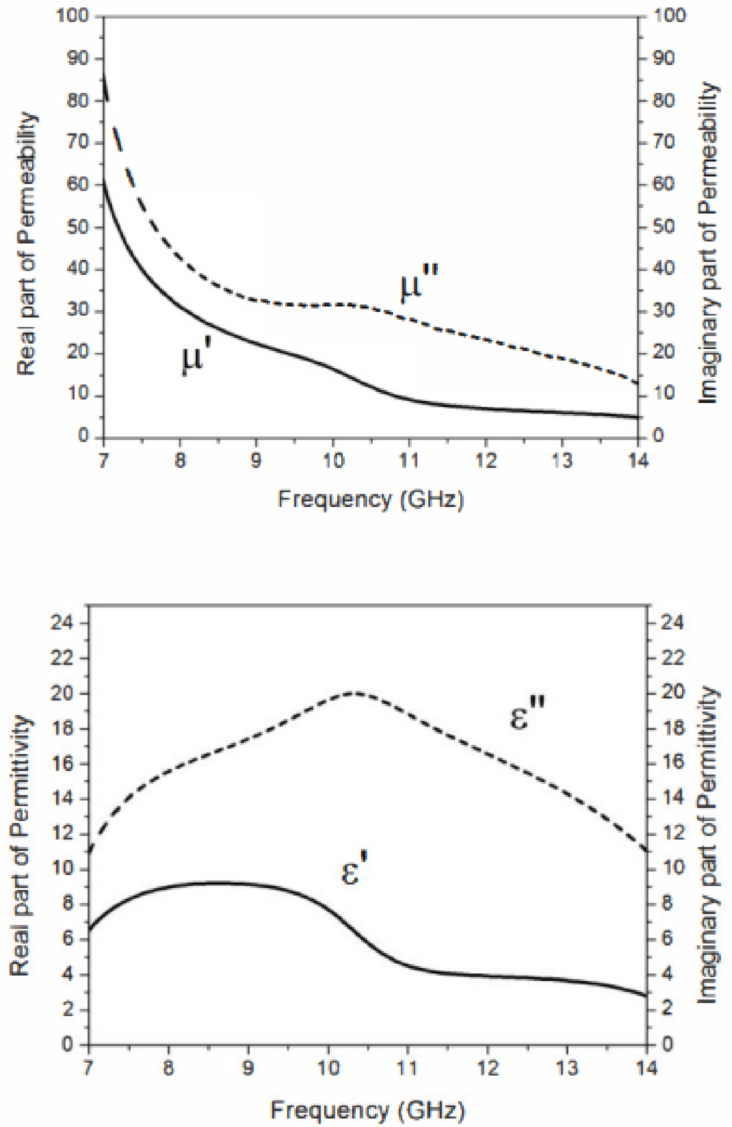


Fig. 3. Complex relative permeability and permittivity of hexagonal ferrite

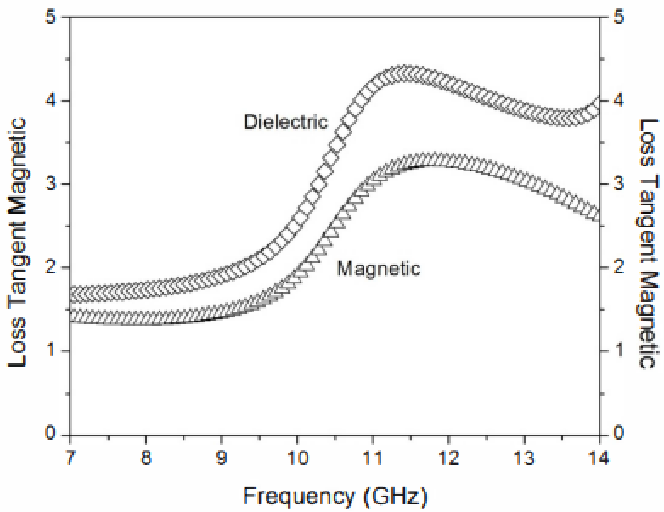
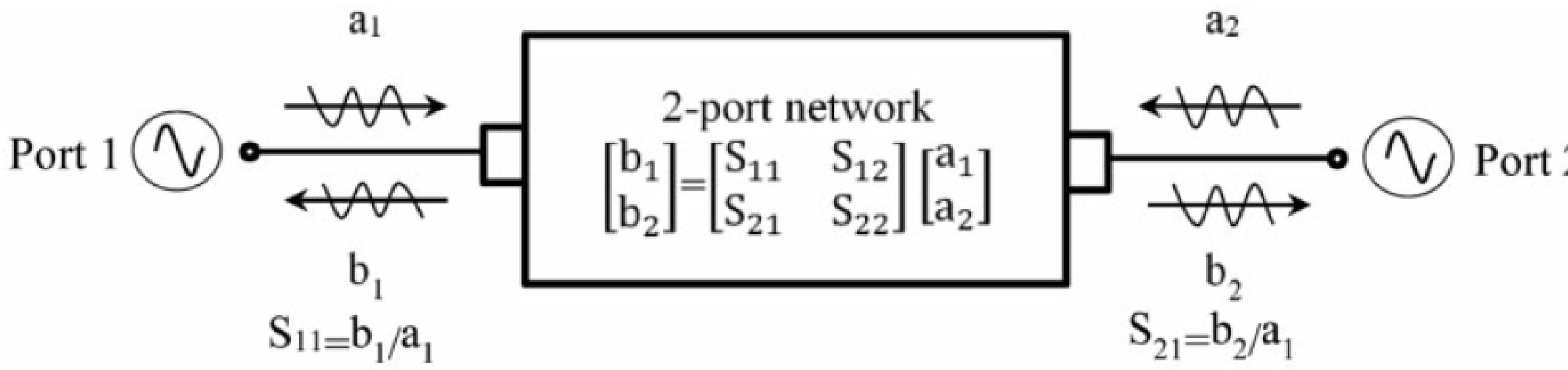


Fig. 4. Loss tangent of hexagonal ferrite

2.2 Scattering Parameters

- Scattering Parameter Example: 2-port



[S]: scattering matrix

S_{11}, S_{12}, S_{21}, S_{22}: scattering parameters

S_{11}: input reflection coefficient

S_{12}: reverse transmission coefficient

S_{21}: forward transmission coefficient

S_{22}: output reflection coefficient

2.3 Vector Network Analyzer

- ❑ What is a VNA (Vector Network Analyzer)?

- Networ analyzer: RF, microwave, millimeter-wave, terahertz; measure S-parameters

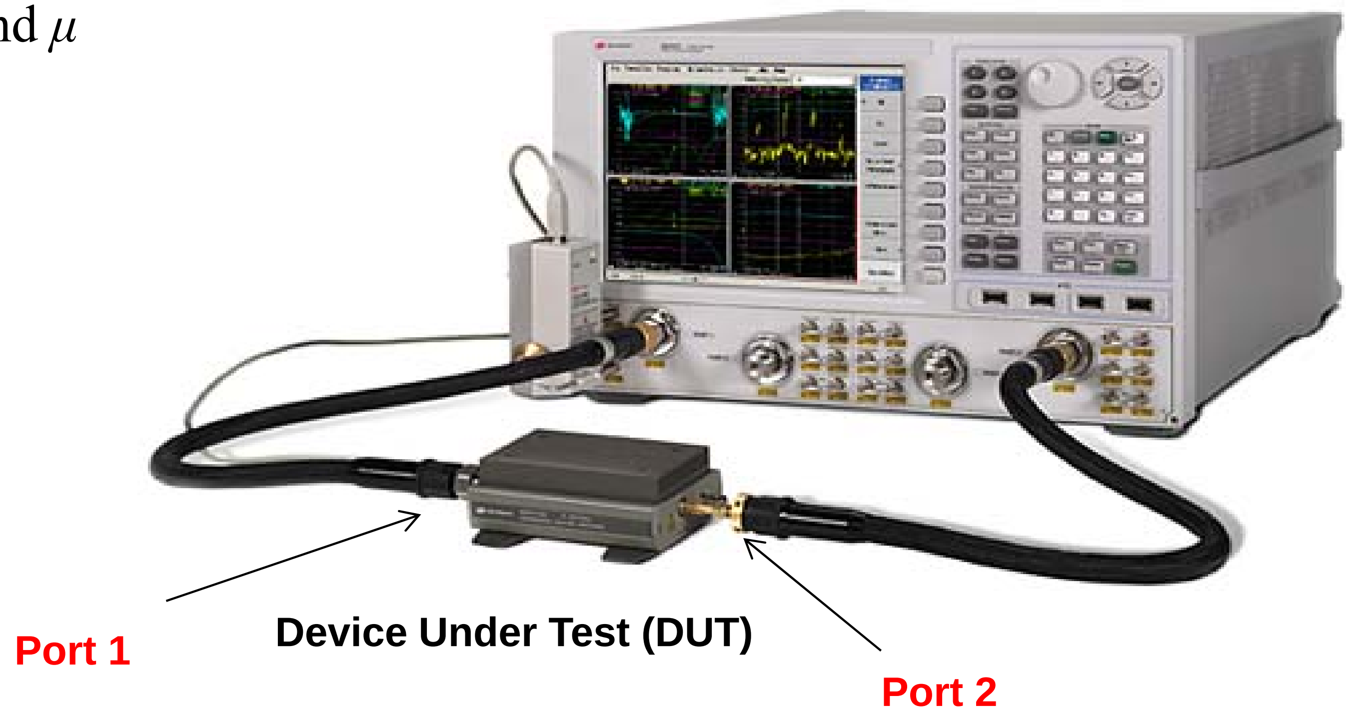
- Vector analyzer: measure mag/phase

- Scalar analyzer: measure mag only

- ❑ VNA for material constants measurments

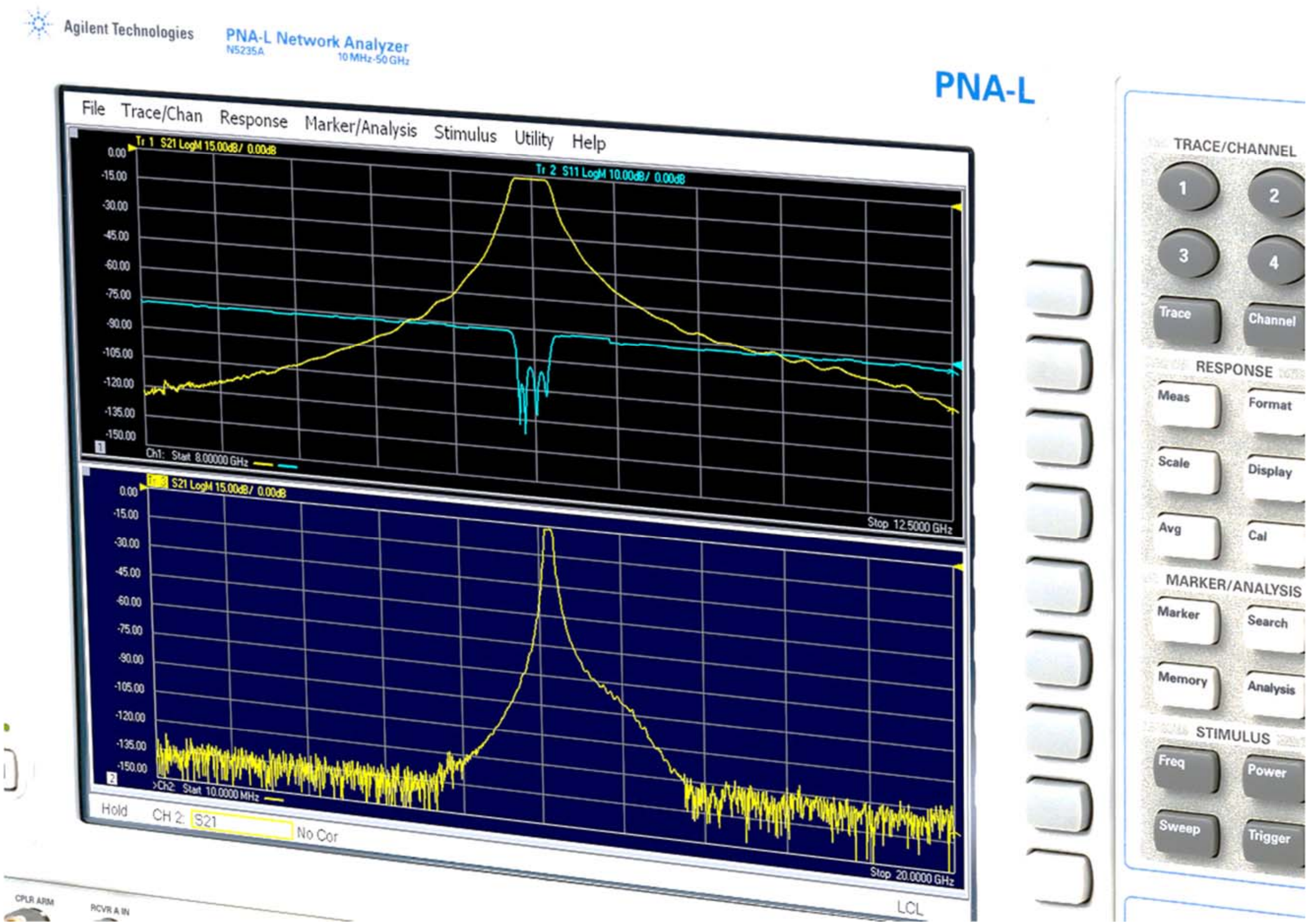
- Measure S-paramters

- Extract ε and μ

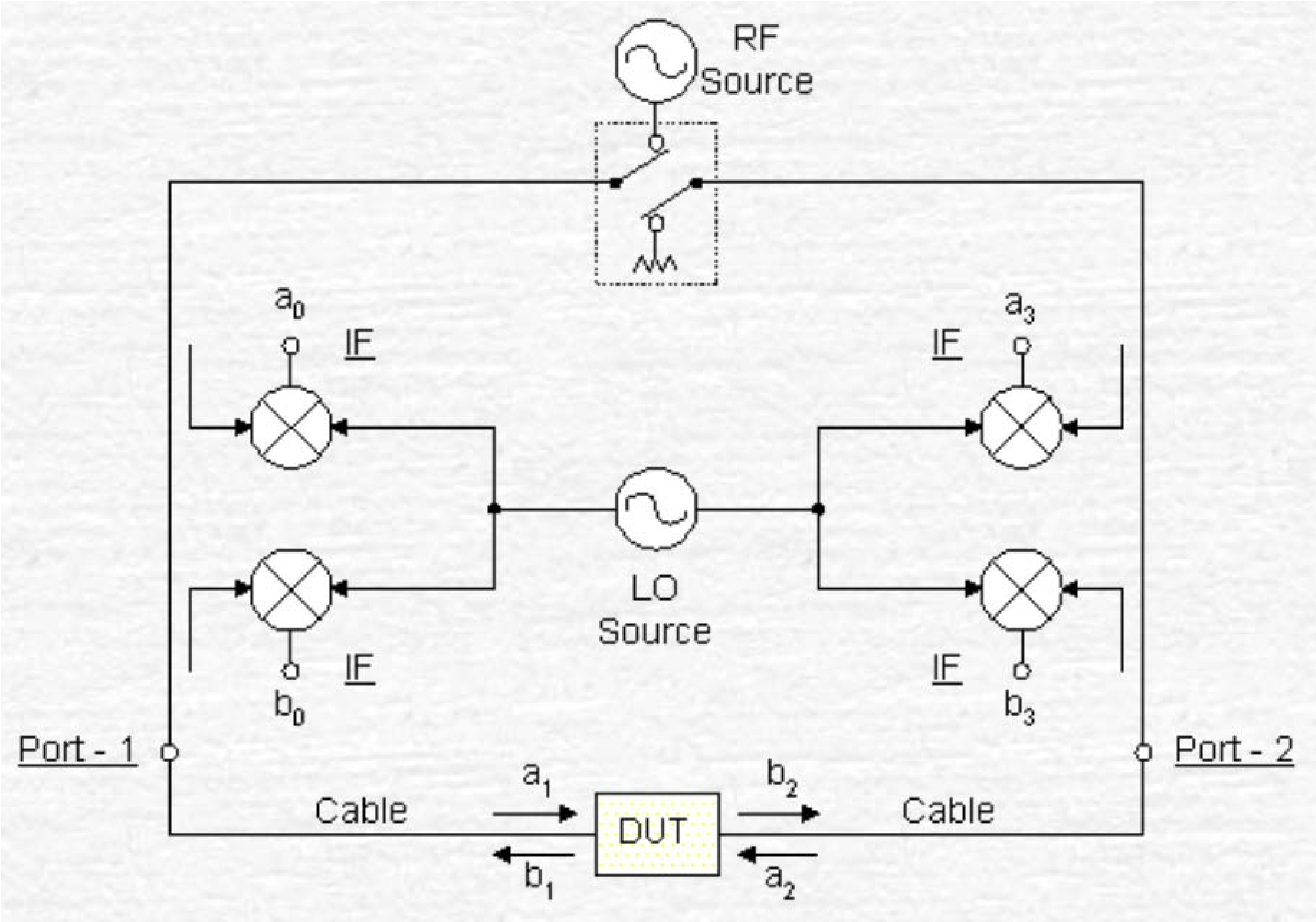


2.4 Vector Network Analyzer

- VNA Example: Agilent N5235A VNA, 10 MHz - 50 GHz



❑ VNA Simplified Block Diagram



2.4 Vector Network Analyzer Calibration

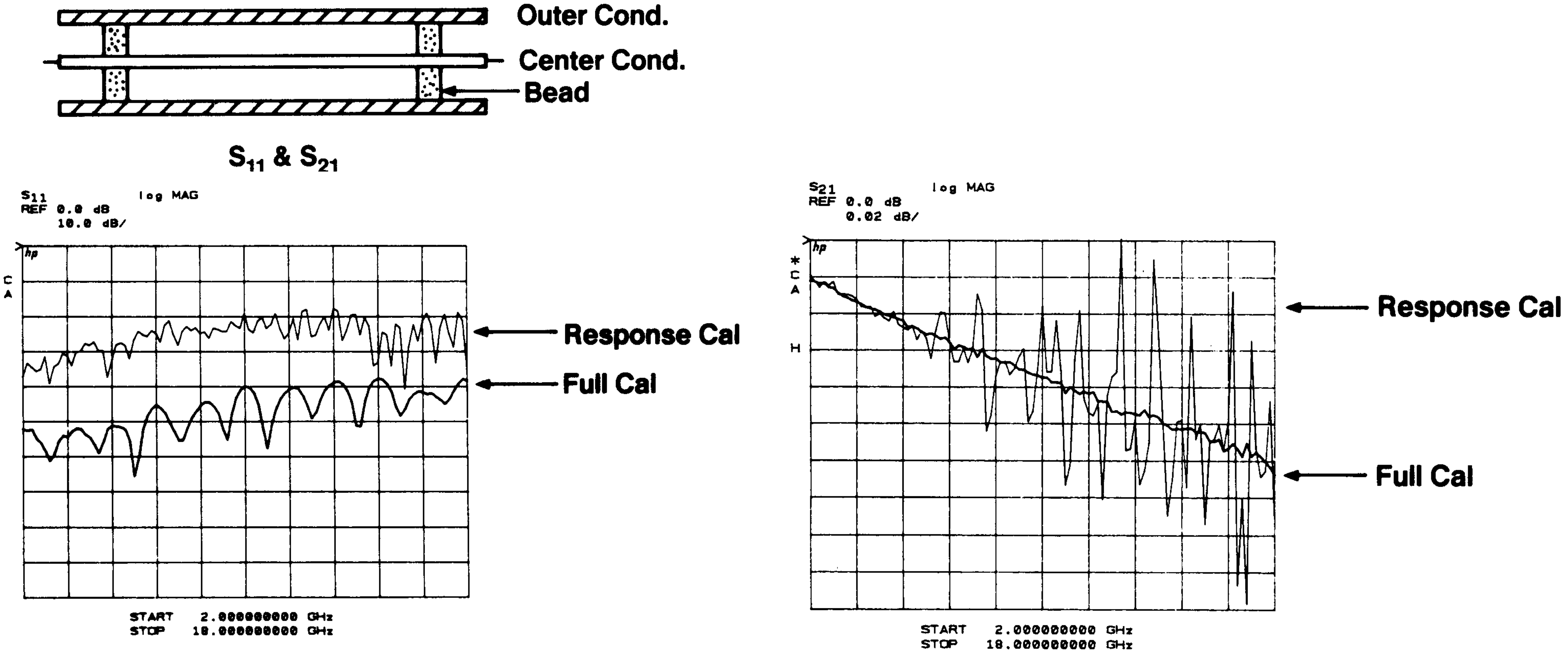
❑ What is the Calibration?

1. Correction of errors within the VNA

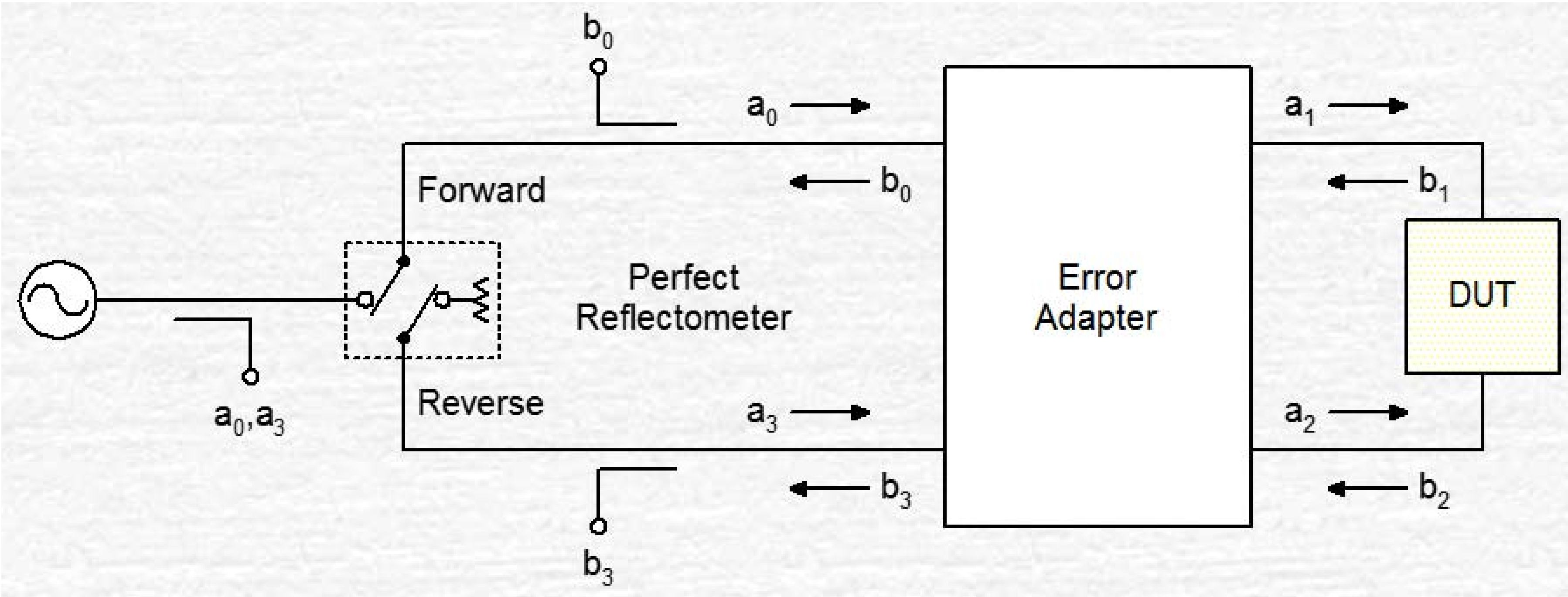
2. Correction of errors added by connector, test cables, and a test fixture

3. Correction of errors due to the combined effects of 1 and 2

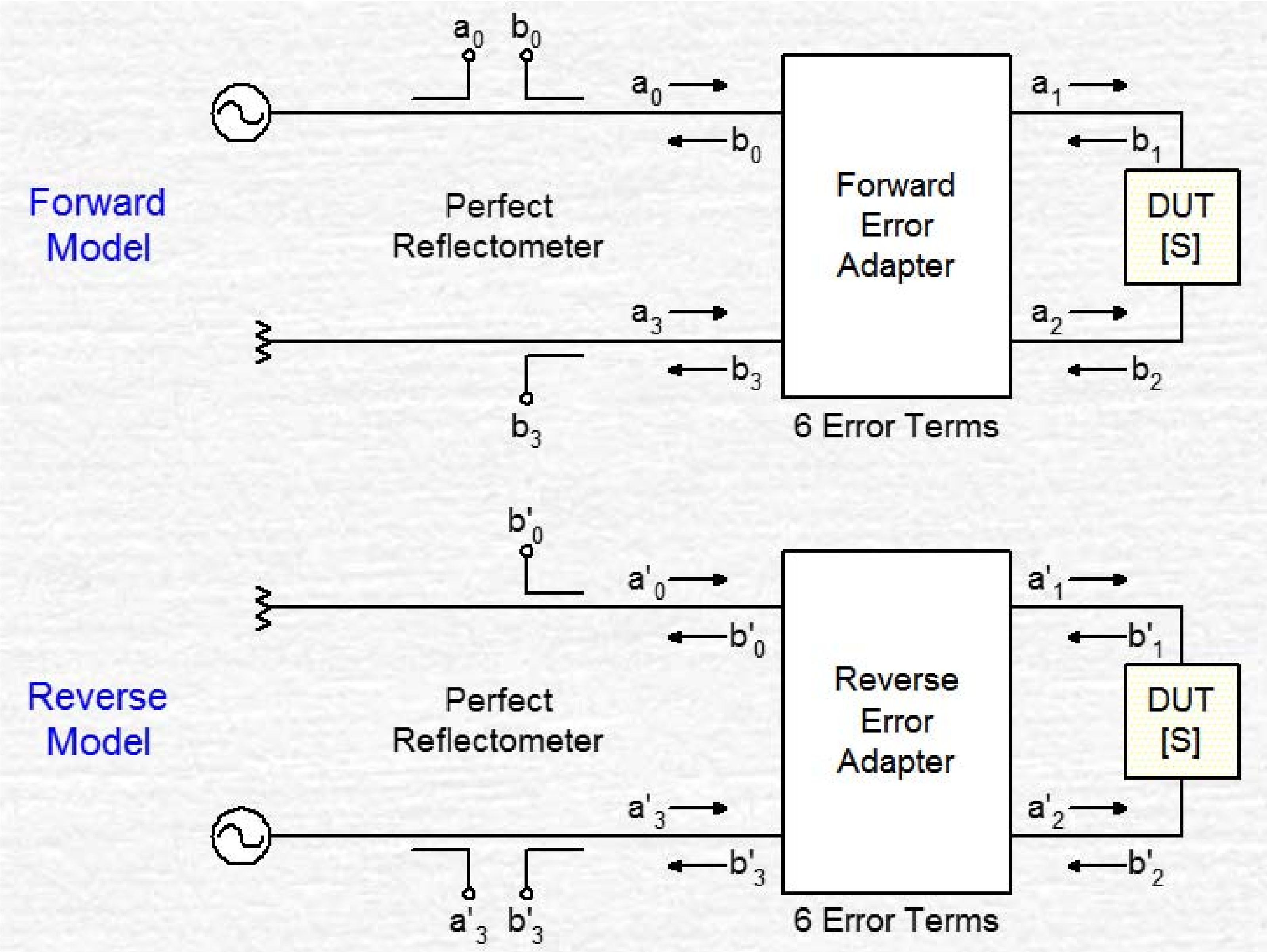
LET'S MEASURE AN AIRLINE (APC-7)



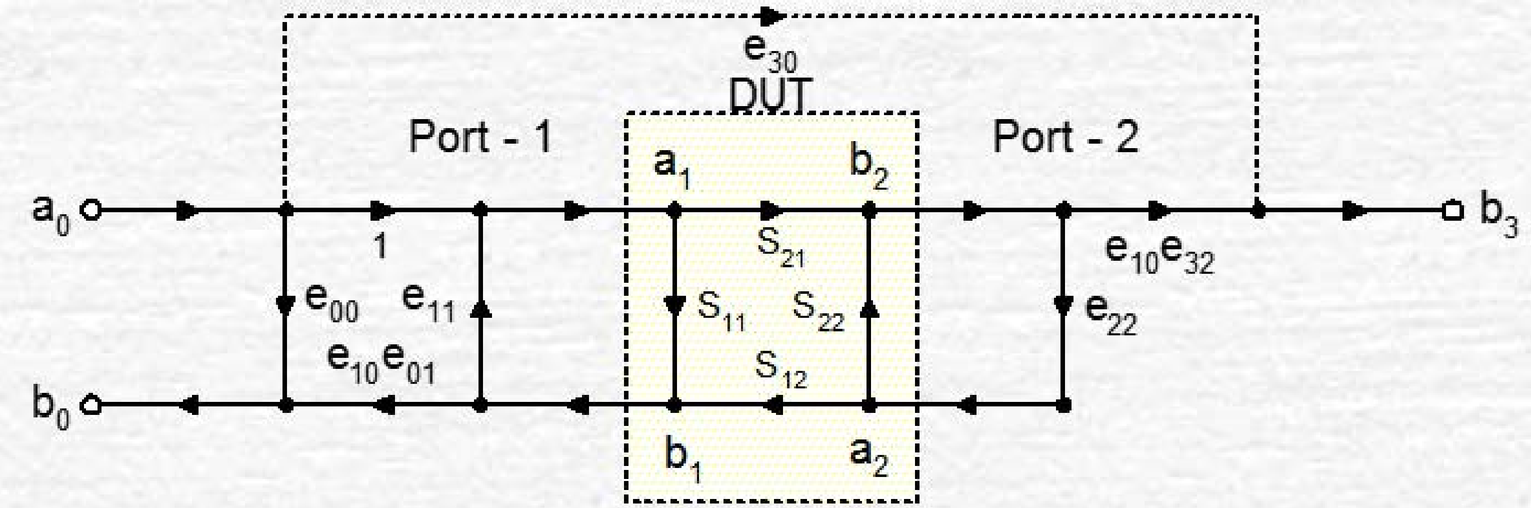
❑ Two-Port Calibratioin: 6-term error model



❑ 6-Term Error Model: Forward & Reverse Models



❑ 6-Term Forward Error Model



e_{00} = Directivity

e_{11} = Port-1 Match

$(e_{10}e_{01})$ = Reflection Tracking

$(e_{10}e_{32})$ = Transmission Tracking

e_{22} = Port-2 Match

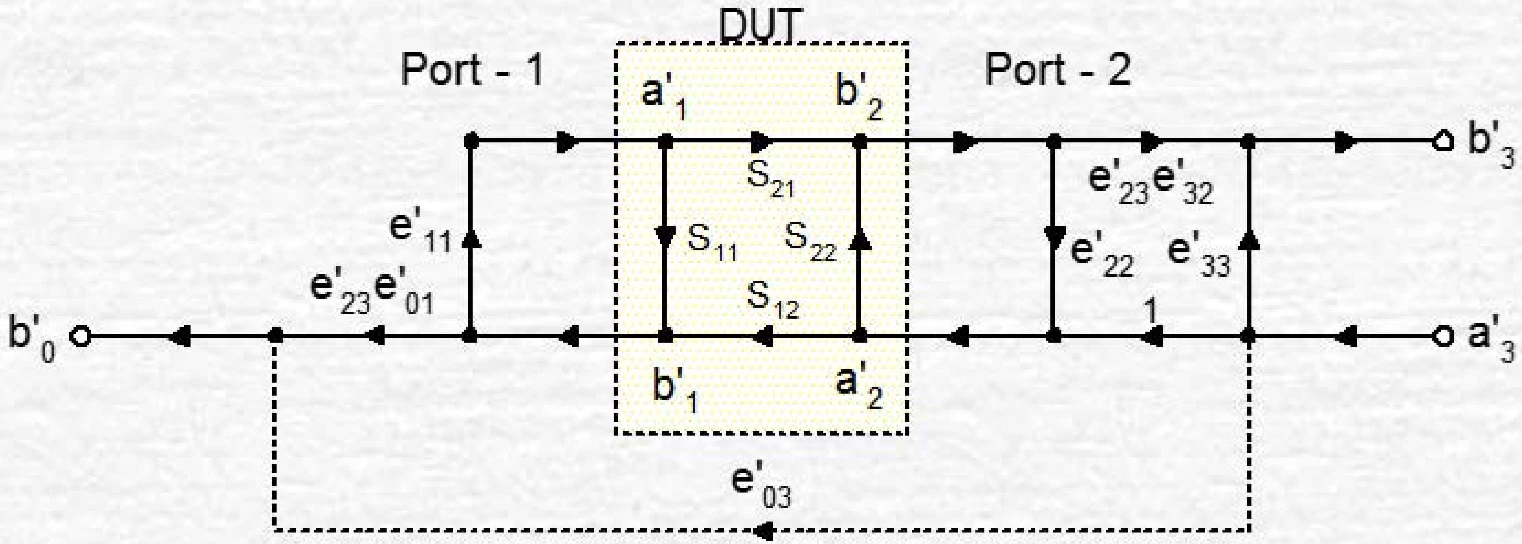
e_{30} = Leakage

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

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

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

❑ 6-Term Reverse Error Model



e'_{33} = Directivity

e'_{11} = Port-1 Match

$(e'_{23}e'_{32})$ = Reflection Tracking

$(e'_{23}e'_{01})$ = Transmission Tracking

e'_{22} = Port-2 Match

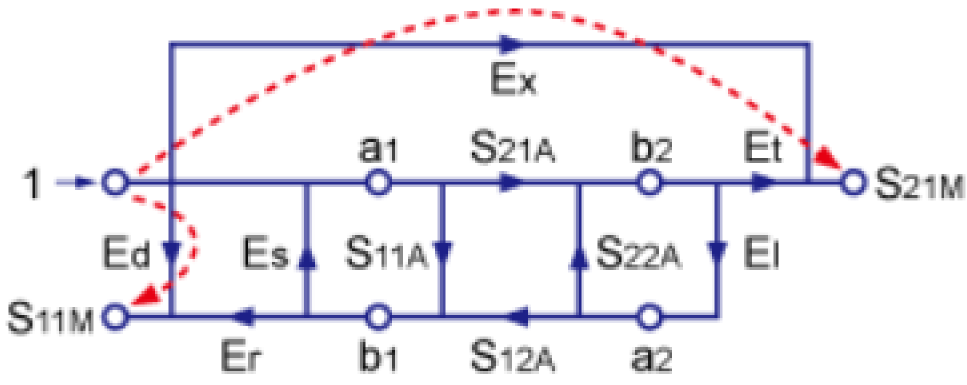
e'_{03} = Leakage

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

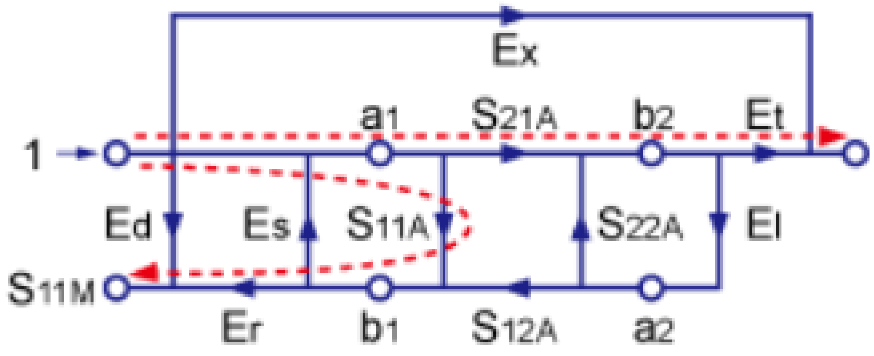
$$S_{12M} = \frac{b'_0}{a'_3} = e'_{03} + (e'_{23}e'_{01})\frac{S_{12}}{1 - e'_{11}S_{11} - e'_{22}S_{22} + e'_{11}e'_{22}\Delta_S}$$

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

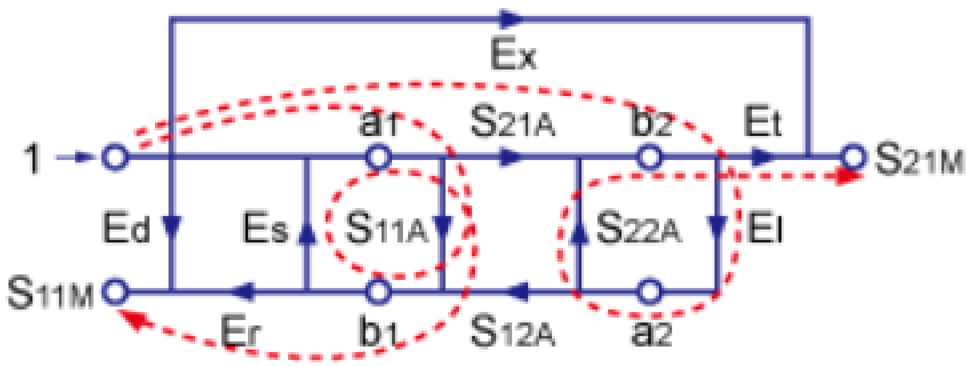
❑ 6-Term Reverse Error Model Summary



Isolation



Frequency Response



Reflection

Ed : Directivity
Es : Source match
Er : Reflection tracking
Et : Transmission tracking
Ex : Isolation (Crosstalk)
El : Load match

❑ Calibration for 6-Term Forward/Reverse Error Model

STEP 1: Calibrate Port-1 using One-Port procedure

Solve for e_{11}, e_{00}, & $(e_{10}e_{01})$, Calculate $(e_{10}e_{01})$ from Δ_e

STEP 2: Connect Z_0 terminations to Ports 1 & 2

Measure S_{21M} gives e_{30} directly

STEP 3: Connect Ports 1 & 2 together

$$e_{22} = \frac{S_{11M} - e_{00}}{S_{11M}e_{11} - \Delta_e}$$

$$e_{10}e_{32} = (S_{21M} - e_{30})(1 - e_{11}e_{22})$$

Use the same process for the reverse model

2.4 Vector Network Analyzer Calibration

❑ 2-Port VNA Calibration

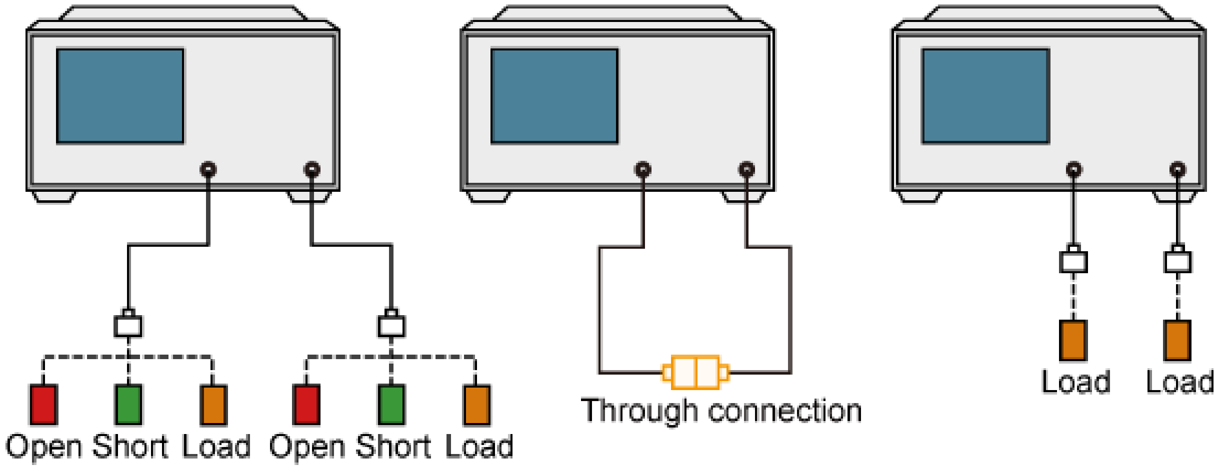
- Port 1 calibration: open, short, load (= match); measure S_{11}

- Port 2 calibration: open, short, load (= match); measure S_{22}

- Leakage calibration: port 1 = match, port 2 = match; measure S_{21} and S_{12}

- Transmission tracking calibration: port 1 and port 2 = connected; measure S_{22}, S_{21} and S_{11}, S_{12}

- 12 measurements for 12 unknowns



❑ DUT S-Parameter Calculation in 6-Term Error Model

$$S_{11} = \frac{\left(\frac{S_{11M} - e_{00}}{e_{10}e_{01}}\right)\left[1 + \left(\frac{S_{22M} - e'_{33}}{e'_{23}e'_{32}}\right)e'_{22}\right] - e_{22}\left(\frac{S_{21M} - e_{30}}{e_{10}e_{32}}\right)\left(\frac{S_{12M} - e'_{03}}{e'_{23}e'_{01}}\right)}{D}$$

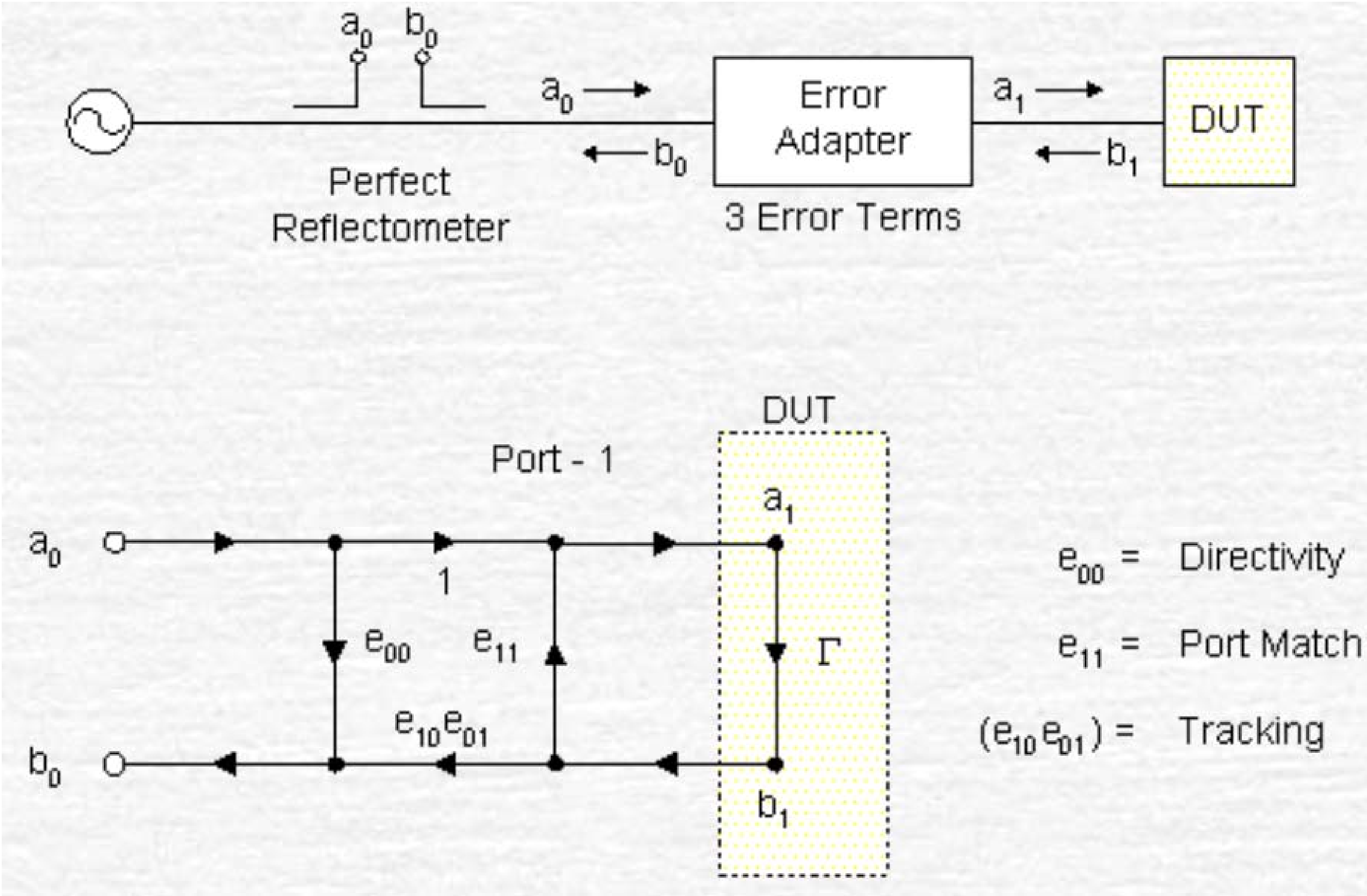
$$S_{21} = \frac{\left(\frac{S_{21M} - e_{30}}{e_{10}e_{32}}\right)\left[1 + \left(\frac{S_{22M} - e'_{33}}{e'_{23}e'_{32}}\right)(e'_{22} - e_{22})\right]}{D}$$

$$S_{22} = \frac{\left(\frac{S_{22M} - e'_{33}}{e'_{23}e'_{32}}\right)\left[1 + \left(\frac{S_{11M} - e_{00}}{e_{10}e_{01}}\right)e_{11}\right] - e'_{11}\left(\frac{S_{21M} - e_{30}}{e_{10}e_{32}}\right)\left(\frac{S_{12M} - e'_{03}}{e'_{23}e'_{01}}\right)}{D}$$

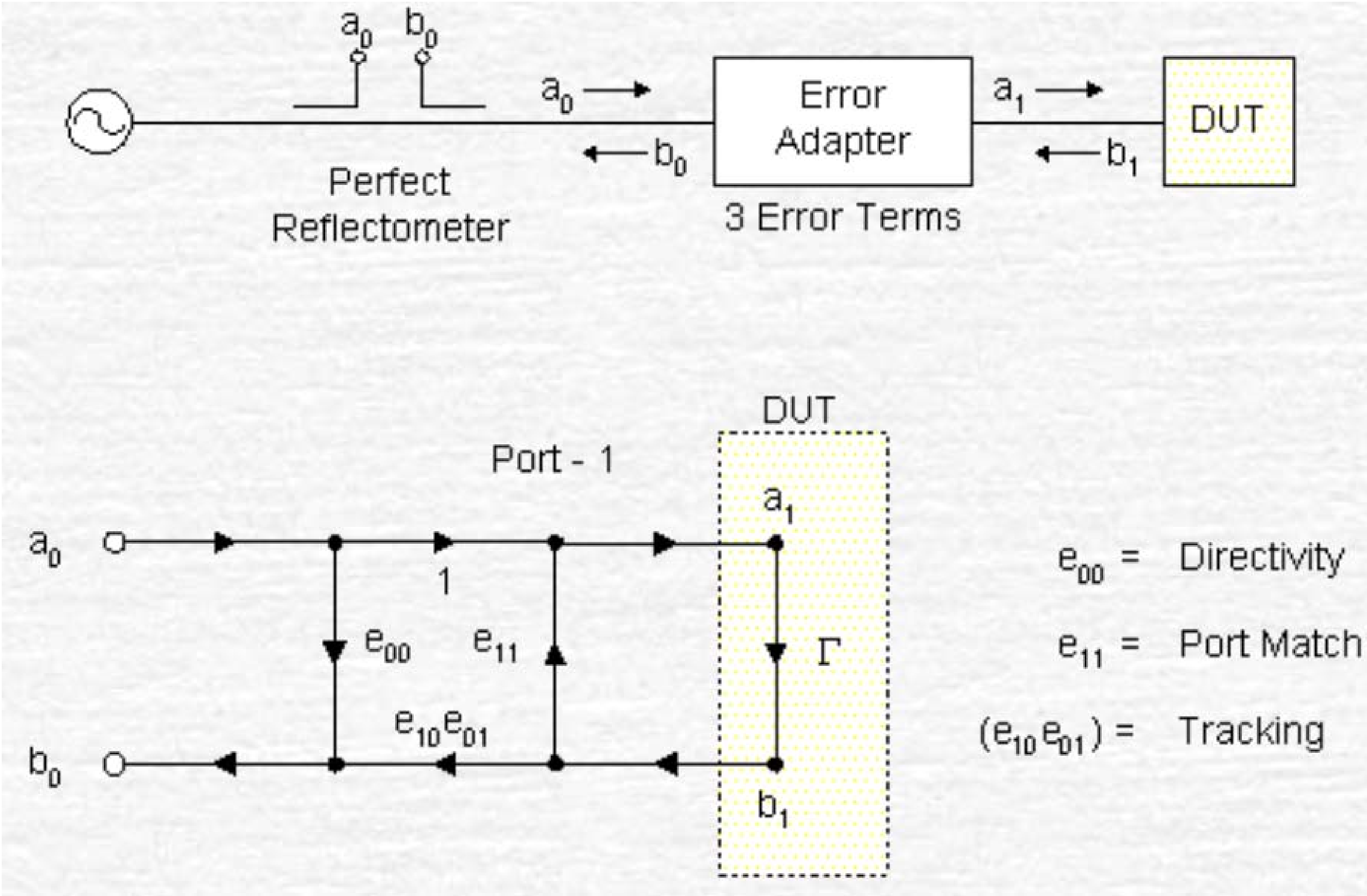
$$S_{12} = \frac{\left(\frac{S_{12M} - e'_{03}}{e'_{23}e'_{01}}\right)\left[1 + \left(\frac{S_{11M} - e_{00}}{e_{10}e_{01}}\right)(e_{11} - e'_{11})\right]}{D}$$

$$D = \left[1 + \left(\frac{S_{11M} - e_{00}}{e_{10}e_{01}}\right)e_{11}\right]\left[1 + \left(\frac{S_{22M} - e'_{33}}{e'_{23}e'_{32}}\right)e'_{22}\right] - \left(\frac{S_{21M} - e_{30}}{e_{10}e_{32}}\right)\left(\frac{S_{12M} - e'_{03}}{e'_{23}e'_{01}}\right)e_{22}e'_{11}$$

❑ One-Port Calibratioin: 3-term error model



❑ One-Port Calibratioin: 3-term error model



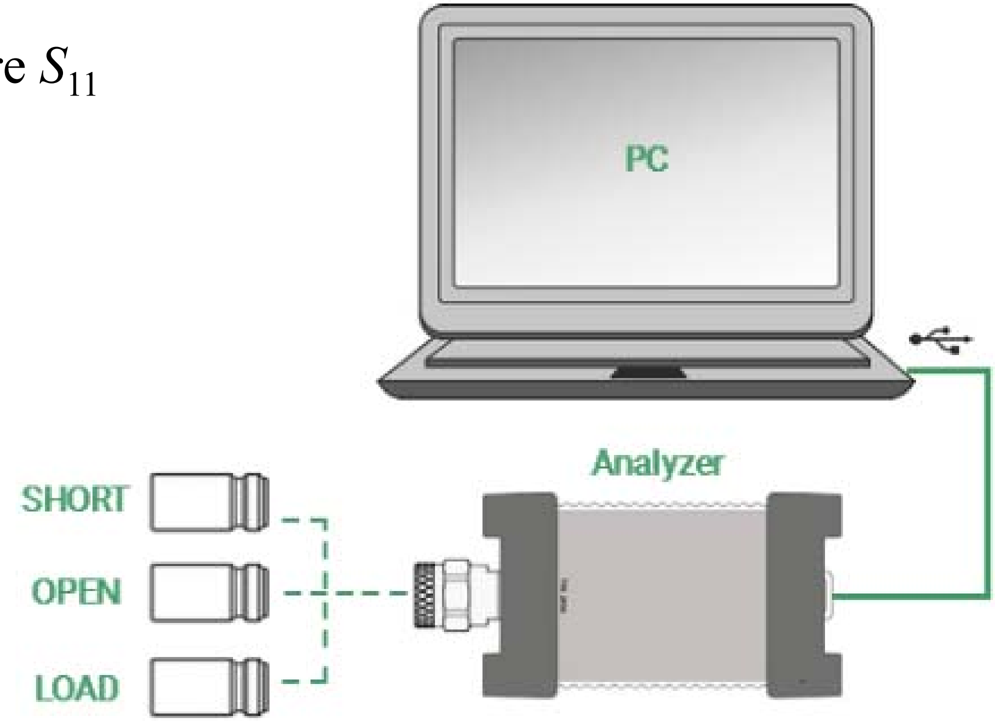
2.4 Vector Network Analyzer Calibration

❑ 1-Port VNA Calibration

- Port 1 calibration: open, short, load; measure S_{11}

- Coaxial system: open, short, load (= match)

- Waveguide: short, offset short, load



❑ 3-Term Error Calibration & Measurement

Measured

$$\Gamma_M = \frac{b_0}{a_0} = \frac{e_{00} - \Delta_e \Gamma}{1 - e_{11}\Gamma}$$

Actual

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

$$\Delta_e = e_{00}e_{11} - (e_{10}e_{01})$$

For ratio measurements there are 3 error terms
The equation can be written in the linear form

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

With 3 different known Γ, measure the resultant 3 Γ_M
This yields 3 equations to solve for e_{00}, e_{11}, and Δ_e

$$e_{00} + \Gamma_1\Gamma_{M1} e_{11} - \Gamma_1\Delta_e = \Gamma_{M1}$$

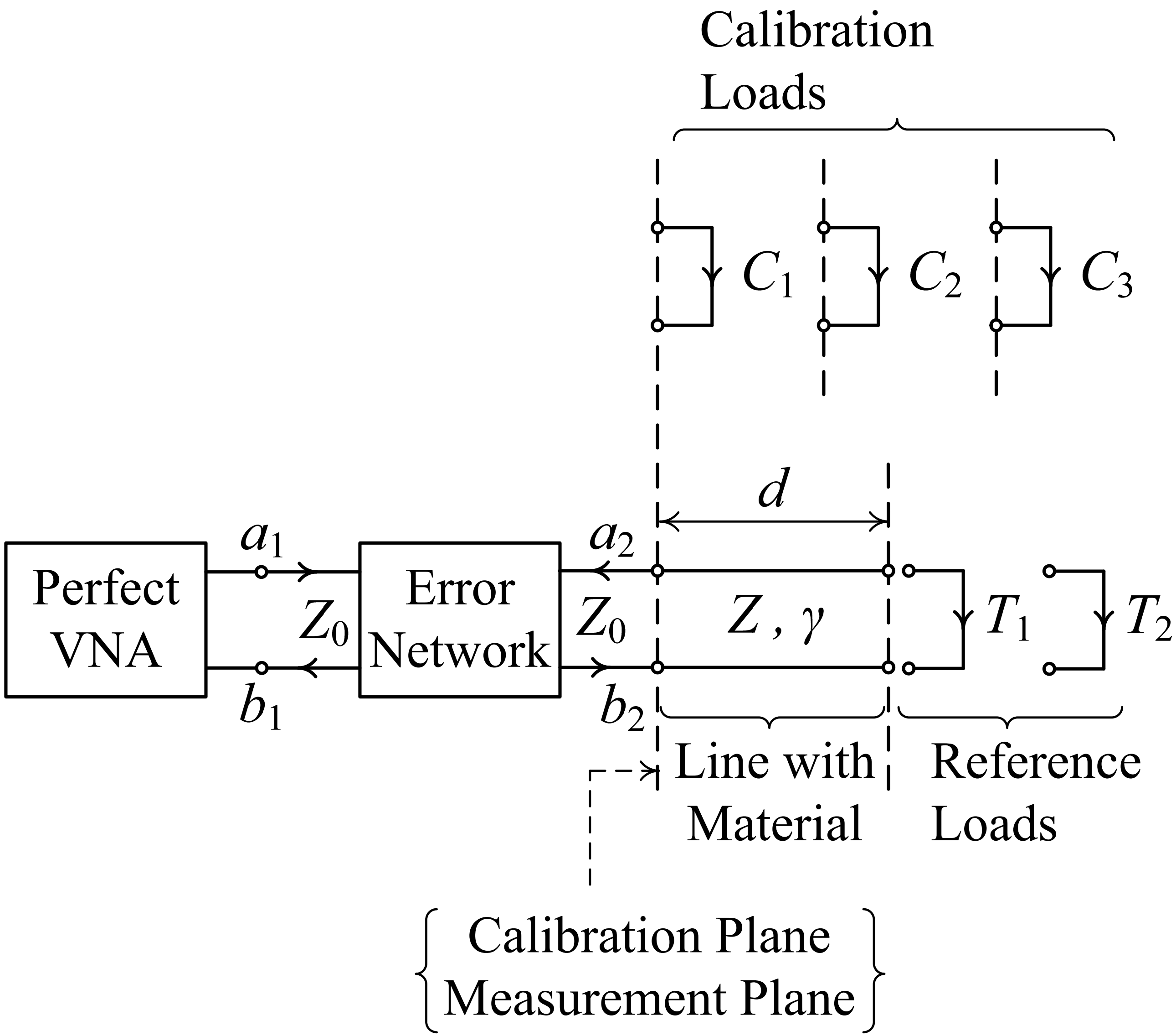
$$e_{00} + \Gamma_2\Gamma_{M2} e_{11} - \Gamma_2\Delta_e = \Gamma_{M2}$$

$$e_{00} + \Gamma_3\Gamma_{M3} e_{11} - \Gamma_3\Delta_e = \Gamma_{M3}$$

Any 3 independent measurements can be used

2.5 Reflection Method for Permittivity and Permeability Measurment

- **Material Constants Measurement Setup**



2.5 Reflection Method for Permittivity and Permeability Measurment

❑ Material Constants Measurement Procedures

1) One-port calibration: $\rightarrow$ Save error parameters.

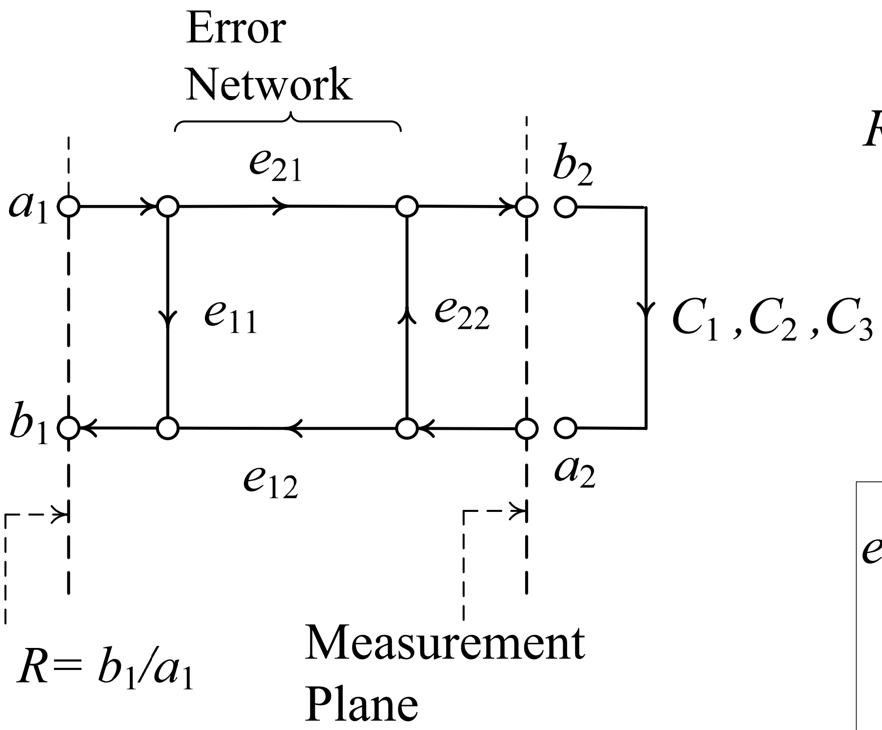
2) Load the test cell with MUT (material under test) with unknow μ_r and ε_r.

3) Connect the first reference load T_1 to the load side of the test cell and measure and save the reflection M_1.

4) Repeat 3 with T_2 to get M_2.

5) From M_1 and M_2, find μ_r and ε_r

❑ 3-Term One-Port Error Parameter Extraction



$$R_n = \frac{b_1}{a_1} = \frac{e_{11} - C_n\Delta}{1 - e_{22}C_n} \quad (n = 1, 2, 3); \; \Delta = e_{11}e_{22} - e_{12}e_{21}$$

$$e_{22} = \frac{R_1(C_2 - C_3) + R_2(C_3 - C_1) + R_3(C_1 - C_2)}{C_1C_2(R_1 - R_2) + C_2C_3(R_2 - R_3) + C_3C_1(R_3 - R_1)}$$

$$\Delta = \frac{(C_pR_p - C_qR_q)e_{22} - (R_p - R_q)}{C_p - C_q} \equiv \Delta_{pq}$$

$p \,\&\, q = 1, 2, 3; \; p \neq q$

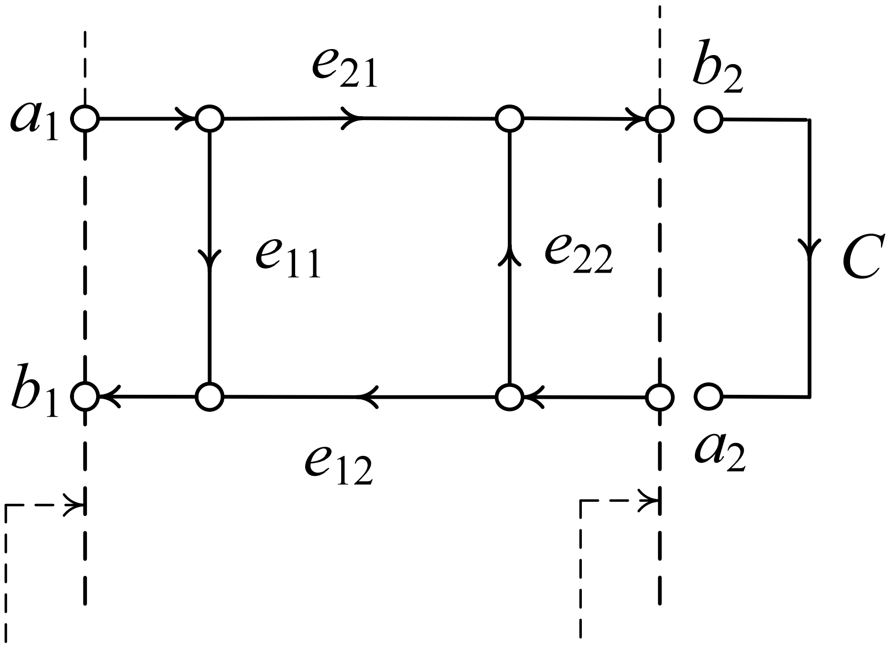
Choose p, q with the smallest $|C_p - C_q|$.

$$e_{11} = R_k + C_k(\Delta - R_k e_{22}) \quad (k = 1, 2, 3)$$

Choose k with the smallest $|C_k|$.

2.5 Reflection Method for Permittivity and Permeability Measurment

- Error-Corrected Reflection Coefficient



$R = b_1/a_1$ $\quad$ $C = b_2/a_2$

$$C = \frac{R - e_{11}}{Re_{22} - \Delta}$$

$$\Delta = e_{11}e_{22} - e_{12}e_{21}$$

❑ Error Network Validity Test

- Lossless and reciprocal network

$$[E^*]^t[E] = [I] \quad \text{(if lossless and reciprocal)}$$

$$[E^*]^t[E] = \begin{bmatrix} e_{11}^* & e_{21}^* \\ e_{12}^* & e_{22}^* \end{bmatrix} \begin{bmatrix} e_{11} & e_{12} \\ e_{21} & e_{22} \end{bmatrix}$$

$$= \begin{bmatrix} |e_{11}|^2 + |e_{21}|^2 & e_{11}^* e_{12} + e_{21}^* e_{22} \\ e_{11} e_{12}^* + e_{21} e_{22}^* & |e_{12}|^2 + |e_{22}|^2 \end{bmatrix}$$

$$= \begin{bmatrix} u_{11} & u_{12} \\ u_{21} & u_{22} \end{bmatrix}$$

❑ Error Network Validity Test

- Stability: Input reflection coefficient should be less than or equal to 1.

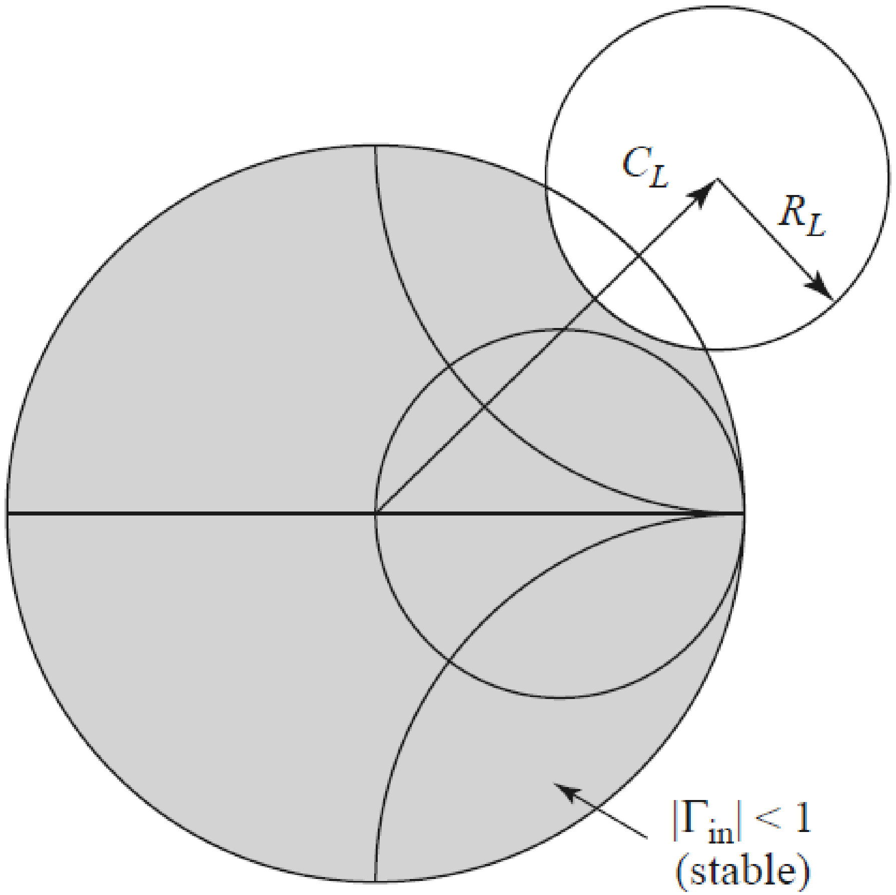
  $|R| \leq 1$ for passive loads

- Stability circle: A network is stable when the load reflection coefficient lies outside the stability circle.

$$|e_{11}| < 1$$

$$C_L = \frac{e_{22}^* - e_{11}\Delta^*}{|e_{22}|^2 - |\Delta|^2}$$

$$R_L = \left| \frac{e_{21}e_{12}}{|e_{22}|^2 - |\Delta|^2} \right|$$



❑ Reciprocity Test

- $S_{mn} = S_{nm}$ (reciprocity)
- Passive devices having only reciprocal materials
- Cables, attenuators, splitters, and combiners

❑ Scattering Parameters of A Lossless Reciprocal Two-Port

$$S_{12} = S_{21}$$

$$|S_{11}|^2 + |S_{12}|^2 = 1, |S_{21}|^2 + |S_{22}|^2 = 1 \to |S_{11}| = |S_{22}| \ \& \ |S_{12}|^2 = 1 - |S_{11}|^2$$

$$S_{11}S_{12}^* + S_{12}S_{22}^* = 0; |S_{11}|^2 + S_{12}S_{12}^* = 1$$

$$S_{11}, S_{12} \text{ given} \to S_{22} = -\frac{S_{12}}{S_{12}^*}S_{11}^*; \ \theta_{22} = (2n+1)\pi + 2\theta_{12} - \theta_{11}$$

$$S_{11}, S_{12} \text{ given} \to S_{11} = -\frac{S_{12}}{S_{12}^*}S_{22}^*; \theta_{11} = (2n+1)\pi + 2\theta_{12} - \theta_{22}$$

$$S_{11}, S_{22} \text{ given} \to S_{12}^2 = \frac{(|S_{11}|^2 - 1)S_{11}}{S_{22}^*}; 2\theta_{12} = -(2n+1)\pi + \theta_{11} + \theta_{22}$$

$$\det([S]) = S_{11}S_{22} - S_{12}S_{21} = e^{j(\theta_{11}+\theta_{22})}$$

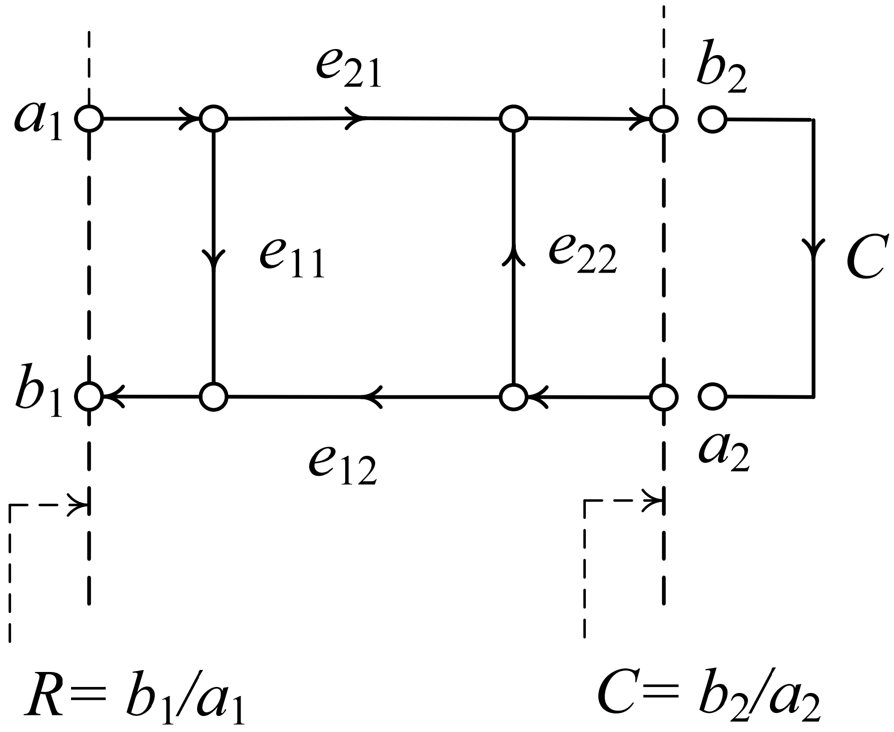
❑ Conditions for Error Parameters

$$e_{11} = ae^{j\theta_{11}}$$

$$e_{22} = ae^{j\theta_{22}}$$

$$e_{12} = e_{21} = \sqrt{1-a^2}\,e^{j\theta_{12}}, \ \theta_{12} = -\frac{2n+1}{2}\pi + \frac{\theta_{11}+\theta_{22}}{2}$$

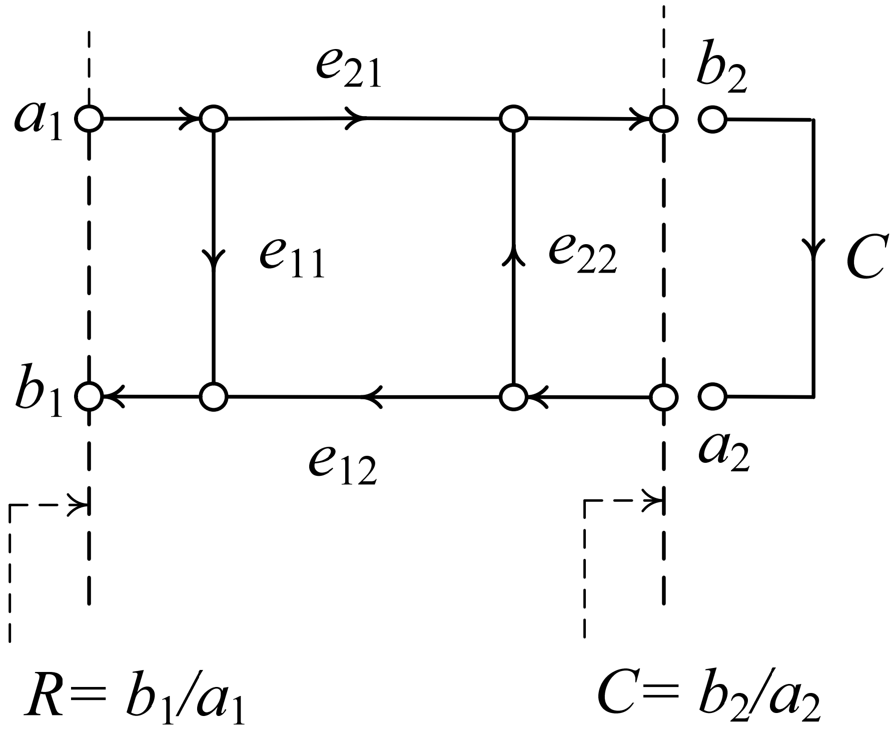
❑ Error-Corrected One-Port Measurement



$$C = \frac{R - e_{11}}{Re_{22} - \Delta}$$

$$\Delta = e_{11}\, e_{22} - e_{12}e_{21}$$

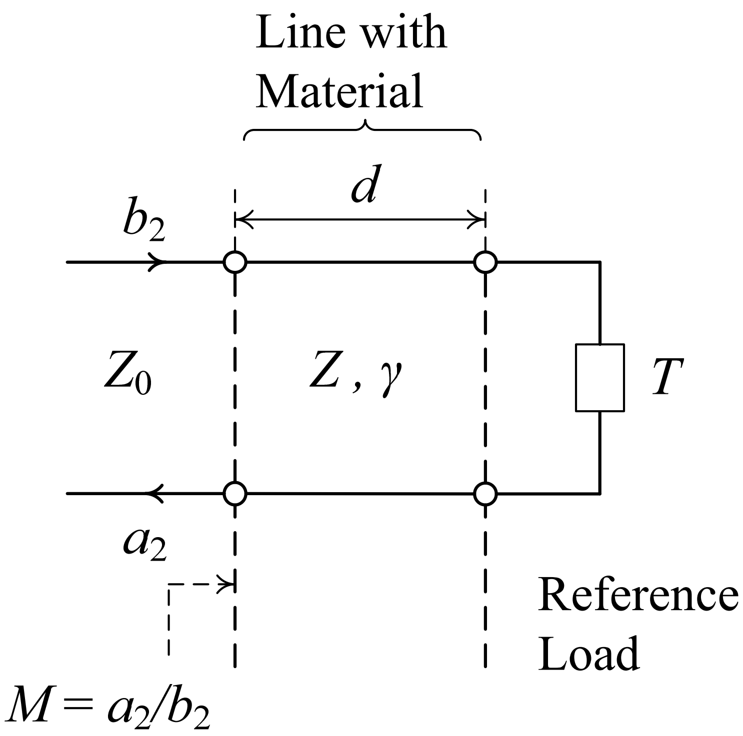
❑ Error-Corrected One-Port Measurement



$$C = \frac{R - e_{11}}{Re_{22} - \Delta}$$

$$\Delta = e_{11} e_{22} - e_{12} e_{21}$$

❑ One-Port Material Test Cell: Governing Equation



$$M = \frac{Z_{\text{in}} - Z_0}{Z_{\text{in}} + Z_0} \rightarrow Z_{\text{in}} = Z_0 \frac{1+M}{1-M}$$

$$\Gamma_{\text{in}} = Ce^{-2\gamma d};\;\; C = \frac{T-Z}{T+Z} = \frac{t-z}{t+z};\; t = \frac{T}{Z_0};\;\; z = \frac{Z}{Z_0}$$

$$Z_{\text{in}} = Z\frac{1+\Gamma_{\text{in}}}{1-\Gamma_{\text{in}}} = Z\frac{1+Ce^{-2\gamma d}}{1-Ce^{-2\gamma d}}$$

$$Z_{\text{in}} = Z_0\frac{1+M}{1-M} = Z\frac{1+Ce^{-2\gamma d}}{1-Ce^{-2\gamma d}}$$

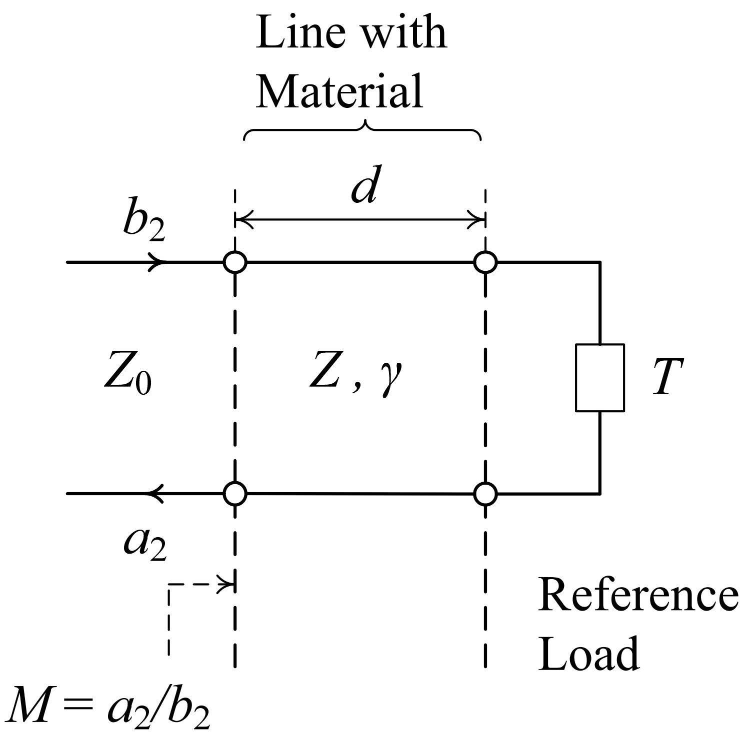
$$s = \frac{1+M}{1-M}$$

$$s = z\frac{1+Ce^{-2\gamma d}}{1-Ce^{-2\gamma d}} \rightarrow C(s+z)e^{-2\gamma d} = s - z$$

$$C = \frac{t-z}{t+z}$$

$$\boxed{(t-z)(s+z)e^{-2\gamma d} = (t+z)(s-z)}$$

❑ One-Port Material Test Cell: Optimum Material Thickness



$$\gamma = \omega\mu_0\varepsilon_0\sqrt{\mu_r(1 - j\tan\delta_m)\varepsilon_r(1 - j\tan\delta_e)} = \alpha + j\beta$$

$$e^{-2\gamma d} = e^{-2\alpha d}e^{-j2\beta d}$$

$$\beta \cong \omega\mu_0\varepsilon_0\sqrt{\mu_r\varepsilon_r} = (2\pi/\lambda_0)\sqrt{\mu_r\varepsilon_r} = 2\pi/\lambda_g$$

$$\lambda_g = \lambda_0/\sqrt{\mu_r\varepsilon_r}$$

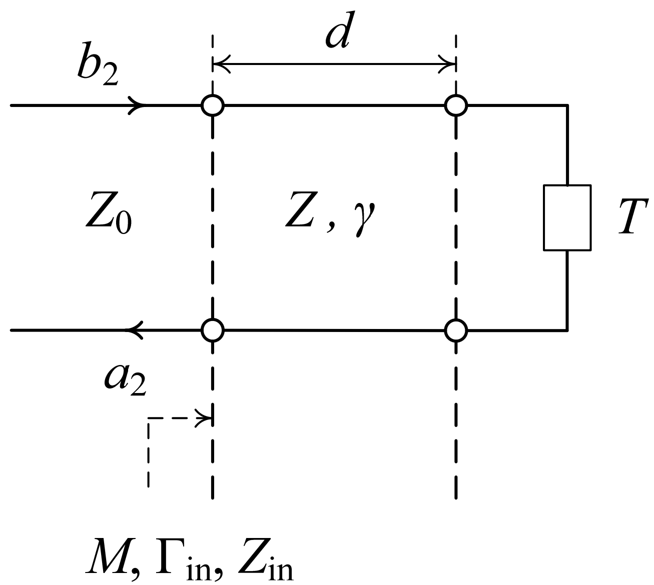
$$f = f_1, \lambda_g = \lambda_{g1}, 2\beta_1 d = \theta_1$$

$$f = f_2, \lambda_g = \lambda_{g2}, 2\beta_2 d = \theta_2 = 2\pi - \theta_1$$

$$\frac{4\pi d}{\lambda_{g2}} = 2\pi - \frac{4\pi d}{\lambda_{g1}}$$

$$\boxed{d = \frac{1}{2}\left(\frac{1}{\lambda_{g1}} + \frac{1}{\lambda_{g2}}\right)^{-1} = \frac{1}{2}\frac{\lambda_{g1}\lambda_{g2}}{\lambda_{g1} + \lambda_{g2}}}$$

❑ One-Port Material Test Cell: Materials Constants Extraction



$$(t-z)(s+z)e^{-2\gamma d} = (t+z)(s-z)$$

$$(t_1-z)(s_1+z)e^{-2\gamma d} = (t_1+z)(s_1-z)$$

$$(t_2-z)(s_2+z)e^{-2\gamma d} = (t_2+z)(s_2-z)$$

Solve for z:

$$\boxed{z = \pm\sqrt{\frac{t_1t_2(s_1-s_2)-s_1s_2(t_1-t_2)}{(s_1-s_2)-(t_1-t_2)}},\mathrm{Re}(z)>0}$$

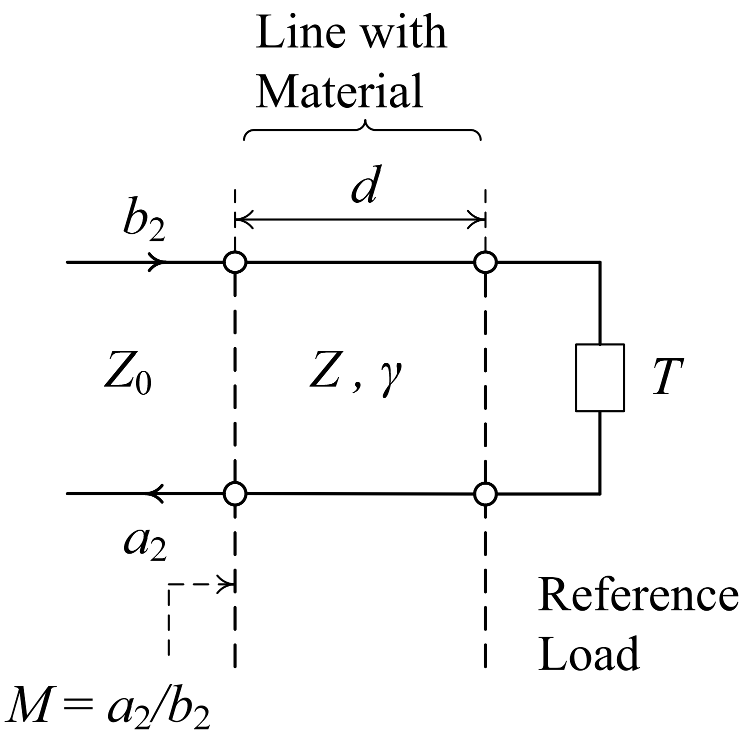
Solve for γ:

$$e^{-2\gamma d} = \frac{(t_i+z)(s_i-z)}{(t_i-z)(s_i+z)} \equiv x_i \ \ (i=1,2)$$

Choose i with the largest $|(t_i-z)(s_i+z)|$

$$\boxed{\gamma = -\frac{1}{2d}\ln x_i}$$

❑ One-Port Material Test Cell: Material Constants Extraction



$$z = \frac{Z}{Z_0} = \sqrt{\frac{\mu_r(1 - j\tan\delta_m)}{\varepsilon_r(1 - j\tan\delta_e)}}$$

$$\gamma = jk_0\sqrt{\mu_r(1 - j\tan\delta_m)\varepsilon_r(1 - j\tan\delta_e)}$$

$$\boxed{\mu_r(1 - j\tan\delta_m) = \frac{\gamma z}{jk_0}}$$

$$\boxed{\varepsilon_r(1 - j\tan\delta_e) = \frac{\gamma / z}{jk_0}}$$

$$k_0 = \omega\sqrt{\mu_0\varepsilon_0} = 2\pi f / c_0$$

2.6 Summary

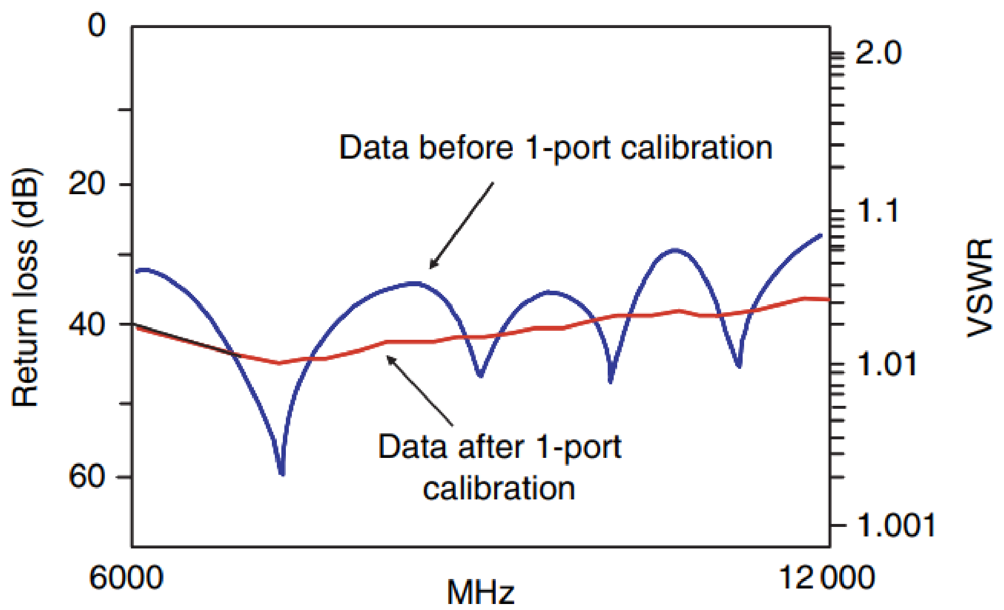
❑ VNA (Vector Network Analyzer)

- Instrument that measures the magnitude and phase of reflection coefficients on a port, and the magnitude and phase of transmission coefficient between ports.
- Reflection coeffient: S_{kk}, k = port number
- Transmission coefficienit: S_{kj}, from port j to port k
- VNA companies: Keysight (World #1), Rhode & Schwarz, Anritsu
- Example: Teledyne LeCroy T3VNA3200, 3.2-GHz VNA, KRW 15,940,000

2.6 Summary

❑ VNA Calibration

- Removing systematic error terms in VNA measurements
- Error terms arise from instrument hardware
- Calibration is required for each measurement setup.
- Type of calibration: one-port calibration, two-port calibration
- One-port calibration: for S_{11} and/or S_{22} measurements. 3 error terms
- Two-port calibtaion: for S_{11}, S_{21}, S_{12} and S_{22} measurements. 6 error terms for each source port



2.6 Summary

❑ Reflection Method of Material Constants Measurements

- Use a transmission line (= a test cell) loaded with a material under test (MUT).

- Measure the input reflection coefficients M_1 and M_2
  with the load side of the test cell terminated with two reference loads T_1 and T_2

- From M_1 and M_2, extract complex μ_r and ε_r.

❑ 1-Port Error Paramter Extraction: Code

```
#---------------------------------------------------------------------------
# VNA calibration numerical experiment: Extract 3-term 1-port error parameters
# [e] given => calculate input reflection with 3 calibration loads => find [e].
from math import *
from cmath import *
#---------------------------------------------------------------------------
def one_port_cal(c1,c2,c3,r1,r2,r3):
# Extract one-port error network parameters
# c1,c2,c3: reflection coefficient of three calibration loads
# r1,r2,r3: input reflection coefficient with c1, c2, and c3 connected to the
#  load side of the error network
# e11,e22,delta: error network parameters. delta=e11*e22-e12*e21
 e22=r1*(c2-c3)+r2*(c3-c1)+r3*(c1-c2)
 e22=e22/(c1*c2*(r1-r2)+c2*c3*(r2-r3)+c3*c1*(r3-r1))
 a12,a23,a31=abs(c1-c2),abs(c2-c3),abs(c3-c1)
 if a12>=a23 and a12>=a31: delta=((c2*r2-c1*r1)*e22-(r2-r1))/(c2-c1)
 elif a23>=a31: delta=((c2*r2-c3*r3)*e22-(r2-r3))/(c2-c3)
 elif a31>a23: delta=((c3*r3-c1*r1)*e22-(r3-r1))/(c3-c1)
 a1,a2,a3=abs(c1),abs(c2),abs(c3)
 if a1>=a2 and a1>=a3: e11=r1+c1*(delta-r1*e22)
 elif a2>=a3: e11=r2+c2*(delta-r2*e22)
 elif a3>a2: e11=r3+c3*(delta-r3*e22)
 return e11,e22,delta
#-----------------------------------------------------------------
rd=pi/180
print('One-port calibration numerical experiment: error parameter extraction ')
print('1. Specify one-port error network parameters e11, e12, and e22 ([e]).')
print('   Specify e11 and e12, and e22 is expressed in terms of e11 and e12.')
print('   mag(e12)=sqrt(1-mag(e11)**2)')
print('2. Specify reflection coefficients C1, C2, and C3 of three calibration loads.')
print('3. Find theoretical input reflection coefficients R1, R2, and R3 of the error network')
print('   with C1, C2, and C3 connected to the error network.')
```

❑ 1-Port Error Paramter Extraction: Code

```
print('4. Extract e11, e12*e21, and e22 from R1, R2, R3, C1, C2, and C3 and')
print('   and compare them with specified values.')
print(' ')
e11m,e11p=map(float,input('Error parameter e11: mag(e11),phase(e11)(deg) = ').split())
e11=rect(e11m,e11p*rd)
#e22m,e22p=map(float,input('Error parameter e22: mag(e22),phase(e22)(deg) = ').split())
#e22=rect(e22m,e22p*rd)
print('Lossless case: mag(e12) = sqrt(1-mag(e11)**2) = ',sqrt(1-abs(e11)**2))
e21m,e21p=map(float,input('Error parameter e21: mag(e21),phase(e21)(deg) = ').split())
e21=rect(e21m,e21p*rd); e12=e21
e22=-e12/e12.conjugate()*e11.conjugate()
delta=e11*e22-e12*e21
while True:
# Define three calibration standards.
 print(' ')
 c1m,c1p=map(float,input('Calibratoin load C1 reflection coefficient: mag(c1),phase(c1)(deg)=').split())
 c1=rect(c1m,c1p*rd)
 c2m,c2p=map(float,input('Calibration load C2 reflection coefficient: mag(c2),phase(c2)(deg)=').split())
 c2=rect(c2m,c2p*rd)
 c3m,c3p=map(float,input('Calibration load C3 reflection coefficient: mag(c3),phase(c3)(deg)=').split())
 c3=rect(c3m,c3p*rd)
# Calculate the input reflection coefficient of the error network with a calibration load.
 r1=(e11-c1*delta)/(1-e22*c1);r1m,r1p=polar(r1);r1p=r1p/rd
 r2=(e11-c2*delta)/(1-e22*c2);r2m,r2p=polar(r2);r2p=r2p/rd
 r3=(e11-c3*delta)/(1-e22*c3);r3m,r3p=polar(r3);r3p=r3p/rd
 print('Theoretical input reflection coefficient with load C1: r1m,r1p = {:.6f}  {:.6f}'.format(r1m,r1p))
 print('Theoretical input reflection coefficient with load C2: r2m,r2p = {:.6f}  {:.6f}'.format(r2m,r2p))
 print('Theoretical input reflection coefficient with load C3: r3m,r3p = {:.6f}  {:.6f}'.format(r3m,r3p))
# Extract the error parameters.
 E11,E22,DELTA=one_port_cal(c1,c2,c3,r1,r2,r3)
 print('Specified [e]: e11,e22,delta = {:.6f}; {:.6f}; {:.6f}'.format(e11,e22,delta))
 print('Extracted [e]: e11,e22,delta = {:.6f}; {:.6f}; {:.6f}'.format(E11,E22,DELTA))
#---------------------------------------------------------------------------------------
```

❑ 1-Port Error Paramter Extraction: Code Execution

```
One-port calibration numerical experiment: error parameter extraction
1. Specify one-port error network parameters e11, e12, and e22 ([e]).
   Specify e11 and e12, and e22 is expressed in terms of e11 and e12.
   mag(e12)=sqrt(1-mag(e11)**2)
2. Specify reflection coefficients C1, C2, and C3 of three calibration loads.
3. Find theoretical input reflection coefficients R1, R2, and R3 of the error network
   with C1, C2, and C3 connected to the error network.
4. Extract e11, e12*e21, and e22 from R1, R2, R3, C1, C2, and C3 and
   and compare them with specified values.

Error parameter e11: mag(e11),phase(e11)(deg) =
0.1 20
Lossless case: mag(e12) = sqrt(1-mag(e11)**2) =  (0.99498743710662+0j)
Error parameter e21: mag(e21),phase(e21)(deg) =
0.995 -120

Calibratoin load C1 reflection coefficient: mag(c1),phase(c1)(deg)=
1 180
Calibration load C2 reflection coefficient: mag(c2),phase(c2)(deg)=
0.01 20
Calibration load C3 reflection coefficient: mag(c3),phase(c3)(deg)=
1 0
Theoretical input reflection coefficient with load C1: r1m,r1p = 1.000024  -48.942140
Theoretical input reflection coefficient with load C2: r2m,r2p = 0.095442  25.159211
Theoretical input reflection coefficient with load C3: r3m,r3p = 1.000025  108.553874
Specified [e]: e11,e22,delta = 0.093969+0.034202j; 0.017365-0.098481j; 0.500013-0.866047j
Extracted [e]: e11,e22,delta = 0.093969+0.034202j; 0.017365-0.098481j; 0.500013-0.866047j
```

2.7 Codes

❑ Material Constants Extraction from Reflection Measurements: Code

```
#----------------------------------------------------------------------
# Permittivity and permeability extraction from reflection measurements
from cmath import *
def zin_one_port_cell(ur,tandm,er,tande,f,d,t):
# d: sample length(m)
# t: terminating impednace normalized by Z0 of input line
# s: input imped normalized by Z0 of test line on the measurment plane
# m: imput reflection coefficient on the measurement plane seen
#   from the test line with Z0 (characteristic impedance)
 pi=3.141592654; j=complex(0,1)
 u=ur*complex(1,-tandm); e=er*complex(1,-tande)
 w=2*pi*f; gam=j*w/3e8*sqrt(u*e)
 z=sqrt(u/e); c=(t-z)/(t+z)
 s=z*(1+c*exp(-2*gam*d))/(1-c*exp(-2*gam*d))
 m=(s-1)/(s+1)
 return s,m
#----------------------------------------------------------------------------
pi=3.141592654;rad=180/pi
while True:
# Specify ur, tand_m, er, and tand_e of the material under test (MUT).
 ur,tdm,er,tde=map(float,input('Material constants: ur,tdm,er,tde=').split())
 u=ur*complex(1,tdm); e=er*complex(1,tde)
# Specify the frequency for material constants extraction.
 f1,f2=map(float,input('Frequency: f1,f2(Hz)=').split())
 j=complex(0,1)
# Calculate the wavelength at f1 and f2.
 g1=j*2*pi*f1/3e8*sqrt(u*e); a1=g1.real; b1=g1.imag
 g2=j*2*pi*f2/3e8*sqrt(u*e); s2=g2.real; b2=g2.imag
 w1=2*pi/b1; w2=2*pi/b2
# Find the optimum thickness of the MUT.
 d_opt=0.5*w1*w2/(w1+w2)
 print('Optimum material thickness: d_opt=',d_opt)
```

❑ Material Constants Extraction from Reflection Measurements: Code

```
# Specify the MUT thickness.
 d=float(input('Material thickness: d(m)='))
# Specify normalized impedance of the two reference loads.
 t1=complex(input('Normalized complex impedance of reference load 1: t1(=T1/Z0) ='))
 t2=complex(input('Normalized complex impedance of reference load 2: t2(=T2/Z0) ='))
# Calculate the reflection coefficient of the test cell with a reference load.
 s1,m1=zin_one_port_cell(ur,tdm,er,tde,f1,d,t1)
 s2,m2=zin_one_port_cell(ur,tdm,er,tde,f1,d,t2)
 m1m,m1p=polar(m1); m1p=m1p*rad
 m2m,m2p=polar(m2); m2p=m2p*rad
 print('Input reflection with T1: mag(m1), phase(m1) = {:.6f}  {:.6f}'.format(m1m,m1p))
 print('Input reflection with T2: mag(m2), phase(m2) = {:.6f}  {:.6f}'.format(m2m,m2p))
# Extract ur, tand_m, er, and tand_e of the MUT
 ds=s1-s2; dt=t1-t2
 z=sqrt((t1*t2*ds-s1*s2*dt)/(ds-dt))
 if z.real<0: z=-z
 if abs((t1-z)*(s1+z))>=abs((t2-z)*(s2+z)):
  x=(t1+z)*(s1-z)/((t1-z)*(s1+z)); gam=-log(x)/(2*d)
 else: x=(t2+z)*(s2-z)/((t2-z)*(s2+z)); gam=-log(x)/(2*d)
 if gam.real<0: gam=-gam
 print('Normalized intrinsic impedance in MUT: z(=Z/Z0) = {:.6f}'.format(z))
 print('Propgation constant in MUT: gamma(= alpha + j*beta) = {:.6f}'.format(gam))
 jk0=complex(0,2*pi/(3e8/f1))
 u=gam*z/jk0; ur=u.real; ui=u.imag; tandm=-ui/ur
 e=gam/z/jk0; er=e.real; ei=e.imag; tande=-ei/er
 print('Exracted: ur,tandm; er,tande = {:.6f} {:.6f} {:.6f} {:.6f}'.format(ur,tandm,er,tande))
 print(' ')
#------------------------------------------------------------------------------------------
```

❑ Material Constants Extraction from Reflection Measurements: Code Run

```
Material constants: ur,tdm,er,tde=
4 0.4 3 0.3
Frequency: f1,f2(Hz)=
1e9 2e9
Optimum material thickness: d_opt= 0.01441770641574161
Material thickness: d(m)=
0.014
Normalized complex impedance of reference load 1: t1(=T1/Z0) =
0+0j
Normalized complex impedance of reference load 2: t2(=T2/Z0) =
1+0j
Input reflection with T1: mag(m1), phase(m1) = 0.499896  52.715221
Input reflection with T2: mag(m2), phase(m2) = 0.106766  4.190018
Normalized intrinsic impedance in MUT: z(=Z/Z0) = 1.171647-0.052202j
Propgation constant in MUT: gamma(= alpha + j*beta) = 25.364954+72.632742j
Exracted: ur,tandm; er,tande = 4.000000 0.400000 3.000000 0.300000
```

III. Writing a PBL Report

3.1 A PBL Report Format

Title

Author(s)

Summary

I. Introduction

II. Theory

III. Experiment

IV. Conclusion

References

3.2 How to Wirte A PBL Report

Title

Example: Reflection Method for Material Constants Measurements

- Title should accurately reflect the content of the PBL report.

- Title should not be too long.

Author(s)

Exmaple: Gildong Hong, Chansoo Lee, and Soonja Kim

- 1st author: the person whose contribution to the report is the greatest

- Last author: the person who supervised the report

Summary

- Summarize the report.

- Six to ten lines long

3.2 How to Wirte A PBL Report

I. Introduction

1) Problem definition:

- What are the material constants?
- Why do you need to know the material constant?
- Why do you need to measure the material constants instead of looking up in the Internet?

2) Existing methods

- Explain available methods for materials constant measurement.

3) Proposed method

- Explain the proposed method used in the report.
- Advantages and limitations of the proposed method.

4) Composition of the report

- Explain shortly the content of following chapters.

3.2 How to Wirte A PBL Report

II. Theory

1) Vector network analyzer (VNA) one-port error model

2) One-port calibtation of a VNA

3) Extracting the material constants from one-port measurement

III. Experiment

1) Code for one-port calibration of a VNA

2) Execution of the one-port calibration code

3) Code for the material constants extraction from one-port measurement

4) Execution of the material constants extraction code

3.2 How to Wirte A PBL Report

IV. Conclusion

- Summarize what you have done.
- Summarize what you have found.
- Suggest further research and applications of the proposed work.

References

- List of papers, reports, theses, and books you used for the report.
- Example

[1] F. L. Niemann, "Transitions from Coaxial Line to Waveguide," in *Microwave Transmission Circuits*, G. L. Ragan, Ed., McGraw-Hill: New York, NY, USA, 1948, pp. 314–361.

[2] S. B. Cohn, "Design of simple broad-band wave-guide-to-coaxial-line junctions," *Proc. IRE*, Vol. 35, pp. 920–926, 1947.

Fin

(End)