Six-Port Reflectometer: an Alternative Network Analyzer for THz Region

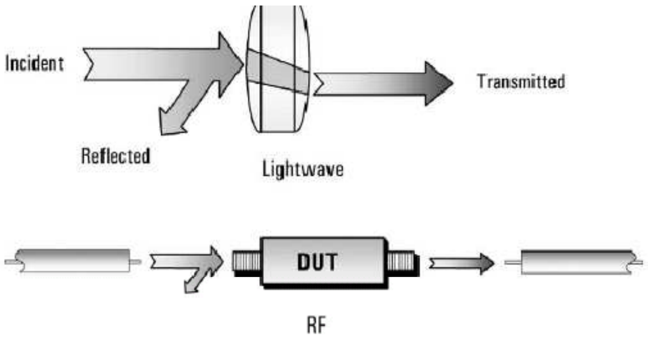
Guoguang Wu

Outline

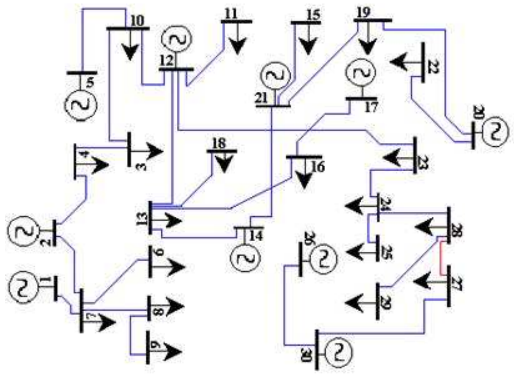
- General Background of Network Analyzer
- Principles of Six-Port Reflectometer
- WR-15 Six-port Reflectometer
  - Design, Measurement Setup
  - Results as Network Analyzer
  - Results as an Embedded Sensor into other Systems
- Other Potential Applications (beyond network analyzer)

What is Network Analyzer?

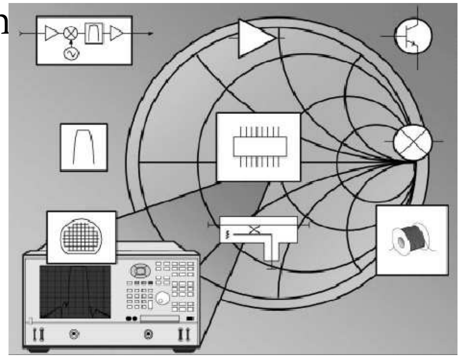
not about computer networks



especially to measure reflection and transmission



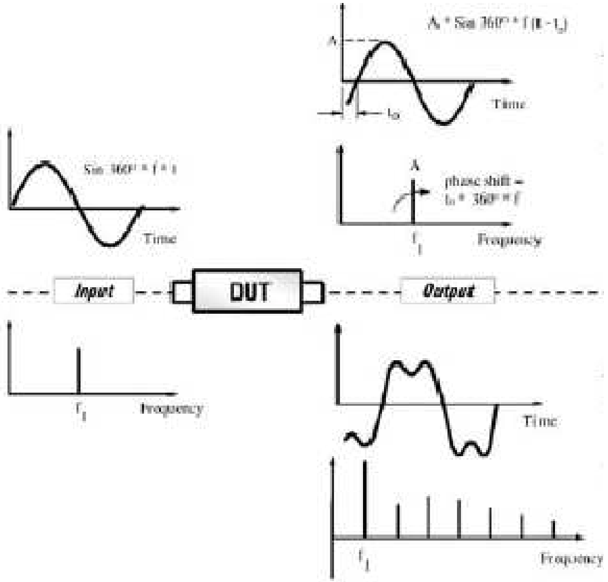
referred to “electrical” networks used to analyze the properties of them



operating frequencies range from 9 kHz to 500 GHz

Why Test Components?

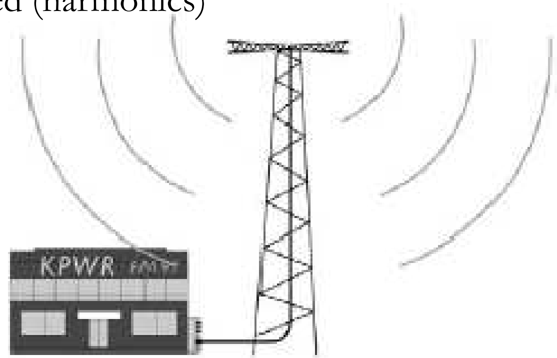
- Verify specifications of "building blocks" for more complex radio-frequency (RF) system
- Ensure distortionless transmission of communications signals



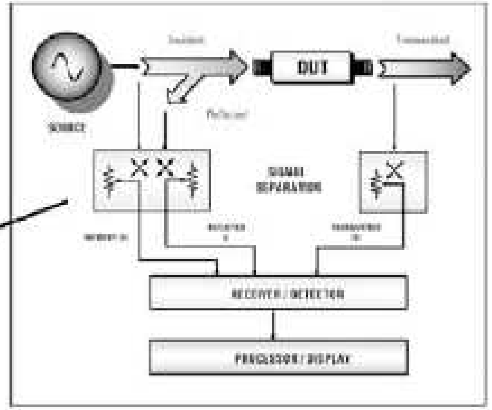
Linear behavior:
input and output frequency are the same
output frequency only undergoes magnitude and phase change

Nonlinear behavior:
output frequency may undergo frequency shift (e.g. with mixers)
additional frequencies created (harmonics)

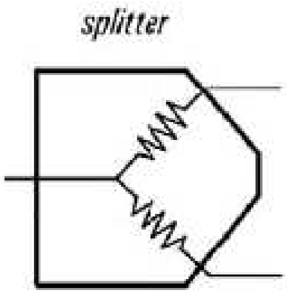
- Ensure good match when absorbing power
  (e.g. an anteanna)

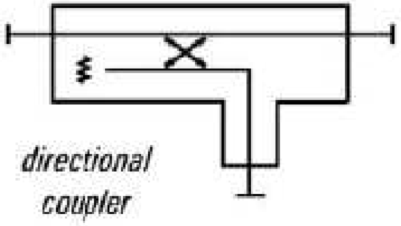


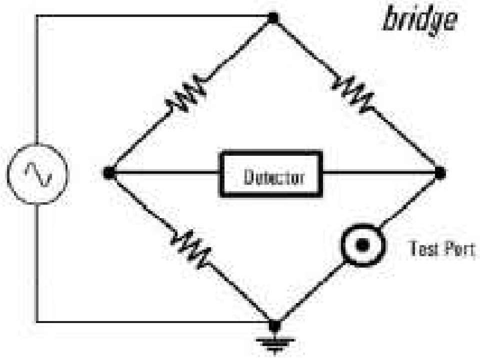
How Commercial Network Analyzer Works? (Signal Separation)



- measure incident signal for reference
- separate incident and reflected signals







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- WR-15 Six-port Reflectometer
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- Other Potential Applications (beyond Network Analyzer)

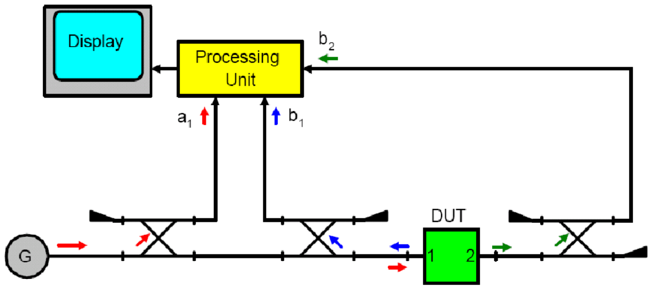
Overview of Six-port Technique

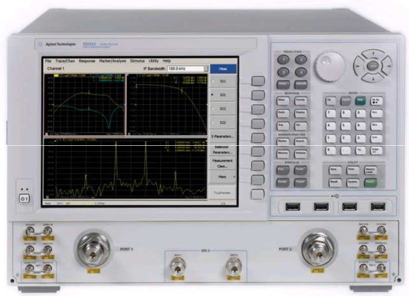
- Engen invented six-port technique in 1977*.
- Six-port technique is a method of network analysis.
- Six-port ***reflectometer*** (SPR): measure only reflection coefficient.
- Six-port ***network analyzer*** (SPNA): measure both reflection and transmission.

*IEEE MTT-25(12), pp1075, 1977

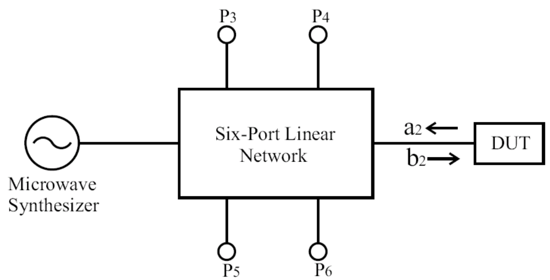
Network Analysis Methodology Comparison

- Conventional (commercial, four-port) NA: signal separation method





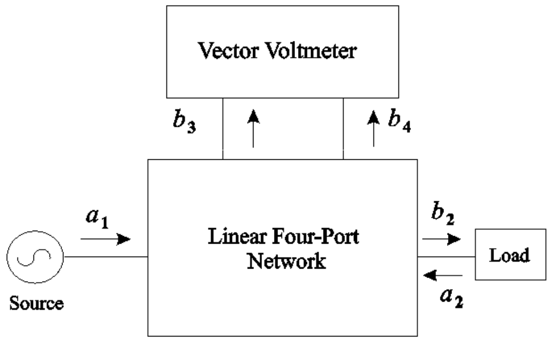
- Six-port VNA (reflectometer): signal interference method



Calibration Procedure Comparison

Commercial VNA

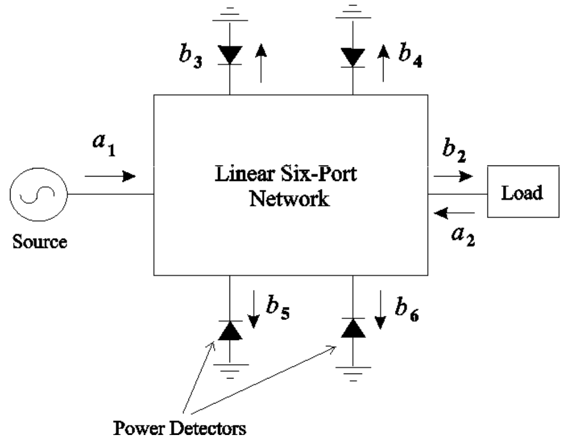
$$b_3, b_4 \rightarrow \frac{a_2}{b_2}(\Gamma)$$



$$\frac{b_3}{b_4} = \frac{A\Gamma + B}{C\Gamma + 1}$$

Six-port reflectometer

$$P_i(|b_i|^2) \rightarrow \frac{b_3}{b_4}(w) \rightarrow \Gamma(\frac{a_2}{b_2})$$

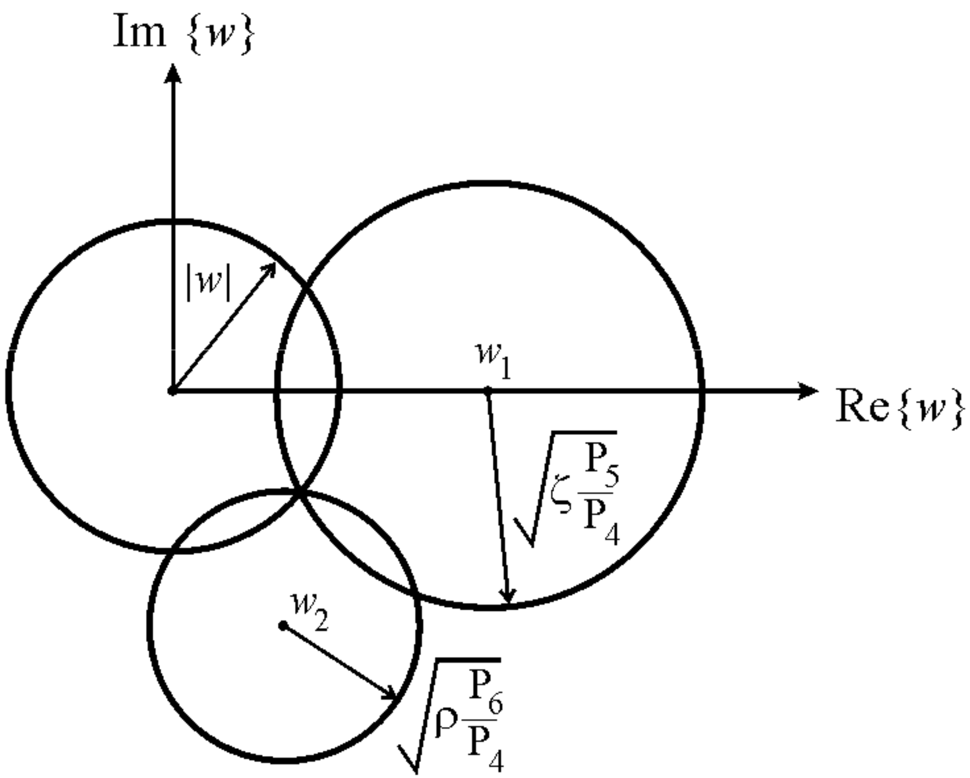


$$\zeta \left|\frac{b_5}{b_4}\right|^2 = |w - w_1|^2$$

$$\rho \left|\frac{b_6}{b_4}\right|^2 = |w - w_2|^2$$

$$|w| = \left|\frac{b_3}{b_4}\right|$$

Six-Port Theory: Determination of *w* and Γ



- Intersection of Circles determines ratio b_3/b_4
- "true" Γ related by bilinear transform: requires four-port calibration
- First step of six-port calibration is to get the value of five "network constants:"

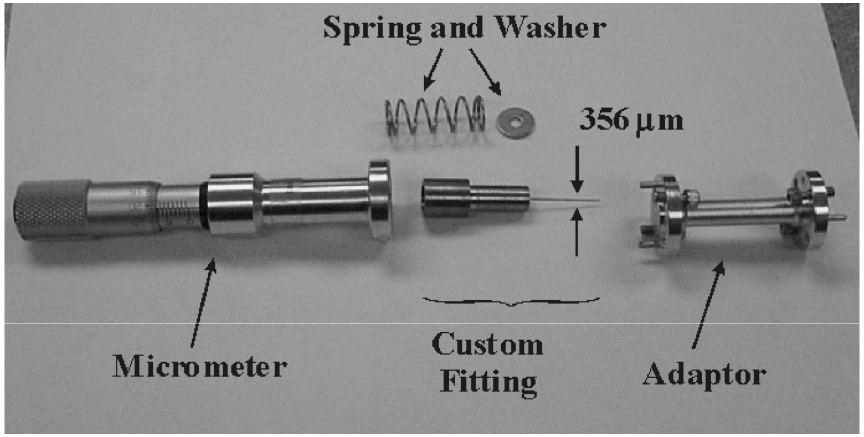
    1. w_1 (real)
    2. w_2 (complex)
    3. ρ (scalar)
    4. ζ (scalar)

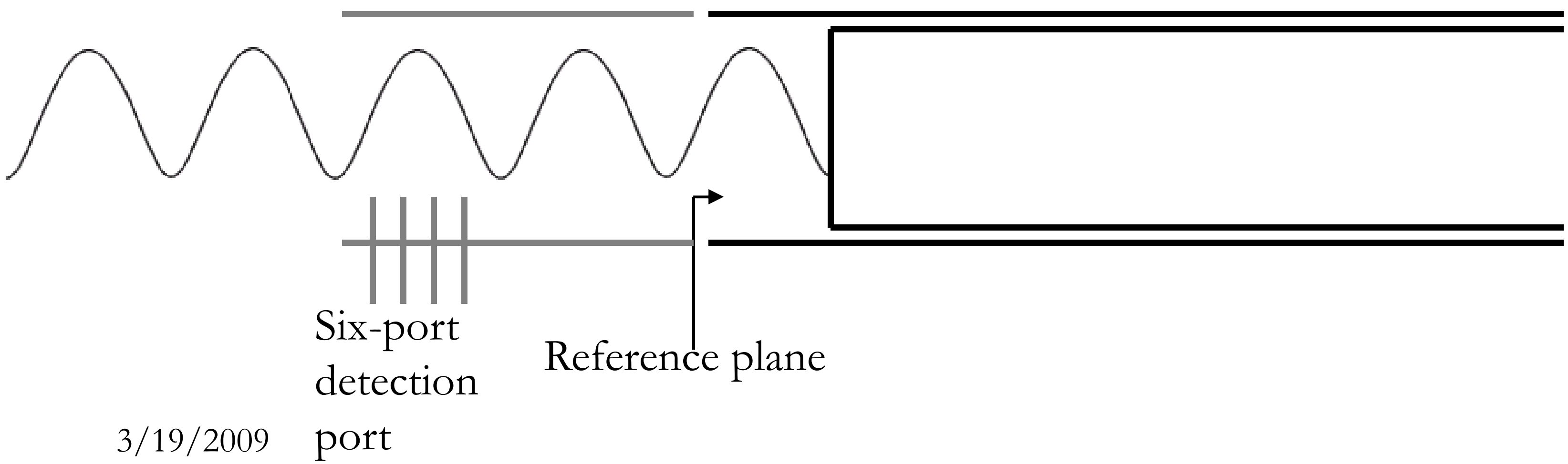
Determining the "Network Constants" — Sliding Termination Method

$$|\Gamma| = c \text{ (constant)}$$

$$\angle\Gamma^{\circ} = f(x),$$

where x is the sliding position





First Step of Six-Port Calibration — Sliding Termination Method

Quadratic Surface in P-space maps out an ellipse:

$$A\left(\frac{P_3}{P_4}\right)^2 + 2B\left(\frac{P_3P_5}{P_4^2}\right) + C\left(\frac{P_5}{P_4}\right)^2 + 2D\left(\frac{P_3}{P_4}\right) + 2E\left(\frac{P_5}{P_4}\right) + F = 0$$

Where,

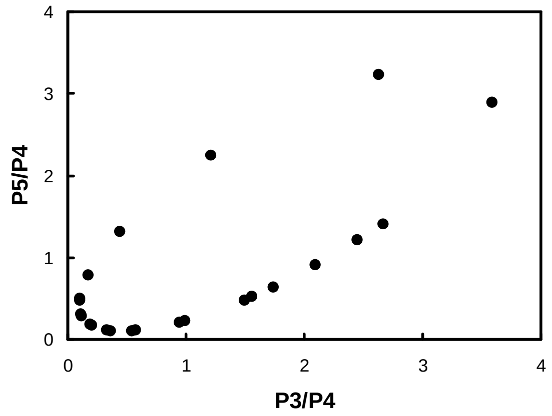
$A = a$
$B = \zeta\,(c - a - b)/2$
$C = \zeta^2 b$
$D = [R^2(b - a - c) + a(a - b - c)]/2$
$E = \zeta\,[R^2(a - b - c) + b(b - a - c)]/2$
$F = [R^4 + R^2(c - a - b) + ab]$

$a = |w_1 - R_c|^2$

$b = |R_c|^2$

$c = |w_1|^2$

$\zeta = 1/|K|^2$



General Six-Port Calibration Strategy

- Measure Response of Power Detectors to Sliding Load
- Plot Power Ratios Against One-Another $\longrightarrow$ Ellipse in P-plane
- Determine Five Coefficients via Least-Squares Fit,

$$\frac{A}{F}, \frac{B}{F}, \frac{C}{F}, \frac{D}{F}, \frac{E}{F}$$

- Algebraically Determine Six-Port "Network Constants"
- Calibrated Effective Four-Port Using One of Several Standard Methods

Comparing Six-port Reflectometer to Conventional Network Analyzer

- **Advantage**

  Simpler structure; fewer components

  Less expensive

  Easily embedded to other systems

  No need for phase-locked signal sources

- **Drawbacks** (mainly due to broadband nature of signal detection)

  Limited dynamic range, typically limited to 50–60 dB

  Sensitive to spurious signals (e.g. harmonics)

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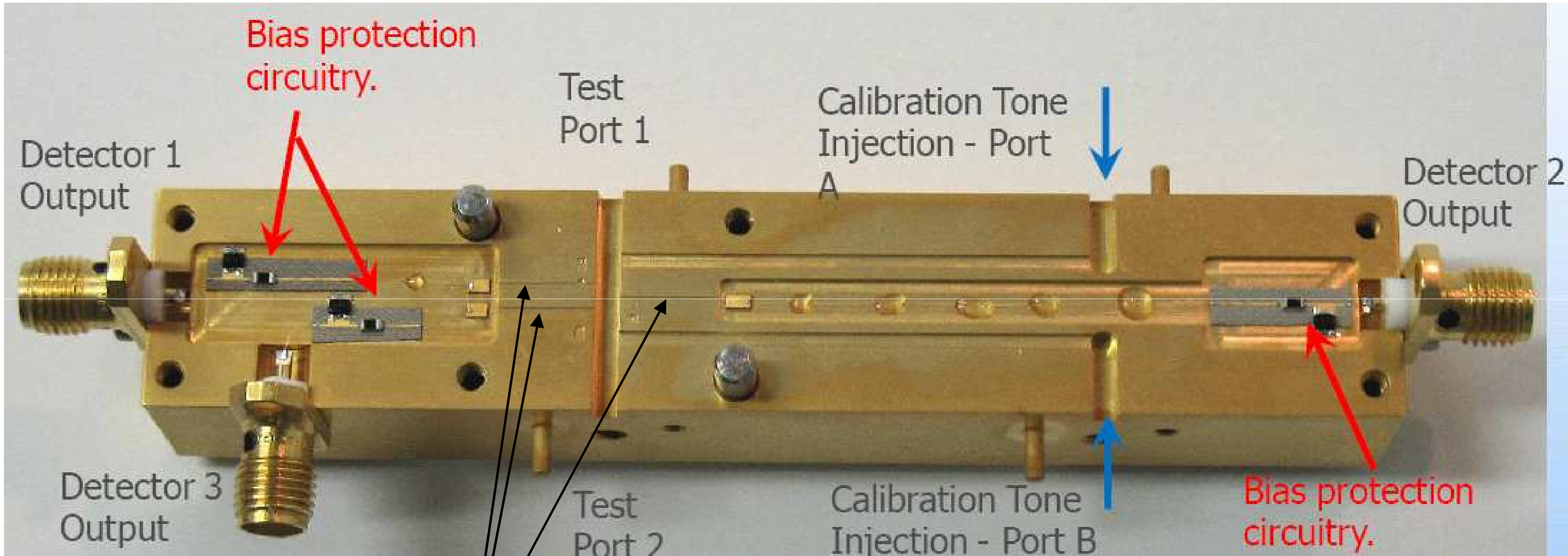
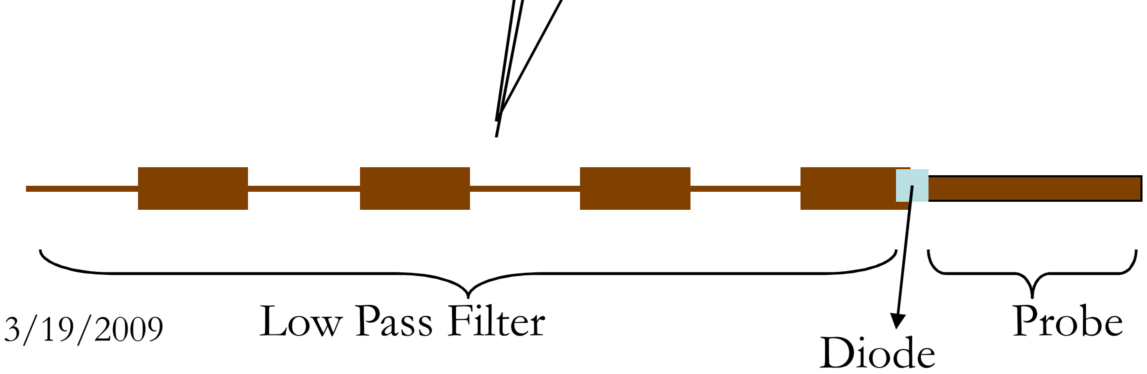
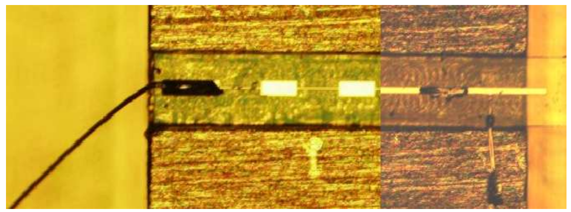
- General Background of Network Analyzer
- Principles of Six-Port Reflectometer
- **<u>WR-15 (V-Band, 50-75 GHz) Six-port Reflectometer</u>**
  - Design, Measurement Setup and Initial Data
  - Results as Network Analyzer
  - Results as an Embedded Sensor into other Systems: measuring mismatch between two adjacent stages in a frequency multiplier chain.
- Other Potential Applications (beyond Network Analyzer)

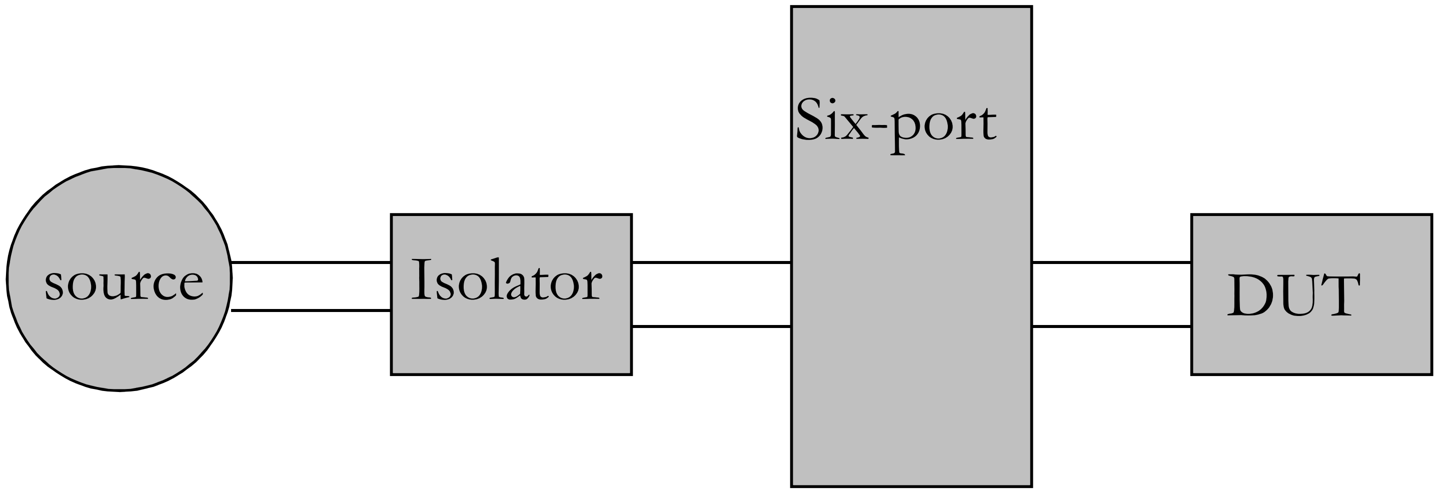
Block Design







Basic Measurement Setup Configuration

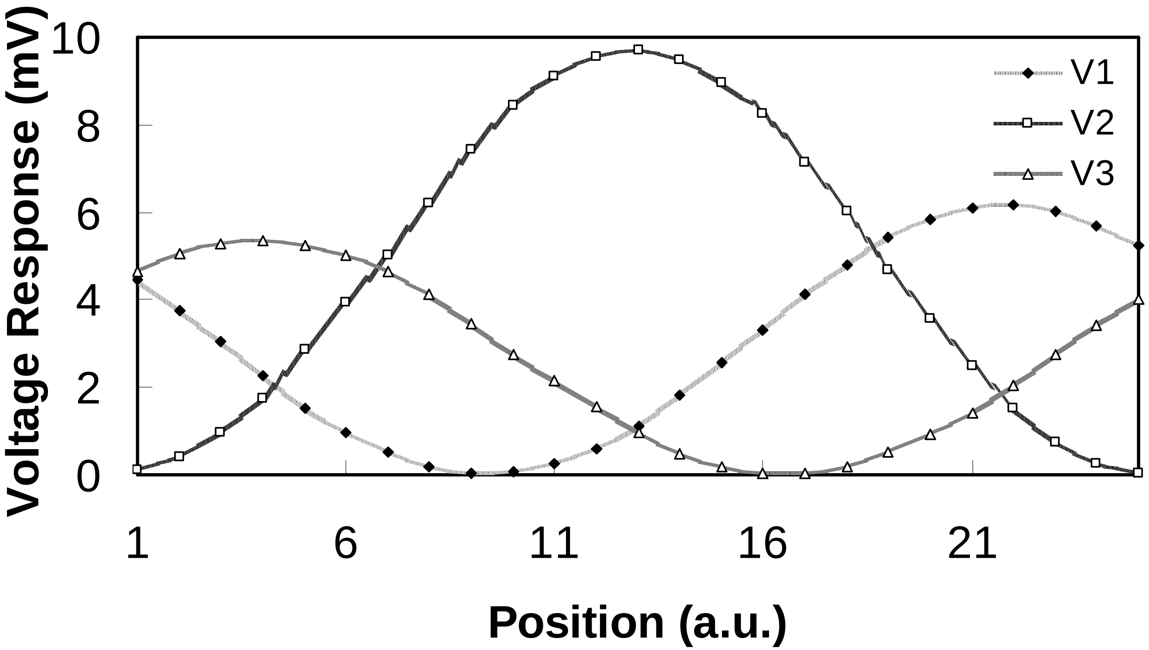


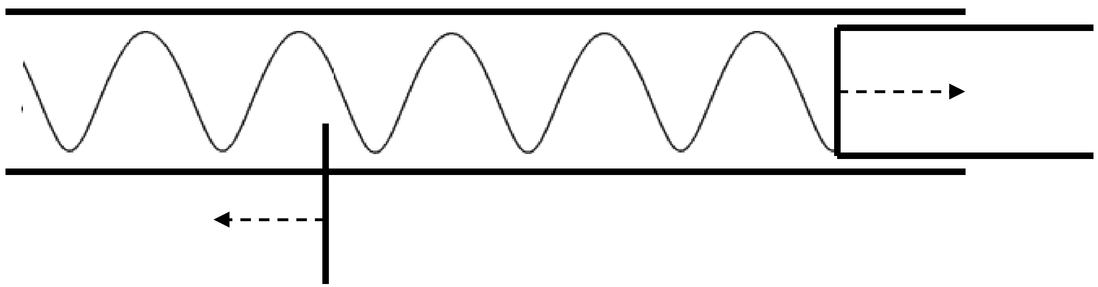
DUT's include

- fixed load, short, sliding shorts, sliding loads: for calibration;
- various WR15 components: as network analyzer;
- frequency multiplier (doubler) D124 B63: as embedded sensor.

Measurement Setup

Initial Data (Standing Wave by Sliding Short) — 67 GHz as an Example





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  - Design, Measurement Setup, and Initial Data
  - **Results as Network Analyzer (measured 7 different components)**
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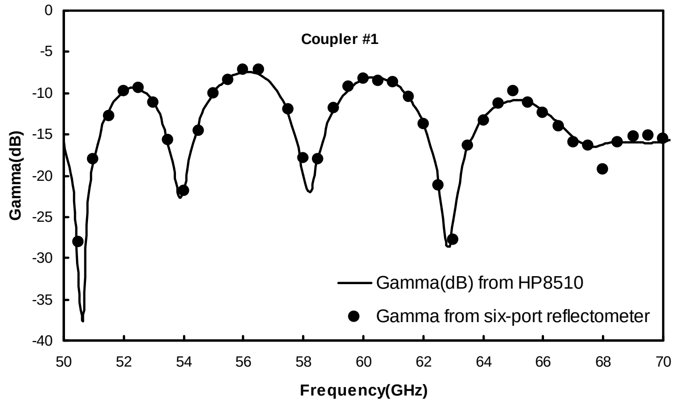
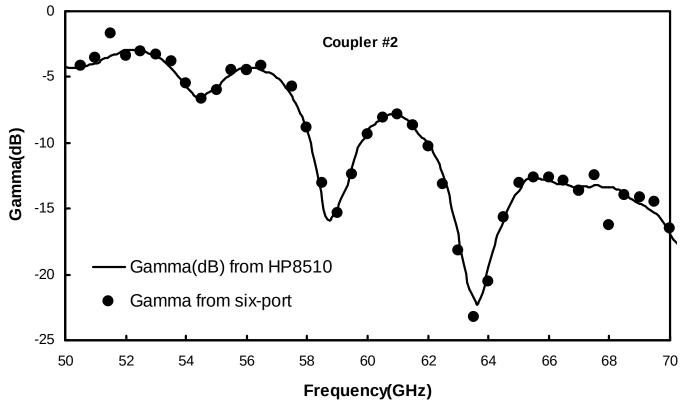
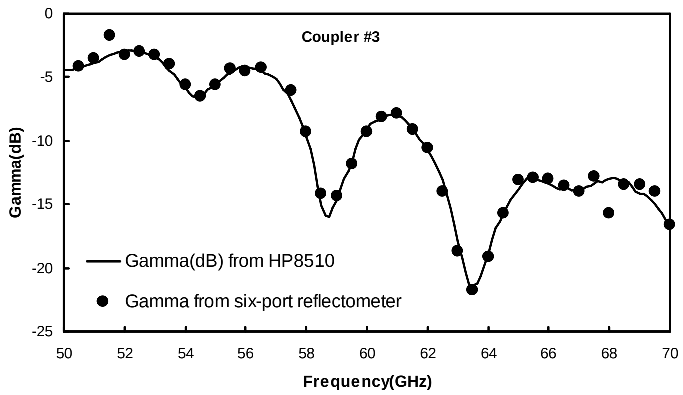
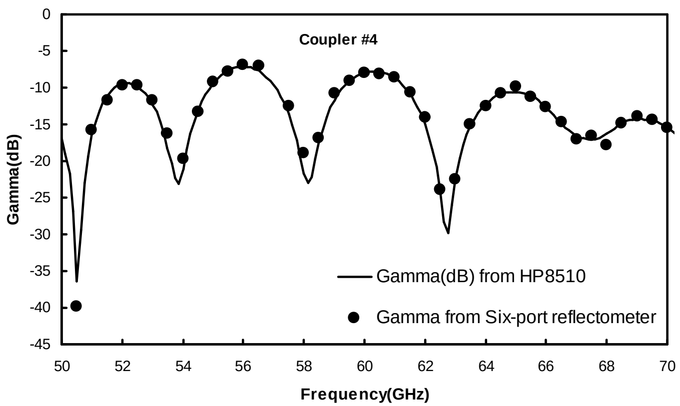
Six-Port Calibration Results Compared to Commercial Network Analyzer for Four Couplers

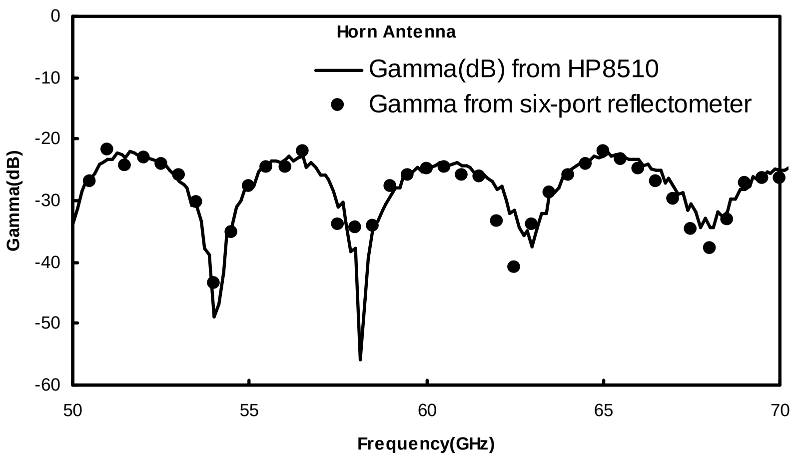


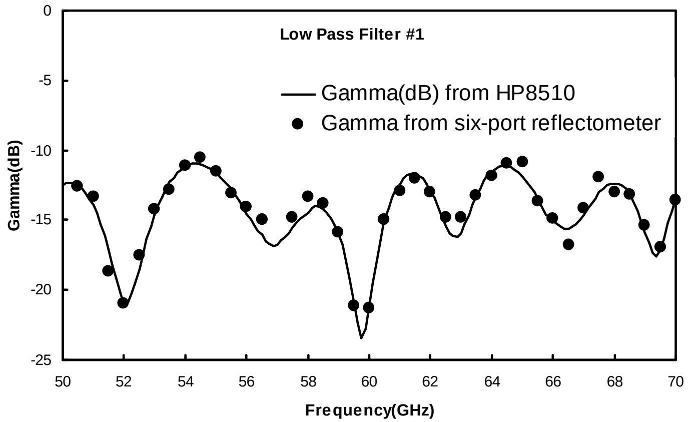


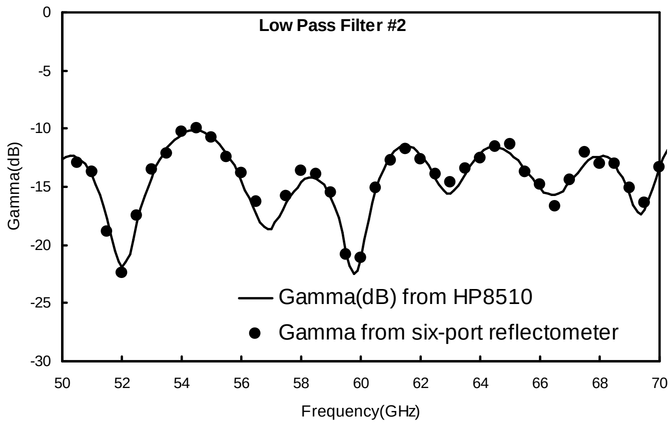




Six-Port Calibration Results Compared to Commercial Network Analyzer for Horn Antenna and Two Low Pass Filters







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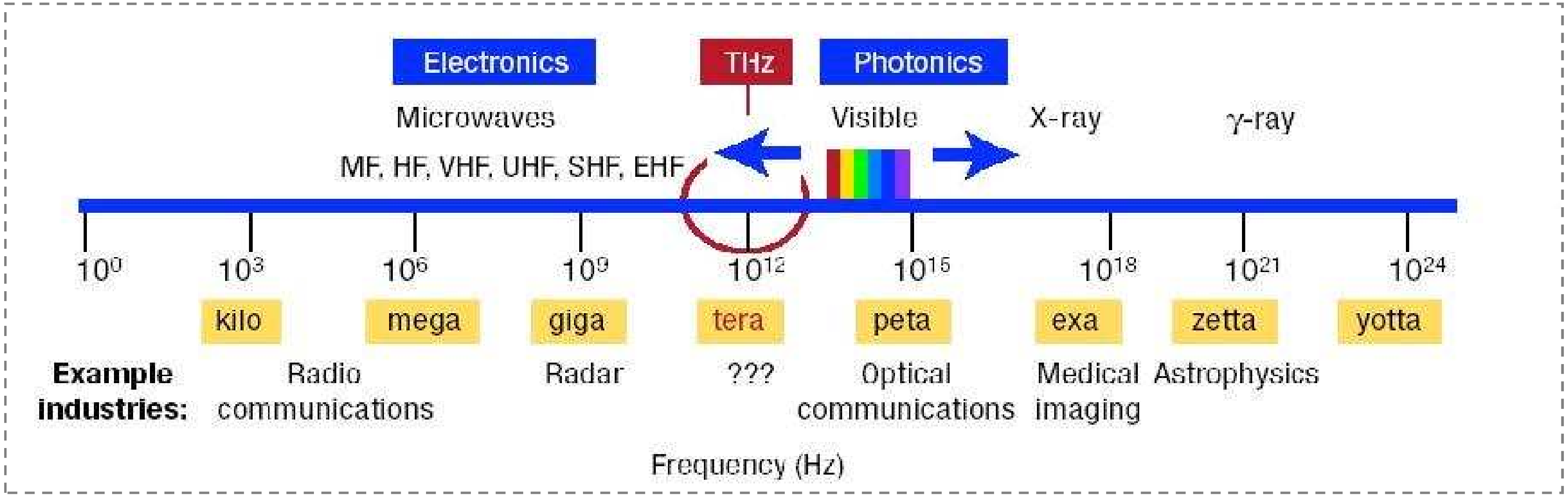
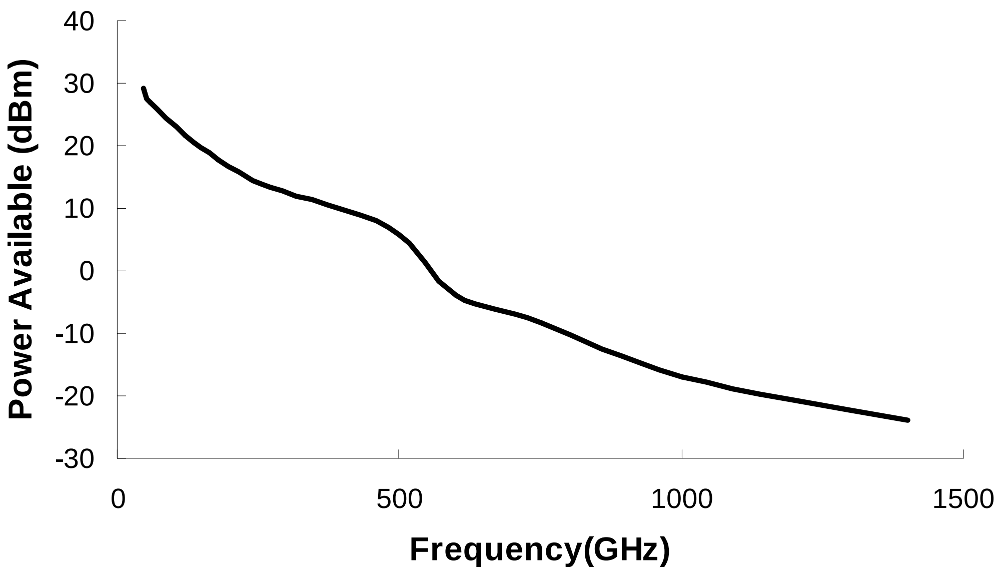
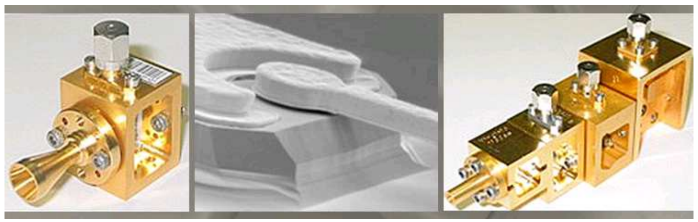
- Other Potential Applications (beyond Network Analyzer)

Why Study a Frequency Multiplier Chain? (THz Gap)

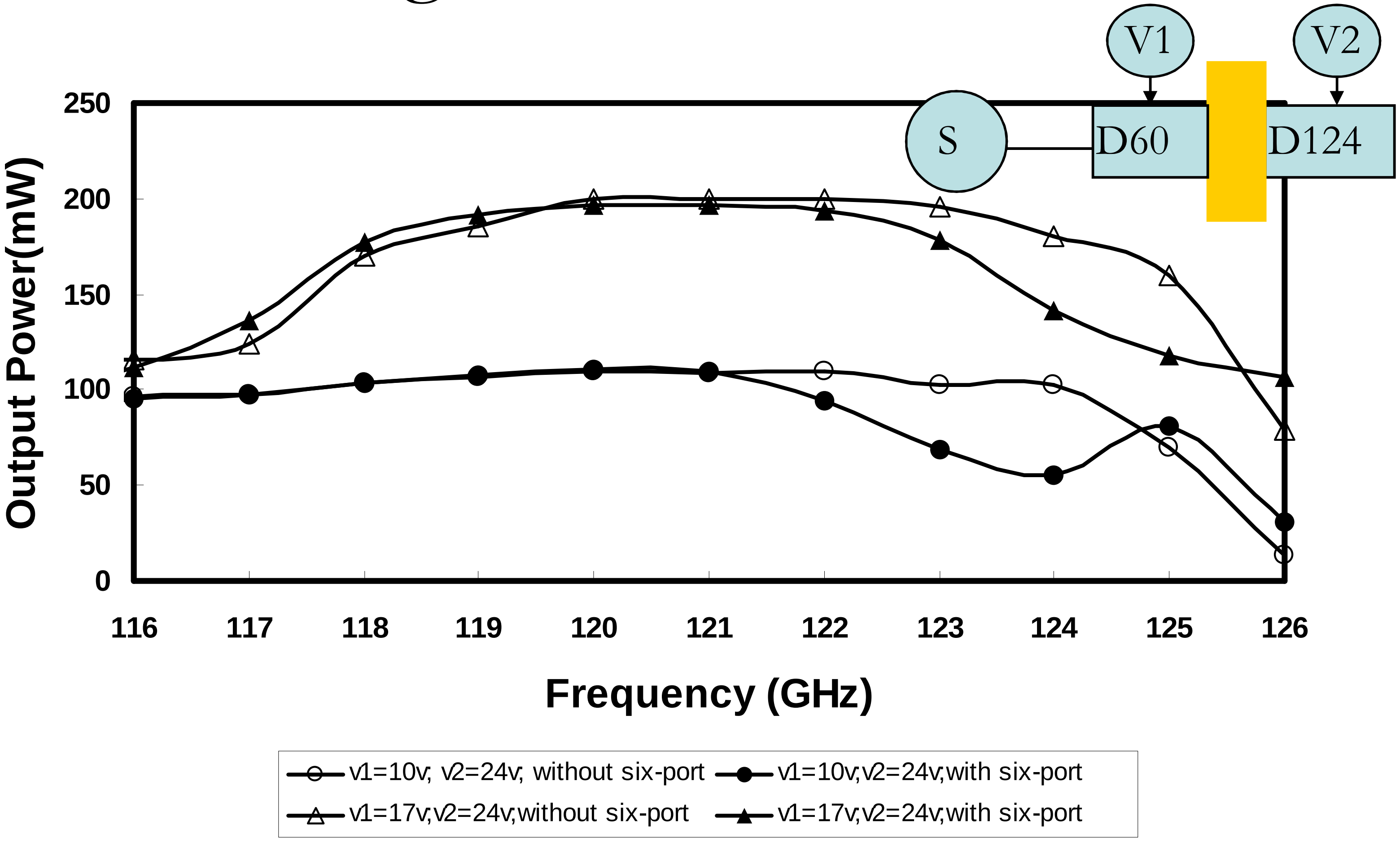




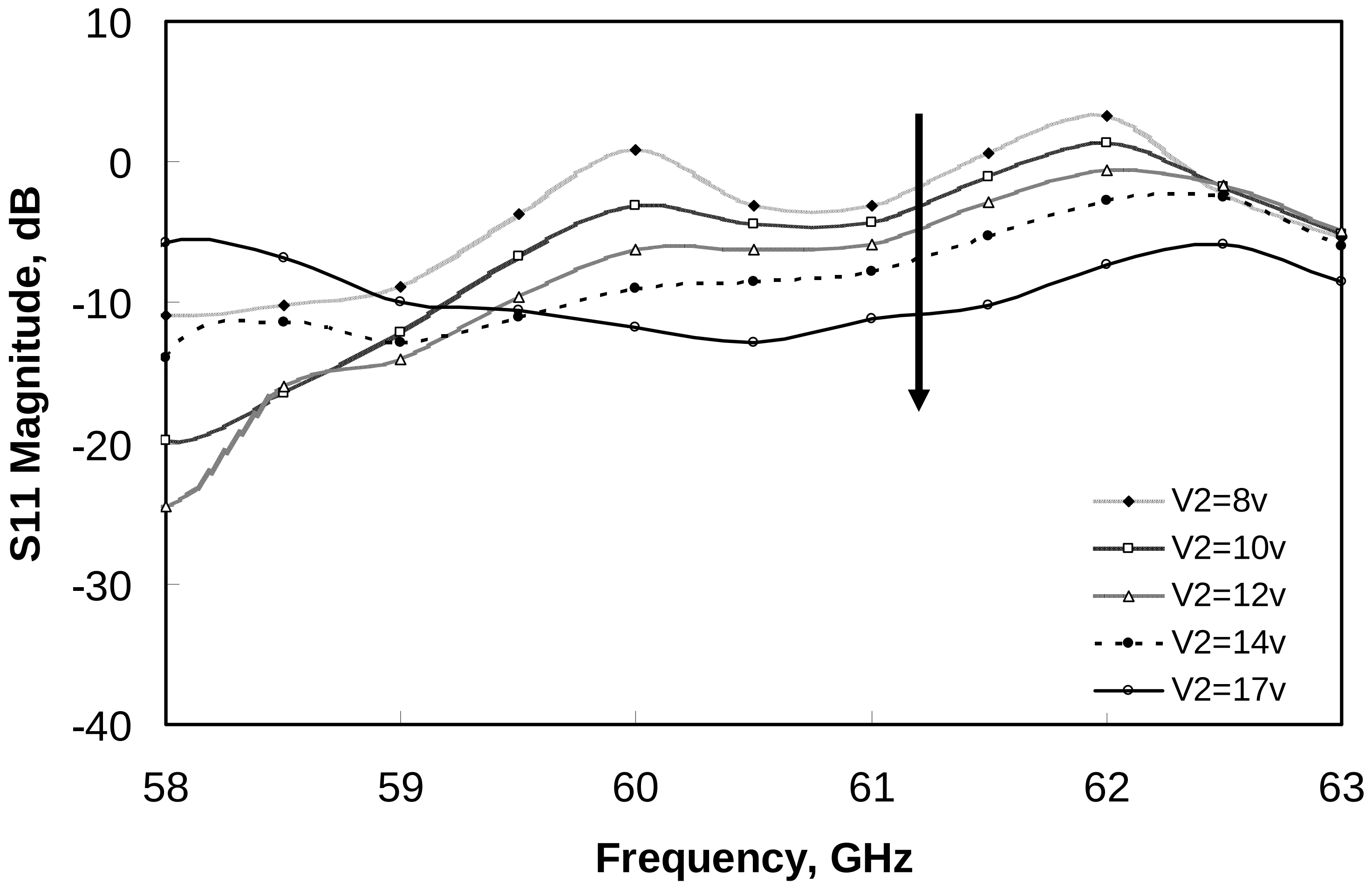


Source: Virginia Diodes, Inc.

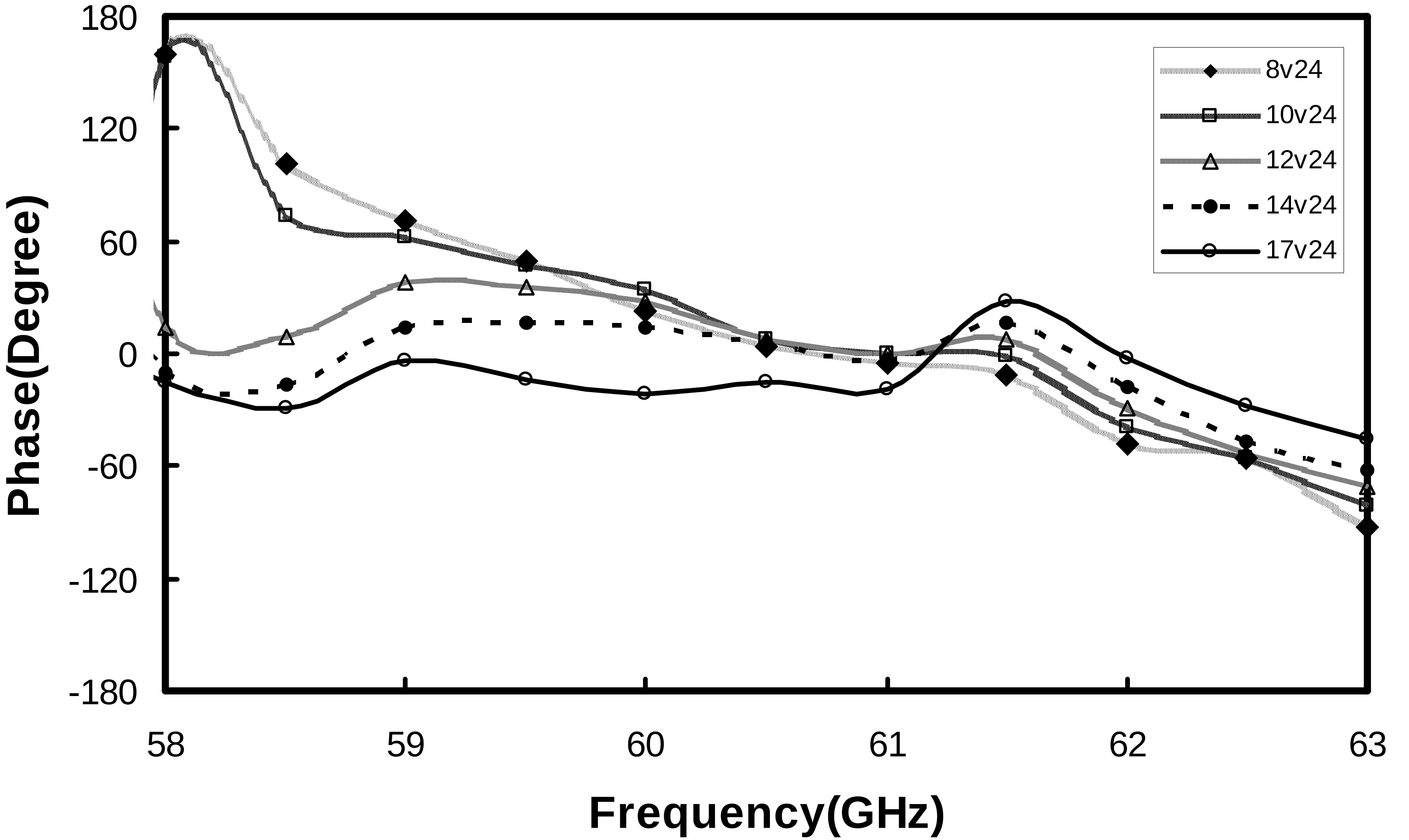
How Output Power Changed by Introducing Six-Port Reflectometer



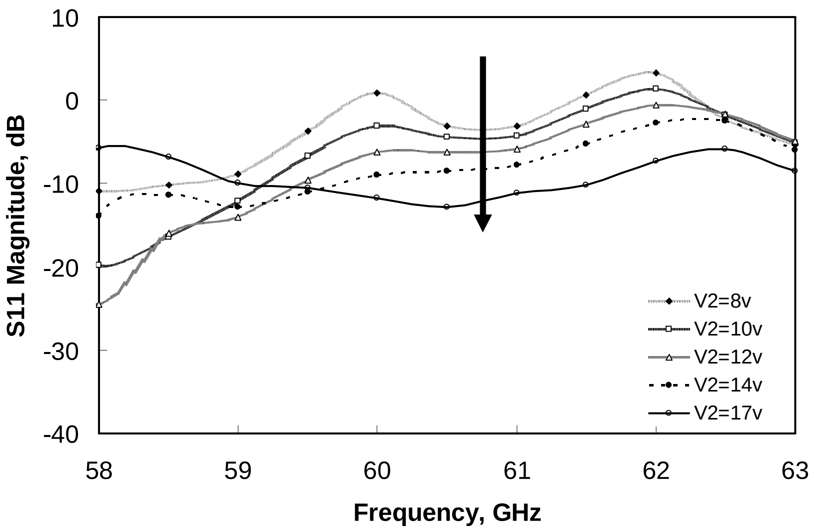
Γ Magnitude Results at V1=24V

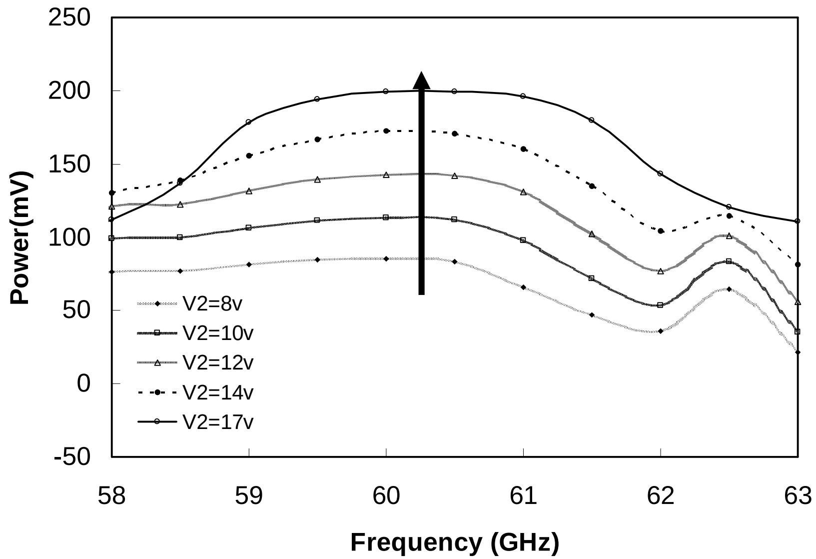


Γ Phase Results at V1=24V



Comparison of $|\Gamma|$ and Output Power at Input Bias of V_1=24 V





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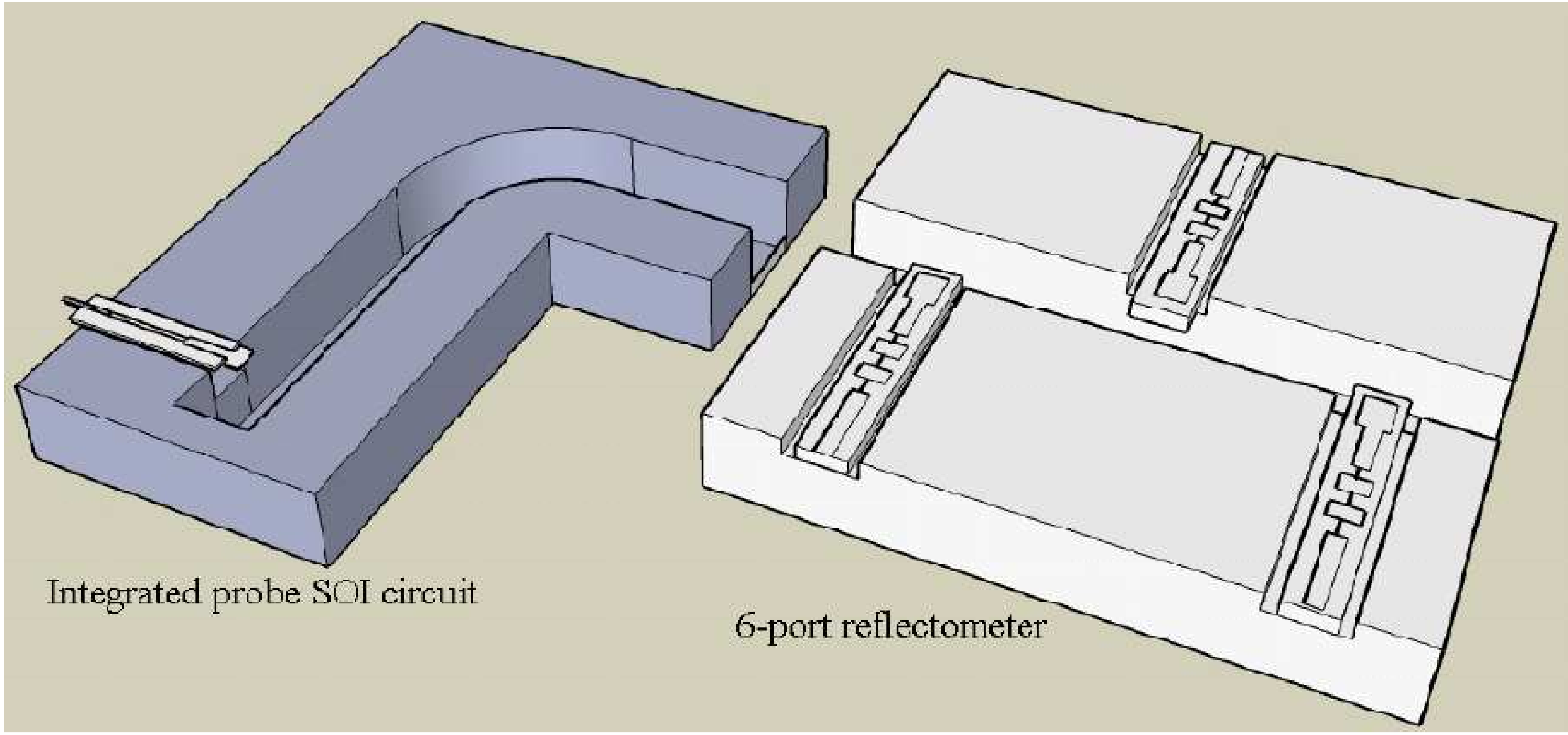
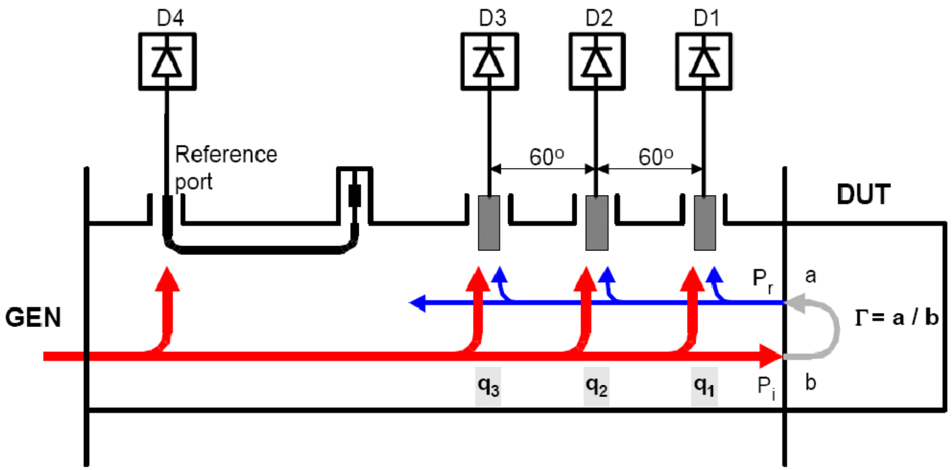
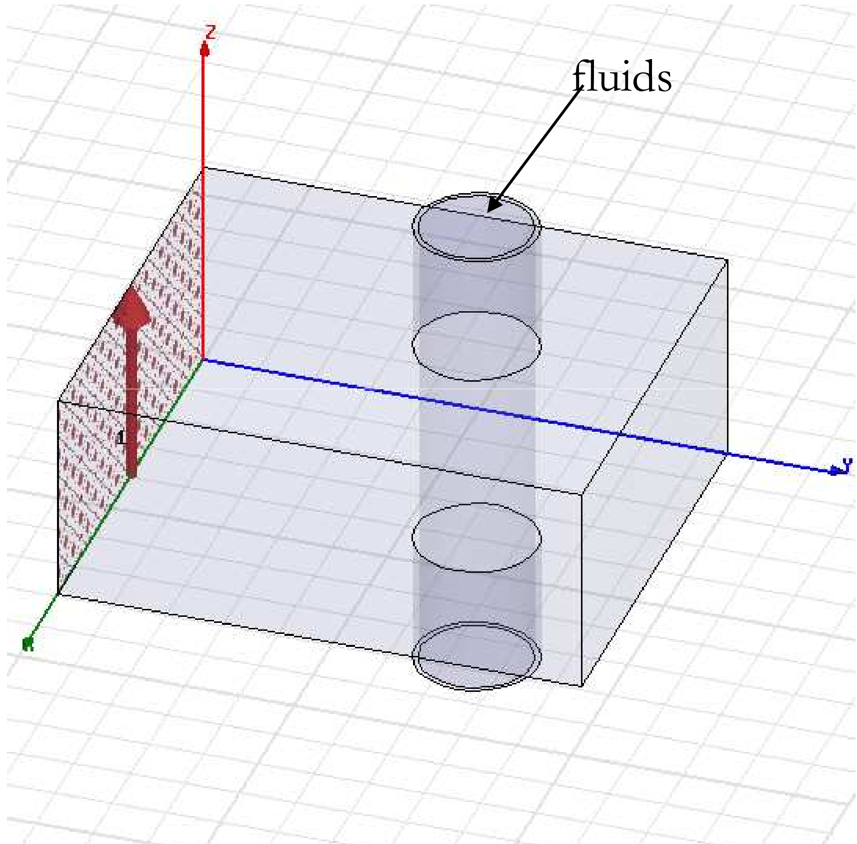
Potential Application I: Near-Field Imaging



Potential Application II: Dielectric Measurements on Fluids





Summary

- Introduced a general background of network analyzer
- Explained principles of Six-Port Reflectometer
- Demonstrated a WR-15 Six-port Reflectometer
  - the results are in great agreement with commercial network analyzer when measuring variant components.
  - used as an embedded sensor into a frequency multiplier chain and measured the mismatch between two adjacent stages
- Proposed other potential applications
  - THz near-field imaging
  - dielectric measurements on polar liquids

Thank You!

Research Motivation

- In-situ monitoring of the performance and operation of adjacent stages in a frequency multiplier chain.
- Directly measure the impedance mismatch between adjacent stages using an embedded sensing circuit (six-port reflectometer).
- Use it for studying the behavior of multipliers and as a guide for adjusting external operating parameters that impact performance of the entire chain.

Appendix I: How to Get Ellipse Eqs.

$$|w|^2 = P_3/P_4 \qquad (2.19)$$

$$|w - w_1|^2 = \zeta\, P_5/P_4 \qquad (2.20)$$

$$|w - w_2|^2 = \rho\, P_6/P_4\,. \qquad (2.21)$$

expanding left hand sides of (2.20) $\longrightarrow$ $(w - w_1)(w^* - w_1^*) = \zeta \dfrac{P_5}{P_4}$

$$|w|^2 - 2\,\mathrm{Re}(ww_1^*) + |w_1|^2 = \zeta \frac{P_5}{P_4} \qquad (2.24)$$

substituting (2.19) into (2.24) and expanding $\mathrm{Re}(ww_1^*)$ $\longrightarrow$

$$\frac{P_3}{P_4} - 2[(\mathrm{Re}(w))(\mathrm{Re}(w_1)) + (\mathrm{Im}(w))(\mathrm{Im}(w_1))] + |w_1|^2 = \zeta \frac{P_5}{P_4} \qquad (2.25)$$

perform exactly the same operations on (2.21):

$$|w|^2 - 2\,\mathrm{Re}(ww_2^*) + |w_2|^2 = \rho \frac{P_6}{P_4} \qquad (2.28)$$

Appendix I: How to Get Ellipse Eqs. (continued)

substitute (2.19) into (2.28) and expand $\mathrm{Re}(ww_2^*)$

$$\frac{P_3}{P_4} - 2[(\mathrm{Re}(w))(\mathrm{Re}(w_2)) + (\mathrm{Im}(w))(\mathrm{Im}(w_2))] + |w_2|^2 = \rho \frac{P_6}{P_4} \qquad (2.29)$$

(2.25) and (2.29) can be solved to determine $\mathrm{Re}(w)$ and $\mathrm{Im}(w)$

$$\mathrm{Re}(w) = \frac{1}{2} \frac{(\mathrm{Im}(w_1))(|w_2|^2 + P_3/P_4 - \rho P_6/P_4) + (\mathrm{Im}(w_2))(\zeta P_5/P_4 - P_3/P_4 - |w_1|^2)}{(\mathrm{Re}(w_2))(\mathrm{Im}(w_1)) - (\mathrm{Re}(w_1))(\mathrm{Im}(w_2))}$$

(2.30)

$$\mathrm{Im}(w) = -\frac{1}{2} \frac{(\mathrm{Re}(w_1))(|w_2|^2 + P_3/P_4 - \rho P_6/P_4) + (\mathrm{Re}(w_2))(\zeta P_5/P_4 - P_3/P_4 - |w_1|^2)}{(\mathrm{Re}(w_2))(\mathrm{Im}(w_1)) - (\mathrm{Re}(w_1))(\mathrm{Im}(w_2))}$$

(2.31)

Appendix I: How to Get Ellipse Eqs. (continued 2)

squaring (2.30) and (2.31) and add them together.

$$a\left(\frac{P_3}{P_4}\right)^2 + b\zeta^2\left(\frac{P_5}{P_4}\right)^2 + c\rho^2\left(\frac{P_6}{P_4}\right)^2 + (c-a-b)\zeta\left(\frac{P_3P_5}{P_4^2}\right)$$

$$+(b-a-c)\rho\left(\frac{P_3P_6}{P_4^2}\right)+(a-b-c)\zeta\rho\left(\frac{P_5P_6}{P_4^2}\right)+a(a-b-c)\frac{P_3}{P_4}$$

$$+b(b-a-c)\zeta\frac{P_5}{P_4}+c(c-a-b)\rho\frac{P_6}{P_4}+abc=0$$

First Step of Six-Port Calibration (Engen's Sliding Termination Method)

Constraining Relation between $|b_3|$, $|b_4|$, $|b_5|$, and $|b_6|$:

$$a\left(\frac{P_3}{P_4}\right)^2 + b\,\zeta^2\left(\frac{P_5}{P_4}\right)^2 + c\,\rho^2\left(\frac{P_6}{P_4}\right)^2 + (c-a-b)\,\zeta\left(\frac{P_3P_5}{P_4^{\,2}}\right) + (b-a-c)\,\rho\left(\frac{P_3P_6}{P_4^{\,2}}\right)$$

$$+ (a-b-c)\,\zeta\,\rho\left(\frac{P_5P_6}{P_4^{\,2}}\right) + a(a-b-c)\frac{P_3}{P_4} + b(b-a-c)\,\zeta\,\frac{P_5}{P_4}$$

$$+ c(c-a-b)\,\rho\,\frac{P_6}{P_4} + abc = 0$$

Where,

$$a = |w_1 - w_2|^2 \qquad b = |w_2|^2 \qquad c = |w_1|^2$$

First Step of Six-Port Calibration — continued

Constrain Γ to lie on a circle (i.e., sliding termination) $\longrightarrow$ maps into circle in w-plane

$$|w - R_c|^2 = R^2 \qquad \text{and recall} \qquad |w - w_2|^2 = \rho \frac{P_6}{P_4}$$

Quadratic Surface in P-space maps out an ellipse:

$$A\left(\frac{P_3}{P_4}\right)^2 + 2\,B\left(\frac{P_3 P_5}{P_4^{\,2}}\right) + C\left(\frac{P_5}{P_4}\right)^2 + 2\,D\left(\frac{P_3}{P_4}\right) + 2\,E\left(\frac{P_5}{P_4}\right) + F = 0$$

Where,

$A = a$

$B = \zeta\,(c - a - b)/2$

$C = \zeta^{\,2} b$

$D = [R^2(b - a - c) + a(a - b - c)]/2$

$E = \zeta\,[R^2(a - b - c) + b(b - a - c)]/2$

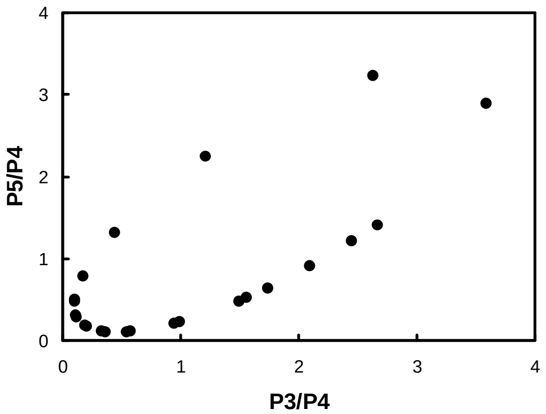
$F = [R^4 + R^2(c - a - b) + ab]$

$a = |w_1 - R_c|^2$

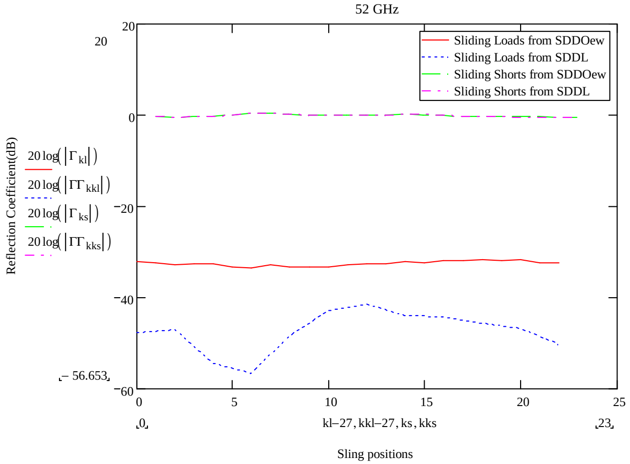
$b = |R_c|^2$

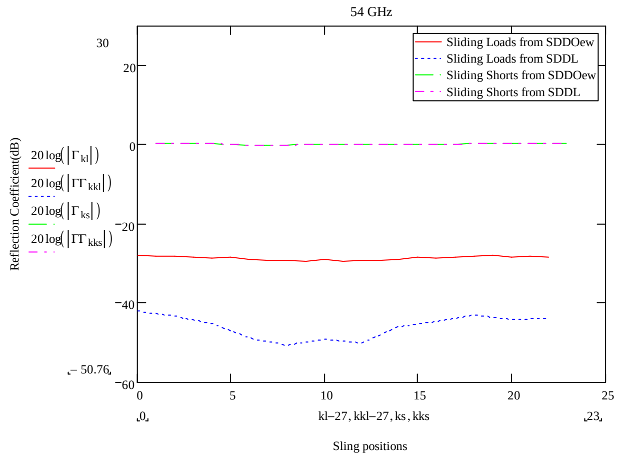
$c = |w_1|^2$

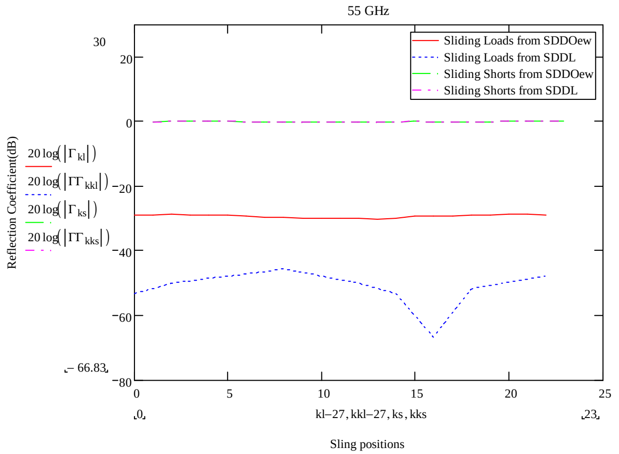
$\zeta = 1/|K|^2$

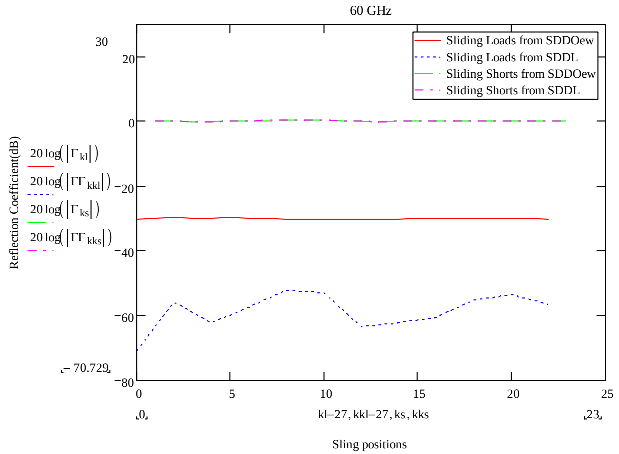


Appendix II: More Examples of Calibration Standard Results

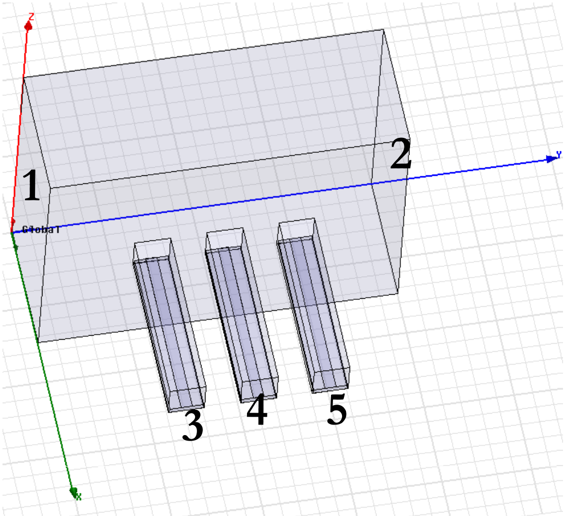








Basic Probe Simulation Model



- Waveguide size: 148*74 (WR15, 50~75GHz)
- Channel size: 20*13
- Channel distance: 40
- Microstrip width: 6
- MLine characteristic impedance Z_0: 50.48 Ohm
- Substrate width:19
- Substrate thickness:3

❖ Unit: mils