Complete mm-Converter Measurement System including Noise Figure

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Most traditional mm-wave test systems test passive devices and only measure linear s-parameters.

Today we are going to present a mm-wave system that can offer a range of measurements suited for active devices....

....and present a system that can measure all of these parameters including noise figure.
Workshop Agenda

• Typical mm-wave System Configurations

• mm-wave Applications

• Calibration

• Noise Figure

• Complete E-Band Converter Test System
Basic mm-wave System Architecture

Network Analyzer is the measurement engine.

**Optional** Test Set Controller interfaces to modules

THz Frequency Extenders provide frequency conversion and signal coupling

- Vector Network Analyzer
- Millimeter Wave Test Set controller
  - Frequency Extenders
  - Frequency Extenders
  - Frequency Extenders
  - Frequency Extenders

Device under test
PNA / PNA-X Network Analyzer

Key Enabling Features:

- 26.5 / 43.5 / 50 / 67 GHz 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

N5247A 4-Port PNA-X
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 modules: 10M-110GHz
- Banded modules: 50 GHz ... 1 THz

Banded Frequency Extenders

<table>
<thead>
<tr>
<th>WR 15</th>
<th>50 – 75 GHz</th>
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<tbody>
<tr>
<td>WR 12</td>
<td>60 – 90 GHz</td>
</tr>
<tr>
<td>WR 12E</td>
<td>54 – 92 GHz</td>
</tr>
<tr>
<td>WR 10</td>
<td>75 – 110 GHz</td>
</tr>
<tr>
<td>WR 6</td>
<td>110 – 170 GHz</td>
</tr>
<tr>
<td>WR 5</td>
<td>140 – 220 GHz</td>
</tr>
<tr>
<td>WR 3</td>
<td>220 – 325 GHz</td>
</tr>
<tr>
<td>WR 2.2</td>
<td>325 – 500 GHz</td>
</tr>
<tr>
<td>WR 1.5</td>
<td>500 – 750 GHz</td>
</tr>
<tr>
<td>WR 1.0</td>
<td>750 – 1.1 THz</td>
</tr>
</tbody>
</table>
Millimeter Wave Configurations

- Two Basic families **Broadband** or **Banded Waveguide** solutions

4-port Broadband

4-port Banded
Broadband Single Sweep System

Single-sweep over 10MHz-110GHz

2-port & 4-port options

Uses 67GHz PNA & PNA-X

DUT Interface = 1mm coax

Features:

• Built-in Kelvin Bias Tees
• Broadband source leveling down to 70 dBm
• True differential Measurements
• Integrated Pulse measurements
• Mixer measurements
• Spectral Power Measurements
Banded Waveguide System

- Bands cover 50 GHz to 1 THz
- 2-port & 4-port options with a Test Set Controller
- 2 Option without a Test Set Controller
- Uses 26.5/40/50/67GHz PNA & PNA-X
- DUT Interface = waveguide

Features:
- Source Power leveling up to 1.1 THz
- True differential Measurements
- Integrated Pulse measurements
- Mixer measurements
- Spectral Power Measurements

Configuration With Test Set Controller

Configuration Without Test Set Controller
Waveguide Banded Solutions Configurations

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

VDI Banded Waveguide Solution Without Test Controller

Farran Banded Waveguide Solution With Proprietary Test Controller
Workshop Agenda

• Typical mm-wave System Configurations

• mm-wave Applications
  – Compression
  – Mixers
  – Pulse
  – IM Spectrum
  – Materials

• Calibration
• Noise Figure
• Complete E-Band Converter Test System
mm-wave Measurements

mm-wave Devices
- Passives
- Amplifiers
- Mixers
- Semiconductors
- Antennas
- Materials

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

• These measurements are typically associated with microwave coaxial devices.

• But, by using a Test Set Controller and calibrating both for s-parameters and power we can now start to offer more complex mm-wave solutions.
mm-wave Compression Setup
mm-wave Compression Measurements

- Calibrate
  - S-Parameters
  - Source Power
  - Receiver power

- Stimulus
  - Sweep source power

- Measure
  - S-Parameters
  - Absolute power
  - Compression

45dB power sweep at 98 GHz
mm-wave Mixer Measurements: Fundamental LO

- RF Input: 77 – 81 GHz
- LO Input: 78 – 82 GHz
- IF Output: 1 GHz
mm-wave Mixer Measurements: Harmonic LO

RF Input: 75-110 GHz

Harmonic Mixer:
IF = 1/6 * RF
LO = 1/8 * RF

IF Output: 100 MHz
LO Input: 9.35 GHz - 13.75 GHz
mm-wave Mixer Measurements

Test Device: WR10 Module

75-110GHz RF → 9.4-13.8GHz LO → 9.4-13.8GHz IF

- Calibrate
  - S-Parameters
  - Source Power
  - Receiver power

- Stimulus
  - Sweep the LO power

- Measure
  - Match
  - Power
  - Conversion Loss
mm-wave Pulse Measurements
Pulse: Techniques

Wideband/synchronous acquisition
No loss in dynamic range for small duty cycles (long PRI's), but there is a lower limit to pulse width.

Narrowband/Asynchronous Acquisition
No lower limit to pulse width, but dynamic range is function of duty cycle.
Pulse: Measurement

- Calibrate
  - S-Parameters
  - Source Power
  - Receiver power

- Stimulus
  - Pulse generation
  - RF Pulse modulation
  - Swept frequency or power

- Measure
  - S-Parameters
  - Absolute power
  - Pulse waveform

100us pulse power waveform at 98GHz
mm-wave IM Spectrum Measurements
mm-wave 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
mm-wave Material Measurements

Free space W-band system

Quasi-optical W-band system
mm-wave Material Measurements

- Calibrate
  - 2-port S-parameters (Methods such as Gated-Reflect-Line)
- Stimulus
  - Sweep frequency
- Measure
  - Permittivity
  - Permeability
  - Sheet resistance
  - Reflectivity
Workshop Agenda

• Typical mm-wave System Configurations
• mm-wave Applications

• Calibration
  – S-Parameter Calibration
  – Power calibration

• Noise Figure
• Complete E-Band Converter Test System
Calibration Interfaces

• Probe calibration
  • Specific probe calibration software
  • Uses basic and advanced cal methods (e.g. LRRM)
  • Uses on-wafer cal standards

• Materials measurement calibration
  • Specific materials measurement calibration software
  • Uses basic and advanced cal methods (e.g. Gated-Reflect-Time)
  • Uses special free-space cal standards

• Waveguide calibration
  • Uses basic calibration methods (SOLT, TRL)
  • Uses rectangular waveguide calibration standards
Calibration Types

• 1-port Cal
  • Short / Offset-Short / Match\(^{(1)}\)

• 2-port "TRL-style" Cal
  • TRL = Thru / Reflect / Line
  • LRL = Line / Reflect / Line
  • TRM = Thru / Reflect / Match\(^{(1)}\)
  • LRM = Line / Reflect / Match\(^{(1)}\)

• 2-port "SOLT-style" Cal
  • Short / Offset Short / Match\(^{(1)}\) / Thru

\(^{(1)}\) Where "Match" is either a Load, Offset Load, or Sliding Load.
Quick-SOLT Calibration

• 2-port "QSOLT"
  • Measure Short / Offset-Short / Match\(^{(1)}\) on one port
  • Measure zero-length thru between ports
  • Measuring four standards results in 2-port calibration
  • Useful for "mate-able" ports (e.g. waveguide)

• 4-port "QSOLT"
  • Measure Short / Offset-Short / Match\(^{(1)}\) on one port
  • Measure zero-length thru between three port pairs
  • Measuring six standards results in 4-port calibration

\(^{(1)}\) Where "Match" is either a Load, Offset Load, or Sliding Load.
Power Calibration
Power Calibration
Components to calibrate

• Source Cal
  • Measures source output power
  • Results in accurate output power at the calibrated level

• Receiver Cal
  • Measures receiver at calibrated power level
  • Results in accurate, fast power measurements

• Receiver Leveling Loop
  • Uses calibrated receiver to measure source power
  • Servo's the source to provide accurate output power
Power Sensor Cal

• A waveguide sensor is used to calibrate a waveguide system

• Calibration process
  • Waveguide sensor is connected to module
  • Source power is calibrated
  • Receiver power is calibrated using source
  • Receiver is used to calibrate source power vs. level

• Correction process
  • Standard 12-term S-parameter correction
  • Receiver is used to monitor source power; Power level is adjusted using receiver leveling
Power Table Cal

• The power table defines the mm-module output power vs. frequency when operated at its maximum (clipped) output power.

• Calibration process
  • Enter the power table into the PNA-X
  • Source power is set to maximum output
  • Receiver power is calibrated using source
  • Receiver is used to calibrate source power vs. level

• Correction process
  • Standard 12-term S-parameter correction
  • Receiver is used to monitor source power; Power level is adjusted using receiver leveling
Probe Calibration

• There are no wafer-based standards for power calibration

• Calibration process
  • Calibrate power at waveguide interface (using sensor or table)
  • Calibrate S-parameters at waveguide interface
  • Calibrate S-parameters at probe tips
  • De-embed source and receiver power cal out to probe tips

• Correction process
  • Standard 12-term S-parameter correction
  • Receiver is used to monitor source power; Power level is adjusted using receiver leveling
Measurement Accuracy

Measurements accuracy is determined by

- Random errors
  - Noise
  - Connector repeatability
  - Cable stability
- Drift & Stability errors
  - Receiver
  - Test set
- Systematic errors
  - Compression & linearity
  - Residual crosstalk
  - Residual calibration errors
Calibration Errors

Residual calibration errors are determined by:

- Accuracy of calibration standards
  - Load - match
  - Offsets & Shims - length, match, loss
- Waveguide irregularities
  - Burrs
  - Rounded corners & sidewalls
  - Flange edge and surface finish
  - Aperture size
- Torque
- Cleanliness
- Alignment
Alignment Errors

Waveguide alignment (a.k.a. connector repeatability)

• Caused by vertical, horizontal, diagonal and rotational offsets\(^{(1)}\)

• More sensitive at higher frequencies

• Use precision UG-387 flange (removable alignment pins)

Traceability

• S-Parameter cal
  • Traceable to mechanical standards
  • Some MM residual errors are large

• Power cal
  • Uses calorimeter and S-parameter cal
  • No industry-wide agreement on traceability
Workshop Agenda

- Typical mm-wave System Configurations
- mm-wave Applications
- Calibration
- Noise Figure
- Complete E-Band Converter Test System
Noise Figure Definition

Noise figure is defined in terms of SNR degradation:

\[ F = \frac{(S_i/N_i)}{(S_o/N_o)} = \frac{(N_o)}{(G \times N_i)} \]

\[ \text{NF} = 10 \times \log (F) \]

Test system is assumed to be 50 \( \Omega \)
Noise Figure Measurement Techniques

Y-factor (hot/cold source)
• Used by NFA and spectrum-analyzer-based solutions
• Uses noise source with a specified “excess noise ratio” (ENR)
• Measures noise figure and gain

\[
\text{Excess noise ratio (ENR) } = \frac{T_{\text{hot}} - T_{\text{cold}}}{290K}
\]

Cold source (direct noise)
• Used by vector network analyzers (e.g. PNA-X)
• Uses cold (room temperature) termination only plus separate gain measurement
• Allows single connection S-parameters and noise figure (and more)
Traditional Y-Factor Technique

\[ T_{\text{hot}} (\text{on}) \]

\[ T_{\text{cold}} (\text{off}) \]

\[ P_{\text{out (hot)}} = kB G_a (T_{\text{hot}} + T_e) \]

\[ P_{\text{out (cold)}} = kB G_a (T_{\text{cold}} + T_e) \]

\[ Y = \frac{P_{\text{out (hot)}}}{P_{\text{out (cold)}}} \]

\[ T_e = \frac{T_{\text{hot}} - Y \times T_{\text{cold}}}{Y - 1} \]

\[ F_{\text{DUT}} = F_{\text{sys}} - \frac{F_{\text{rcv}} - 1}{G_a_{\text{DUT}}} \]

\[ F_{\text{sys}} = 1 + \frac{T_e}{290} \]

Calibration:

Y-factor yields gain and noise figure
Cold Source Technique

\[ P_{out} = kBG_a(T_{cold} + T_e) \]

\[ F_{sys} = \frac{P_{out}}{kT_oBG_a} \]

Calibration:

\[ F_{DUT} = F_{sys} - \frac{F_{rcv} - 1}{G_{DUT}} \]

Need to know available gain very accurately
\( (G_a \text{ is function of } S_{11}, S_{22} \text{ and } \Gamma_s) \)
4-Port 43.5/50 GHz PNA-X Options 419, 423, H29

Noise source used for calibration only

RF jumpers

Mechanical switch

Receivers

Pulse generators

Source 1

Source 2

Signal combiner

Pulse modulator

Pulse modulator

To receivers

10 MHz - 3 GHz

3 – 26.5 GHz

Test port 1

Test port 2

Test port 3

Test port 4

Noise receivers

Impedance tuner for noise figure measurements

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PNA-X Versus NFA Comparison (Overlaid)

- Vector calibration
- Scalar calibration with 6 dB source attenuator
- Scalar calibration with 3 dB source attenuator
- Scalar calibration with no source attenuator
- NFA noise figure

Note: PNA-X NF traces offset by one graticule for clarity
Complete mm-wave Measurement System

- Is it possible to bring all these Applications together into one complete system?

- Can we measure Noise Figure at mm-wave frequencies?
Workshop Agenda

• Typical mm-wave System Configurations

• mm-wave Applications

• Calibration

• Noise Figure

• Complete E-Band Converter Test System
E-Band Wireless Market is becoming Commercialized

Wireless E-Band systems are now becoming prevalent.

They offer

- High data rate, 1Gb/s to University Campuses
- Driven by the increasing need for file, music and video sharing at Universities

The market is growing such that E-Band systems are now not just R&D projects, but are generating requirements for 100’s of system components. This means that customers expect commercial test systems to reduce test time and unit cost.
E-Band Requirements

Typical E-Band wireless systems include receivers. Receivers are generally characterised by their Noise Figure.

Which commercial test system can measure the Noise Figure of an E-Band down-converter? None!
E-Band Requirements

How do you calibrate a test system to measure a device that has mm-wave waveguide In and coax RF Out?

This measurement was traditionally attempted on a Spectrum Analyser, UNCALIBRATED

.....well, until now...
E-Band Requirements

How do you also measure mm-wave Gain, Compression, Spurs, Return Loss at high power?

and bi-directionally?

and with a Single Connection?
Introducing the new PNA-X Solution!

PNA_X can measure:
1. mm-wave Noise Figure
2. Gain & Compression
3. IMD’s
4. Spurs
5. Return Loss
6. Detector
Customer Need

A UK customer wanted to test an E-Band Transceiver

- DUT is an E-band mm-wave to IF Rx down-converter, and
- An IF to E-band mm-wave Tx up-converter
- WR-12 Waveguide/SMA
- 6-port dut
- For Production.
Customer Requirement

**Rx Path**
- Noise Figure required
- 74 GHz in, 4 GHz IF
- Gain of Rx 20dB, NF 7dB

**Tx Path**
- High power output on Tx +26dBm
- Gain, Compression, LO Feedthrough, Return Losses
- 12 GHz IF in, 84 GHz out
- Tx Detector voltage measurement

- Tx/Rx module with separate paths, but **single connection required**
- Manufacturing, so test time under 4 mins per unit
- Customer supplied fixture and software control
Customer Device
Birds Eye View

Push Fit SMA Connectors

Tx IF  Rx IF
Tx LO  Rx LO
DC
Customer Device and Fixture

Side View

DUT

Tx LO

Rx LO

Fixture

Tx RF

Rx RF

IF/LO

All E-Plane Bends.

WR-12 Waveguide
Outstanding Problems

1. There is no commercial solution for Noise Figure measurement on a mm-wave device

2. Tx high power output, requires attenuator to protect mm-wave head, **BUT** we also need to measure Return Loss?

3. How do we measure in both Rx and Tx directions, with a single connection?
Agilent Solution

Noise Figure at mm-wave

• Use a system with a 4-port PNA-X & Test Set Controller
• Actually need to measure Noise Power at 4 GHz IF
• Set up separate channels to measure DUT Converter Gain and Noise Power
• Fully error corrected Scalar Conversion Gain and Scalar NF
• Use on-board Equation Editor to calculate NF on a 3rd Trace
Agilent Solution
Can we measure Return Loss through Attenuators?

• A Low Power path was created, to measure the Return Loss and a High Power path with attenuation to measure saturated power and compression
• Mechanical switching to switch in/out High Power path
• Novel de-embedding used to de-embed the attenuator
Agilent Solution

How do we measure as a single connection?

• Use a mm-wave Test Set Controller

• With a 4-Port PNA-X

• Rear panel connections

• This enabled Port 2 on controller to drive the Tx mm-wave head, as well as using port 2 on PNA-X to measure the Rx IF R/L, and NF.
PNA-X Solution

Diagram showing the connections between various components:
- Ext LO In
- Tx Detector Out
- Analog In
- SRC OUT
- CPLR IN
- DC IN
- Rx LO Input
- Tx RF Input
- REF IF
- RF
- LO
- 60-90 GHz Extender
- Splitter

Other notes:
- Anticipate
- Accelerate
- Achieve

Brand: Agilent Technologies
Rx Measurements

Single Connection

- Return Losses
- IF Spurs
- Gain Compression
- Noise Figure
Tx Measurements

Single Connection

- Return Losses
- Gain Compression & I/P, O/P Power
- IF Spurs
Test System
Test System
Conclusions

E-Band mm-wave transceivers are becoming commercialized and as a result components are being tested in Production.

The typical measurements are very demanding, and are not typically done on VNA’s.

The PNA-X system will measure all parameters including mm-wave NF, with Error Correction.

The customer can now make all these measurements on a device in under 4 minutes, compared to 15-20 minutes manually.