

Active Device Characterization At Millimeter Wave Frequencies



Suren Singh
Lead Application Engineer Millimeter and THz
Solutions
Agilent Technologies

Agenda

- **Millimeter wave and THz applications**
- **Measurement Solution**
 - Basic system architecture
 - Capability Enabling Active Device Measurements
- **Active Device Measurements**
 - SCMM Broadband Amplifier Characterization
 - SCMM of 60 GHz Tx / Rx components
 - IMD Spectrum measurements
 - THz Power Calibration
 - Materials Measurements at THz
- **Q&A**

Millimeter Wave Frequency Band Applications

Millimeter Wave Component Test

- On Wafer Device Characterization
- Wireless HDMI & WiGiG (E-Band)
- Automotive Radar Components (E& W-Band)

Antenna

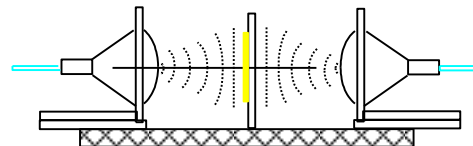
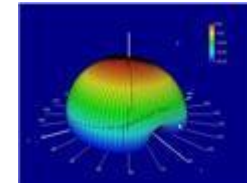
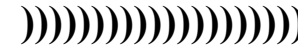
- Integrated on-wafer antenna arrays
- (Sub) mm-wave interferometer for astrophysics (Emerging)
- Atacama Large Millimeter Array (ALMA) (NRAO, ESO, IRAM)
- Deep Space Radio Telescopes

Materials and Imaging

- Free space material measurements.
- Security Imaging Systems
- Corrosion Detection
- Bio-fuel (Emerging)

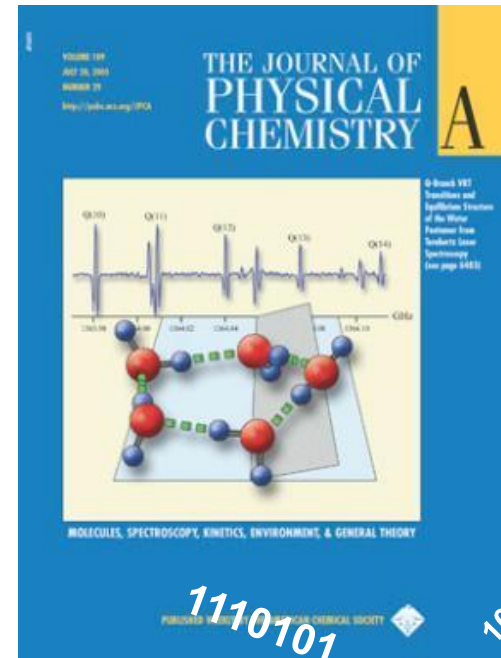


HD Disc Player

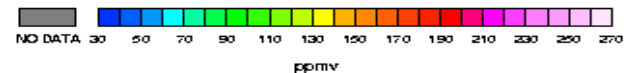
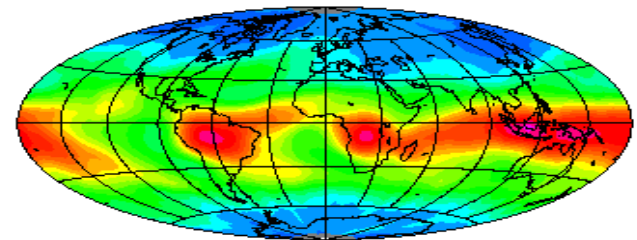


THz Frequency Applications

- Radio Astronomy
- Atmospheric Studies
- Chemical / Molecular Spectroscopy
- Plasma and Accelerator Diagnostics
- Biological Imaging
- Materials Characterization
- General Test and Measurement



UARS MLS 215hPa Water Vapor
DJF 1991-1994



Agenda

- **Millimeter wave and THz applications**
- **Measurement Solution**
 - Basic system architecture
 - Capability Enabling Active Device Measurements
- **Active Device Measurements**
 - SCMM Broadband Amplifier Characterization
 - SCMM of 60 GHz Tx / Rx components
 - IMD Spectrum measurements
 - THz Power Calibration
 - Materials Measurements at THz
- **Q&A**

Measurement Driven Architecture

Millimeter wave Devices

- Passive Devices
- Amplifiers
- Mixers
- Semiconductors
- Antennas
- Materials



Millimeter wave Measurements

- S-Parameters (N-port, Differential)
- Absolute power
- Gain compression
- Pulsed measurements
- Material parameters
- Time domain

Measurement Driven Architecture

Millimeter wave Measurements

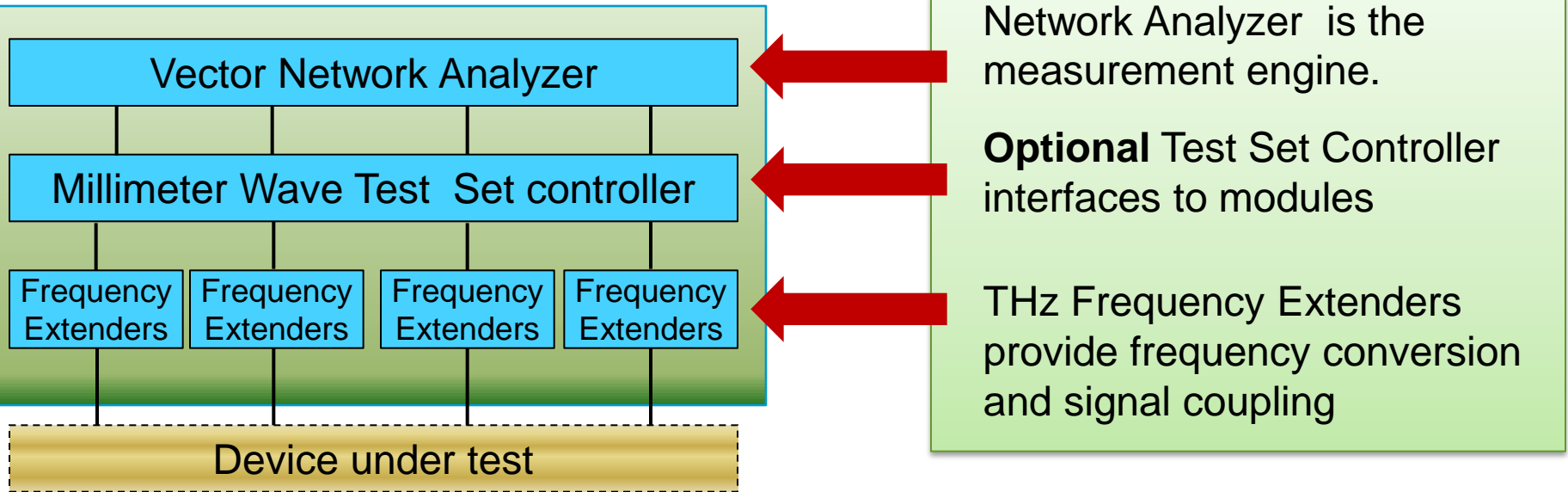
- S-Parameters (N-port, Differential, Translated)
- Absolute power
- Gain compression
- Pulsed measurements
- Material parameters
- Time domain



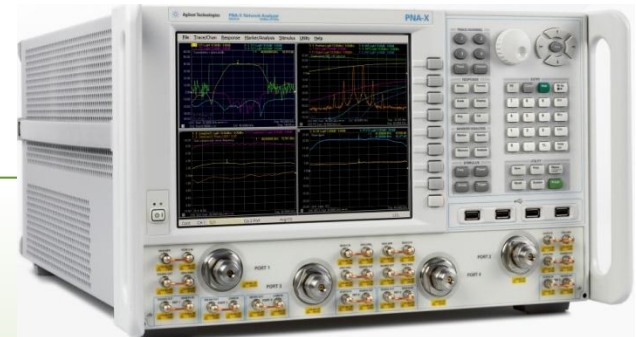
Millimeter wave Features

- Calibration: S-Parameters & Power
- Bias Tee
- Differential Source
- Remote Modules
- Measure & level power
- Pulse drive and measure
- Measure mixers
- Measure multi-ports
- Wide dynamic range
- Measure multiple bands
- Probing

Solution Architecture



PNA / PNA-X Network Analyzer



N5247A 4-Port PNA-X

Key Enabling Features:

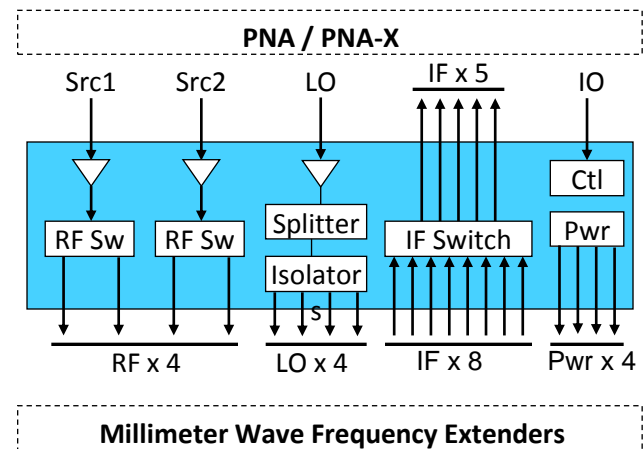
- 26.5 /43.5/50/67GHz versions
- Configurable Test set options
- Rear panel RF / LO Output
- Rear panel direct IF Access
- Test set controller interface
- Frequency Offset Capability
- Dual, spectrally pure sources with low phase noise
- Integrated pulse measurements
- Source Power Calibration & Receiver power leveling
- Broadband match corrected power Calibration

Millimeter Wave Test Set Controller

- Provides LO & RF distribution to modules
- Provides DC power to modules
- 2-port (N5261A) and 4-port (N5262A) versions
- Flexible setup: measure multiple bands
- Mixer Measurements without external Sources
- Easily switch between PNA/PNA-X and mm-wave mode

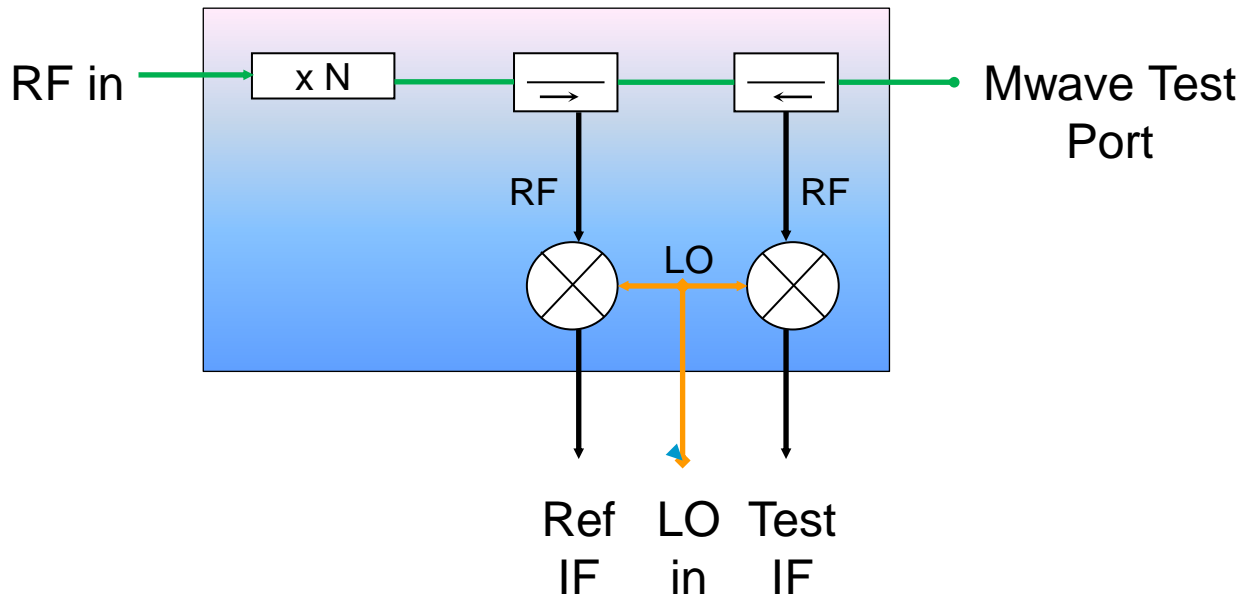


Four Port N5262 A Test Set Controller



Millimeter Frequency Extenders

- Broadband Extenders: 10M-110GHz
- Banded Extenders: 50 GHz ... 1 THz



Banded Frequency Extenders

WR 15	50 – 75 GHz
WR 12	60 – 90 GHz
WR 12E	54 – 92 GHz
WR 10	75 – 110 GHz
WR 6	110 – 170 GHz
WR 5	140 – 220 GHz
WR 3	220 – 325 GHz
WR 2.2	325 – 500 GHz
WR 1.5	500 – 750 GHz
WR 1.0	750 – 1.1 THz

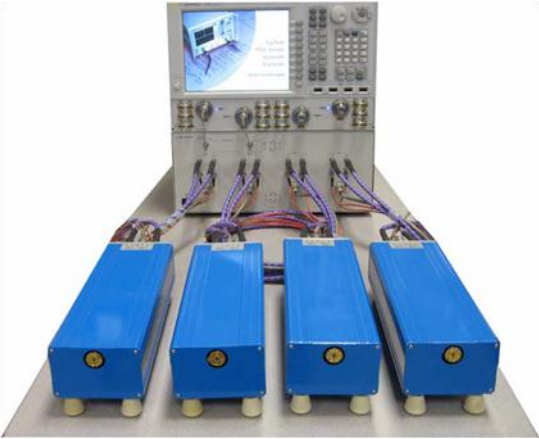


MHz to 110 GHz Broadband Solution

- Single-sweep over 10MHz-110GHz
- 2-port & 4-port options
- Based on N5247A 67 GHz PNA
- 1.0 mm Test Port
- Key Features:
 - Built in Kelvin Bias Tees
 - Power leveling
 - Settable Power to -50 dBm
 - True differential drive
 - Pulse measurements
 - Mixer measurements



Banded Waveguide solutions to 1.1 THz



PNA / PNA-X Banded Waveguide Solution With Test Set Controller



Banded Waveguide solution Without Test Controller



Banded Waveguide solution With Proprietary Test Controller

Agenda

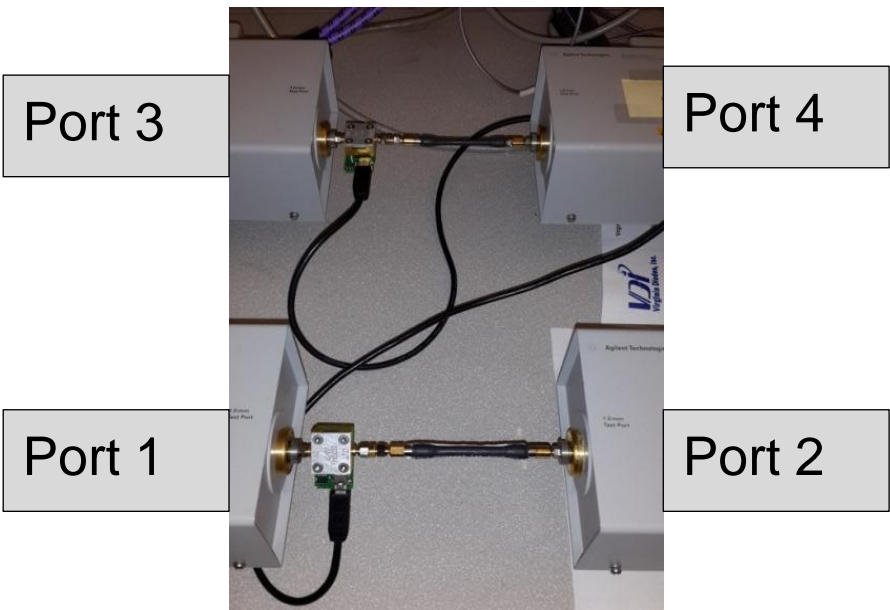
- **Millimeter wave and THz applications**
- **Measurement Solution**
 - Basic system architecture
 - Capability Enabling Active Device Measurements
- **Active Device Measurements**
 - **SCMM Broadband Amplifier Characterization**
 - SCMM of 60 GHz Tx / Rx components
 - IMD Spectrum measurements
 - THz Power Calibration
 - Materials Measurements at THz
- **Q&A**

Broadband Amplifier Measurement Application

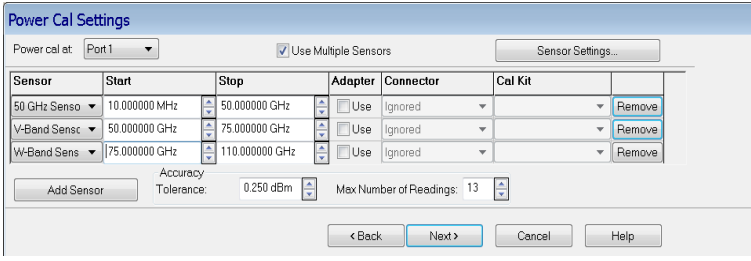
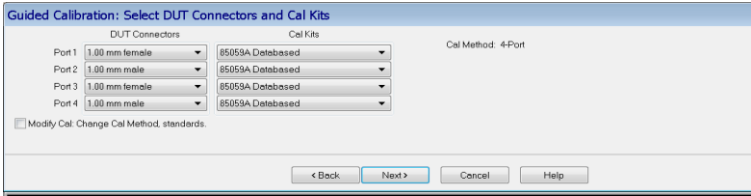
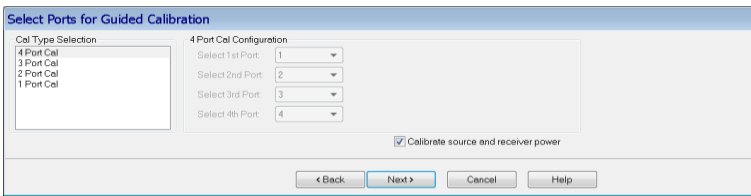
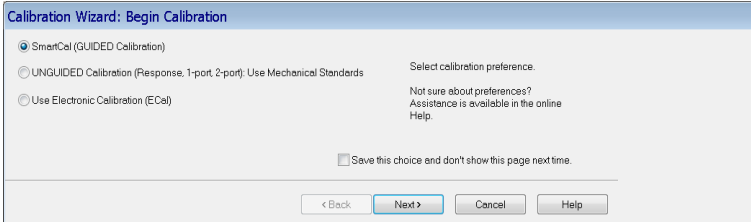
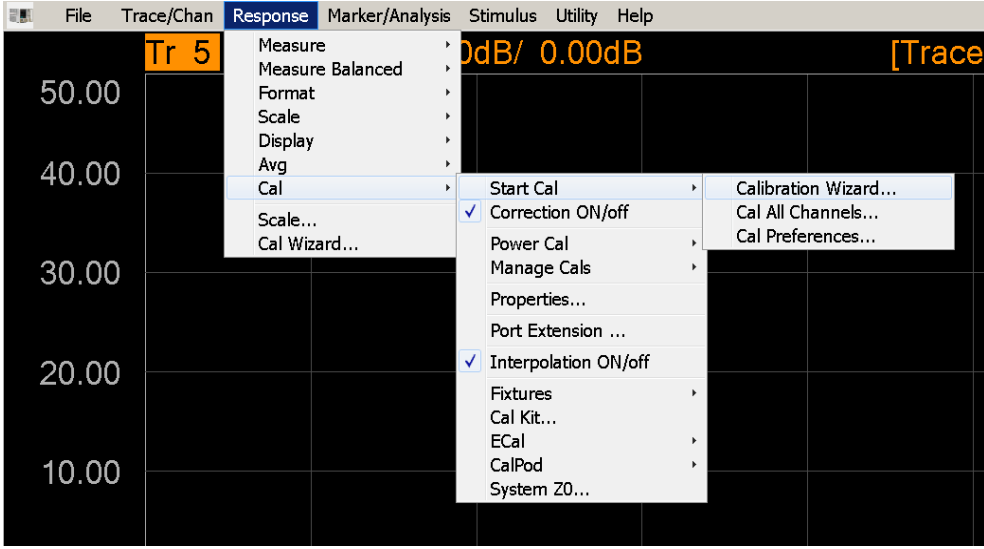


Measurement Requirements

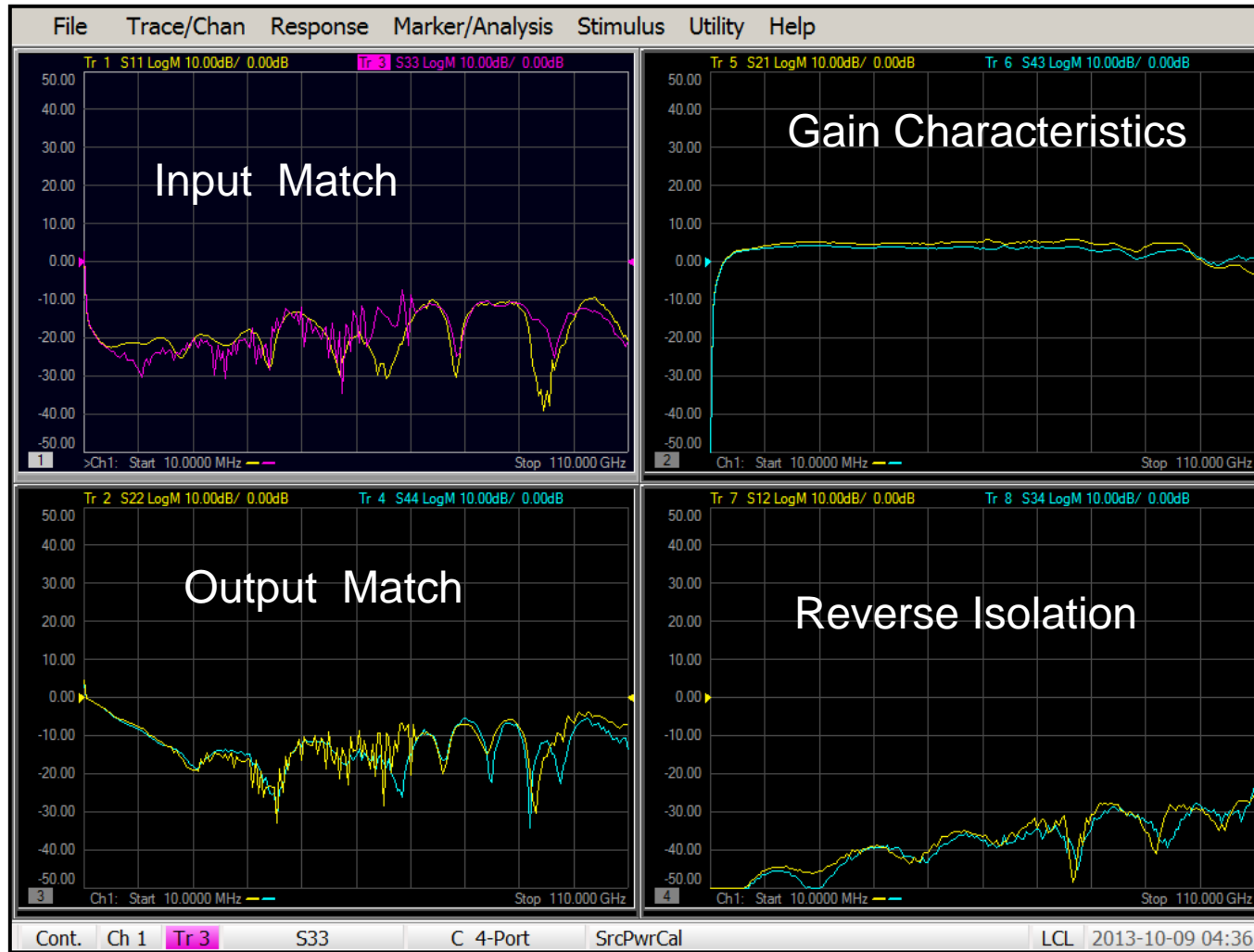
- Single Connection Measurement
- Input match
- Output match
- Amplifier gain
- Amplifier compression
- Amplifier pulsed response
- 4 Port True Differential



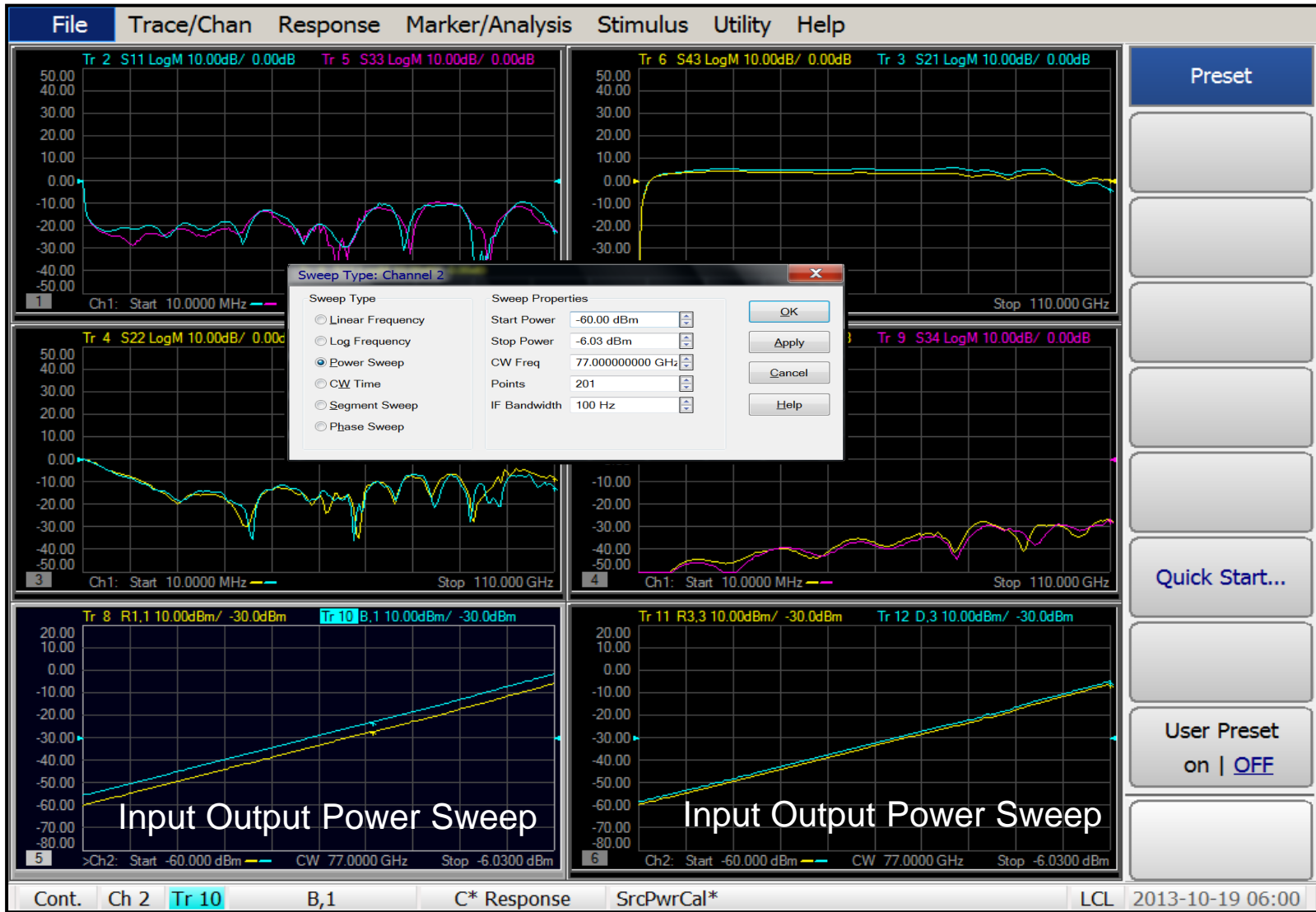
4- Port Match corrected Source power Calibration



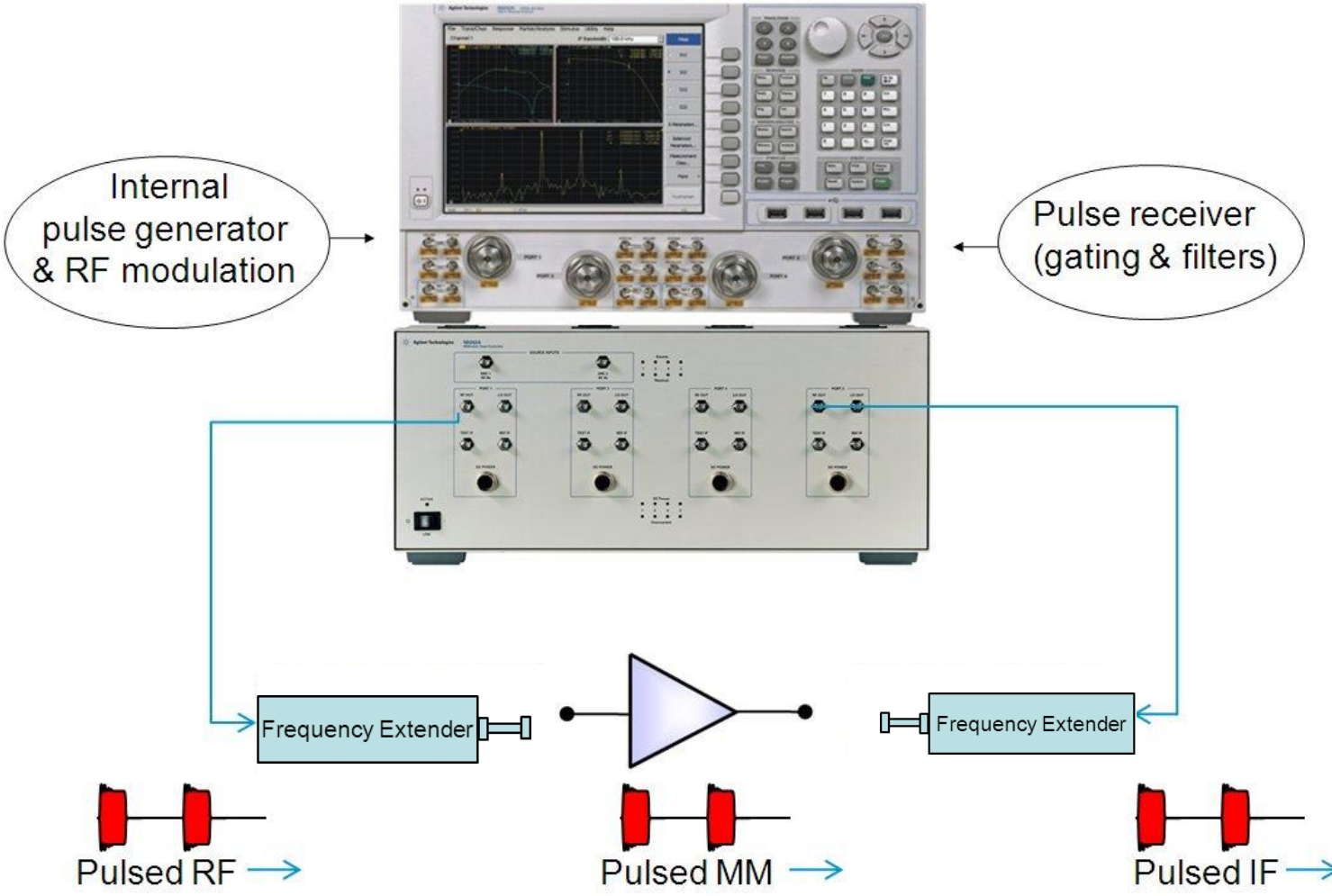
Broadband Amplifier Match and Gain Results



Broadband Amplifier Adding Power Sweep



Broadband Amplifier Adding Pulsed Response



Broadband Amplifier Adding Pulsed Response

File Trace/Chan Response Marker/Analysis Stimulus Utility Help

Name	Width	Delay	Pulse Gen
Source1	100.000 usec	50.000 usec	Pulse1
Source2	100.000 usec	50.000 usec	Pulse1
Rcvr A	3.620 usec		Pulse0
Rcvr B	3.620 usec		Pulse0
Rcvr C	3.620 usec		Pulse0
Rcvr D	3.620 usec		Pulse0
Rcvr R1	3.620 usec		Pulse0
Rcvr R2	3.620 usec		Pulse0
Rcvr R3	3.620 usec		Pulse0
Rcvr R4	3.620 usec		Pulse0

Preset

Quick Start...

User Preset on | OFF

Tr 2 S11 10.00dB/ Tr 5 S33 10.00dB/ Tr 6 S43 10.00dB/ Tr 3 S21 10.00dB/ Tr 4 S22 10.00dB/ Tr 7 S44 10.00dB/

Ch1: Start 10.0000 MHz

Ch1: Start 10.0000 MHz Stop 110.000 GHz

Ch2: Start -60.000 dBm Stop -6.0300 dBm

Ch2: Start -60.000 dBm Stop -6.0300 dBm

Tr 1 S12 10.00dB/ Tr 9

Ch1: Start 10.0000 MHz Stop 110.000 GHz

Ch2: Start -60.000 dBm Stop -6.0300 dBm

Ch2: Start -60.000 dBm Stop -6.0300 dBm

Tr 13 R1,1 10.00dBm/ -60.0dBm Tr 14 B,1 10.00dBm/ -60.0dBm

Ch3: Start 0.00000 s Stop 200.03 us

Amp 1 Input output Pulse Profile

Tr 15 R3,3 10.00dBm/ -50.0dBm Tr 16 D,3 10.00dBm/ -50.0dBm

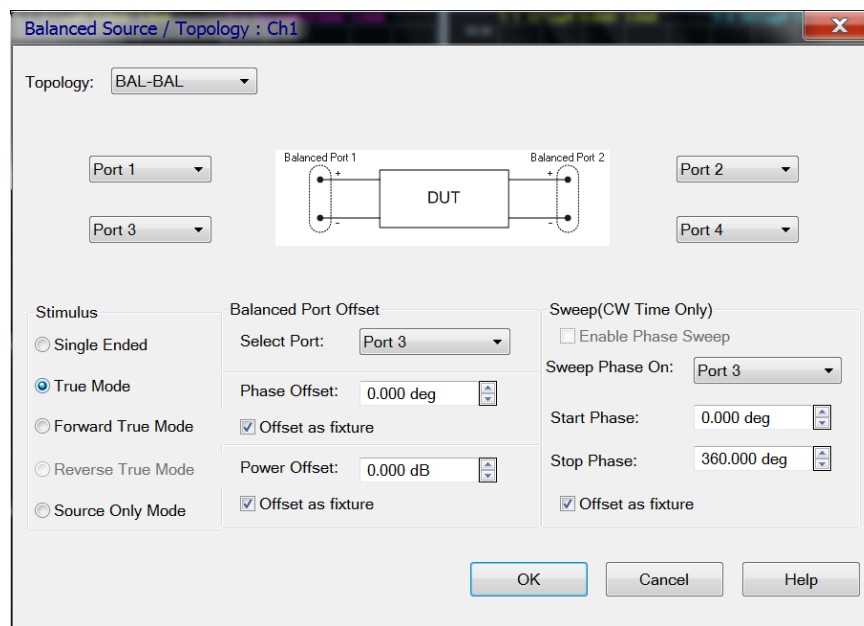
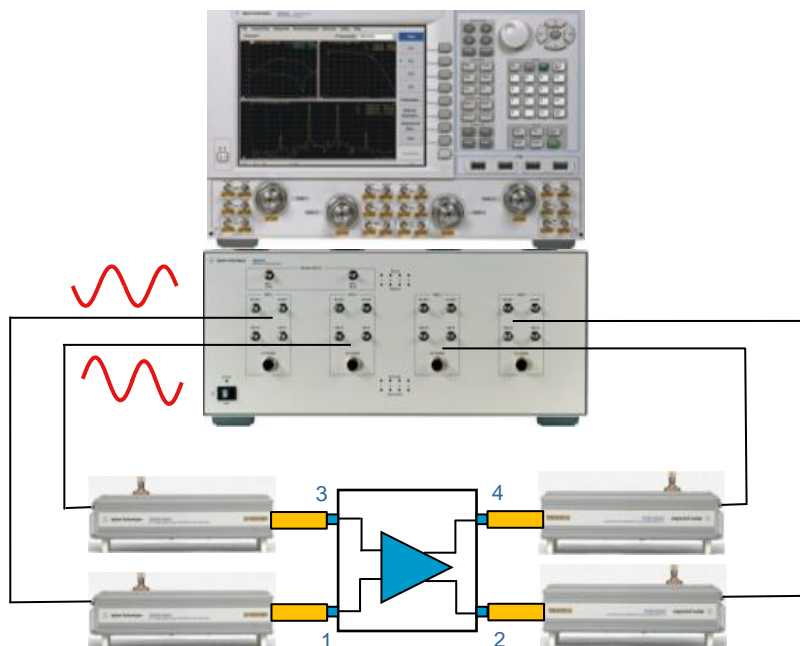
Ch3: Start 0.00000 s Stop 200.03 us

Amp 2 Input output Pulse Profile

Cont. Ch 3 Tr 15 R3,3 C* Response SrcPwrCal* | P

LCL 2013-10-19 06:19

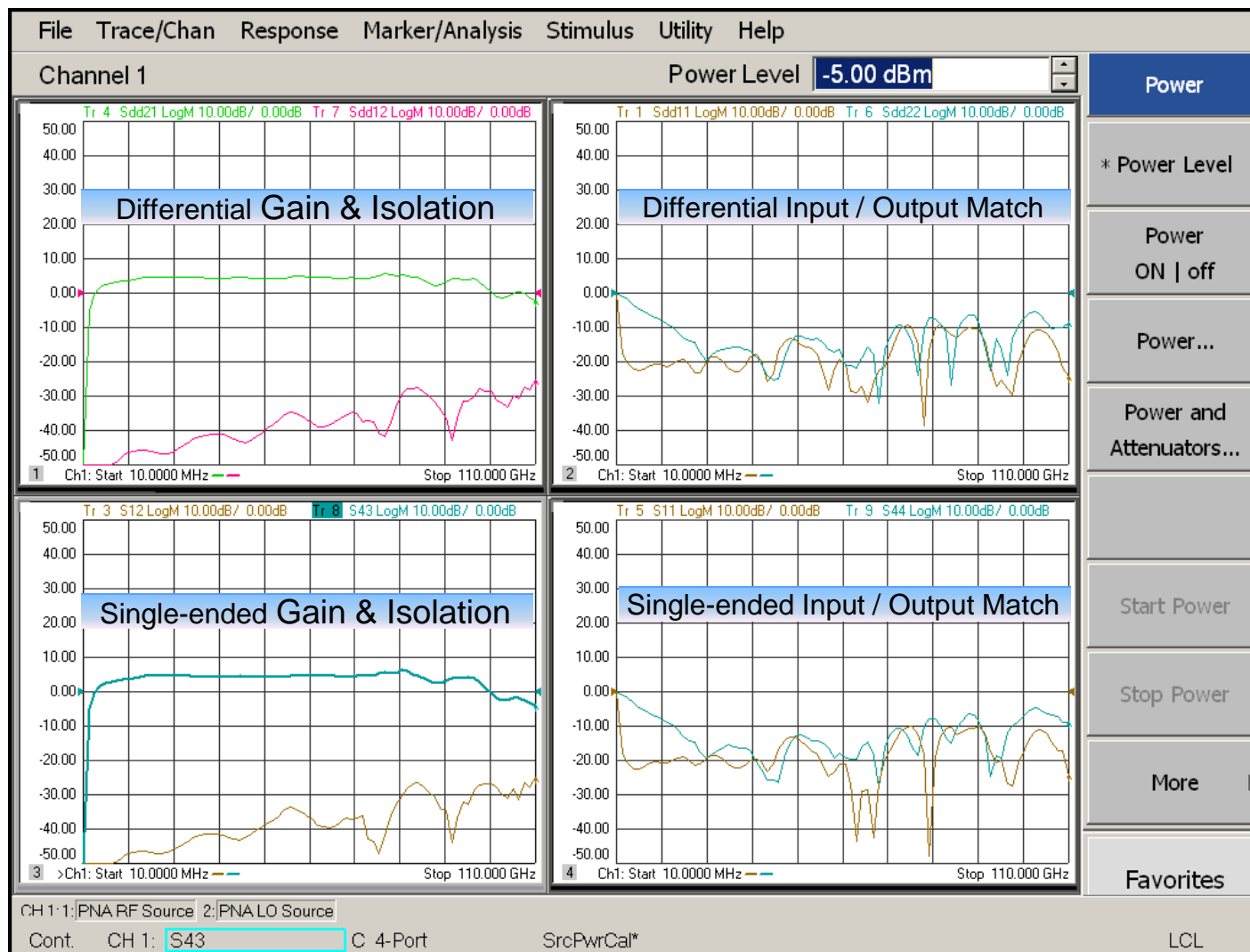
Broadband Amplifier Adding True Mode Measurements



Integrated True-mode Stimulus Application: iTMSA (Option 460)

- Applies DUT/VNA mismatch-corrected true-differential or true-common-mode stimulus in forward, reverse or both directions.
- Precisely control amplitude and phase offsets.
- Make fully-error-corrected balanced measurements on balanced-input and balanced-output as well as one port single-ended and one port balanced devices.

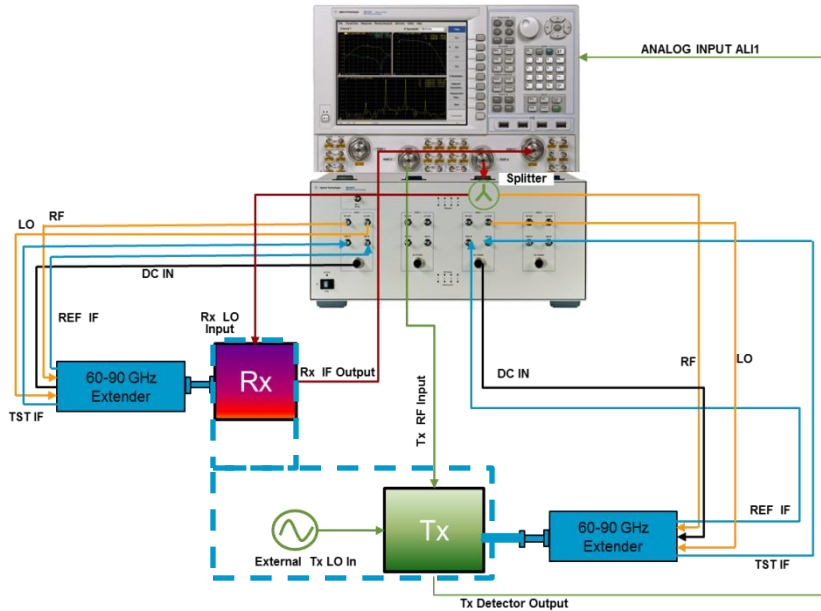
Broadband Amplifier Adding True Mode Measurements



Agenda

- **Millimeter wave and THz applications**
- **Measurement Solution**
 - Basic system architecture
 - Capability Enabling Active Device Measurements
- **Active Device Measurements**
 - SCMM Broadband Amplifier Characterization
 - **SCMM of 60 GHz Tx / Rx components**
 - IMD Spectrum measurements
 - THz Power Calibration
 - Materials Measurements at THz
- **Q&A**

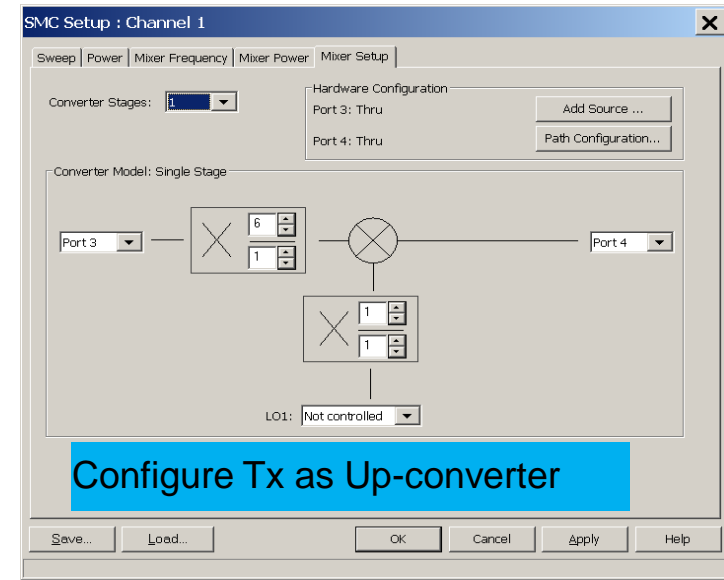
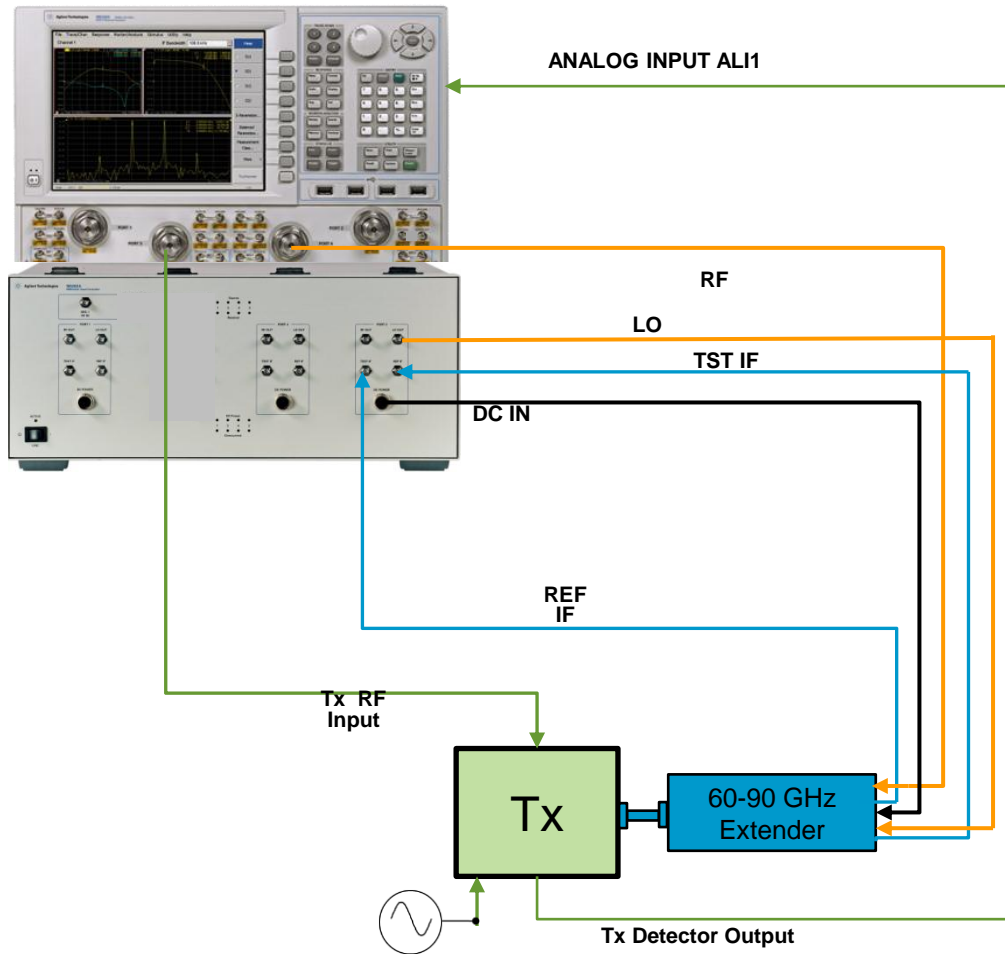
SCMM of 60 GHz Tx/Rx Components



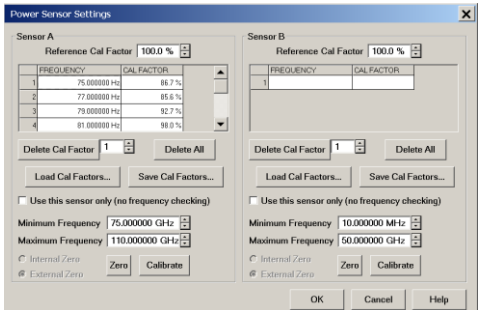
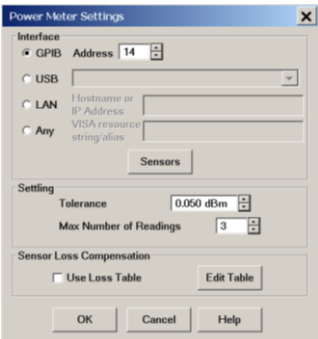
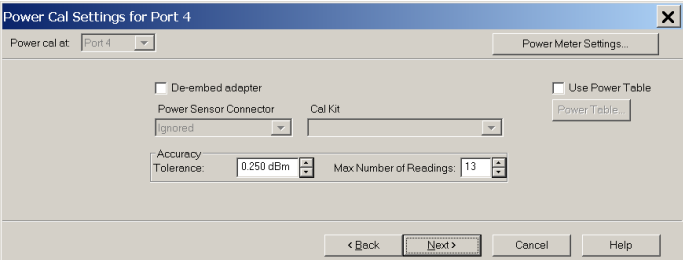
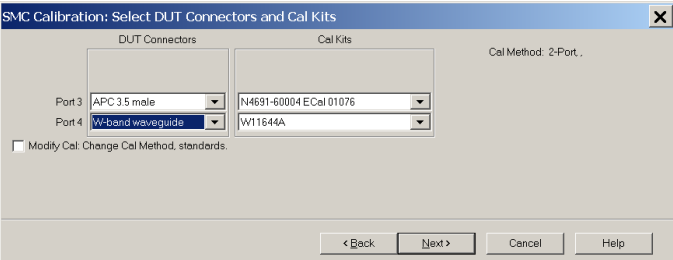
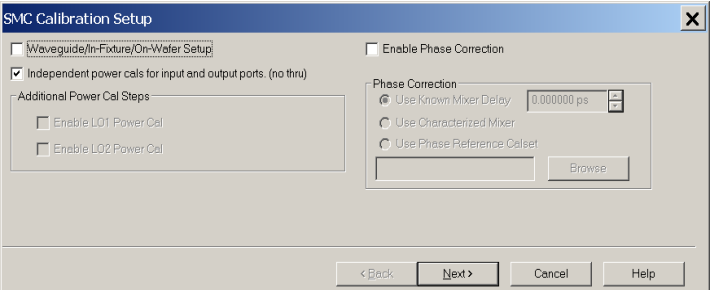
Measurement Requirements

- Conversion and S-Parameters of Tx
- Spectrum of Tx output with RF applied
- Spectrum measurement of Tx output for LO Leakage
- Tx Detector versus Output power
- Tx Detector vs. Input Power Sweep
- Rx Conversion and S-Parameters
- Rx Power Sweep of input Power
- Rx Swept LO Response
- Rx Noise Figure measurement

Tx Measurement Configuration Using SMC



Tx Measurement Configuration - Calibration



Using SMC Calibration allows for independent calibration of each port.

Adding Conversion and S-Parameters of Tx

SMC Setup : Channel 2

Sweep | Power | Mixer Frequency | Mixer Power | Mixer Setup

Mixer Frequency

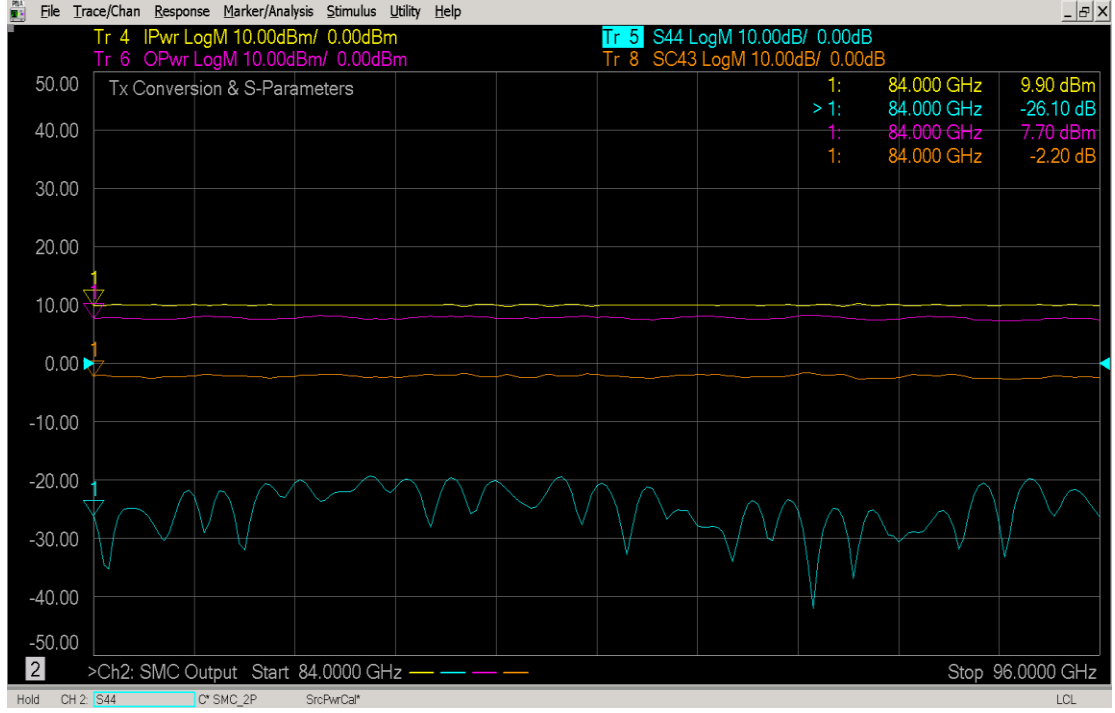
Input: Start/Stop, 14.000000000 GHz, 16.000000000 GHz, Calc Input

LO1: Fixed, 0 Hz, Input > LO

Output: Start/Stop, + 84.000000000 GHz, 96.000000000 GHz, Calc LO
 - 84.000000000 GHz, 96.000000000 GHz, Calc Output

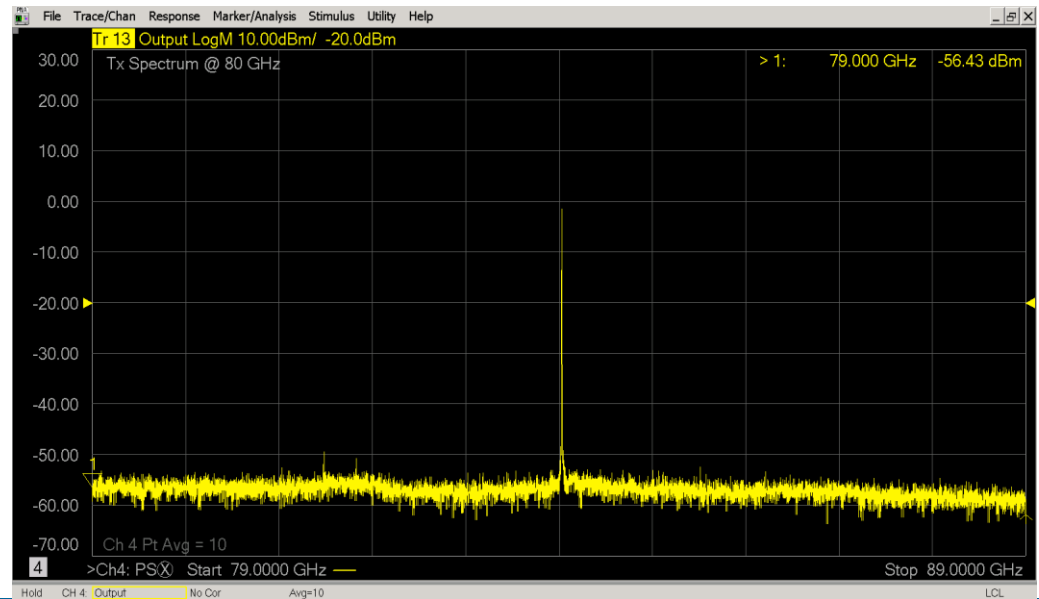
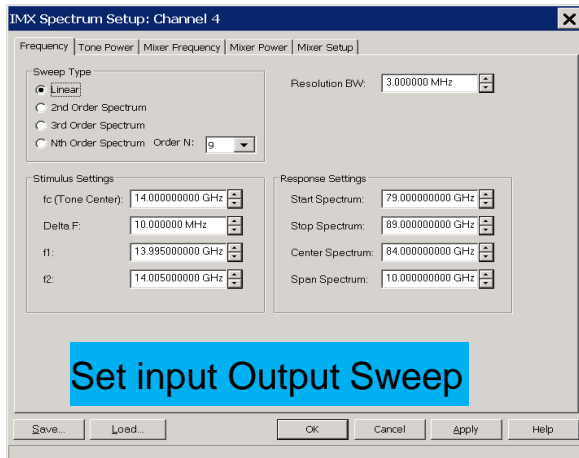
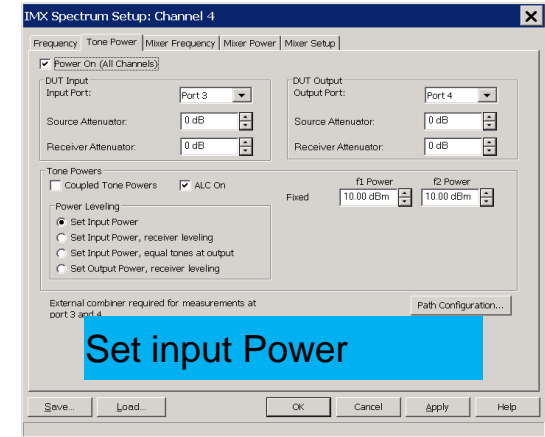
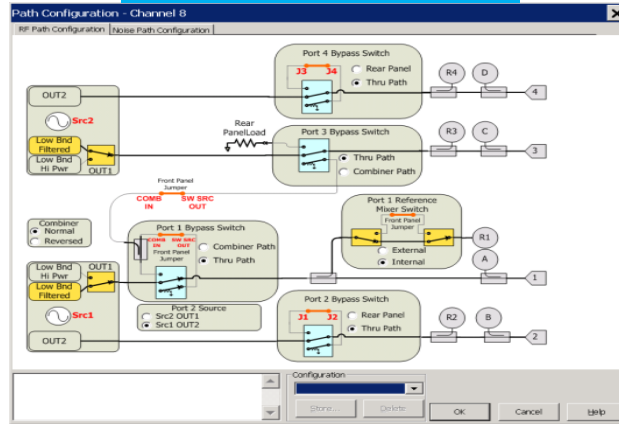
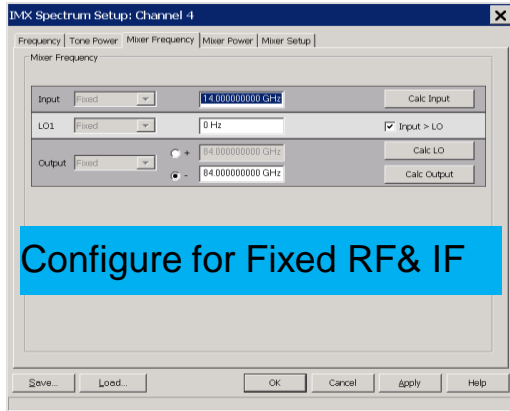
Configure for swept RF/ IF output Fixed LO

Save... Load... OK Cancel Apply Help

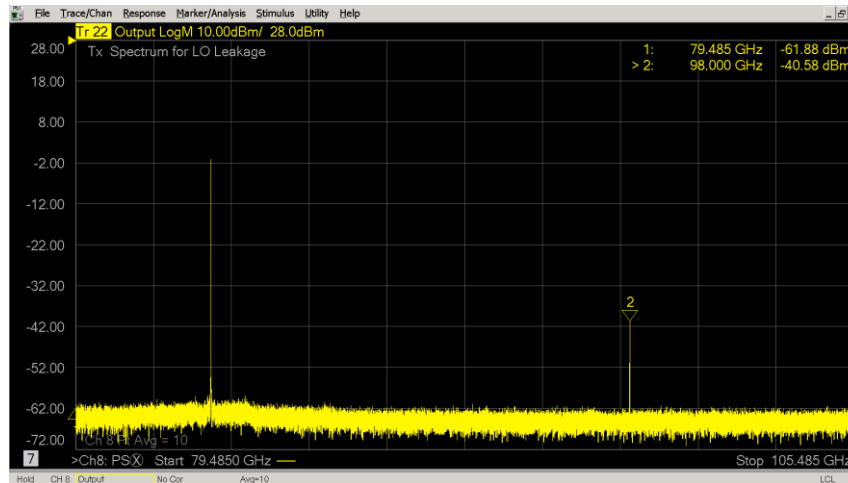
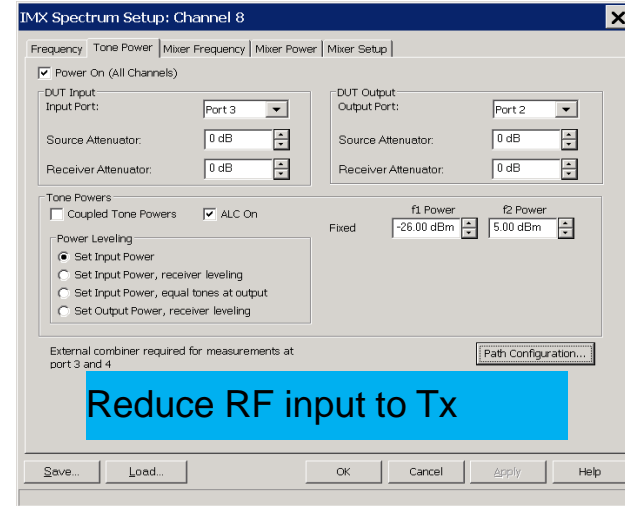
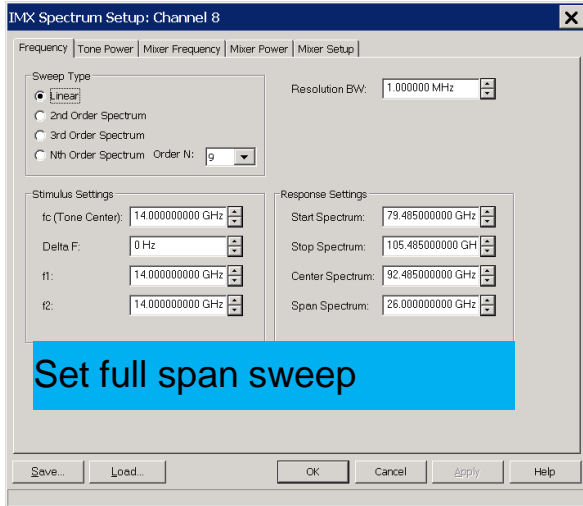


Adding Spectrum of Tx output with RF applied Using IMDx

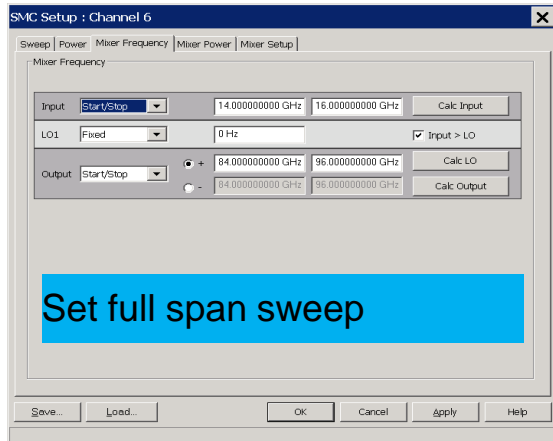
Configure Signal Path



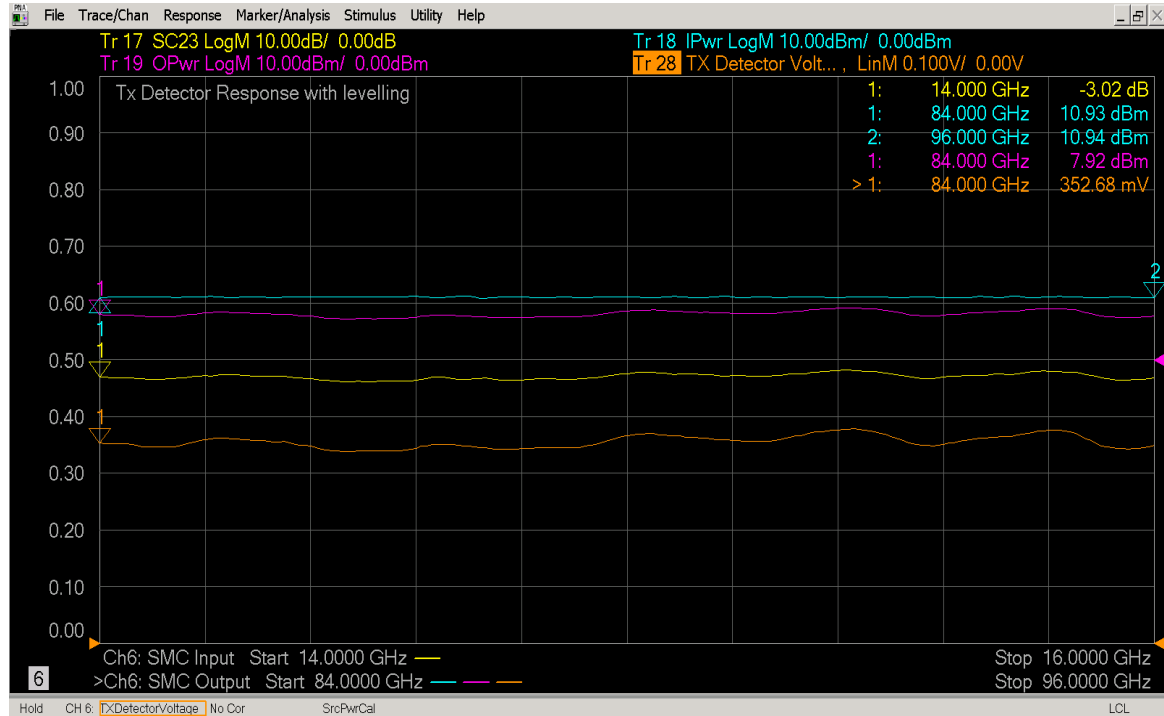
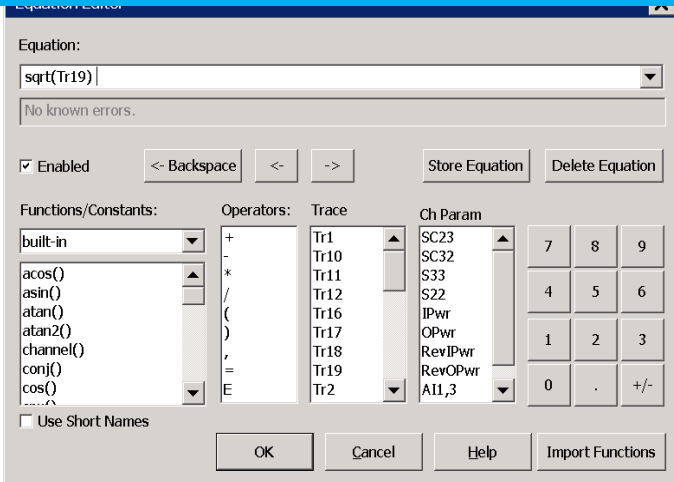
Adding Spectrum measurement of Tx output for LO Leakage – Uses IMDx



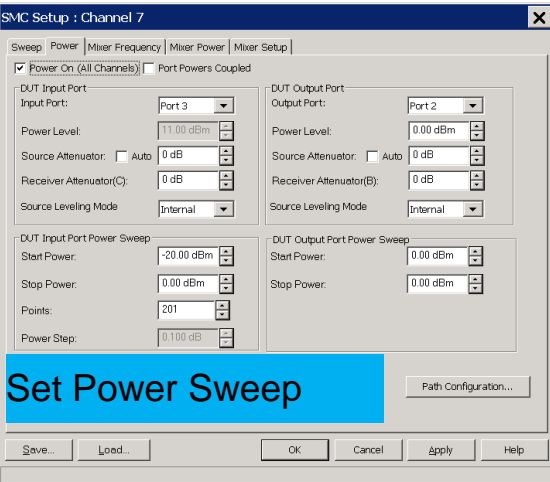
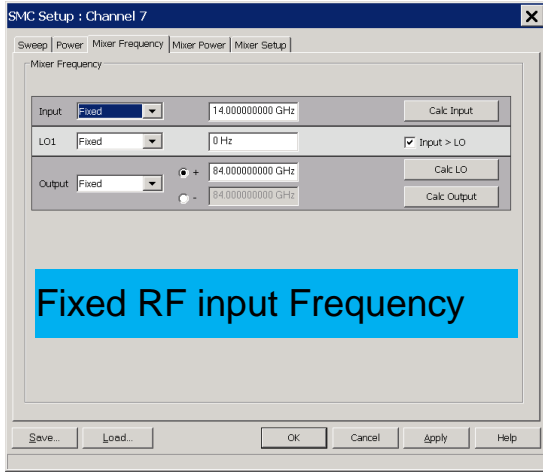
Adding Tx Detector versus Output power - Simulated



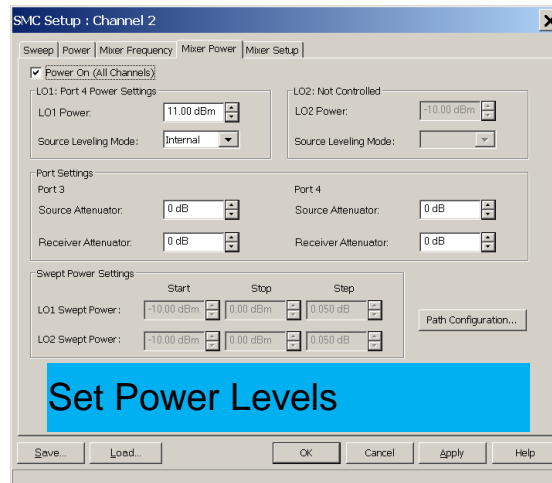
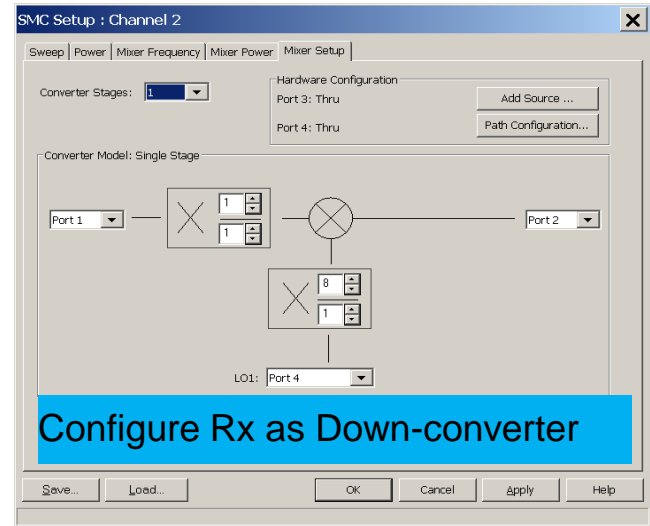
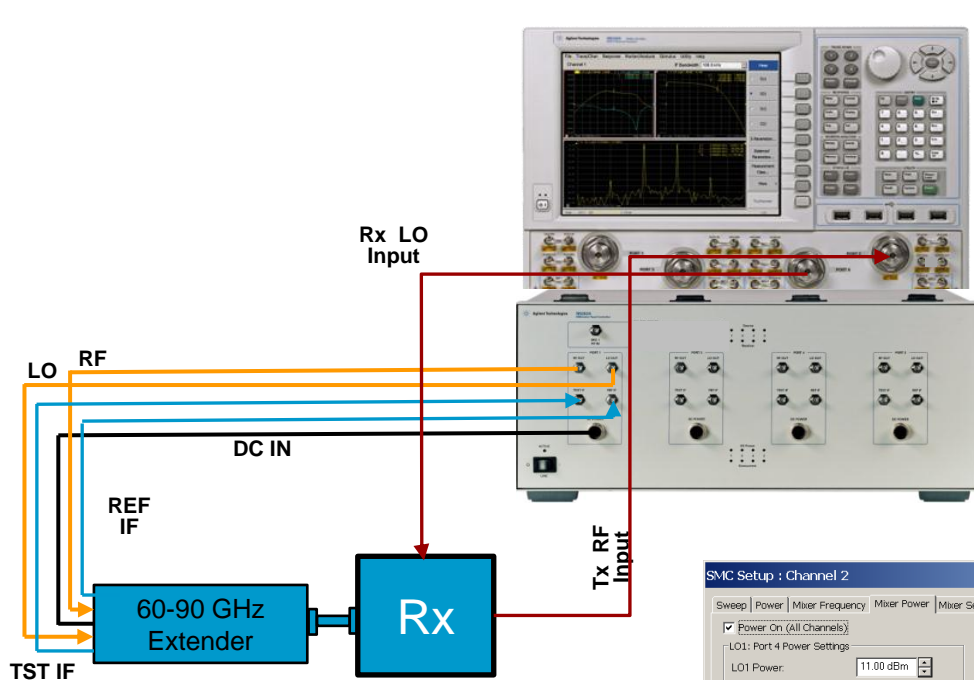
Use Equation Editor to simulate Detector voltage



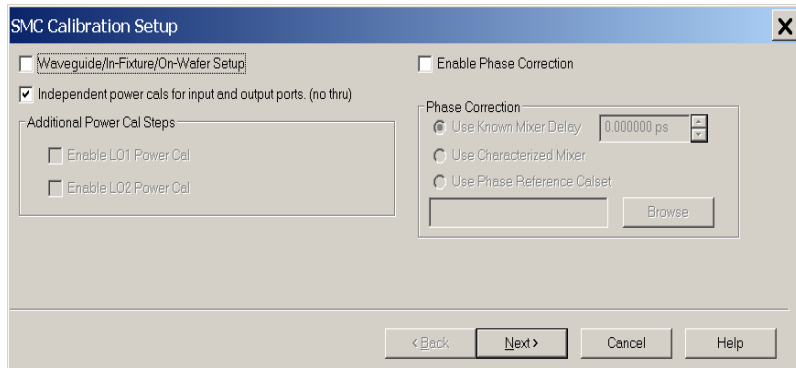
Adding Tx Detector vs. Input Power Sweep - Simulated



Rx Measurement Configuration Using SMC



Rx Measurement Configuration - Calibration



SMC Calibration Setup

Wavguide/In-Fixture/On-Wafer Setup

Independent power cals for input and output ports. (no thru)

Additional Power Cal Steps

Enable LO1 Power Cal

Enable LO2 Power Cal

Phase Correction

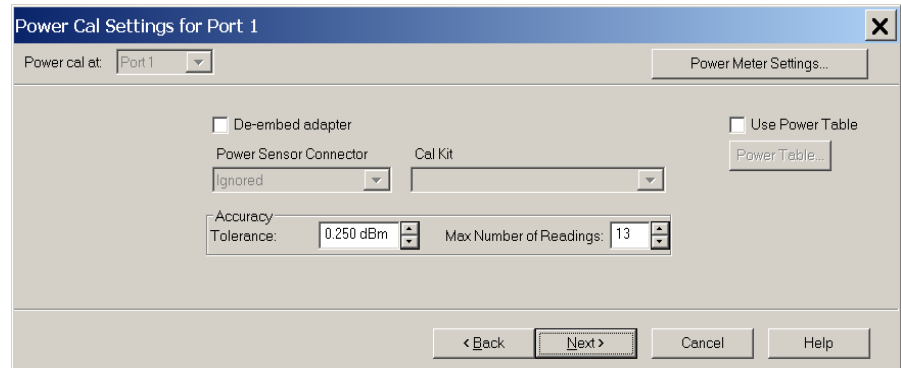
Use Known Mixer Delay 0.000000 ps

Use Characterized Mixer

Use Phase Reference Calset

Browse

< Back Next > Cancel Help



Power Cal Settings for Port 1

Power cal at: Port 1

Power Meter Settings...

De-embed adapter

Power Sensor Connector: Ignored

Cal Kit:

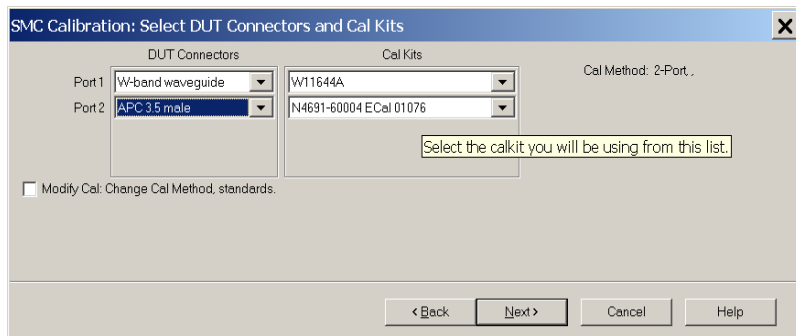
Use Power Table

Power Table...

Accuracy Tolerance: 0.250 dBm

Max Number of Readings: 13

< Back Next > Cancel Help



SMC Calibration: Select DUT Connectors and Cal Kits

DUT Connectors

Port 1: W-band waveguide

Port 2: APC 3.5 male

Cal Kits

W11644A

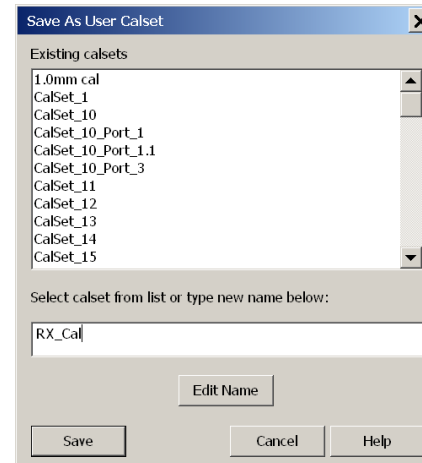
N4691-60004 ECal 01076

Cal Method: 2-Port

Select the calkit you will be using from this list.

Modify Cal: Change Cal Method, standards.

< Back Next > Cancel Help



Save As User Calset

Existing calsets

- 1.0mm cal
- CalSet_1
- CalSet_10
- CalSet_10_Port_1
- CalSet_10_Port_1.1
- CalSet_10_Port_3
- CalSet_11
- CalSet_12
- CalSet_13
- CalSet_14
- CalSet_15

Select calset from list or type new name below:

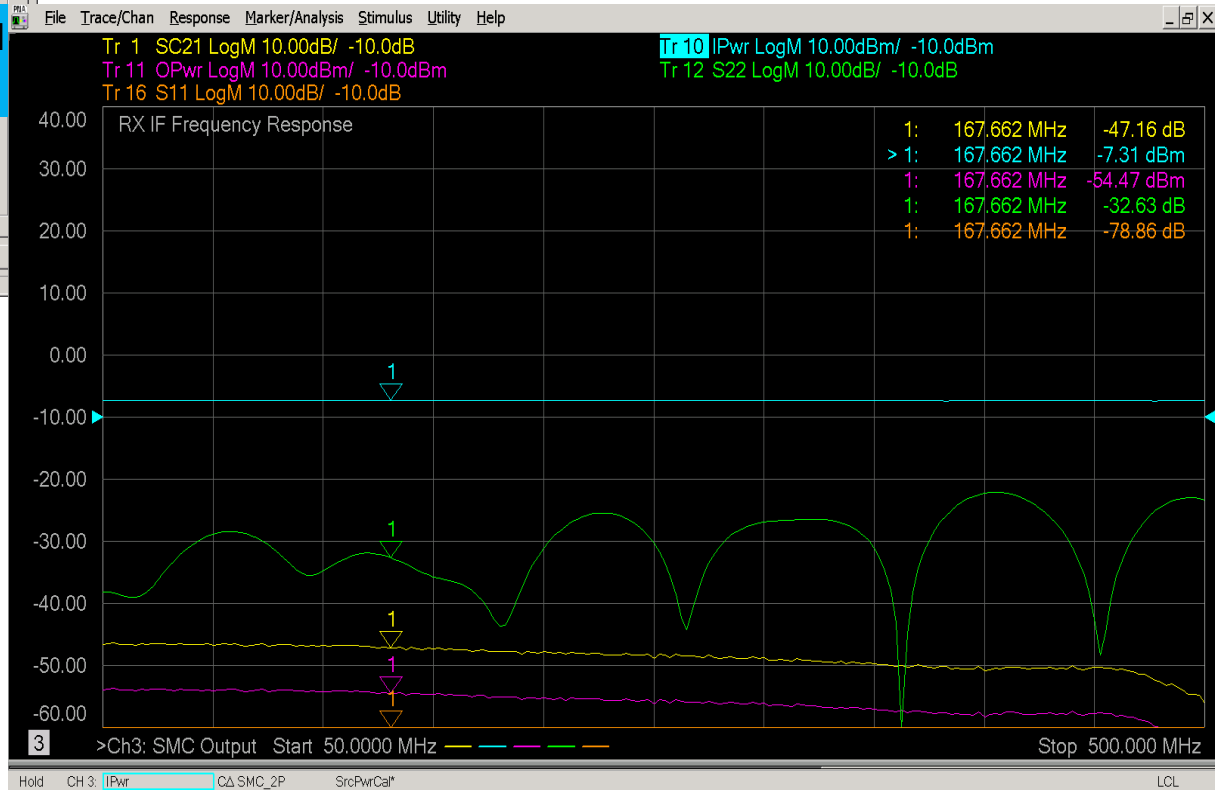
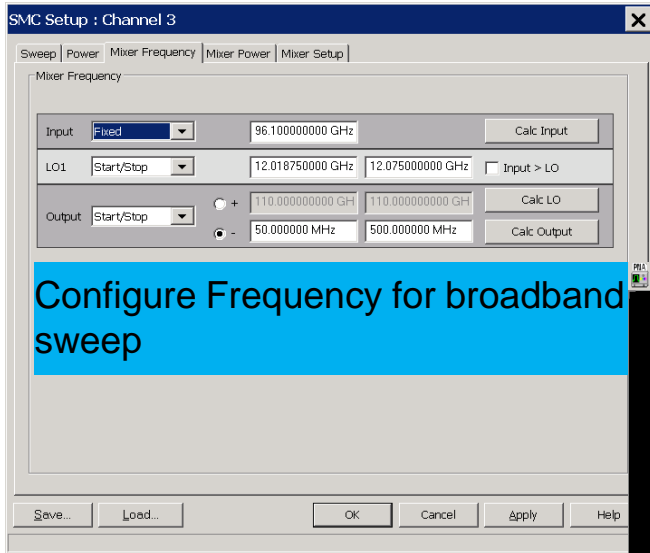
RX_Cal

Edit Name

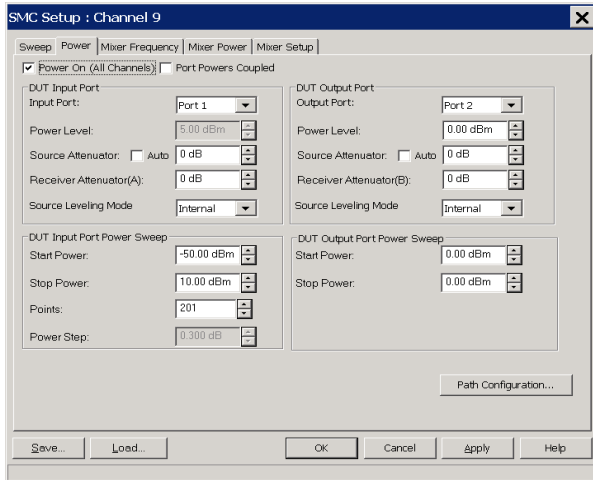
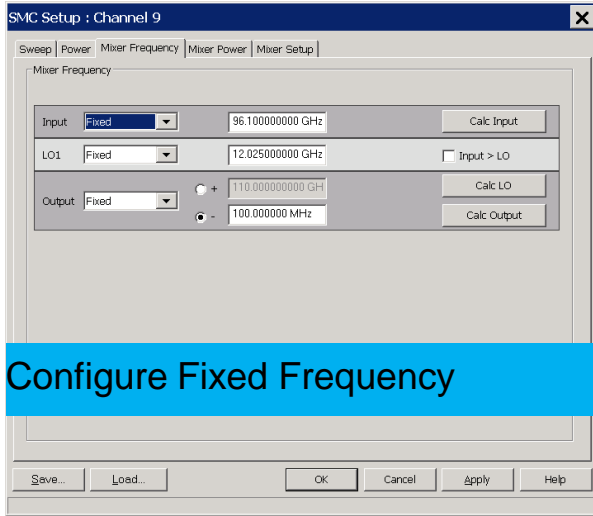
Save Cancel Help

Using SMC Calibration allows for independent calibration of each port.

Adding Rx Conversion and S-Parameters



Adding Rx Power Sweep of Input Power

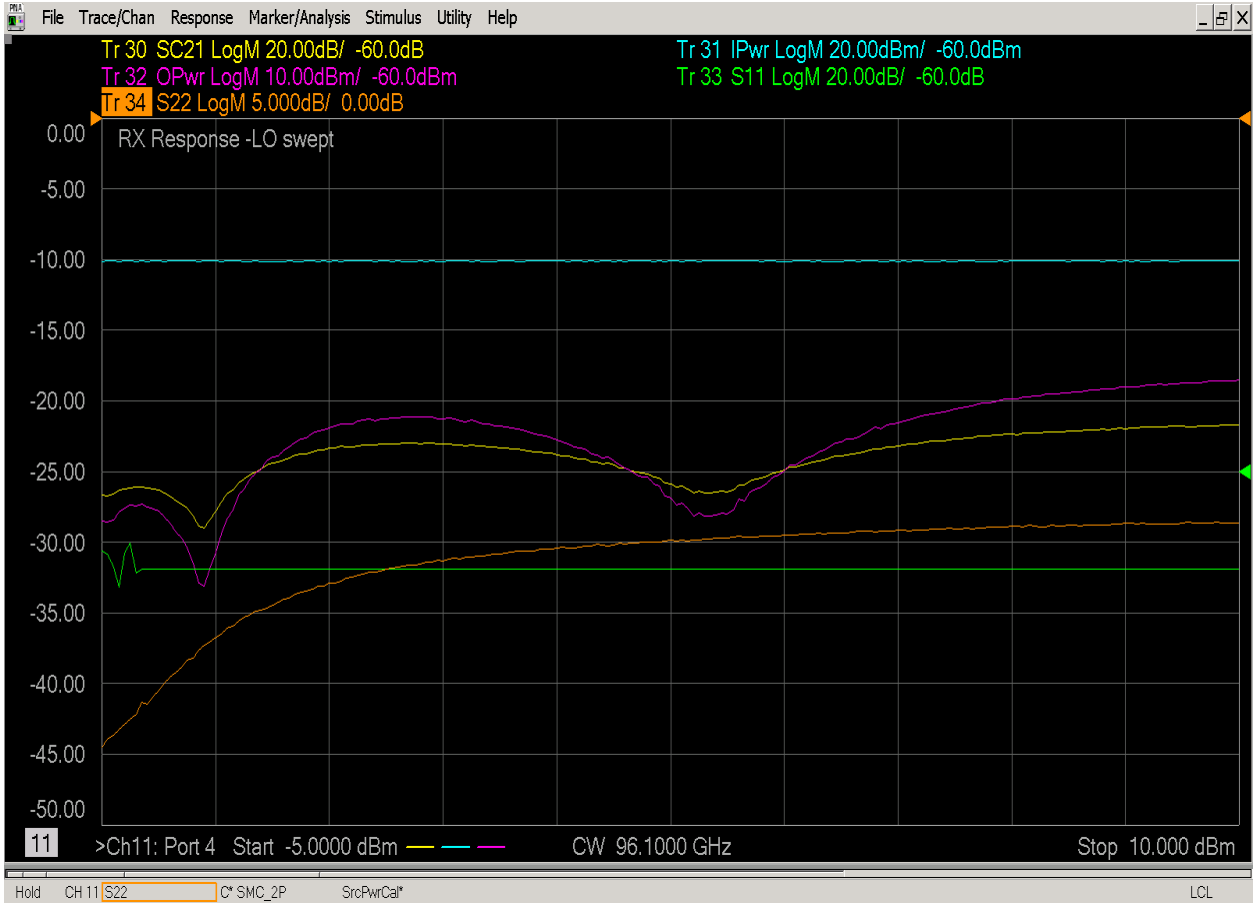


Adding Rx Swept LO Response

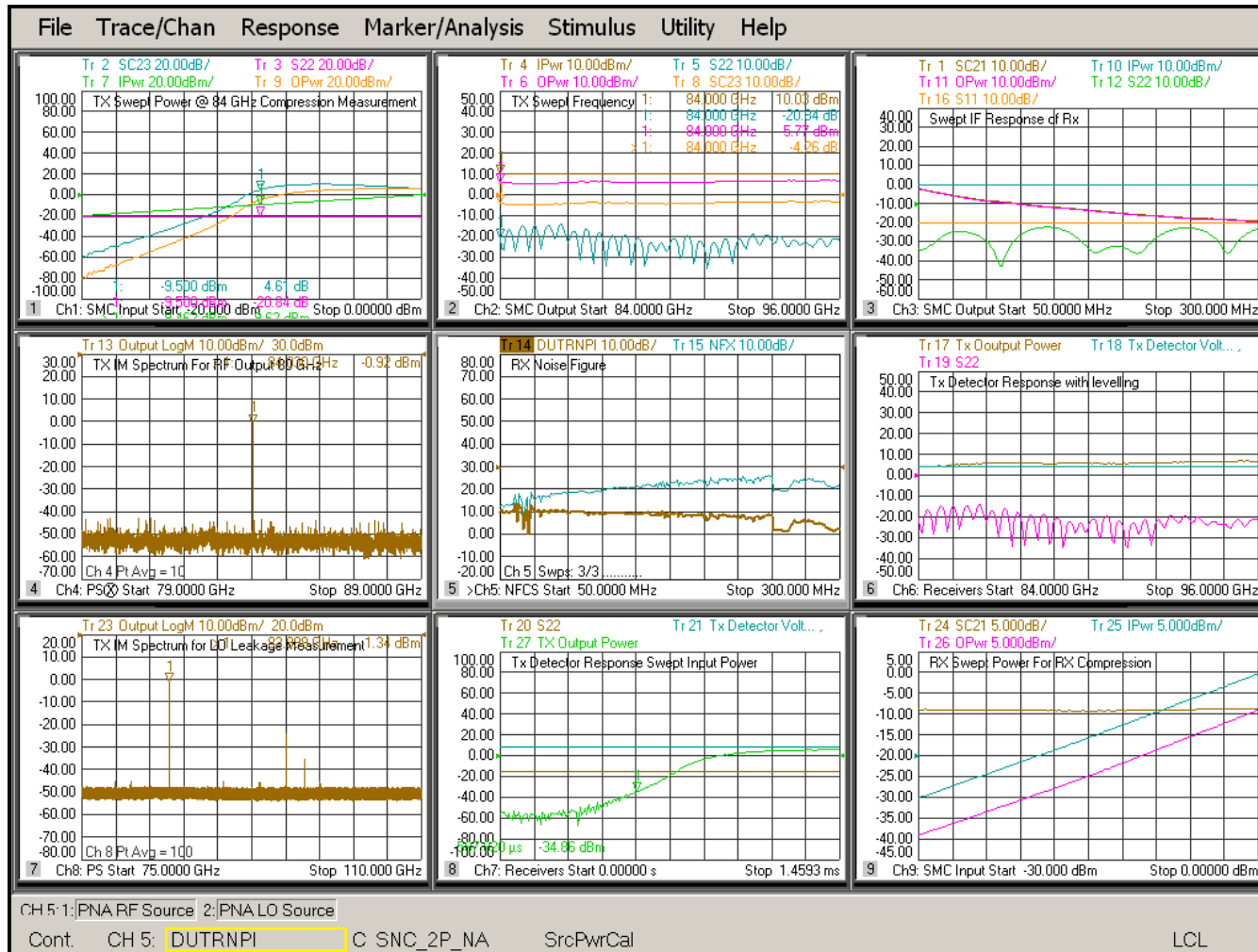
The SMC Setup dialog box for Channel 11 includes the following sections:

- Power On (All Channels):** Checked.
- LO1: Port 4 Power Settings:** LO1 Power: 11.00 dBm, Source Leveling Mode: Internal.
- LO2: Not Controlled:** LO2 Power: -10.00 dBm, Source Leveling Mode: (empty).
- Port Settings:** Port 3 and Port 4 Source and Receiver Attenuators are all set to 0 dB.
- Swept Power Settings:** LO1 Swept Power: Start -5.00 dBm, Stop 10.00 dBm, Step 0.075 dB; LO2 Swept Power: Start -10.00 dBm, Stop 0.00 dBm, Step 0.050 dB.

A blue callout box at the bottom of the dialog reads: **Configure LO Power Sweep**



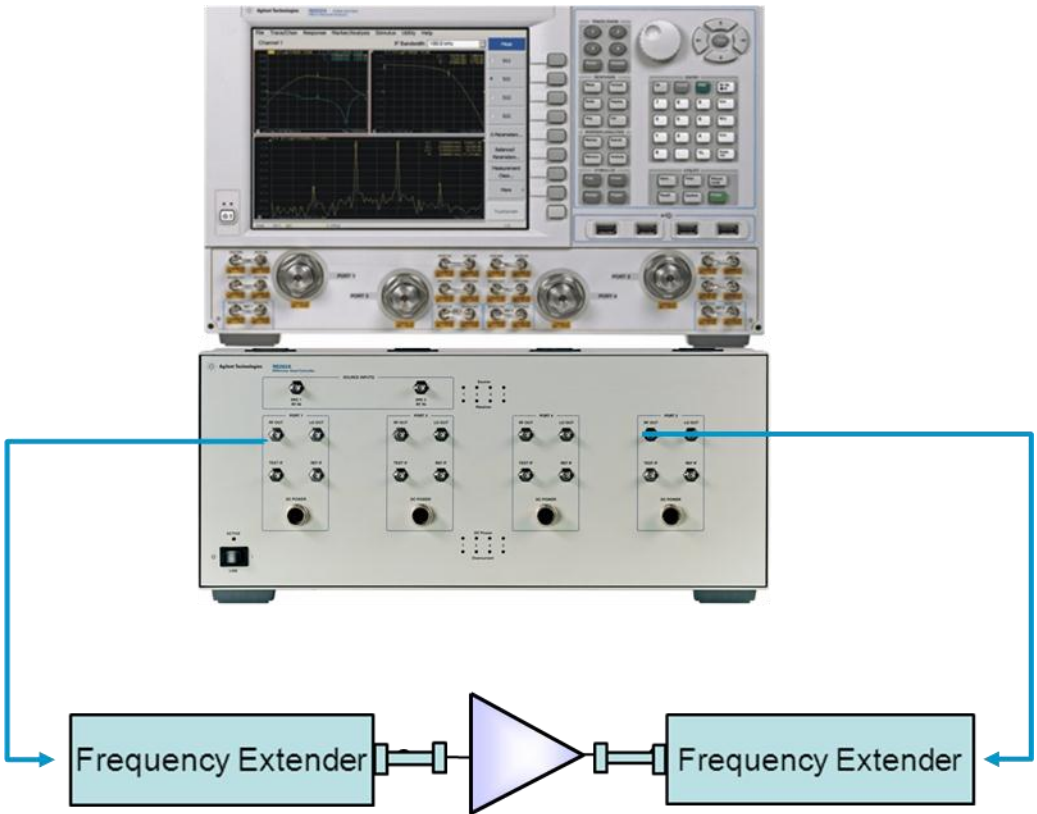
Summary SCMM of 60 GHz Tx / Rx components



Agenda

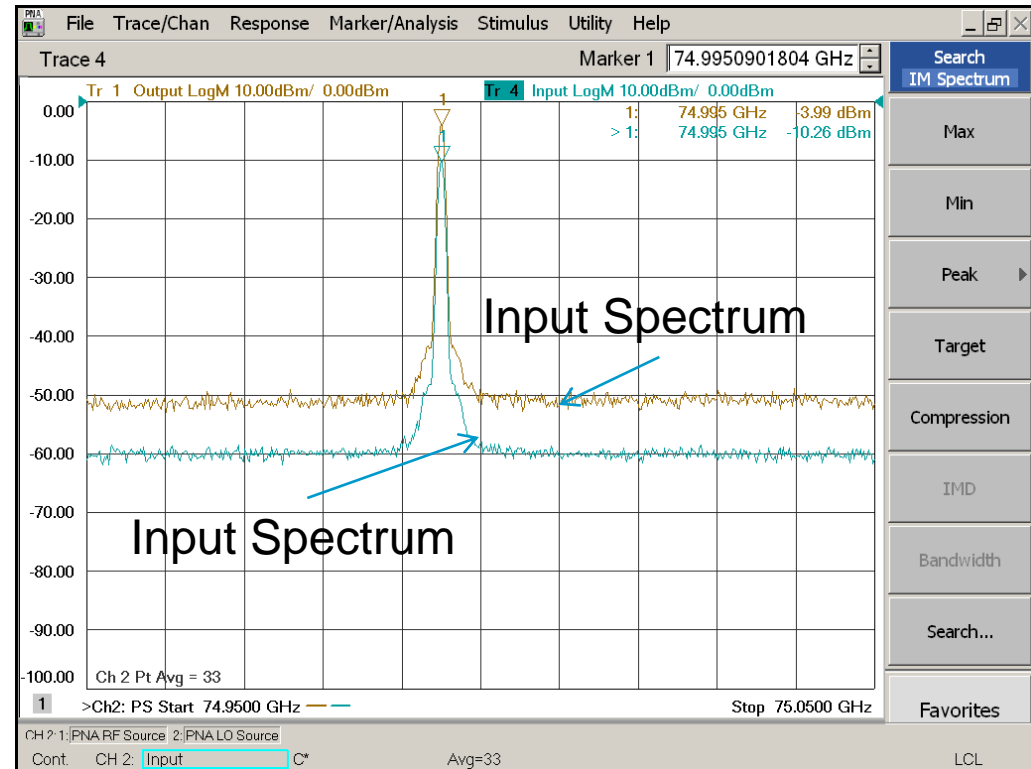
- **Millimeter wave and THz applications**
- **Measurement Solution**
 - Basic system architecture
 - Capability Enabling Active Device Measurements
- **Active Device Measurements**
 - SCMM Broadband Amplifier Characterization
 - SCMM of 60 GHz Tx / Rx components
 - **IMD Spectrum measurements**
 - THz Power Calibration
 - Materials Measurements at THz
- **Q&A**

Measurement Setup



IM Spectrum: Measurement

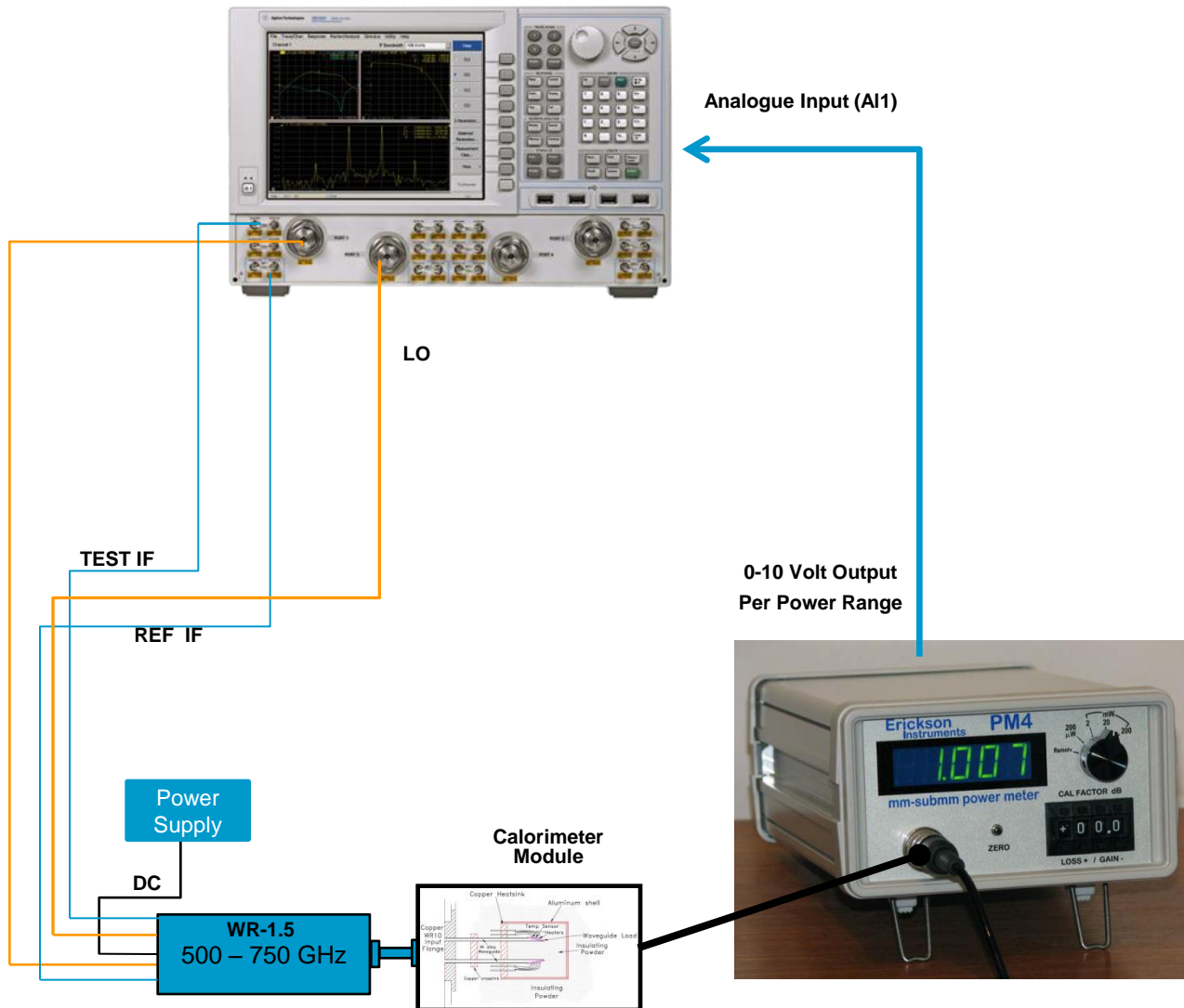
- Measurement Setup
 - Assign Measurement class
 - Set Path configuration to Thru path
 - Setup the port power to correct
- Stimulus
 - Set start and stop frequency
- Measure
 - Input and output Spectrum



Agenda

- **Millimeter wave and THz applications**
- **Measurement Solution**
 - Basic system architecture
 - Capability Enabling Active Device Measurements
- **Active Device Measurements**
 - SCMM Broadband Amplifier Characterization
 - SCMM of 60 GHz Tx / Rx components
 - IMD Spectrum measurements
 - **THz Power Calibration**
 - Materials Measurements at THz
- **Q&A**

THz Power Calibration WR1.5 System Configuration



Sweep Setting – PM-4 200 μ Watt Range

Sweep Setup

1 Channel

Stepped Sweep - sweep moves in discrete steps

40.000 sec Dwell Time - delay before measuring each point

0 usec Sweep Delay - delay before first point of sweep

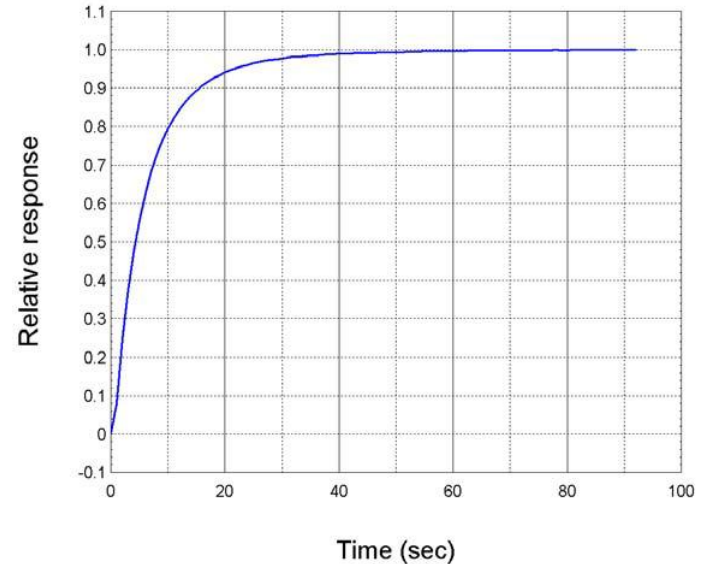
Fast Sweep - reduce measurement settling time

Sweep Sequence

Standard

Point Sweep: measure all parameters before stepping to the next point

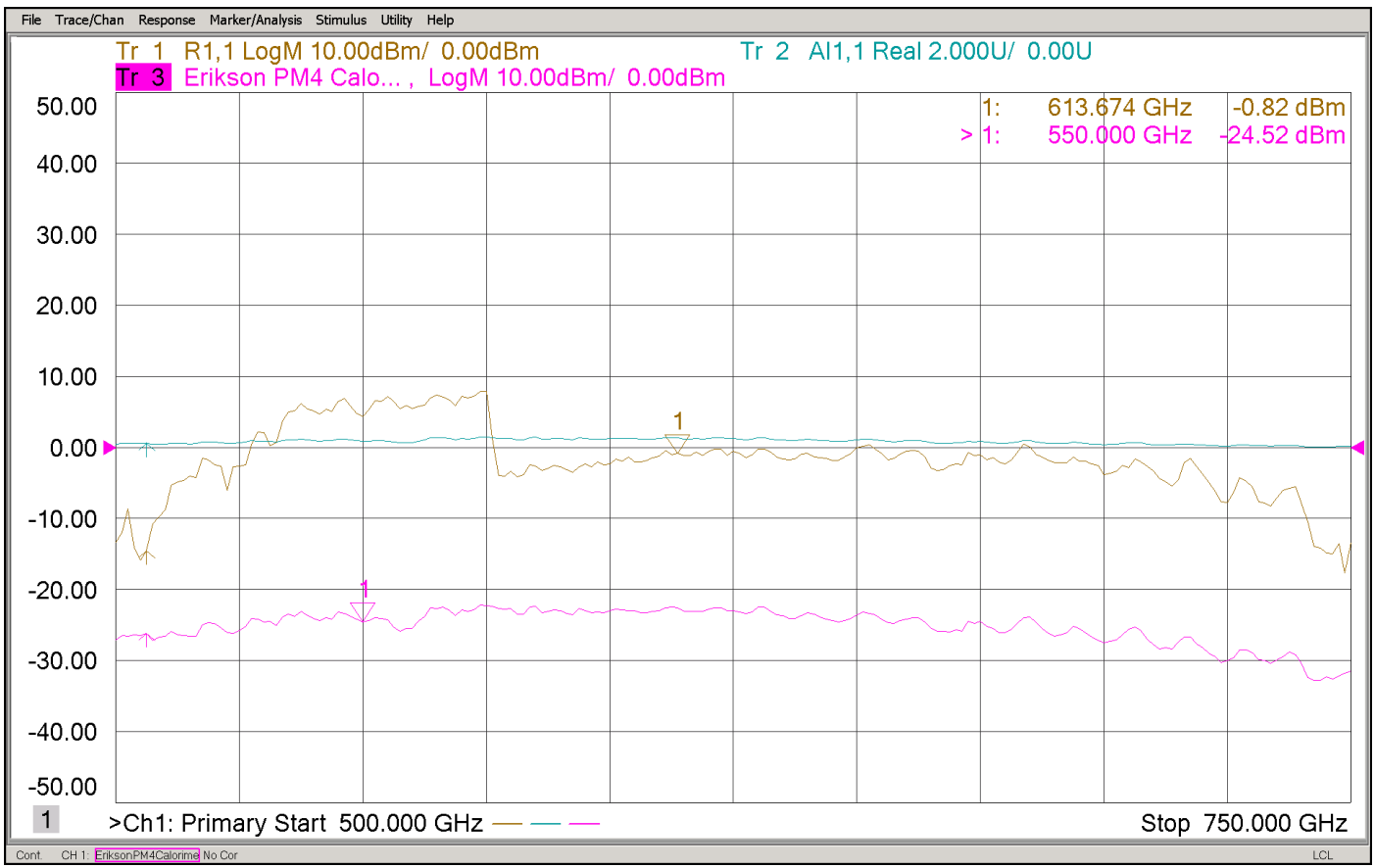
OK Cancel Help



PM4 Port Power Characterization

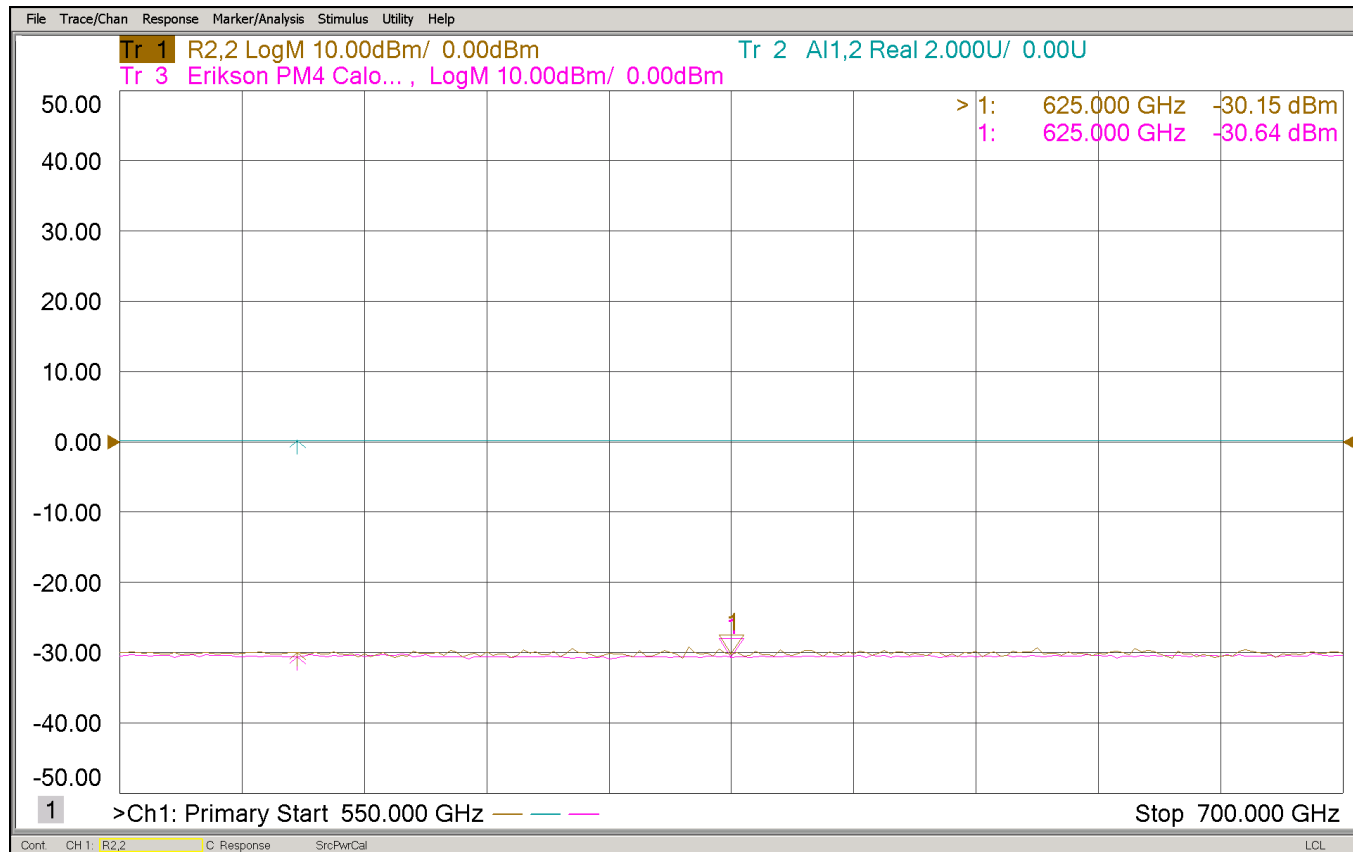
1. Measurement of power with the PM4 at these frequencies are very sensitive and require at least a 20 second settling time for a valid measurement
2. Configure the system to sweep the frequency range of interest as well as the number of points
3. In this example we use 500 GHz - 750 GHz with 201 point characterization, while it is not required for the source calibration it provides the full characterization
4. Turn off RF to the Frequency extender zero and calibrate the Calorimeter
5. Turn on the RF and save the measurement results as a file.

PM4 Port Power Characterization



- Note Trace 3 above is created by using the equation editor to convert the analog input AI1,1 into a power reading of dBm.
- In this example we do this by taking the displaying the $(\sqrt{\text{Tr}2/50})$, in which 50 is the 10V to 200 uWatt range
- Save Trace 3 above into a file and add the RF power setting used, in this example we used +3 dBm

Verification of calibration

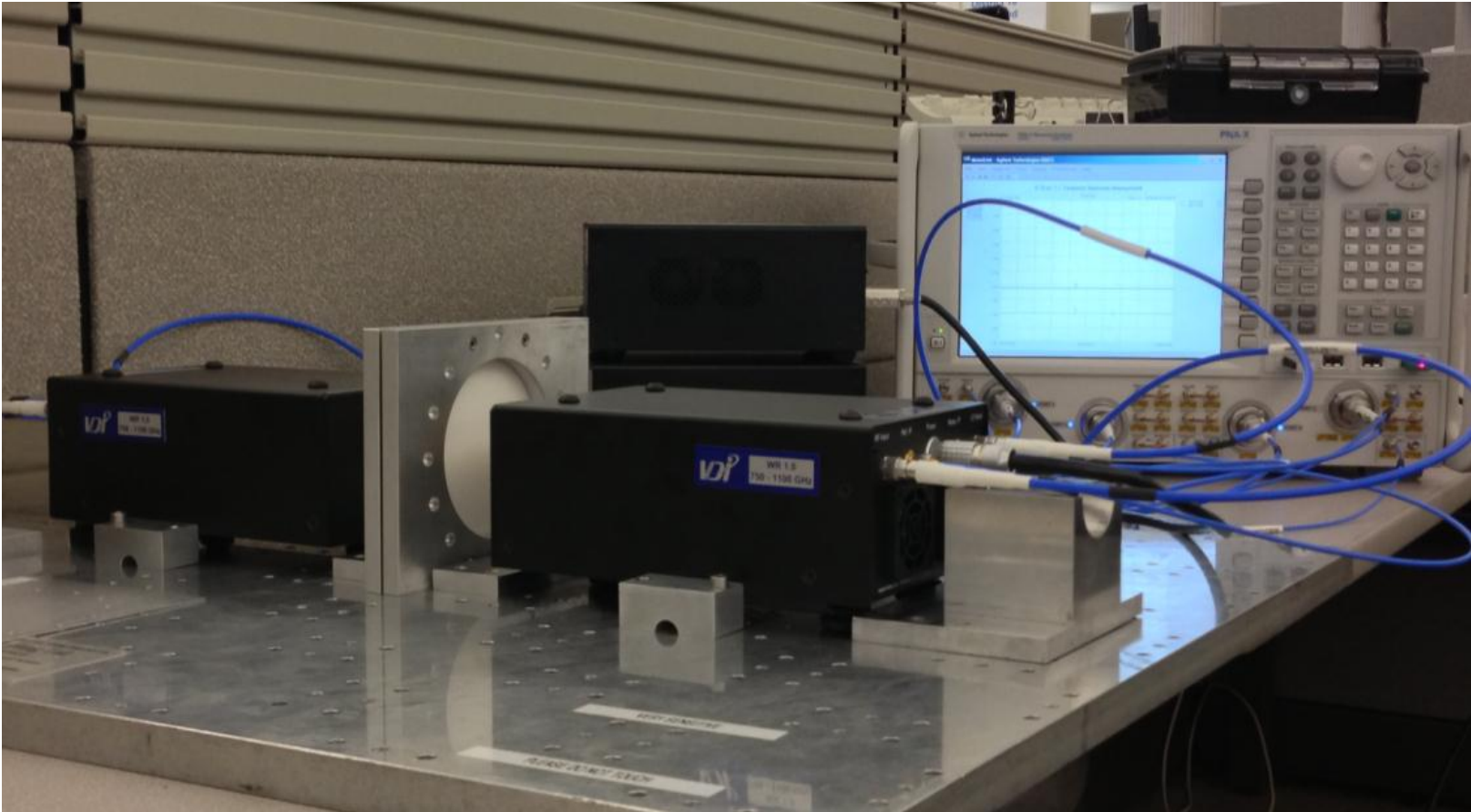


Measurement of port 2 source power as shown by the PNA-X receiver R2,2 in comparison to the actual measured PM4 power at port 2.

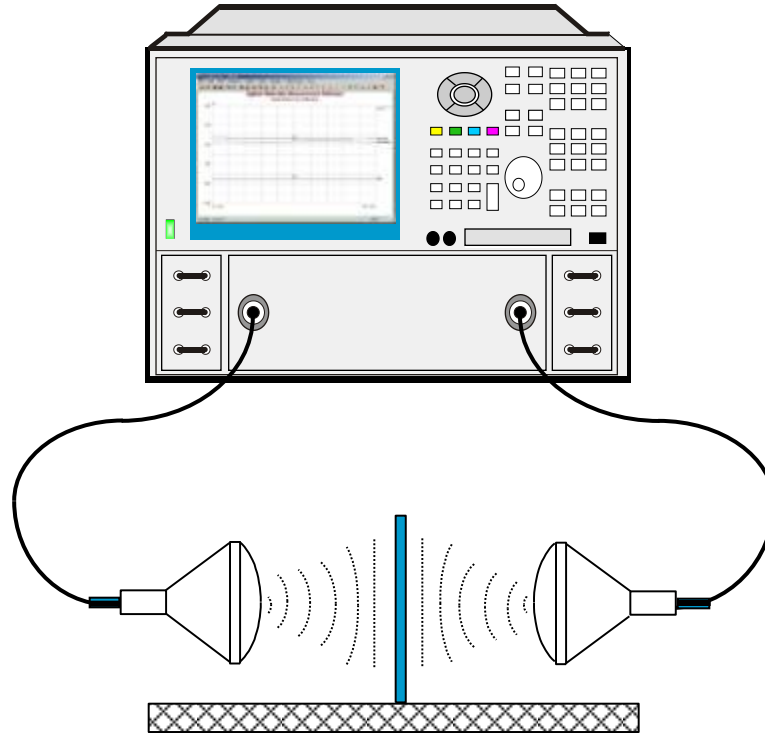
Agenda

- **Millimeter wave and THz applications**
- **Measurement Solution**
 - Basic system architecture
 - Capability Enabling Active Device Measurements
- **Active Device Measurements**
 - SCMM Broadband Amplifier Characterization
 - SCMM of 60 GHz Tx / Rx components
 - IMD Spectrum measurements
 - THz Power Calibration
 - **Materials Measurements at THz**
- **Q&A**

THz Materials Measurement Solution

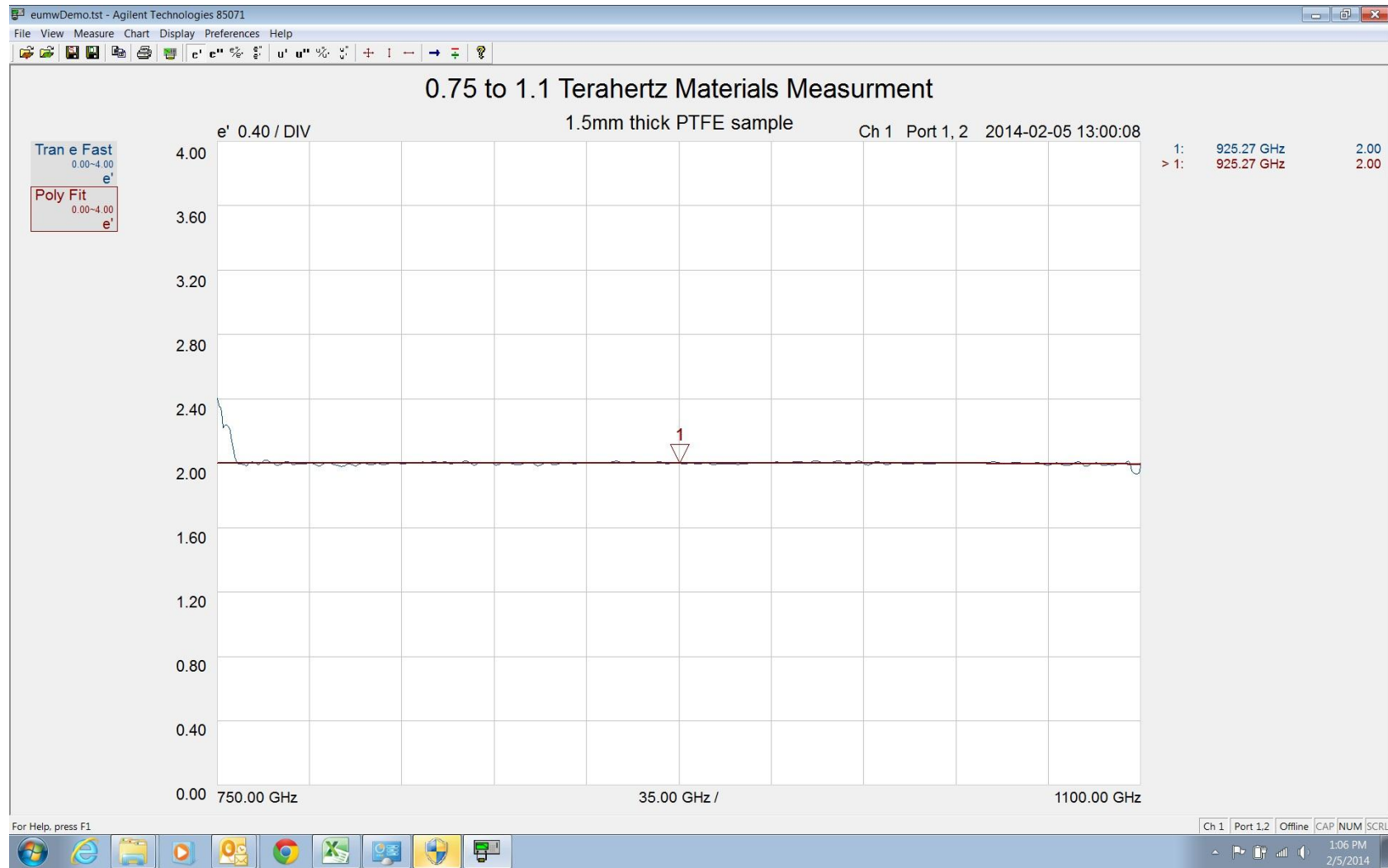


Calibration is Required

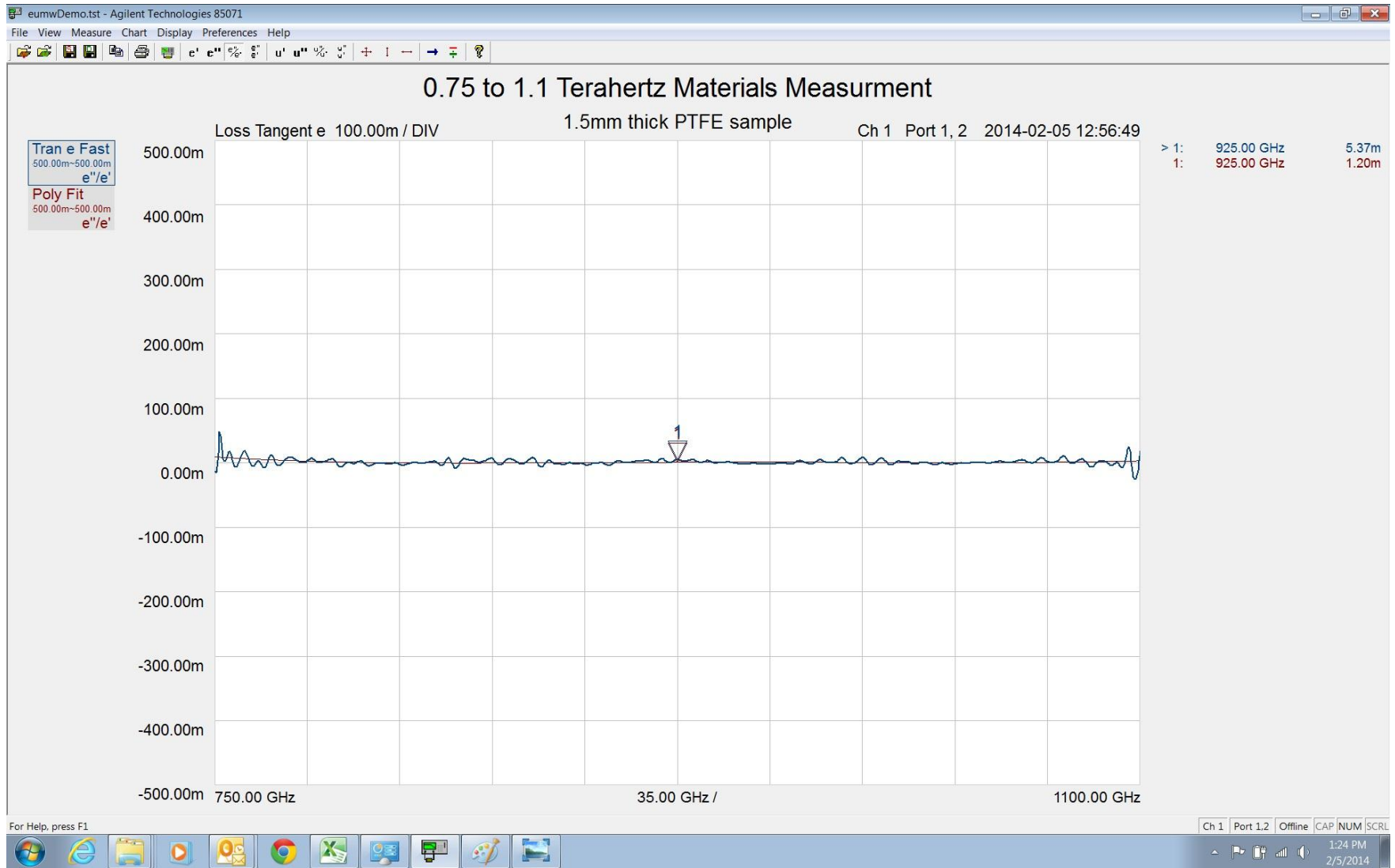


Before a measurement can be made, a calibration must be performed to remove systematic errors.

THz Materials Measurements ϵ' Real Part Permittivity



THz Materials Measurements ϵ'/ϵ'' Tan Delta



Agenda

- **Millimeter wave and THz applications**
- **Measurement Solution**
 - Basic system architecture
 - Capability Enabling Active Device Measurements
- **Active Device Measurements**
 - SCMM Broadband Amplifier Characterization
 - SCMM of 60 GHz Tx / Rx components
 - IMD Spectrum measurements
 - THz Power Calibration
 - Materials Measurements at THz
- Q&A

Thank You

