THz Test and Measurement Technology and Techniques

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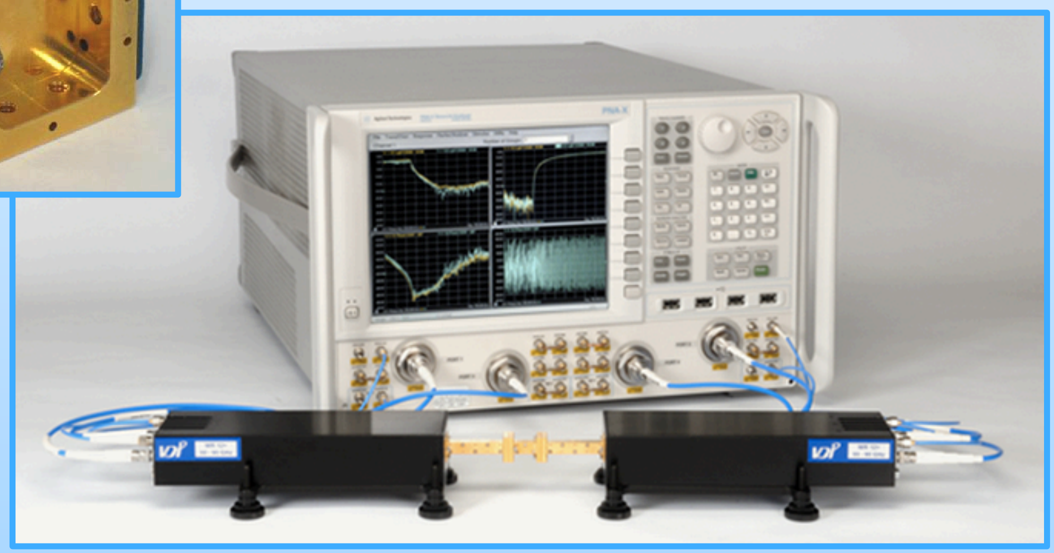

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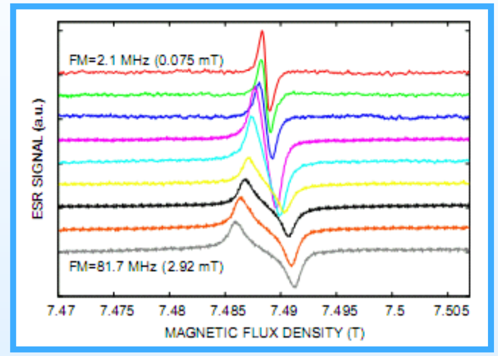
www.vadiodes.com

Outline

- Introduction
  - Schottky Diode Technology
  - Solid-State THz Mixers & Multipliers
- THz Frequency Extension
  - Source Extenders
  - Spectrum Analyzer Extenders
- THz Vector Network Analysis
  - Waveguide Measurements
  - Quasi-optical Measurements
  - THz Wafer Probing
- Conclusions

ALMA (NRAO)



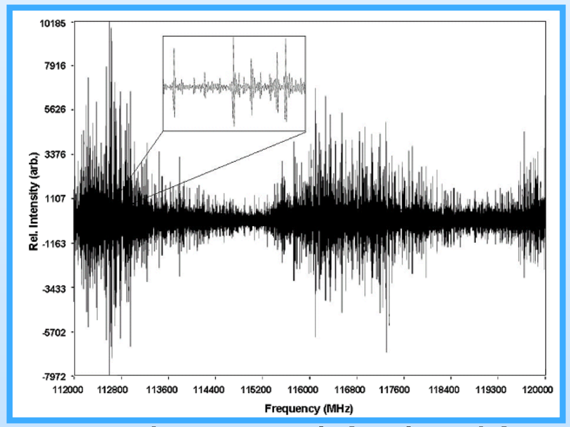
Nafradi et al (EPFL)

Applications

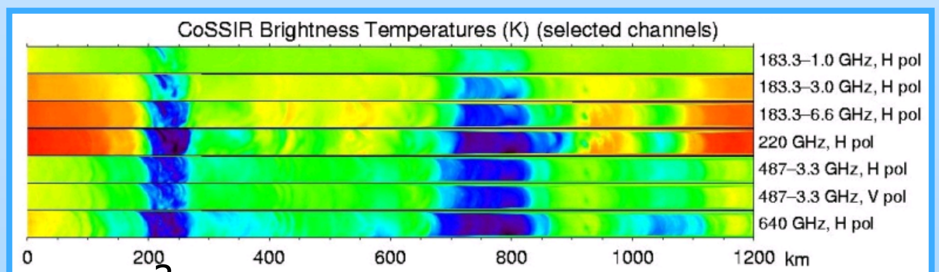
- *Spectroscopy*
- *Imaging*
- *Communications*

- *Molecular Spectroscopy*
- *Radio Astronomy, Atmospheric*
- *EPR/NMR/DNP*
- *Plasma Diagnostics*
- *Weather Monitoring*

- *General Test & Measurement*



Widicus et al (CalTech)



Wang et al (NASA-GSFC)

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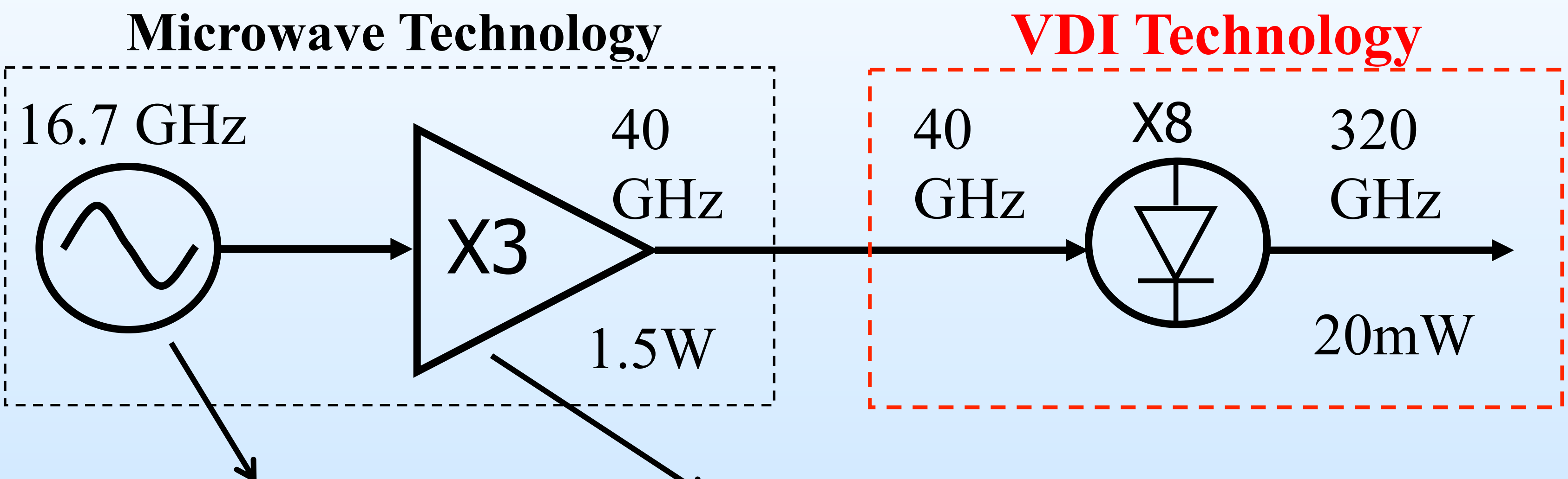
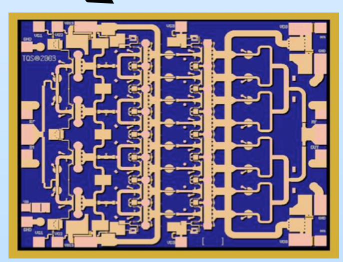
Core Technology: Use nonlinear devices to extend the frequency range of traditional microwave electronics




Herley-CTI


Triquint

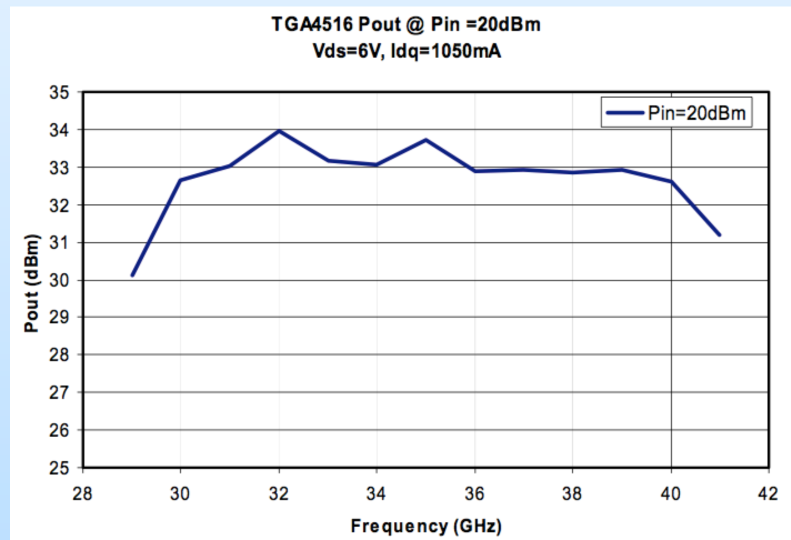
- Microwave technology developed for large scale commercial applications
  - Communications (Satellite, Point-to-Point, Personal)
  - Radar

Example: Triquint 2W 30-40 GHz Amp

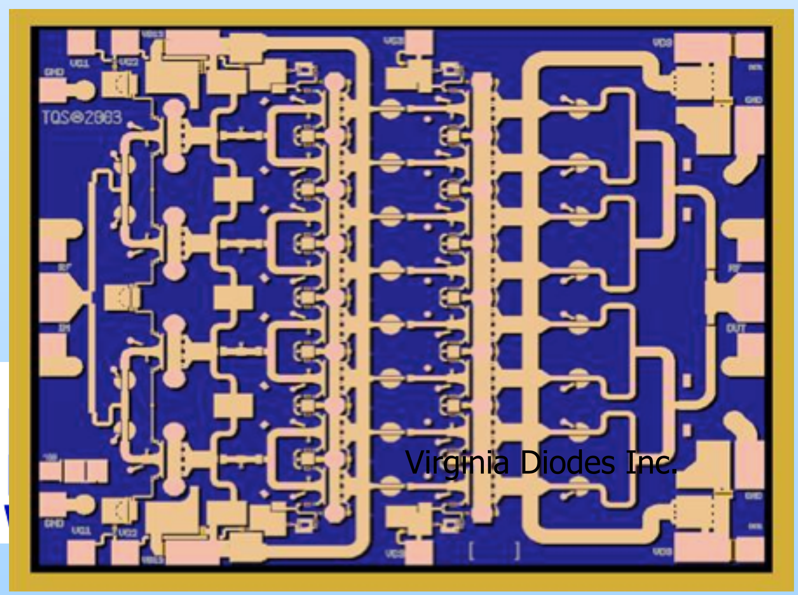
- Chip developed for Radar and Satellite Communications
  - Chip size 2.5x3 mm
- The same chip can be used to drive THz multiplier chains
  - 2 W at 30-40 GHz
  - 0.75 W at 70 GHz
  - 200 mW at 140 GHz
  - etc…
- Microwave technology enables THz solid-state systems

Key Features

- 30 - 40 GHz Bandwidth
- > 33 dBm Nominal Psat @ Pin = 20dBm
- 18 dB Nominal Gain
- Bias: 6 V, 1050 mA Idq (1.9A under RF Drive)
- 0.15 um 3MI MMW pHEMT Technology



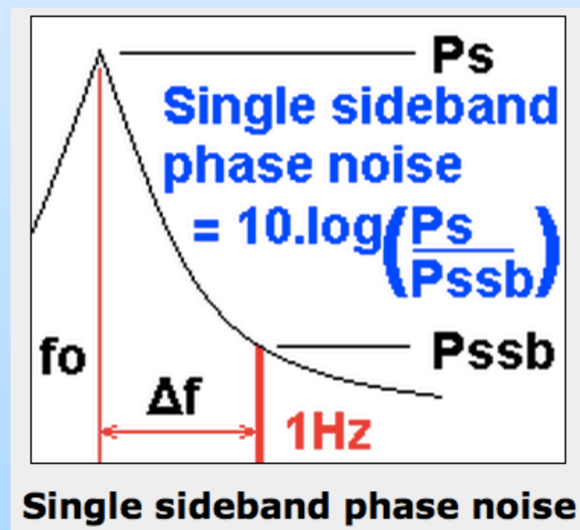
http://www.triquint.com/products/p/TGA4516-TS



Example: Herley-CTI Synthesizer

- Fast-switching synthesizers
  - Very narrow linewidths
    - Hertz widths are possible even at THz
    - Allow narrowband filtering to reduce noise
    - 14 GHz → Phase noise -107 dBc/Hz @ 1 kHz offset
  - Compact and ruggedized
- THz multipliers can extend synthesizers to > 3 THz
  - Phase noise rises upon frequency multiplication by 20*log(N)
  - Can achieve excellent THz phase noise
    - e.g. 1 THz → -70 dBc/Hz @ 1 kHz offset

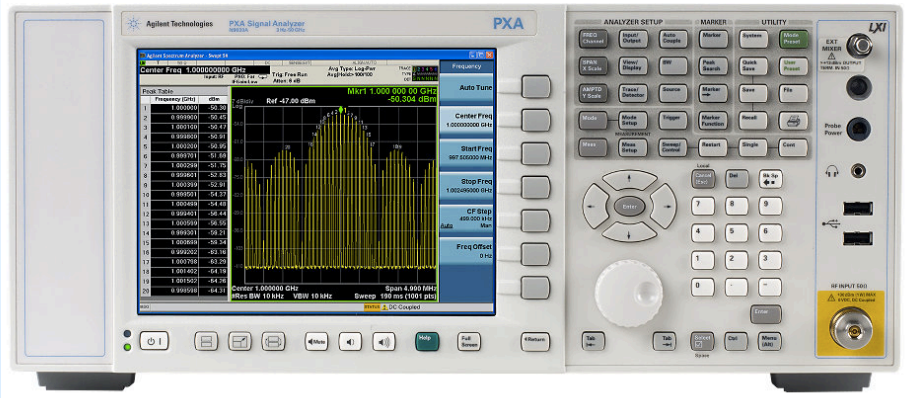
www.aspen-electronics.com/files/CTI/XS.pdf



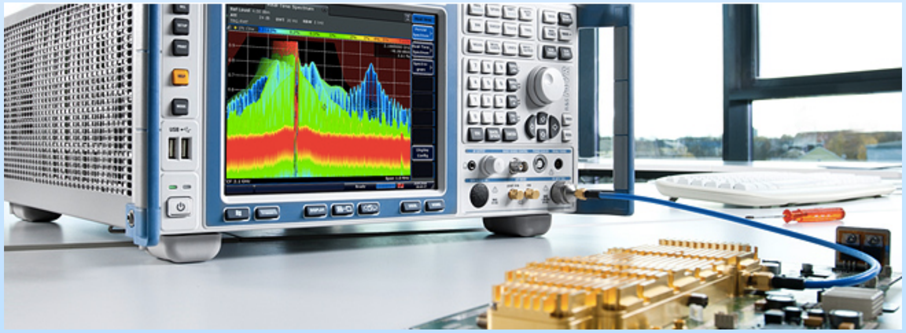
www.telestrian.co.uk/phasenoise.html

Test & Measurement: Spectrum Analyzers

- Sophisticated instrument to analyze microwave signals
  - Spectral purity
  - Phase noise
  - Communication Signal Demodulation
  - …
- A core microwave test capability
  - Along with sources and vector network analyzers
- Can be extended to THz using the Schottky technology

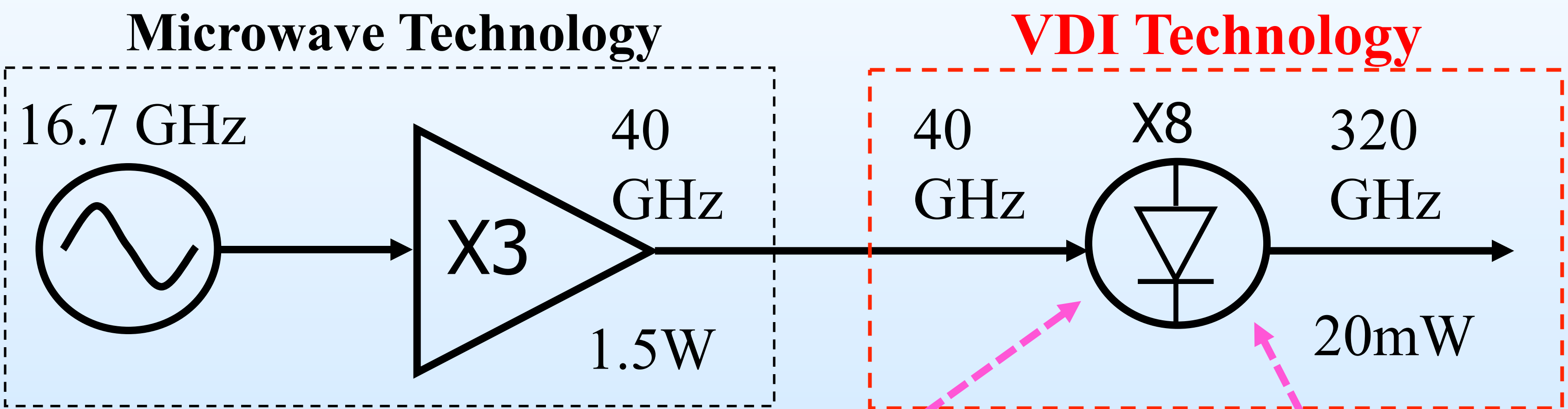


Agilent PXA



Rohde & Schwarz FSU

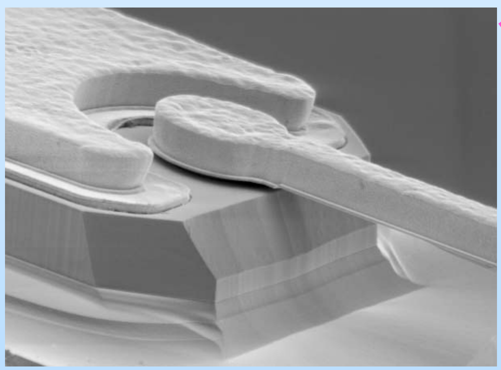
Core Technology: Use nonlinear devices to extend the frequency range of traditional microwave electronics



Schottky Diodes

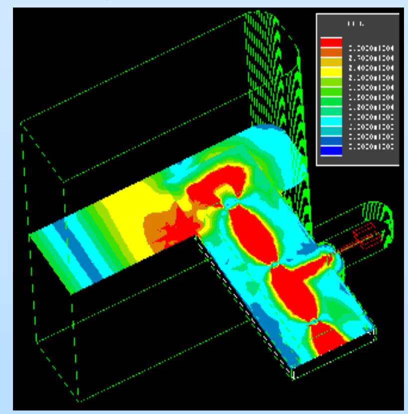
Planar

Advanced fabrication technology



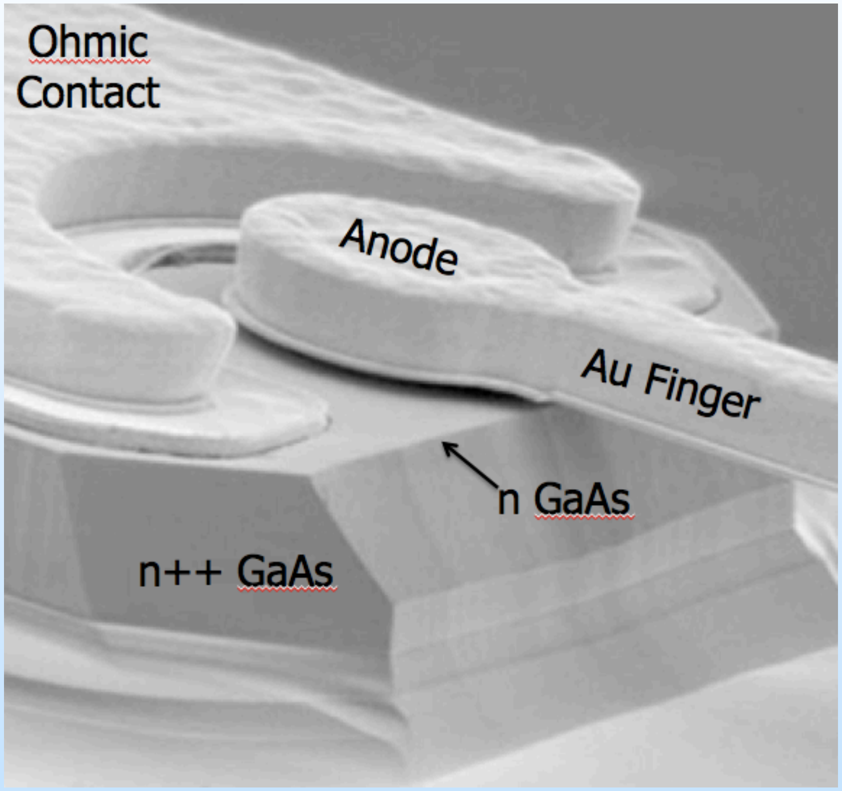
CAD Design

- **First-time design**
- **Broadband & Tunerless**
- **High Efficiency**



Schottky Diodes

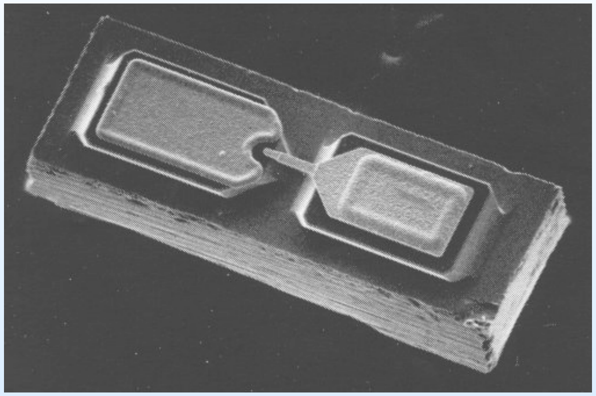
- Metal-semiconductor junction
  - Majority carrier device
  - Cutoff frequencies well into the THz
  - Room temperature operation
  - Improves with cooling
- Diode is well modeled by relatively simple quasi-static I-V and C-V equations
- Well-developed fabrication technology
  - Air-bridge used to reduce capacitance
    - Low capacitance is important for THz



$$I_d = I_{SAT}\left(e^{\left(\frac{V_j - I_d R_S}{V_0}\right)} - 1\right)$$

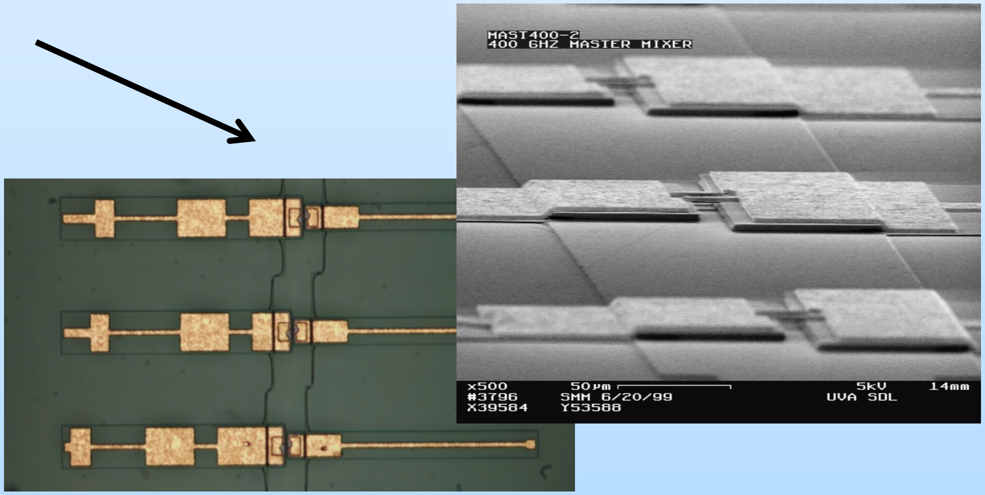
VDI Planar Diode Fabrication Technology

- Planar Schottky Diodes
  - Mechanically rugged
  - Photolithographic reproducibility



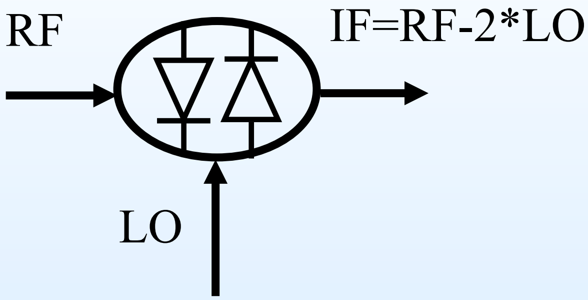
Flip-chip Planar Diode

- Integration of Diode with Coupling Circuitry
  - Operation to higher frequencies (>3 THz)
  - More repeatable assembly

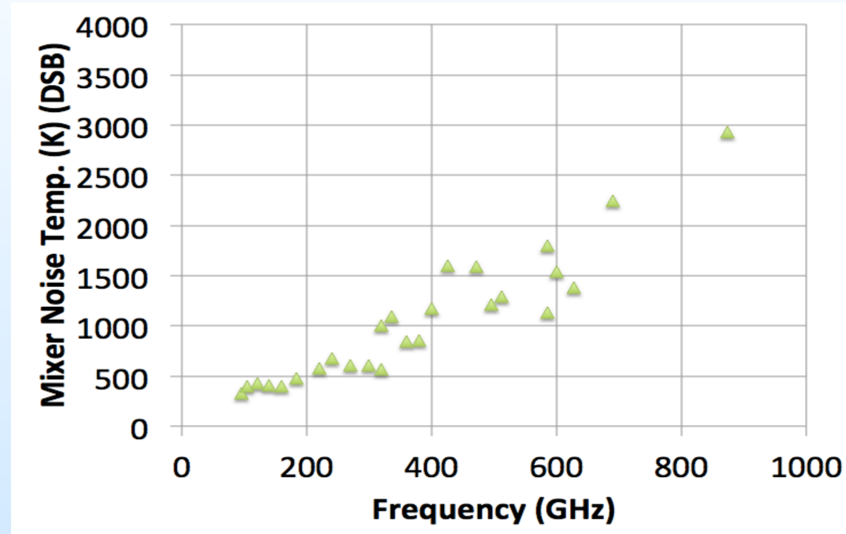


Integrated Planar Diodes

VDI Heterodyne Mixers

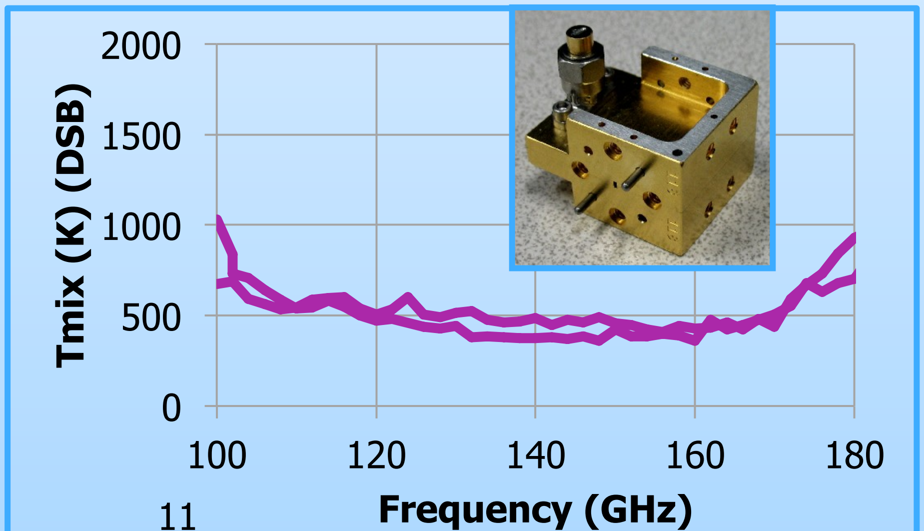


VDI Mixer Performance Summary



- Mixers available from WR-15 (50-75 GHz) to WR-0.4 (2-2.8 THz)
- Single & Anti-parallel Schottky mixers
  - Room temperature operation
  - Operation at High IF
- Full waveguide band design
  - Excellent Sensitivity
  - Tunerless
  - Planar & rugged

Measured Performance of WR-6.5SHM



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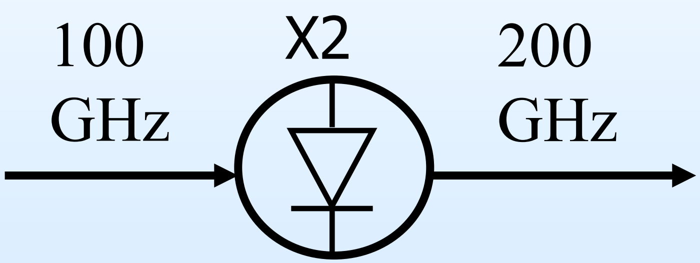
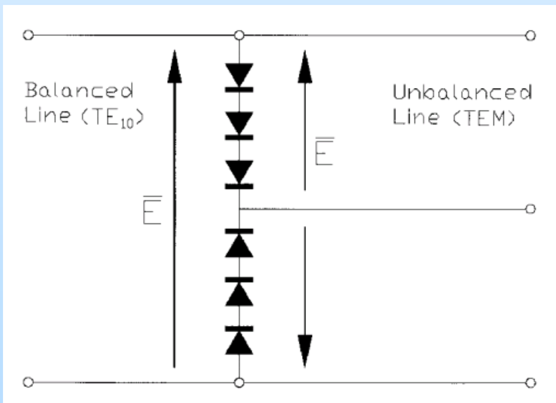
Schottky Diode Frequency Multipliers

- Careful choice of circuit configuration
  - Balanced design allows for broad bandwidth and high efficiency
  - Spatial mode filtering between harmonics
- Multiple diodes for increased power handling
- CAD Design to allow tunerless operation
  - First try success

Diode Multiplier

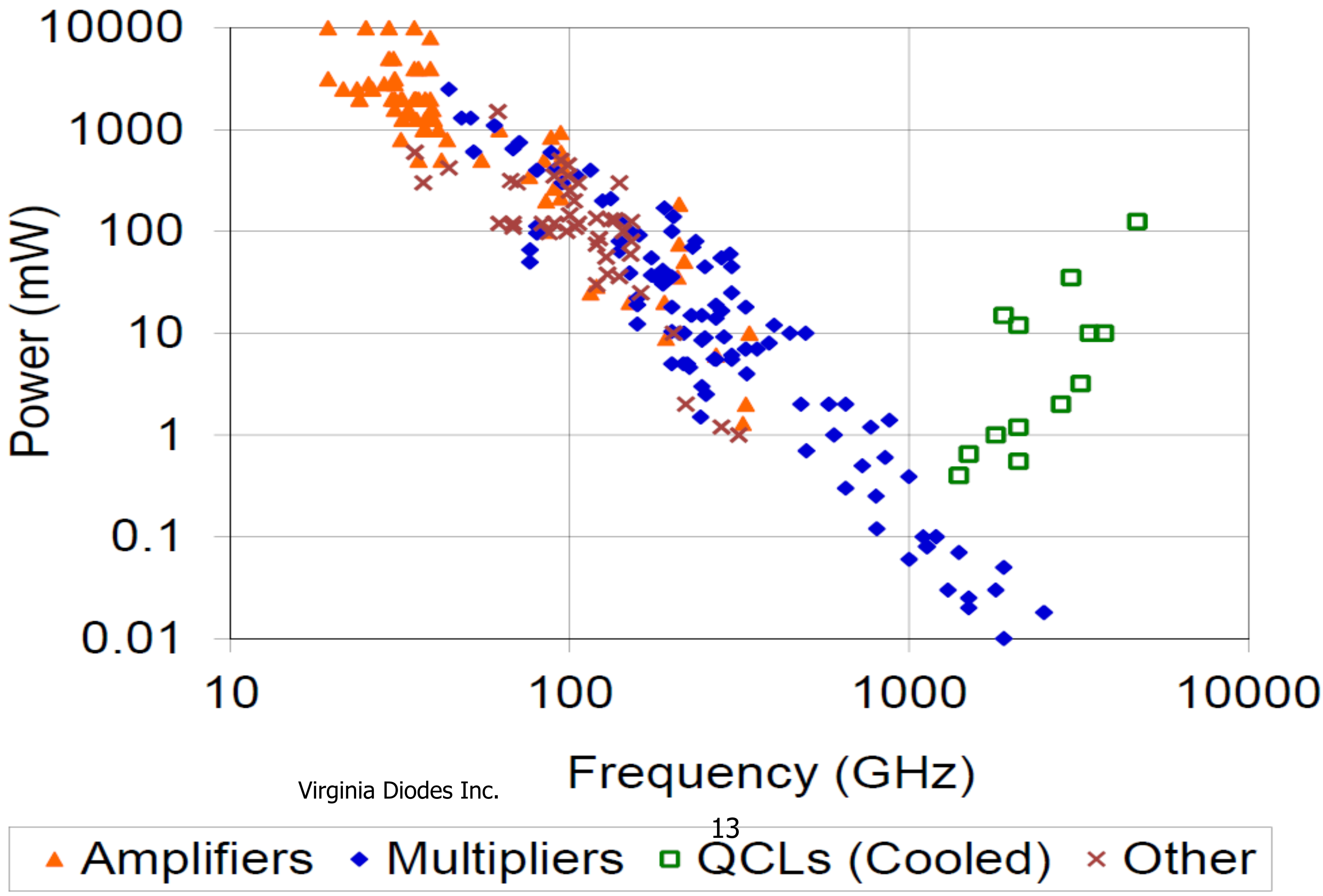


Balanced Circuit Topology



Porterfield et al (MTT, 1999)

Power from Multipliers



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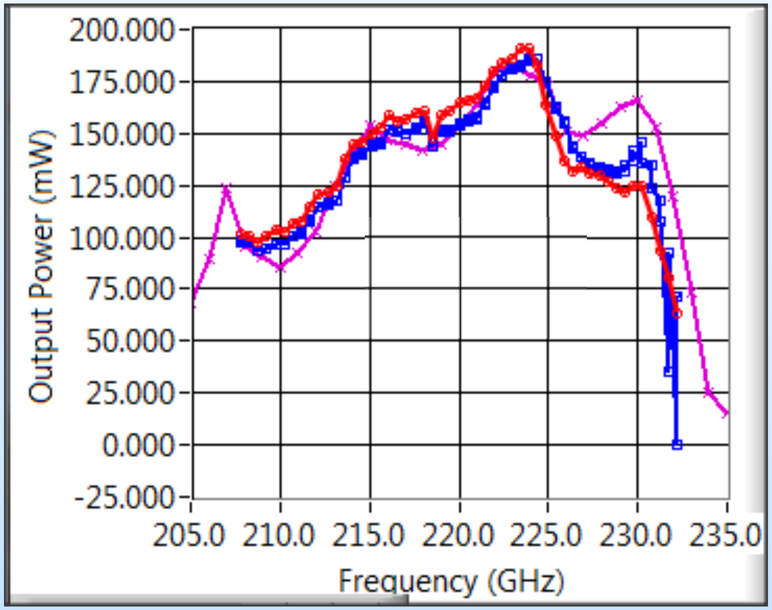
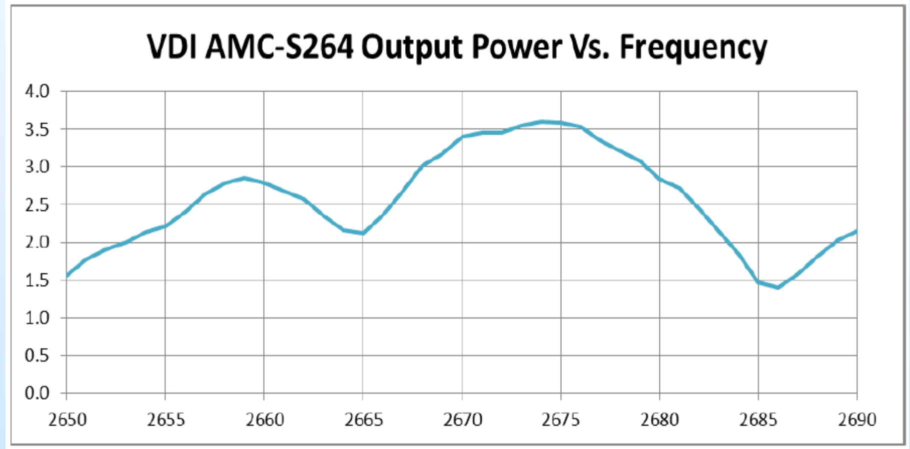
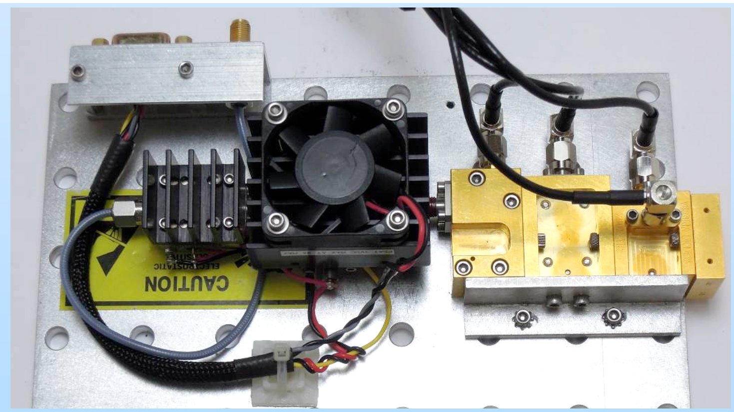
Recent High Power Multiplier Results

180 mW @ 224 GHz

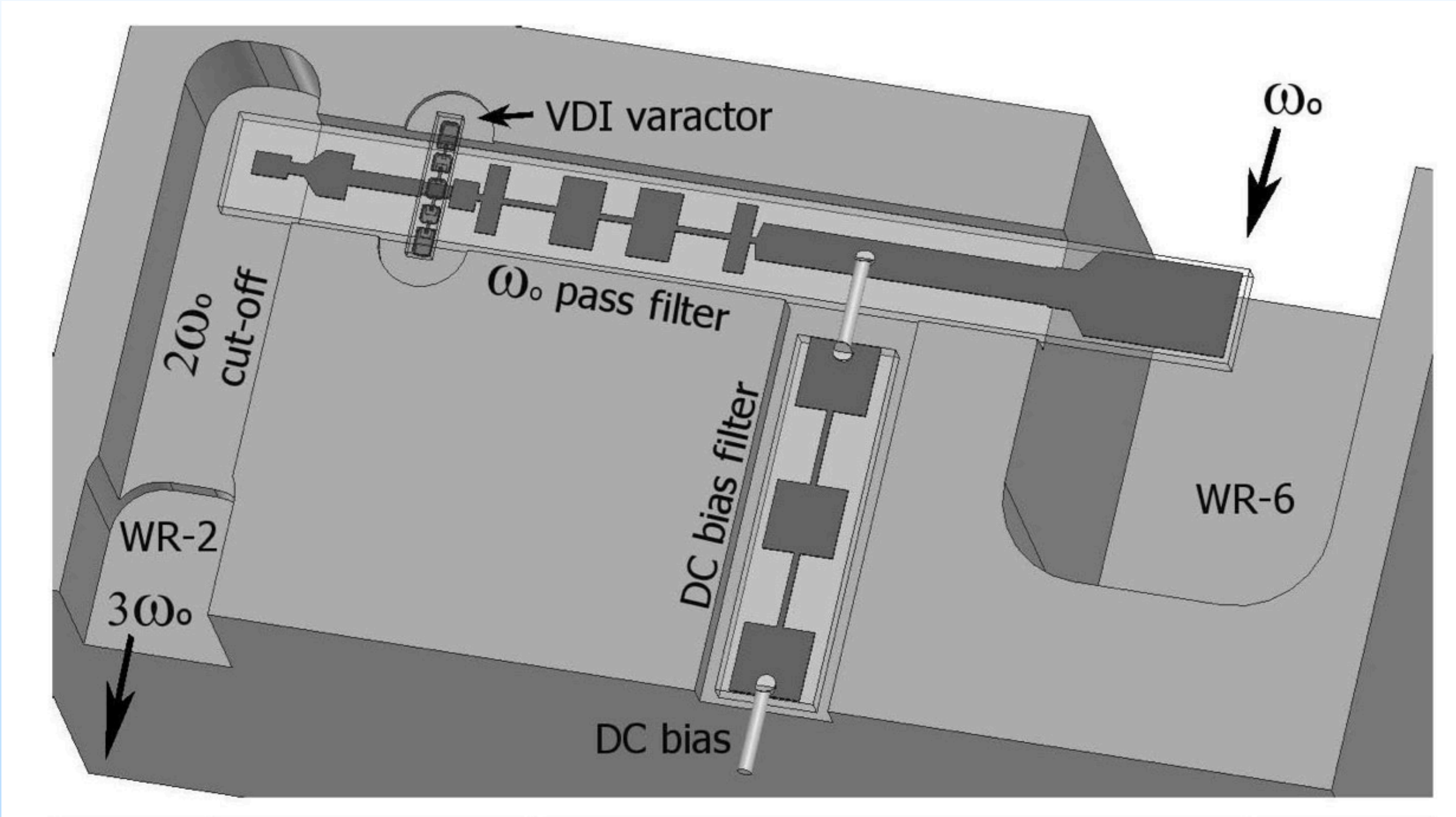


3 uW @ 2.7 THz





Waveguide Based Components: Varactor Frequency Tripler



Porterfield, 2007 IMS Symp. Dig., pp. 337-340

Rectangular Waveguide

- Why rectangular guide?
  - Low loss guiding structure at THz
    - Microstrip ~ 1 dB/mm @ 600 GHz
    - Waveguide ~0.08 dB/mm @ 600 GHz
  - High power handling
  - Many techniques for integration of device with guide

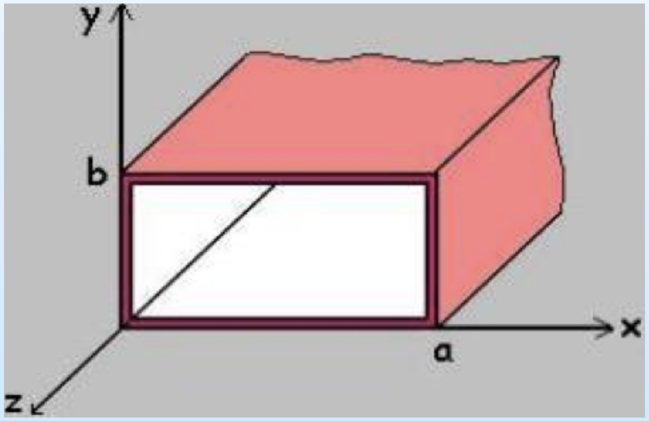


Figure from www.ee.bilkent.edu.tr

Rectangular Waveguide – TE10 Mode

- Single-mode Operation
  - High pass filter
    - Blocks lower harmonics
  - Operate with only TE10 mode propagating
    - TE20 mode is next highest mode
    - Turns on at 2 times the TE10 cutoff frequency
  - Operating range approx. 1.25 to 1.9 times the TE10 cutoff frequency
    - To reduce the effect of dispersion on performance

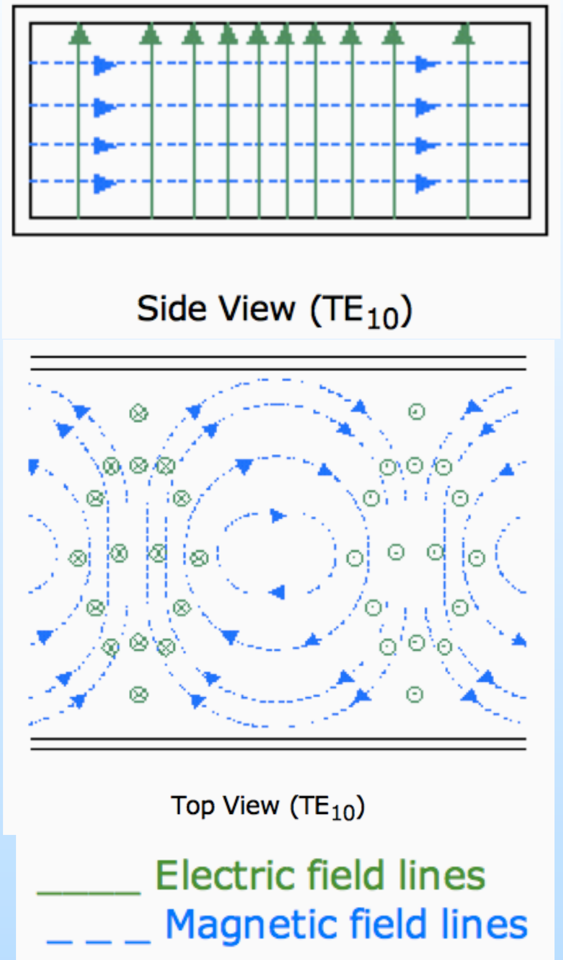


Figure from www.rfcafe.com

Waveguide Sizes and Frequency Ranges

VDI Designation	Internal Dimensions (µm)		Cut-off frequency (GHz)	Suggested min. frequency (GHz)	Suggested max. frequency (GHz)	Calculated Loss (dB/cm) for Au *		Alternate Designations	
	Width	Height				At min. frequency	At max. frequency		
WR-15	3759	1880	39.9	50	75	0.022	0.015	V	-
WR-12	3099	1549	48.4	60	90	0.030	0.020	E	-
WR-10	2540	1270	59.01	75	110	0.039	0.027	W	-
WR-8.0	2032	1016	73.77	90	140	0.059	0.038	F	WR-8
WR-6.5	1651	825.5	90.79	110	170	0.081	0.052	D	WR-6
WR-5.1	1295	647.5	115.75	140	220	0.12	0.074	G	WR-5
WR-4.3	1092	546	137.27	170	260	0.14	0.1	-	WR-4
WR-3.4	864	432	173.49	220	330	0.2	0.14	-	WR-3
WM-710 (WR-2.8)	710	355	211.12	260	400	0.28	0.18	-	-
WM-570 (WR-2.2)	570	285	262.98	330	500	0.37	0.25	-	-
WM-470 (WR-1.9)	470	235	318.93	400	600	0.5	0.34	-	-
WM-380 (WR-1.5)	380	190	394.46	500	750	0.67	0.47	-	-
WM-310 (WR-1.2)	310	155	483.54	600	900	0.95	0.64	-	-
WM-250 (WR-1.0)	250	125	599.58	750	1100	1.3	0.88	-	-
WM-200 (WR-0.8)	200	100	749.48	900	1400	2	1.2	-	-
WM-164 (WR-0.65)	164	82	914	1100	1700	2.6	1.7	-	-
WM-130 (WR-0.51)	130	65	1153	1400	2200	3.7	2.3	-	-
WM-106 (WR-0.43)	106	53	1414.1	1700	2600	5.1	3.2	-	-
WM-86 (WR-0.34)	86	43	1743	2200	3300	6.3	4.3	-	-

* Waveguide loss calculated according to IEEE P1785.1

THz Waveguide Interface Standards

IEEE P1785: A New Standard for Waveguide Above 110 GHz

The Microwave Theory and Techniques Society (MTT-S) of the IEEE has recently launched an activity to develop an international standard to define waveguides used at frequencies of 110 GHz and above—specifically, rectangular metallic waveguides. The standard's Working Group (P1785) has already met several times and is looking to define both the dimensions of the waveguides (and associated frequency bands) and their interfaces (that is flanges).

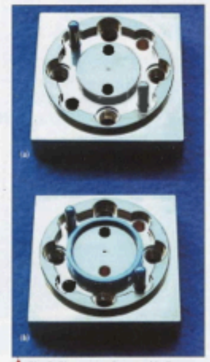
- Three proposed parts to the standard
  - Part 1: Define waveguide dimensions and associated frequency bands
  - Part 2: Define waveguide interfaces (i.e. flanges)
  - Part 3: Recommendations for Interface Performance and Uncertainty Specifications
- Part 1 is published and Part 3 is approved
- Part 2 still under development
- See http://grouper.ieee.org/groups/1785/

CABLES & CONNECTORS SUPPLEMENT

TABLE III

EXTENDED FREQUENCY BANDS AND WAVEGUIDE DIMENSIONS FOR THE IEEE STANDARD

Waveguide Name	Aperture Width (μm)	Aperture Height (μm)	Cut-off Frequency (GHz)	Minimum Frequency (GHz)	Maximum Frequency (GHz)
WM-71	71	35.5	2111.2	2600	4000
WM-57	57	28.5	2629.7	3300	5000



CONCLUSION

The IEEE is well on its way to publishing a standard for defining rectangular metallic waveguides for use at frequencies above 110 GHz. Already, there are many applications emerging for the use of this part of the electromagnetic spectrum—millimetre-wave, submillimeter-wave, terahertz, etc. Therefore, the publication of this standard is timely, and should serve our industry well for many years to come. ■

Ridler et al., Microwave Journal Cables & Connectors Supplement, Mar. 2011, pp. 20-24.

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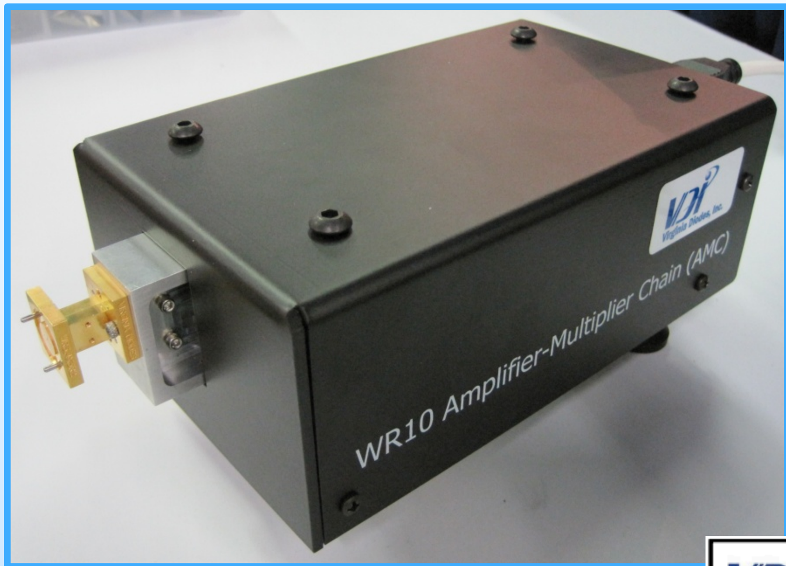
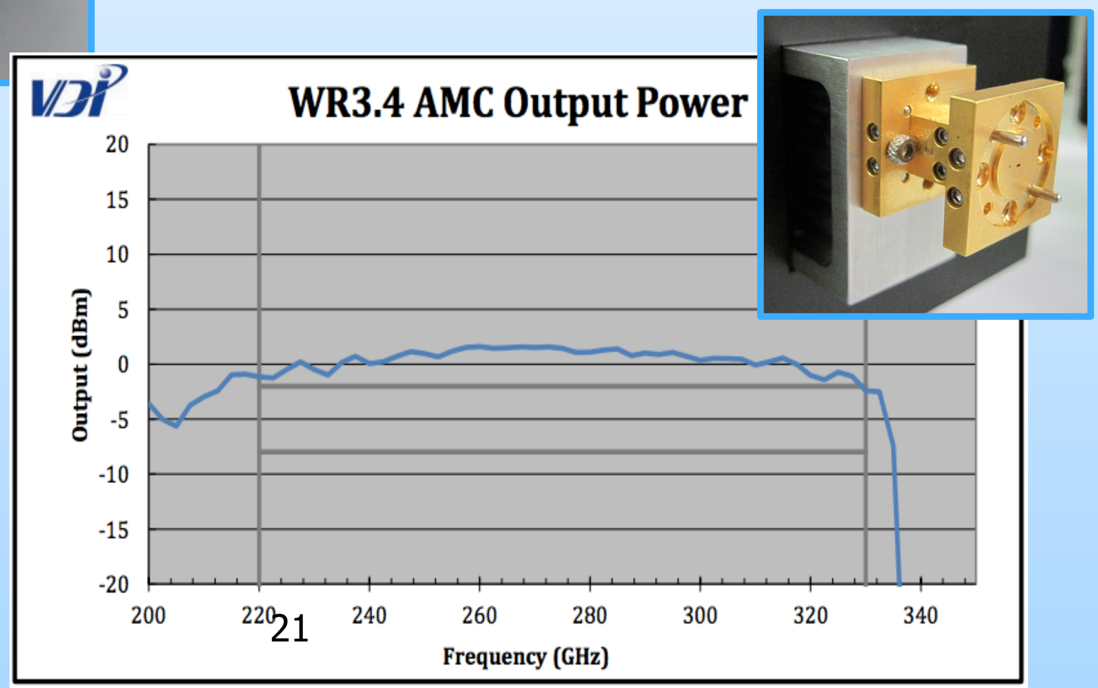
Virginia Diodes Synthesizer Extenders



- WR-3.4 (220-330 GHz) Frequency Extender for Synthesizers
  - Tunerless, instantaneous sweeping over > 40% bandwidth
- AM modulation and Power Control capability
  - Voltage controlled
  - Can also be controlled by drive synthesizer



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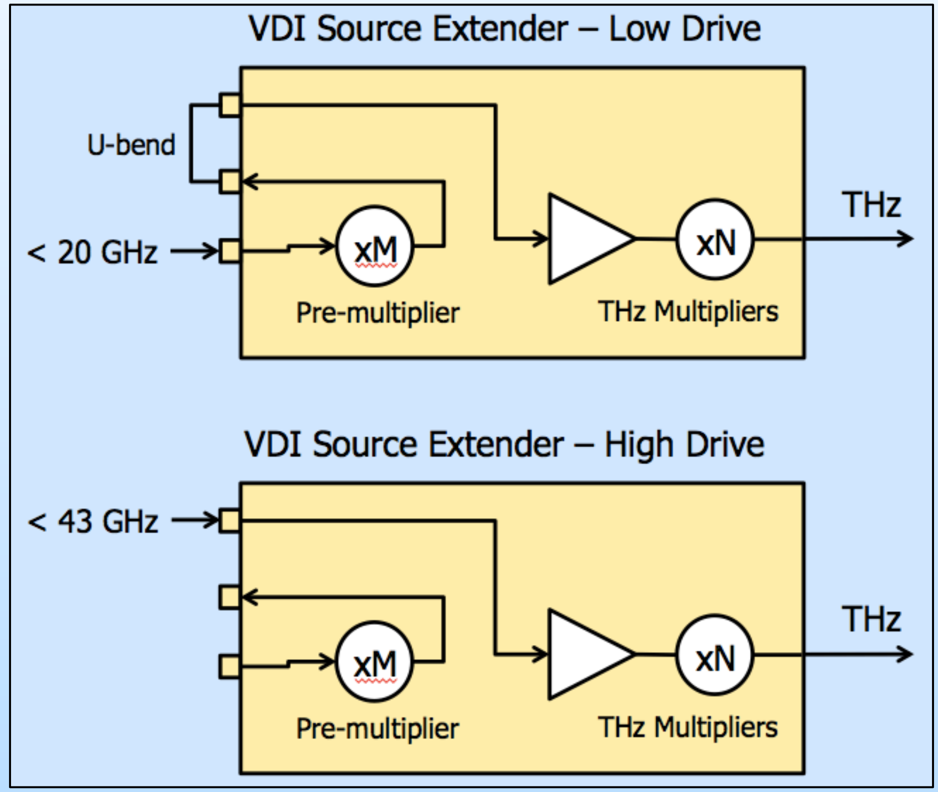
Virginia Diodes Synthesizer Extenders

- Low Drive – for use with <20 GHz sources
- High Drive – improved harmonic performance



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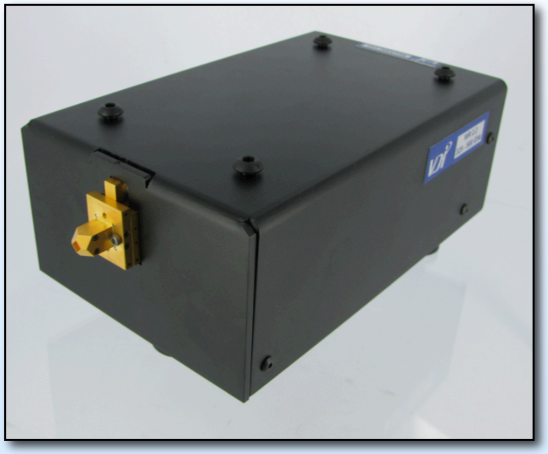
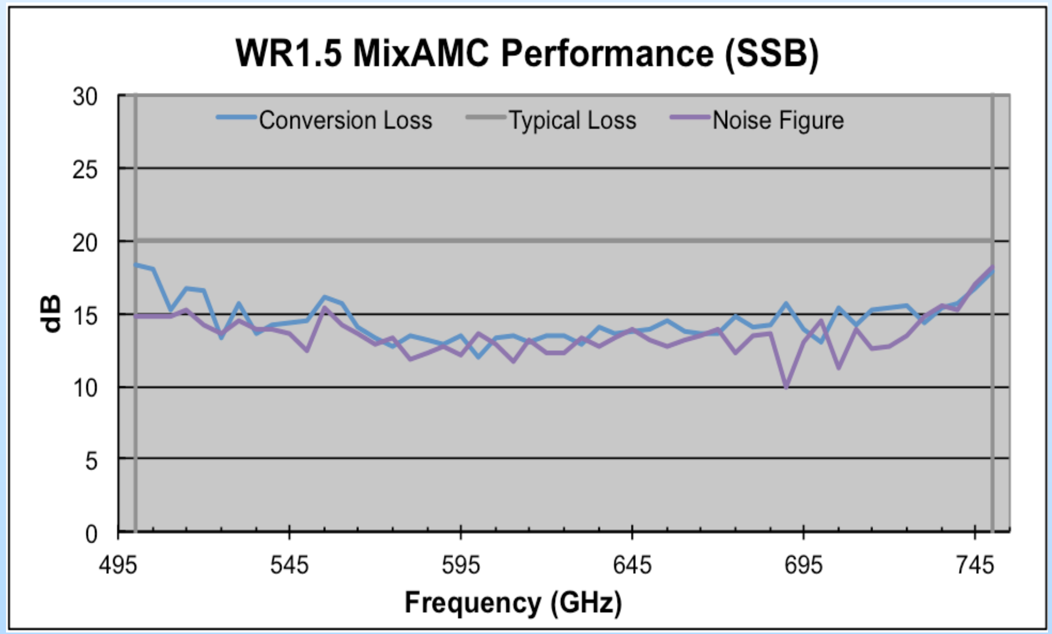
VDI Amplifier/Multiplier Chain (AMC) Standard Product List					
VDI Part #	Band (GHz)	RF Input Mode	Mult. Factors	Output Power (dBm)	
				Typical	Minimum
WR1.0AMC	750 - 1,100	Standard	81	-23	-33
		High	27		
WR1.5AMC	500 - 750	Standard	54	-21	-30
		High	18		
WR2.2AMC	325 - 500	Standard	36	-10	-18
		High	12		
WR2.8AMC	260 - 400	Standard	24	-6	-12
		High	12		
WR3.4AMC	220 - 330	Standard	18	-2	-8
		High	9		
WR4.3AMC	170 - 260	Standard	18	2	-5
		High	6		
WR5.1AMC	140 - 220	Standard	12	4	0
		High	6		
WR6.5AMC	110 - 170	Standard	12	8	2
		High	4		
WR8.0AMC	90 - 140	Standard	3	9	3
		High	9		
WR9.0AMC	82.5 - 125	Standard	9	14	10
		High	3		
WR10AMC	75 - 110	Standard	6	14	10
		High	3		

Virginia Diodes Spectrum Analyzer Extenders



- Fullband down-conversion and frequency extension of microwave spectrum analyzers into the THz range
  - Coverage from 75GHz-1,100GHz
  - IF Bandwidth to 40 GHz
  - Turnkey operation



Virginia Diodes Spectrum Analyzer Extenders

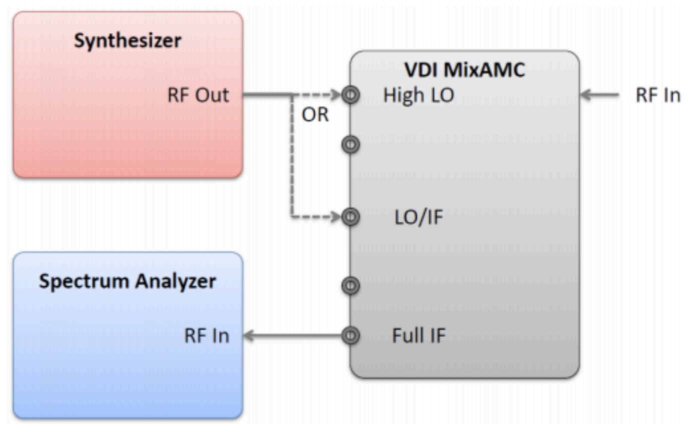
- State-of-the-Art Sensitivity
- Displayed Average Noise Level (DANL)
  - A measure of the minimum detectable signal with 1 Hz bandwidth

VDI Part #	RF Band (GHz)	SSB Conversion Loss (dB)	Displayed Average Noise Level (dBm/Hz)*
		Intrinsic Mixer**	
WR1.0MixAMC	750 - 1,100	30	-135
WR1.5MixAMC	500 - 750	20	-150
WR2.2MixAMC	325 - 500	17	-150
WR2.8MixAMC	260 - 400	15	-150
WR3.4MixAMC	220 - 330	14	-150
WR4.3MixAMC	170 - 260	14	-150
WR5.1MixAMC	140 - 220	12	-150
WR6.5MixAMC	110 - 170	12	-150
WR8.0MixAMC	90 - 140	12	-150
WR10MixAMC	75 - 110	11	-150

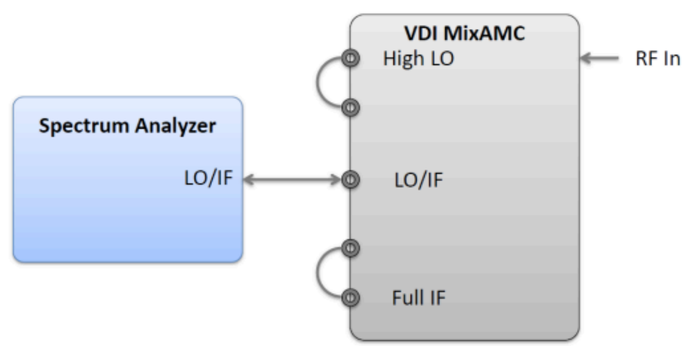
Virginia Diodes Spectrum Analyzer Extenders

- Extender can be reconfigured by the user depending upon the measurement requirements

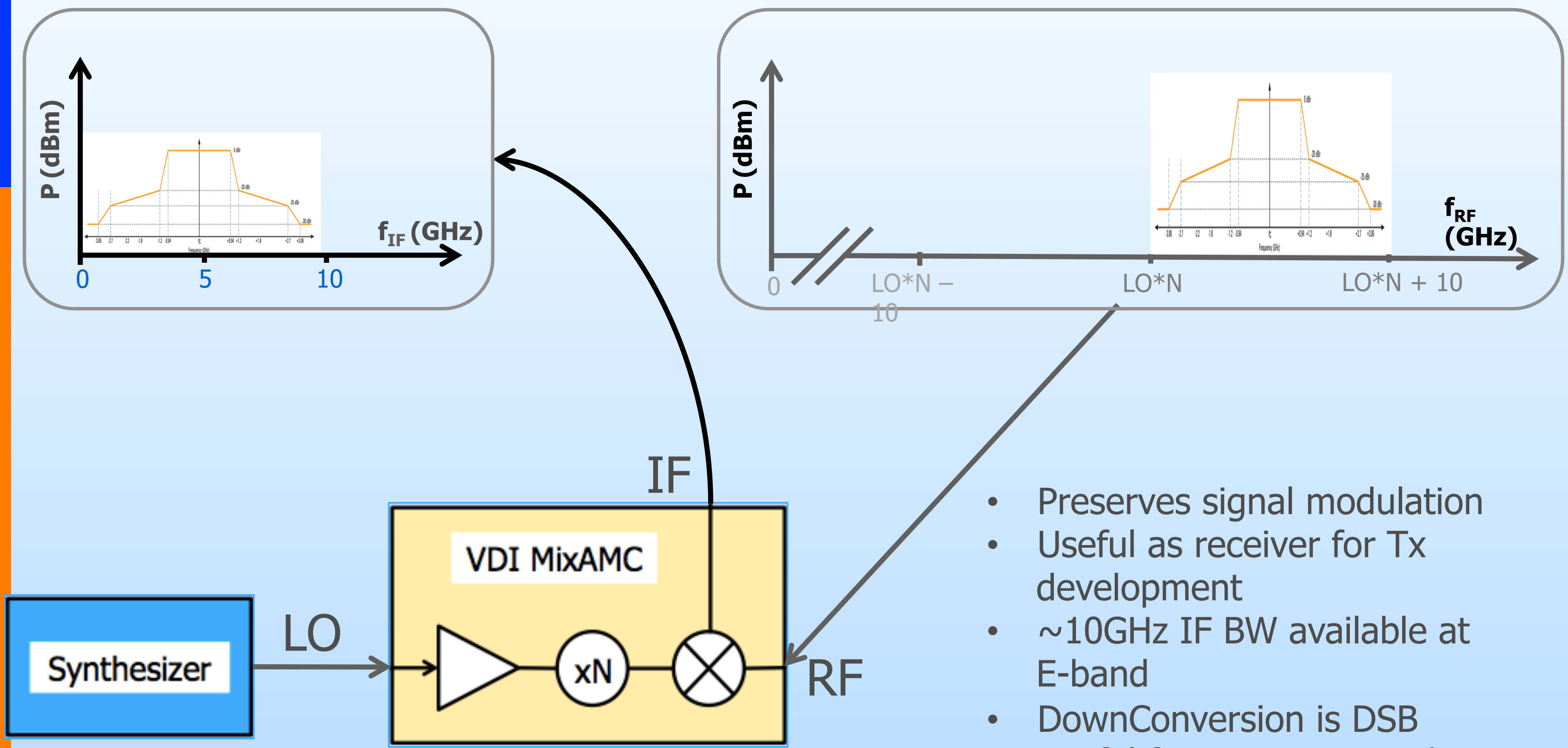
VDI MixAMC Setup for Block Downconversion



VDI MixAMC Setup for Spectrum Analyzer Extension



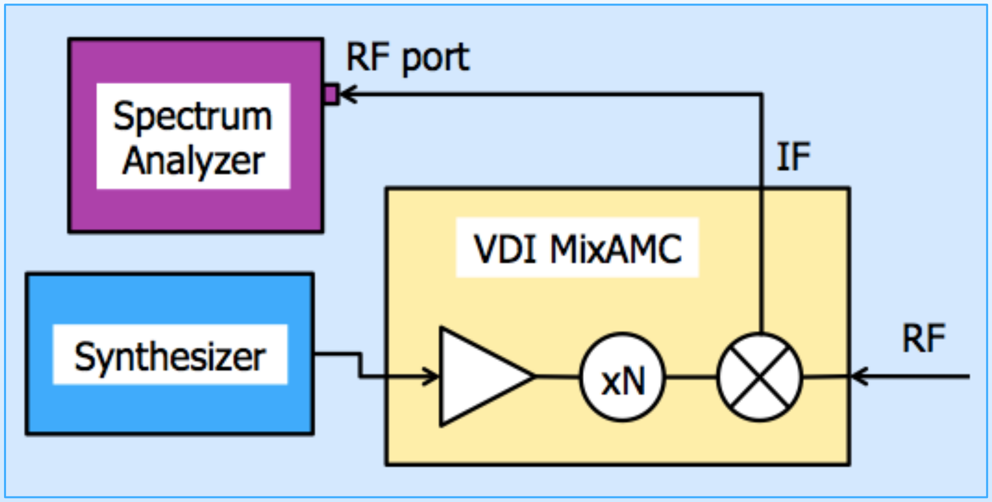
Block Down Conversion



- Preserves signal modulation
- Useful as receiver for Tx development
- ~10GHz IF BW available at E-band
- DownConversion is DSB
- Useful for spectrum mask measurements

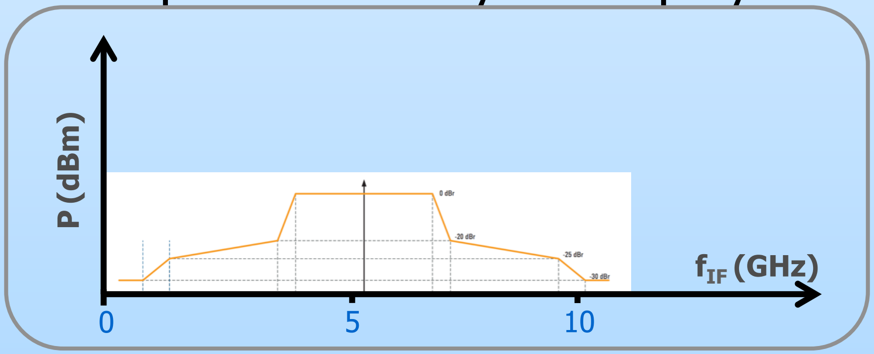
MixAMC & Spectrum Analyzers: Block Downconversion

- General principles of Block Downconversion
  - MixAMC is driven by external synthesizer, and a block of RF signals are downconverted and fed into the Spectrum Analyzer (SA)
  - RF signals (both upper and lower sideband) are downconverted to IF
  - External synthesizer fixed while SA sweeps over its range
  - RF coverage limited by IF bandwidth of mixer (or SA maximum frequency)
  - Maximum IF ranges from 8 GHz up to > 40 GHz, depending upon the waveguide band



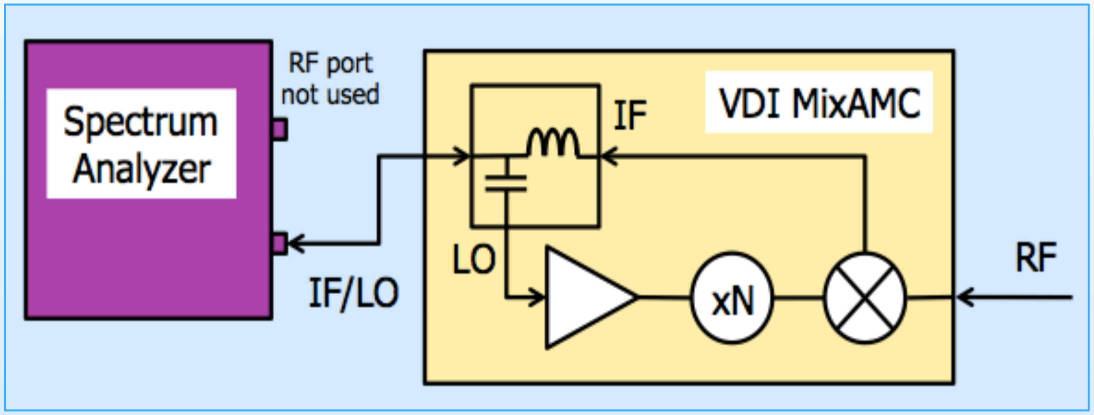
- Uses of block downconversion
  - General analysis of THz signals
  - Requires User analysis
  - Can be used for signals that drift, or for wideband communication signals
  - The THz signal is reproduced at the IF by heterodyne mixing process
    - e.g. can be used in a communication system, spectral information is preserved

Spectrum Analyzer Display

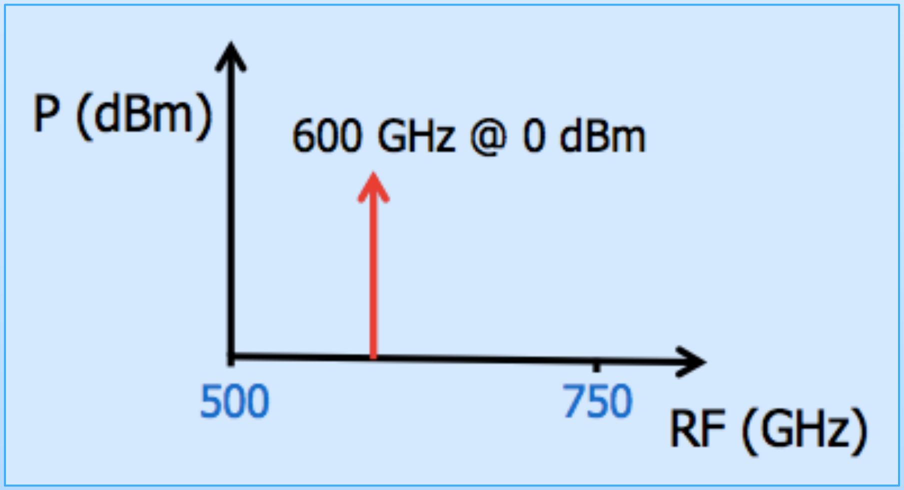


MixAMC & Spectrum Analyzers: Frequency Analyzer Extension

- General principles of Spectrum Analyzer Extension
  - MixAMC drive by LO signal from Spectrum Analyzer
  - Swept across full band of mixer
  - RF coverage set by mixer RF bandwidth
  - Full waveguide band systems available (> 40% BW)
- Uses of Frequency Analyzer Extension
  - General signal analysis
  - Signal identification used to determine the actual frequency of the RF signal and remove spurious signals
  - Signal ID of limited use for drifting signals
    - e.g. banded communication signal or free-running oscillator
    - Spectral information won't be preserved to time variant signals
    - Conversion loss table used to adjust power level

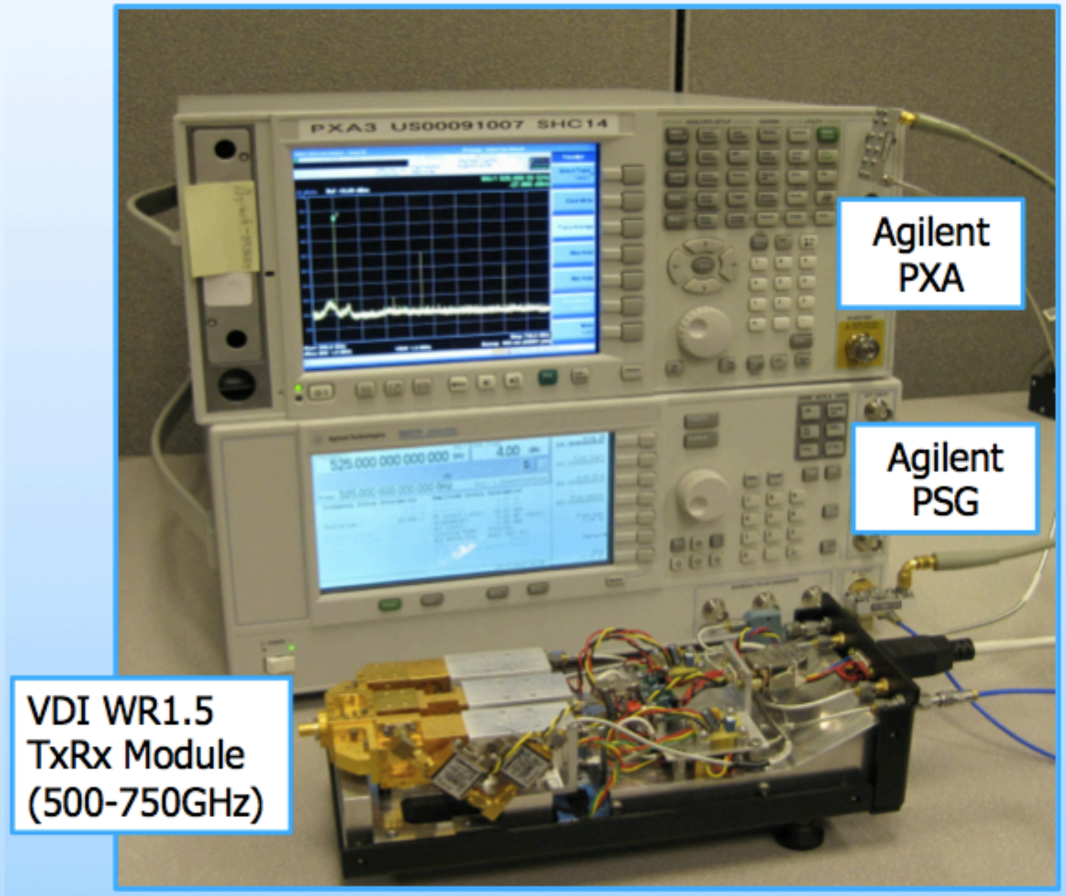


Spectrum Analyzer Display



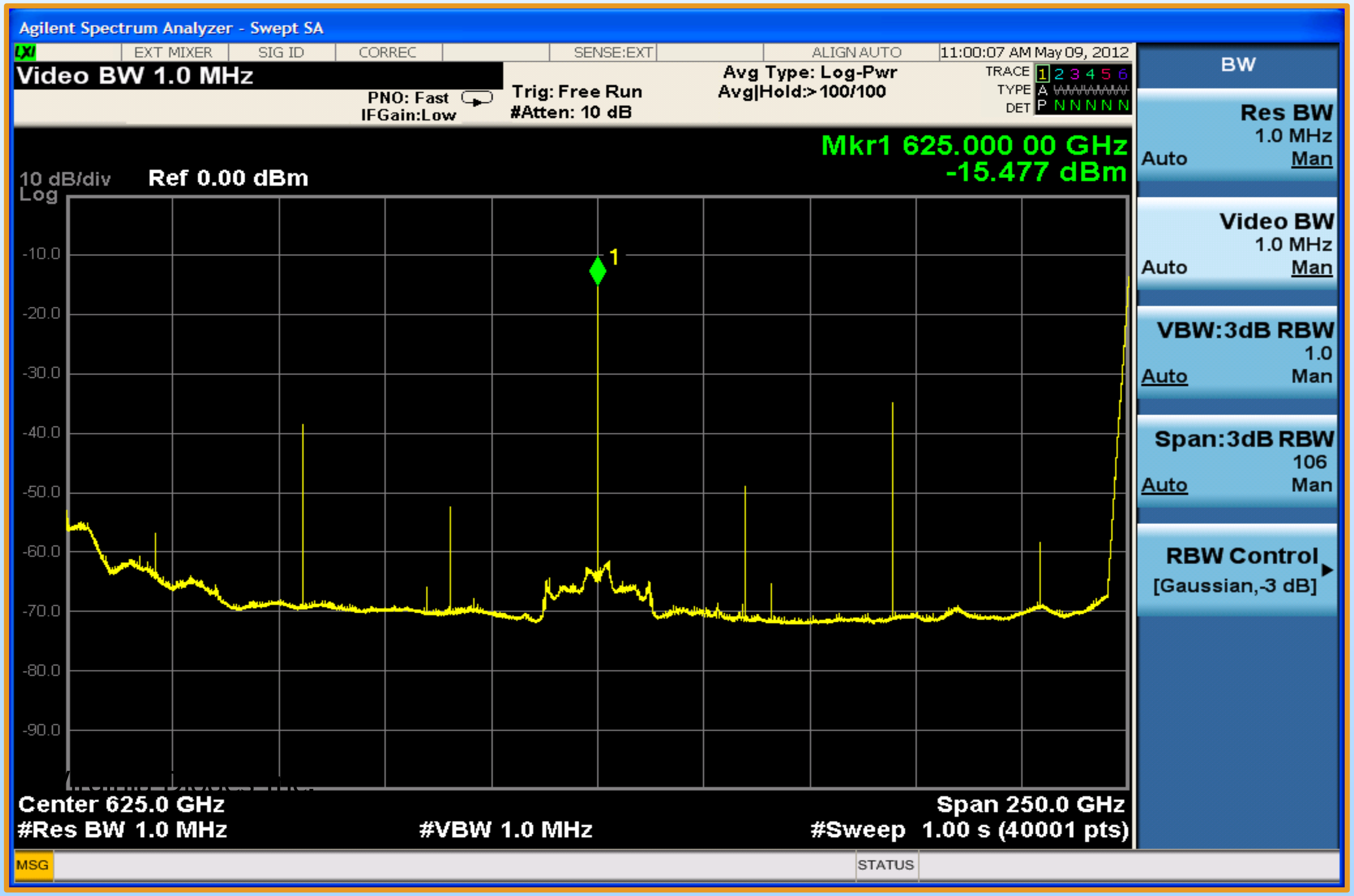
Demonstration of Signal Analysis

- Use VDI MixAMC to extend a microwave spectrum analyzer to 500-750 GHz
- Test the harmonic purity and phase noise of VDI 500-750 GHz source



Spectral purity of a 625 GHz Signal

- Measurement of 625 GHz VDI source
- All signal are harmonically related to microwave drive synthesizer
  - Harmonics more than 20 dB down from carrier
  - No spurious (i.e. non-harmonic) signals present



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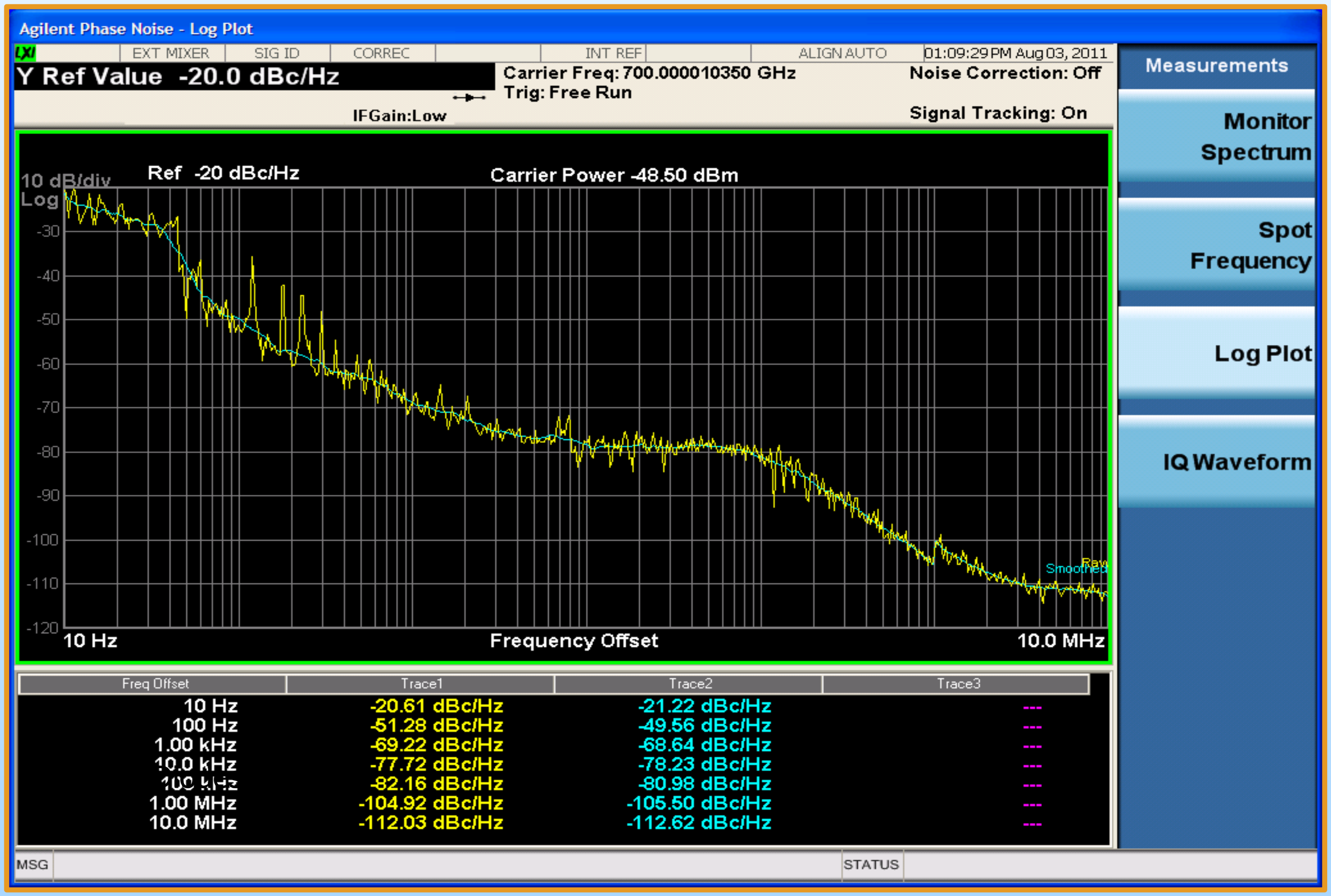
Phase Noise Measurement at 700 GHz

- Phase noise follows the theoretical 20*log(N) behavior
  - No excess phase noise added by source



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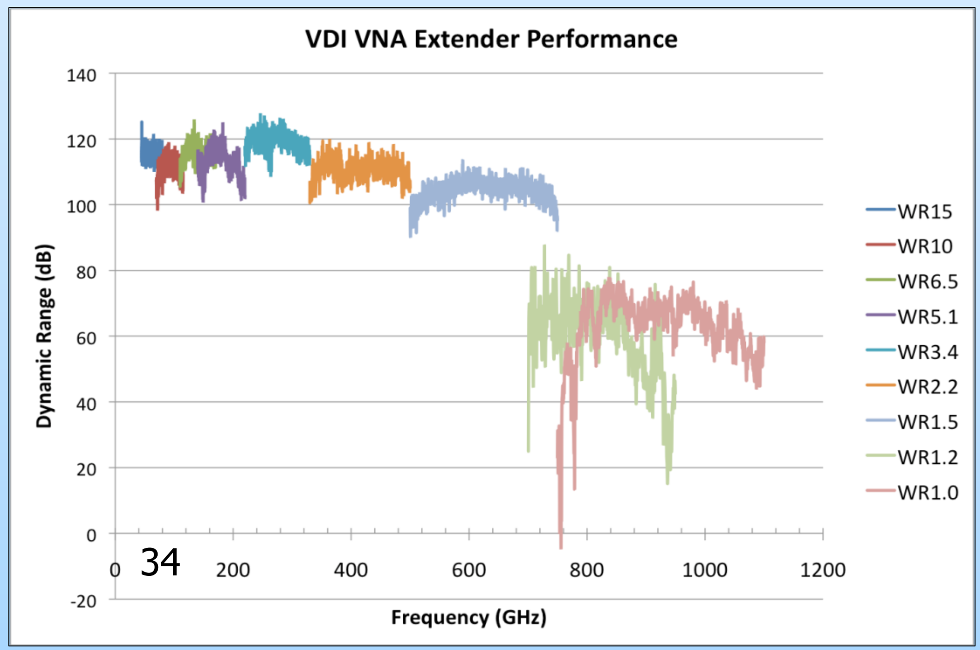
Outline

- Introduction
  - Schottky Diode Technology
  - Solid-State THz Mixers & Multipliers
- THz Frequency Extension
  - Source Extenders
  - Spectrum Analyzer Extenders
- **THz Vector Network Analysis**
  - Waveguide Measurements
  - Quasi-optical Measurements
  - THz Wafer Probing
- Conclusions

Virginia Diodes VNA Extenders

- VDI Extenders from WR-10 (75-110 GHz) thru WM-250 (750-1100GHz)
  - State-of-the-art Dynamic range
    - 120 dB (typ.) at WR-10 (70-110 GHz)
    - 120 dB (typ.) at WR-5.1 (140-220 GHz)
    - 100 dB (typ.) at WM-380 (500-750 GHz)
    - 70 dB (typ.) at WM-250 (750-1100 GHz)
  - Excellent amplitude and phase stability
  - Fully calibrated measurements



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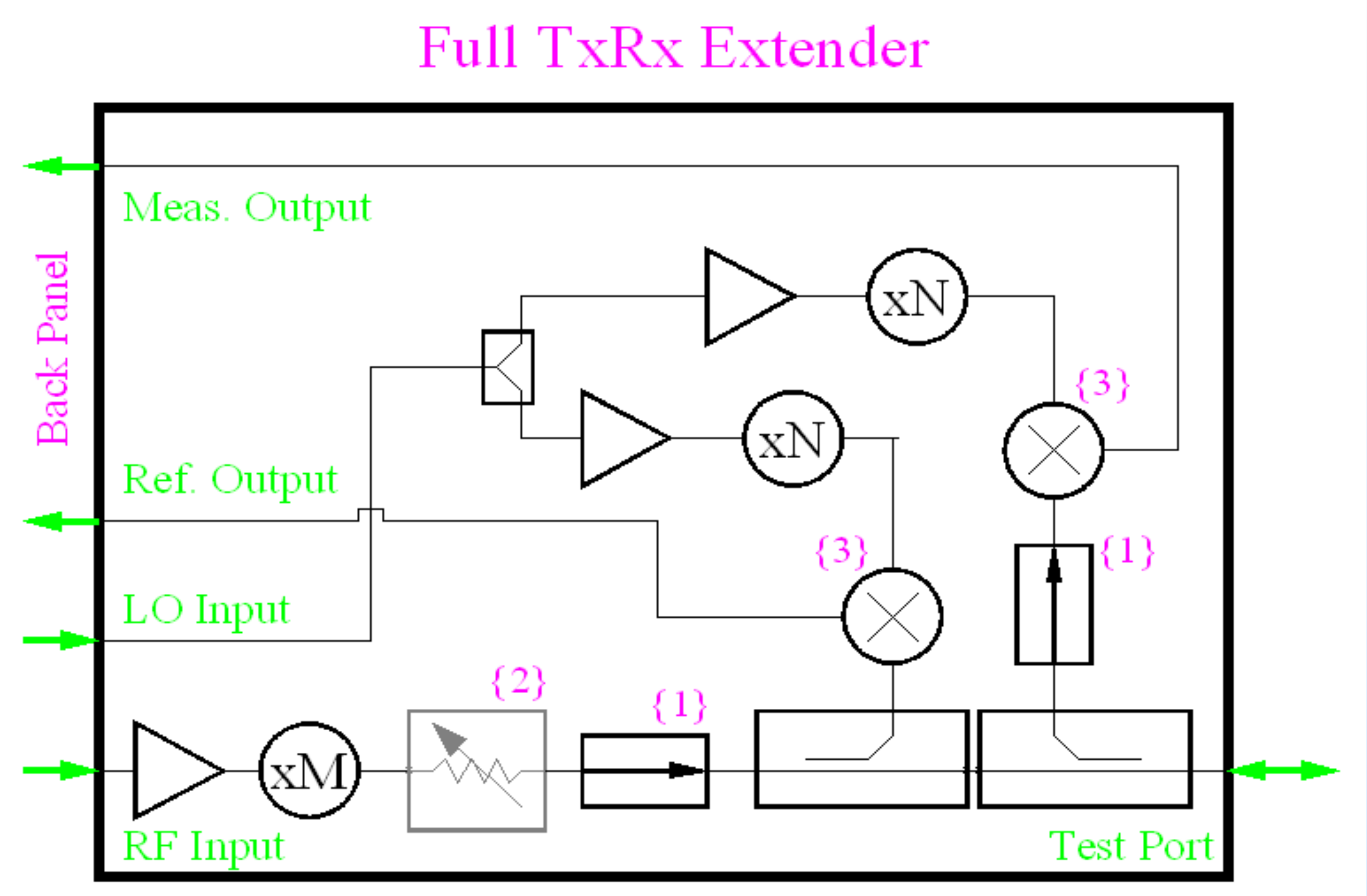
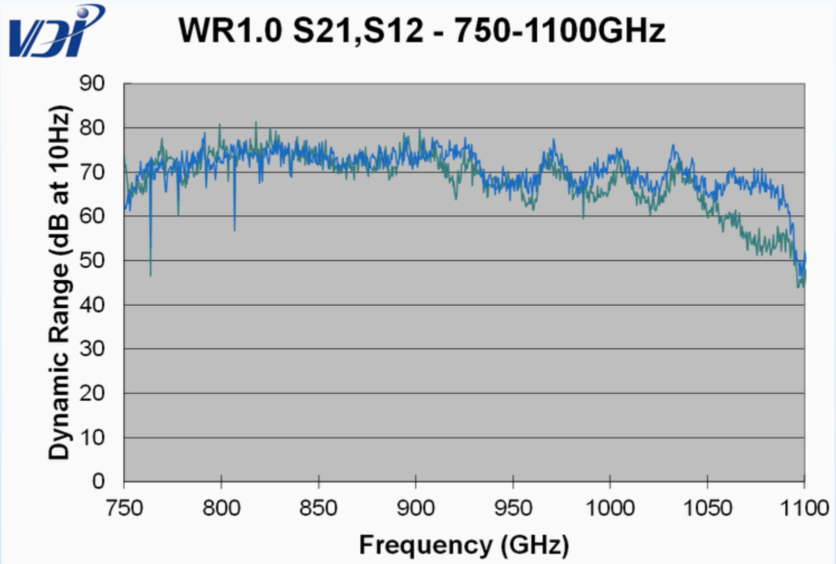
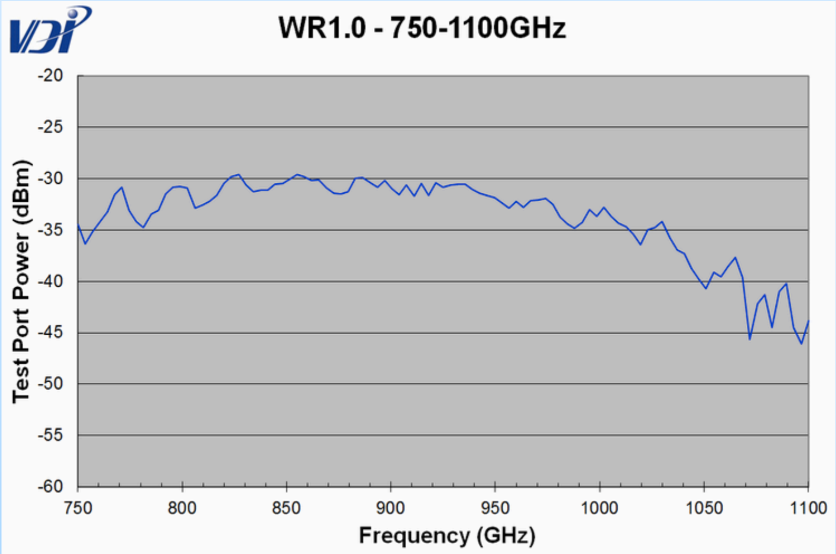
VNA Extender Diagram



WM-250 VNA Extender

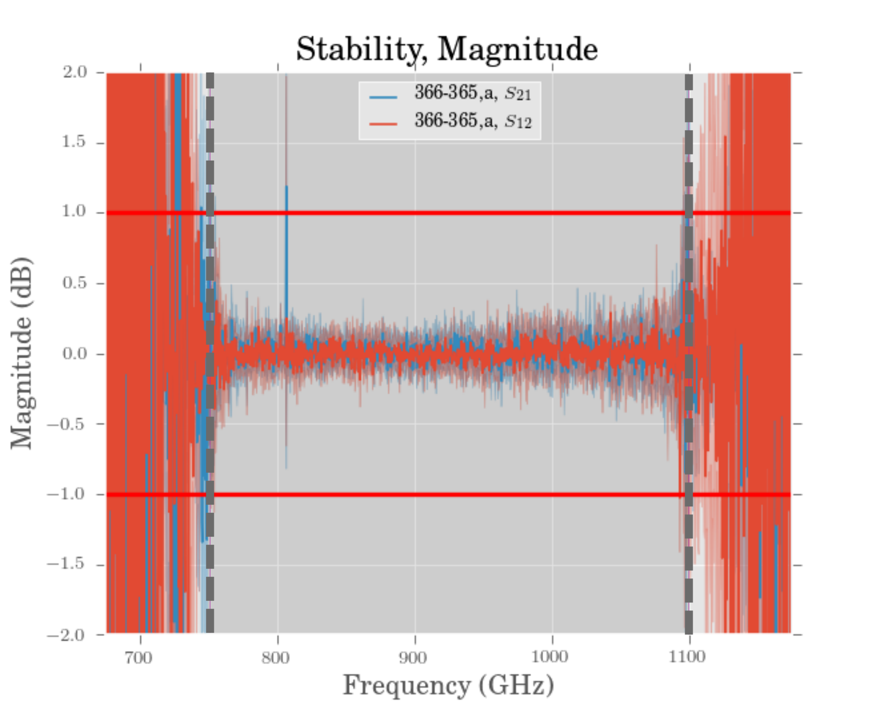
- Dynamic Range: 60 dB typical at 10Hz BW
- Dynamic Range: 40 dB minimum at 10Hz BW
- Magnitude Stability: ±1 dB
- Phase Stability: ±15°
- Test Port Power: -35 dBm
- Test Port Input Limit (dBm, saturation/damage): -20/13
- Directivity: 30 dB
- Typical Dimensions: 8 x 5 x 3 inches

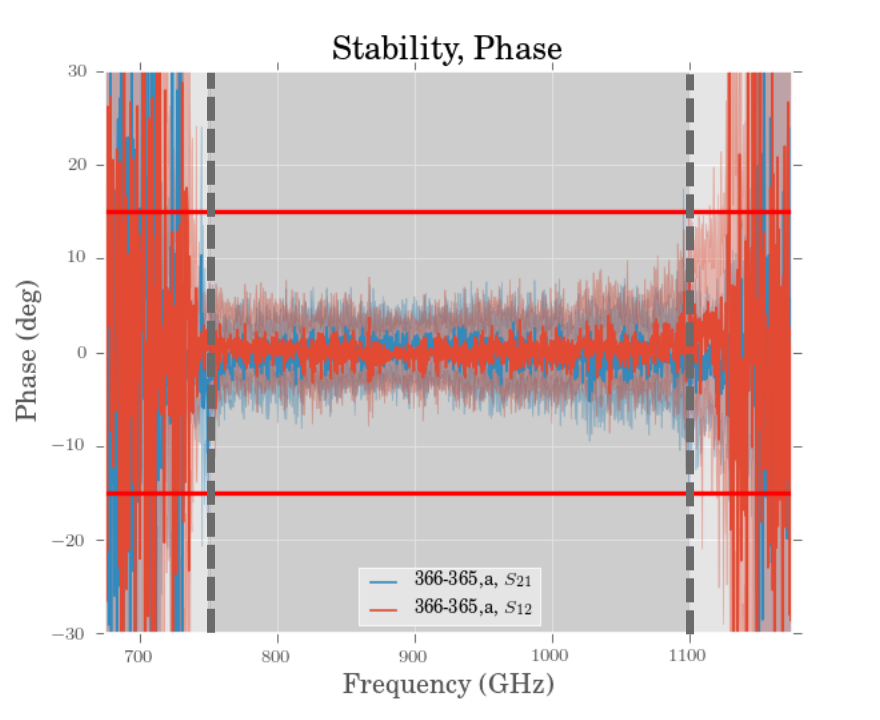




WM-250 – Amplitude & Phase Stability

- Look at amplitude & phase stability of system over one hour
  - Stability is important to maintain the calibration during the measurements
  - Measured for full 2-port WR-1.0 extender
  - 1-port stability typically 5-10 times better
- Stability was measured in general laboratory space
  - Poorly controlled thermal environment
  - Significantly improved performance can be achieved in a controlled thermal environment





THz Waveguide Calibration

- mm-Wave waveguide calibration methods
  - Short-Open-Load-Thru (SOLT, TOSM)
    - Open typically uses ¼-wave delayed short
  - Thru-Reflect-Line (TRL, LRL)
    - Line is typically a ¼-wave thru shim
  - Many others possibilities as well…
- Sub-mm wave introduces a new set of challenges
  - Thru-Reflect-Line (TRL, LRL)
    - ¼-wave shims difficult to fabricate and fragile
    - Common to instead use two lines with ¼-wave difference in length
      - However, this means more connections and interfaces ◊ less accuracy
  - Short-Open-Load-Thru (SOLT, TOSM)
    - Challenging to achieve a high return loss load

Machined Quarter-wave Delay Short

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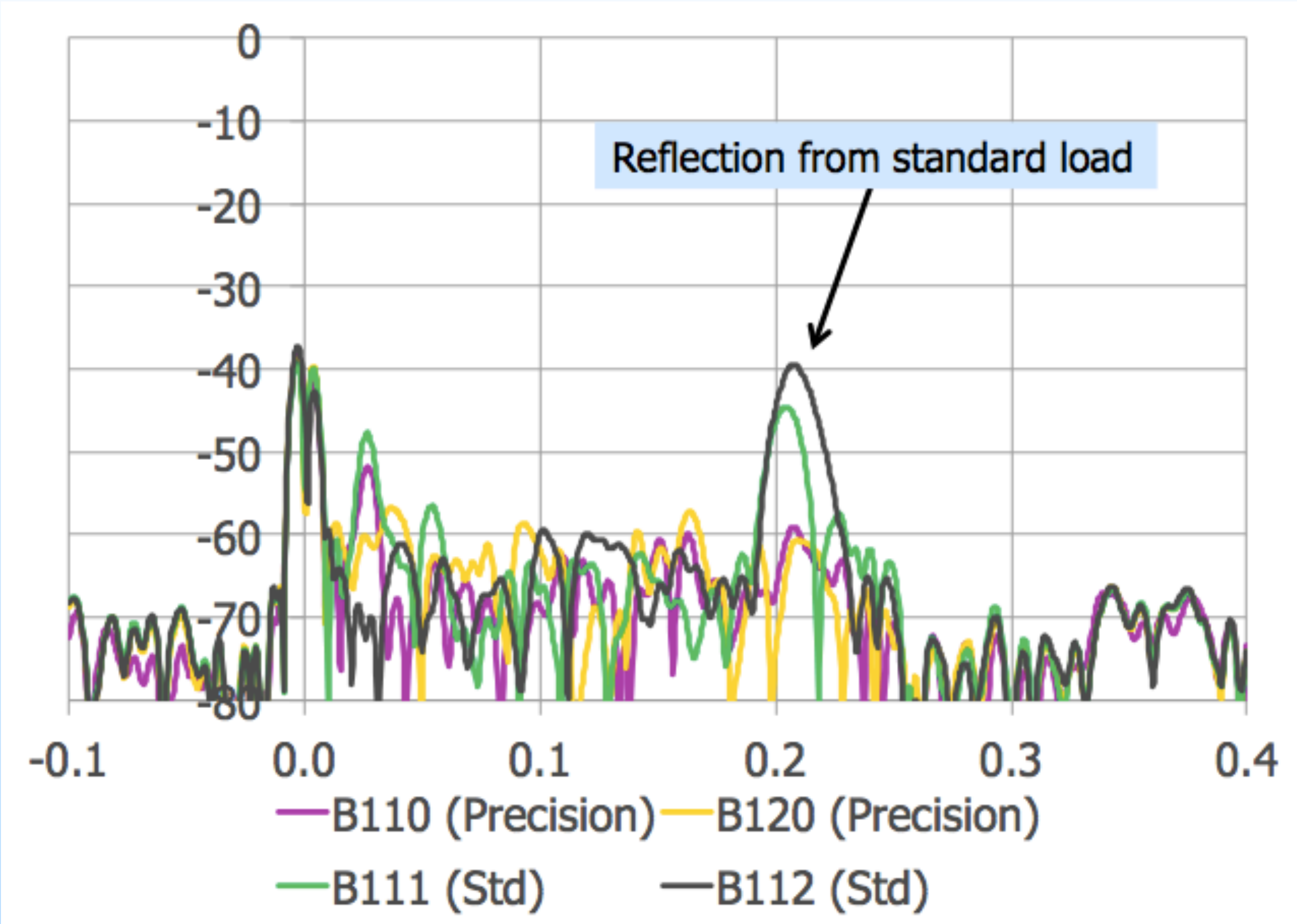
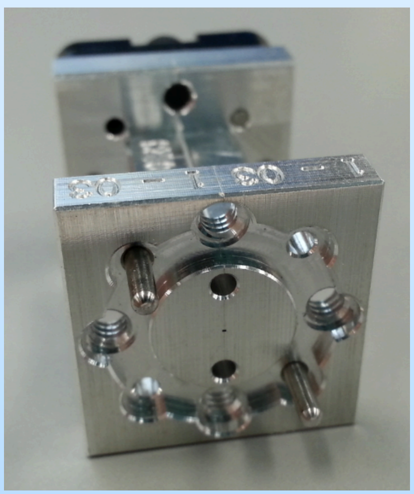
WM-380 Precision Loads



WM-250 Calibrated Measurements

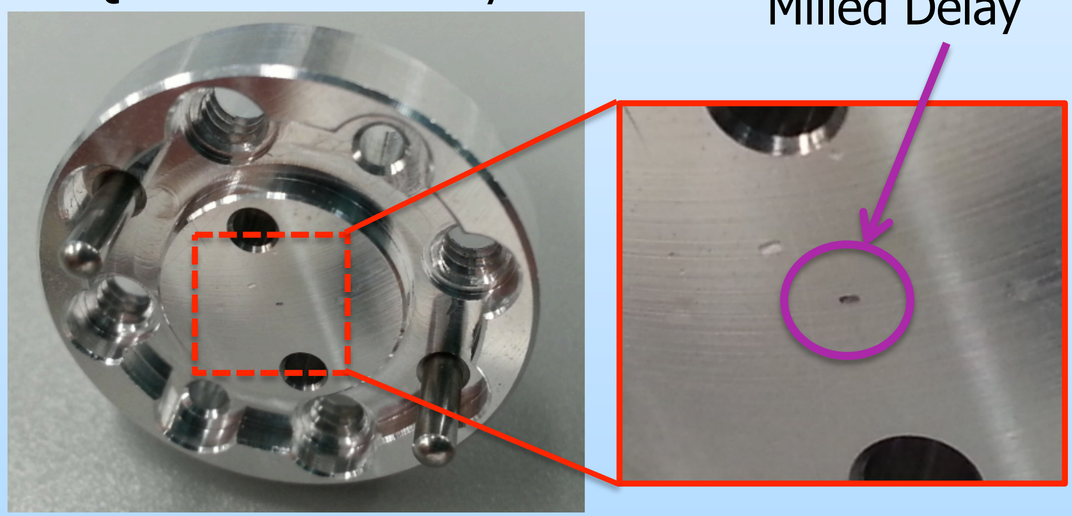
- Calibrated measurements were performed using the Extender
- Short-Open-Load-Thru calibration method
  - ¼-wave delay was used as the Open standard
- 1 kHz IF Bandwidth for calibrated measurements

Precision Load



Quarter-wave Delay

WR-1 Waveguide Milled Delay



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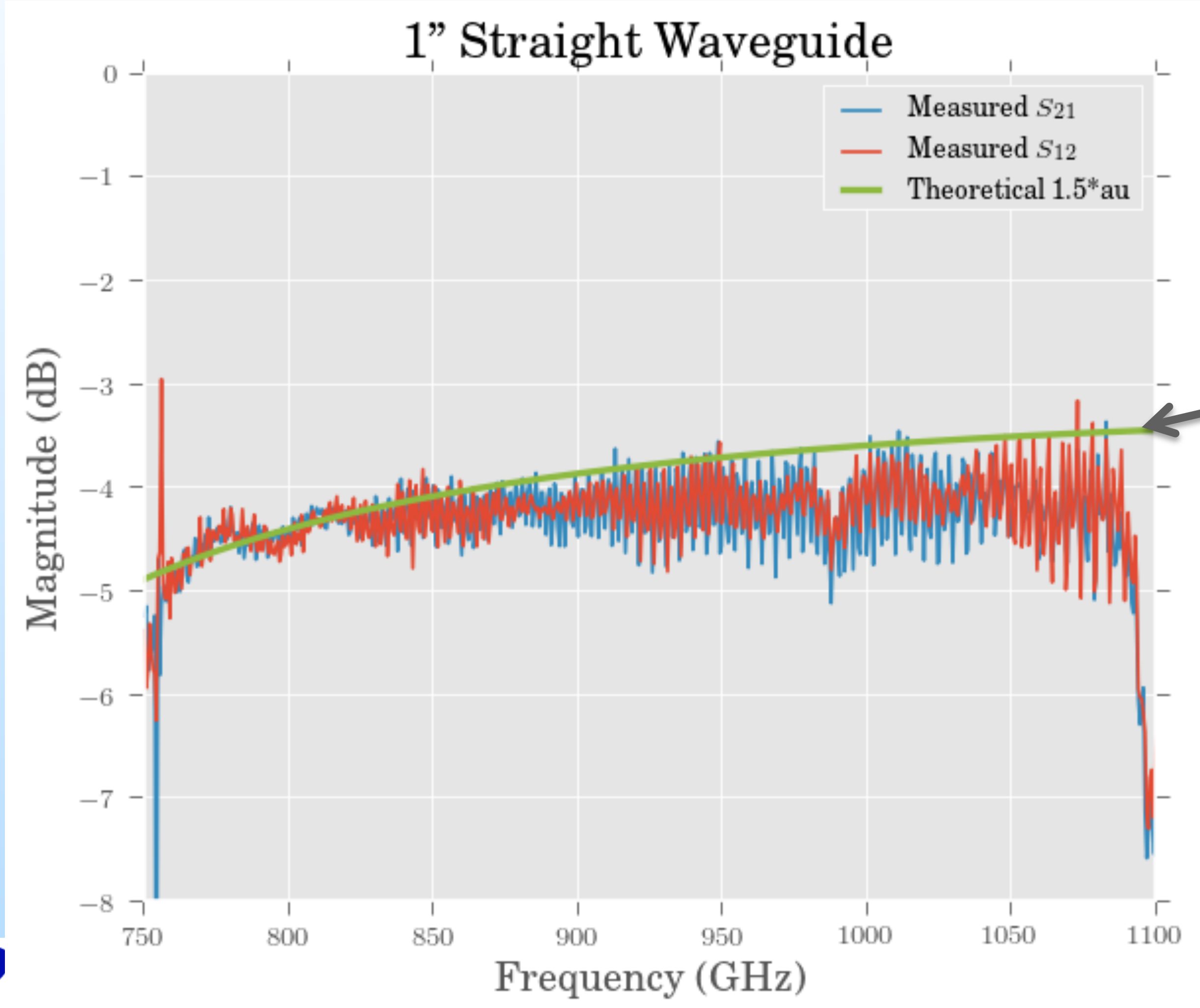
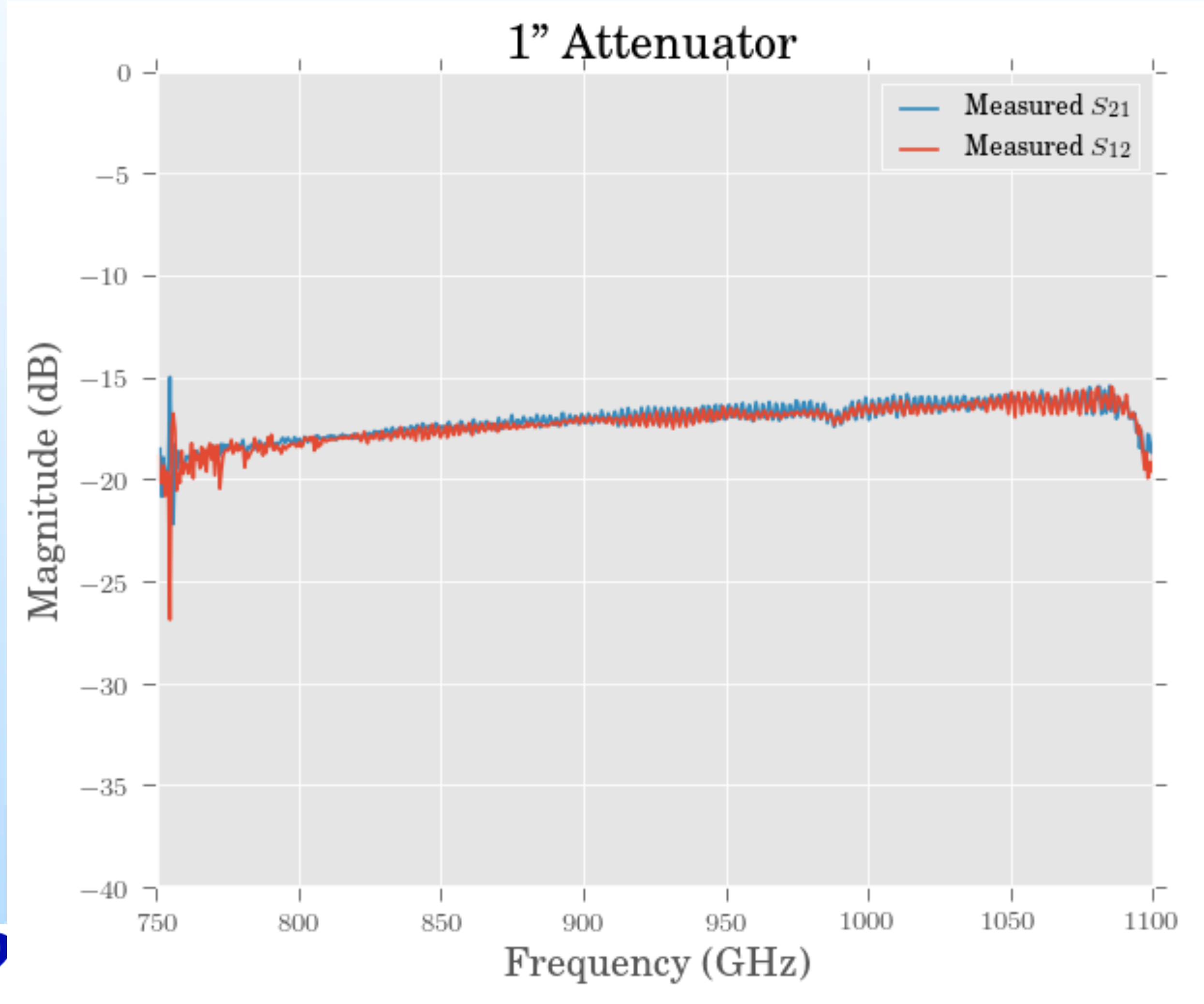
Measurement of 1" Waveguide Straight

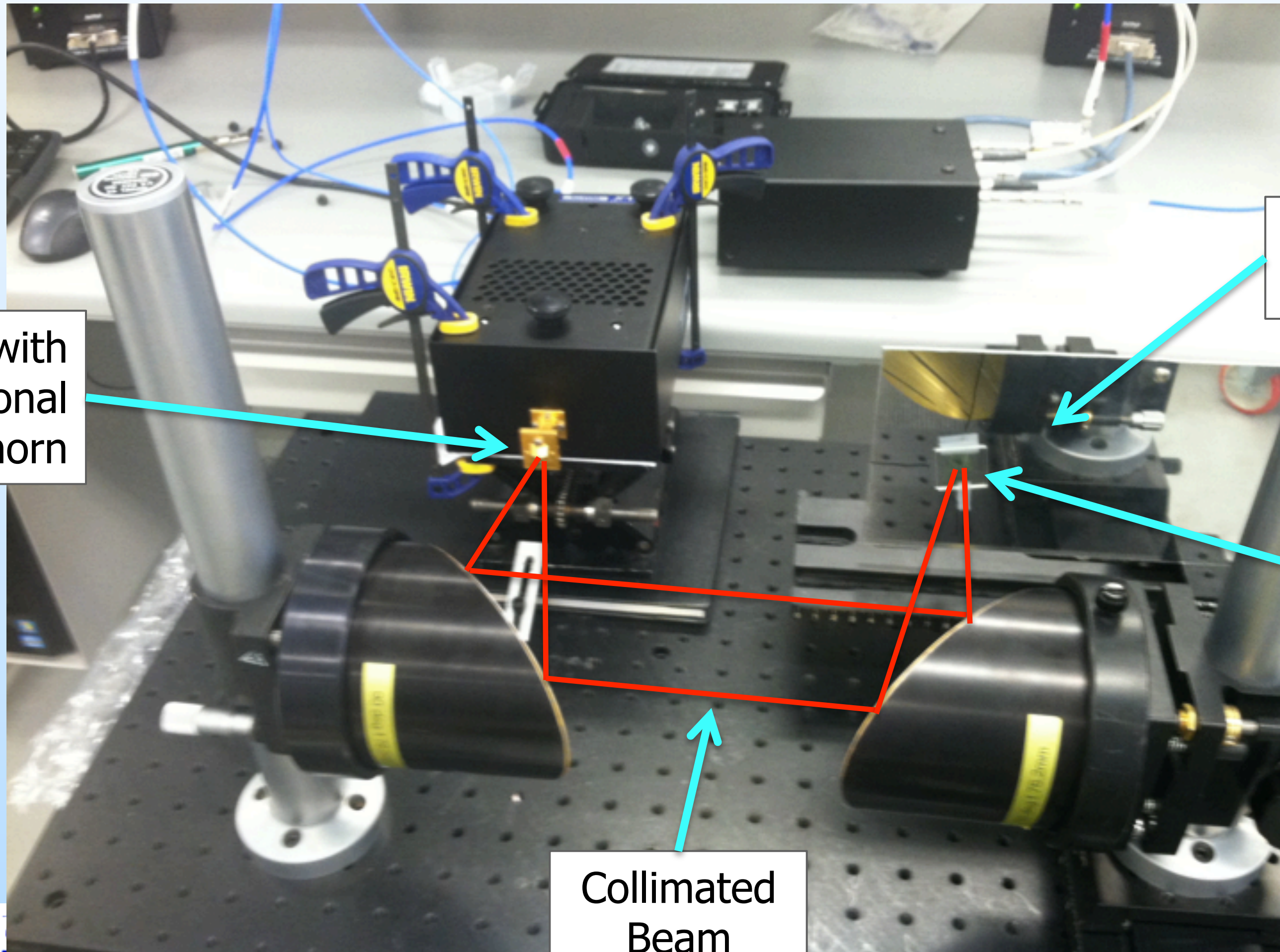


Ideal loss X 1.5 to account for surface roughness

Measurement of Waveguide Attenuator

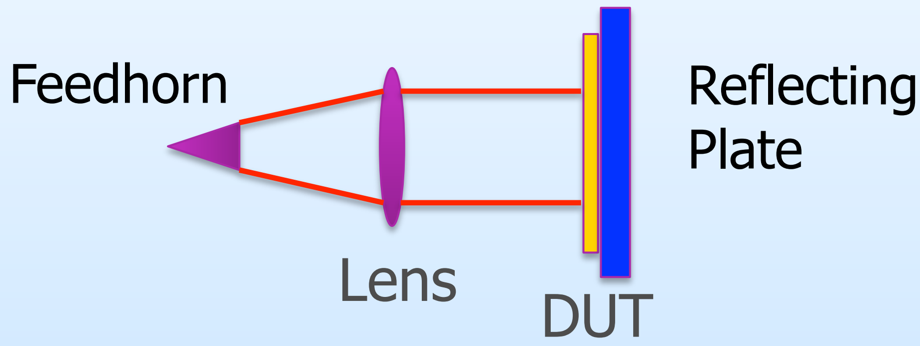


One-Port Quasi-Optical Measurement Setup



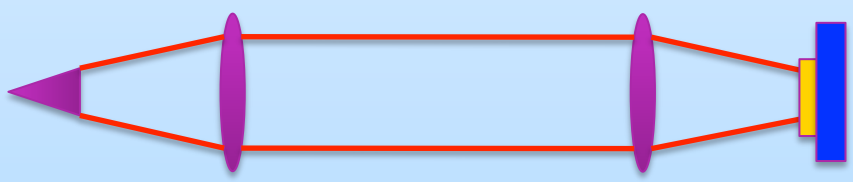
One-Port Quasi-Optical Measurements

1-Port Measurement in Collimated Beam



- Requires large sample
- Sample in collimated beam

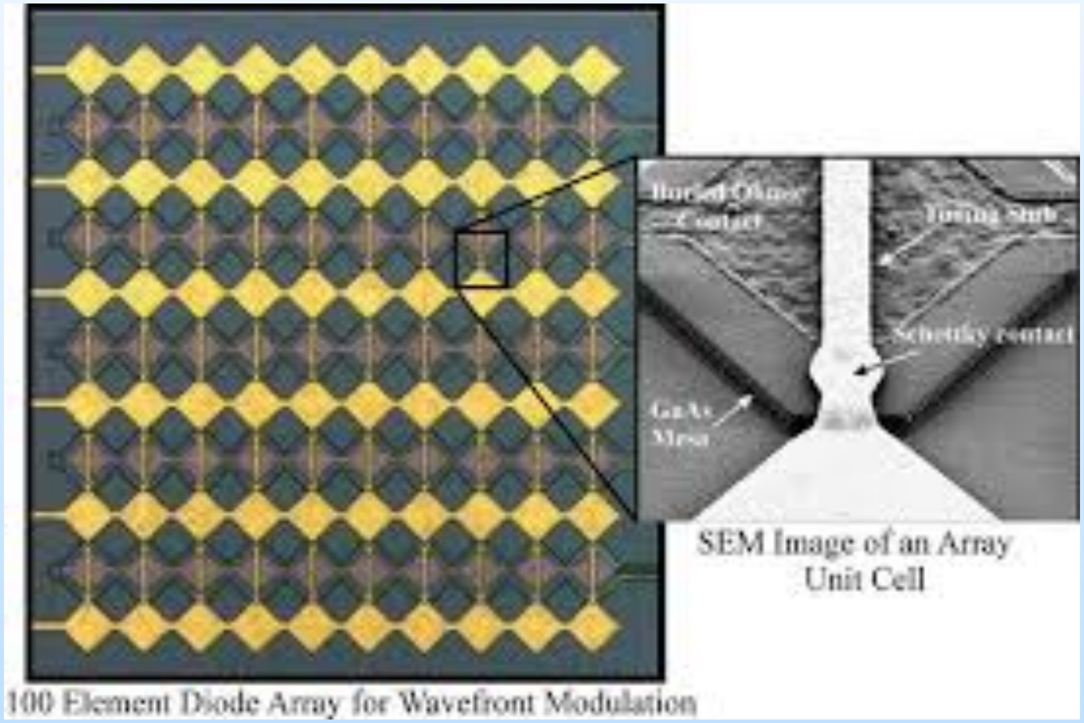
1-Port Measurement in Focused Beam



- Can use small sample
- Good for devices (grid arrays, focused optics, …)

Quasi-Optical Grid Array Sideband Generator

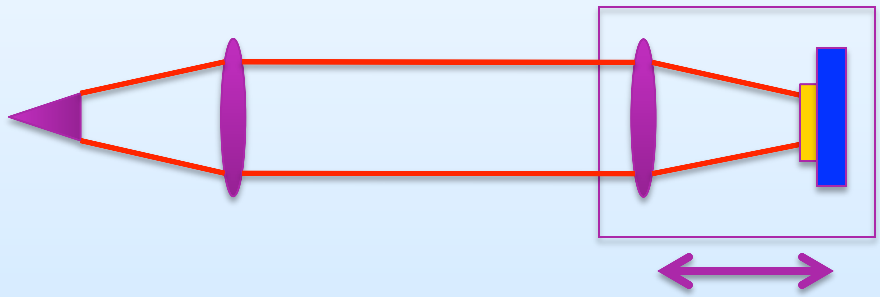
1.6 THz 100 Element Diode Array



University of Virginia

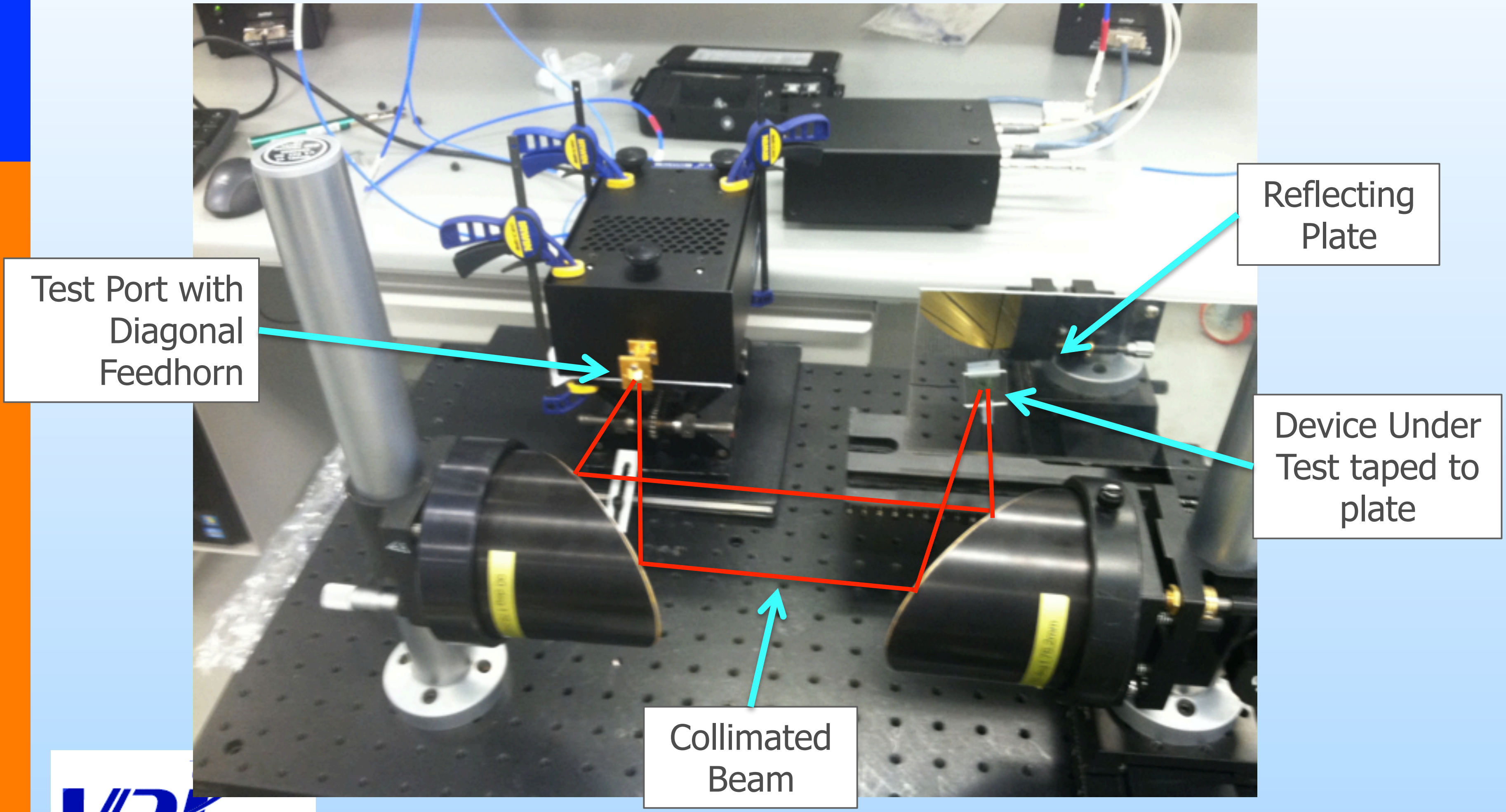
Quasi-Optical Measurement Calibration

Measurement of Sample in Focused Beam

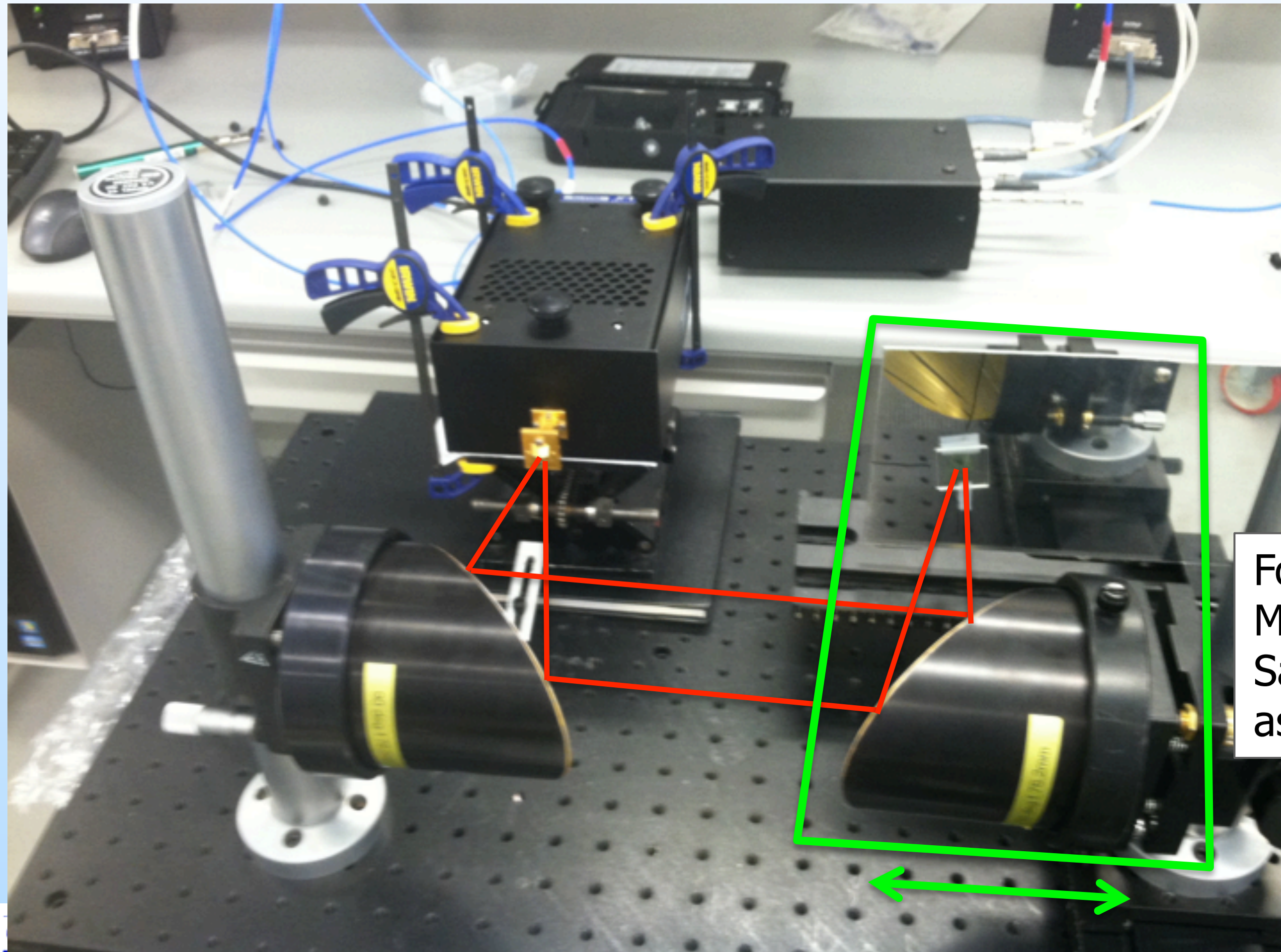


- Slide lens and sample as a unit
  - Translation occurs in collimated section
  - Improved accuracy, minimal effect on focusing
    - e.g. see Arsenovic 2013 MTT
  - Measure multiple delay lengths

One-Port Quasi-Optical Measurement Setup



Quasi-Optical Measurement Setup



Focusing Mirror and Sample move as a unit

Over-Determined Least Squares Calibration

- For calibration, use an un-weighted least squares method
  - e.g. see Wong 2004 ARFTG
- Calibration standards
  - Series of delayed reflections with known delay distances
    - Metal plate at focal point of QO system
    - Metal plate and focusing mirror are both mounted on the same moving stage
  - Matched load
    - Used absorber at 45 degree angle as rough termination
  - Measurement bandwidth 300 Hz

Over-determined Least Squares Calibration

Uncertainty Analysis of the Weighted Least Squares VNA Calibration

Ken Wong , Senior Member IEEE, Agilent Technologies, Inc.

64th ARFTG Conference

B. Least Squares solution

Better accuracy can be achieved by measuring more than three standards. Using n calibration standards, equation (3) becomes:

$$\begin{bmatrix} 1 & \Gamma_{m1}\Gamma_{a1} & -\Gamma_{a1} \\ 1 & \Gamma_{m2}\Gamma_{a2} & -\Gamma_{a2} \\ 1 & \Gamma_{m3}\Gamma_{a3} & -\Gamma_{a3} \\ \vdots & \vdots & \vdots \\ 1 & \Gamma_{mn}\Gamma_{an} & -\Gamma_{an} \end{bmatrix} * \begin{bmatrix} e_{00} \\ e_{11} \\ \Delta_e \end{bmatrix} = \begin{bmatrix} \Gamma_{m1} \\ \Gamma_{m2} \\ \Gamma_{m3} \\ \vdots \\ \Gamma_{mn} \end{bmatrix} \quad (5)$$

Equation (5) can be rewritten as a linear matrix equation:

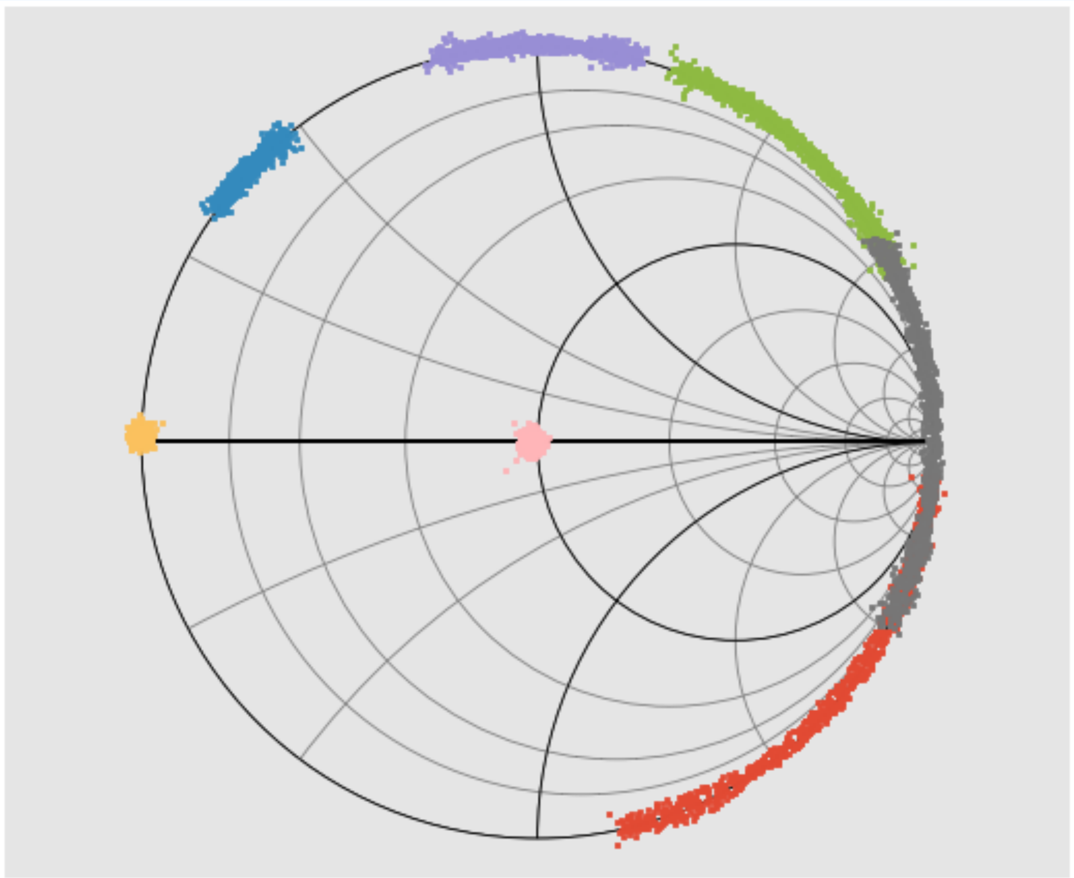
$$A \bullet E = M \quad (6)$$

The least squares solution to equation (6) is given as:

$$E = \left(A^H \bullet A\right)^{-1} \bullet A^H \bullet M \quad (7)$$

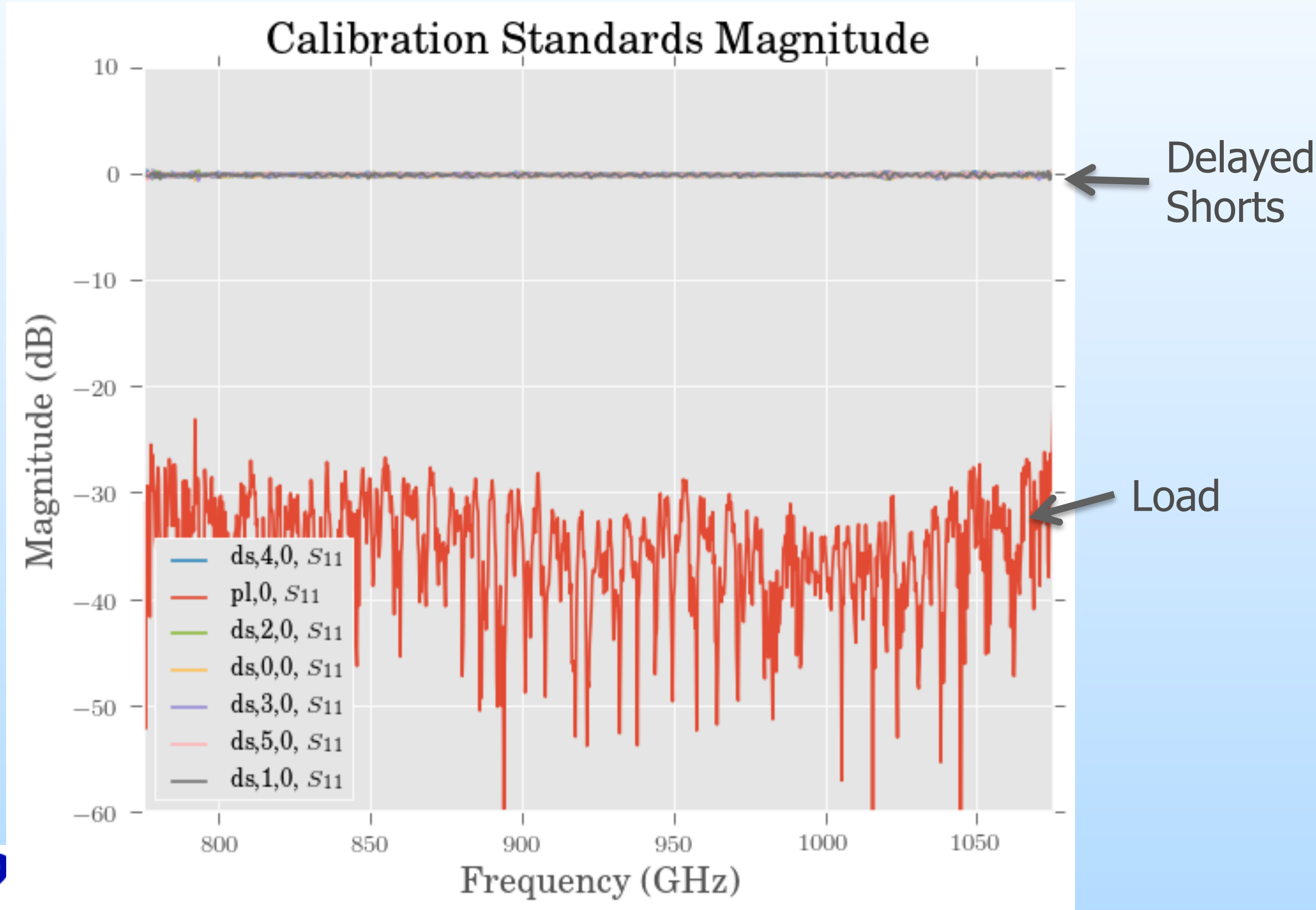
where A^H is the conjugate transpose of A.

Evaluation of Calibration Quality

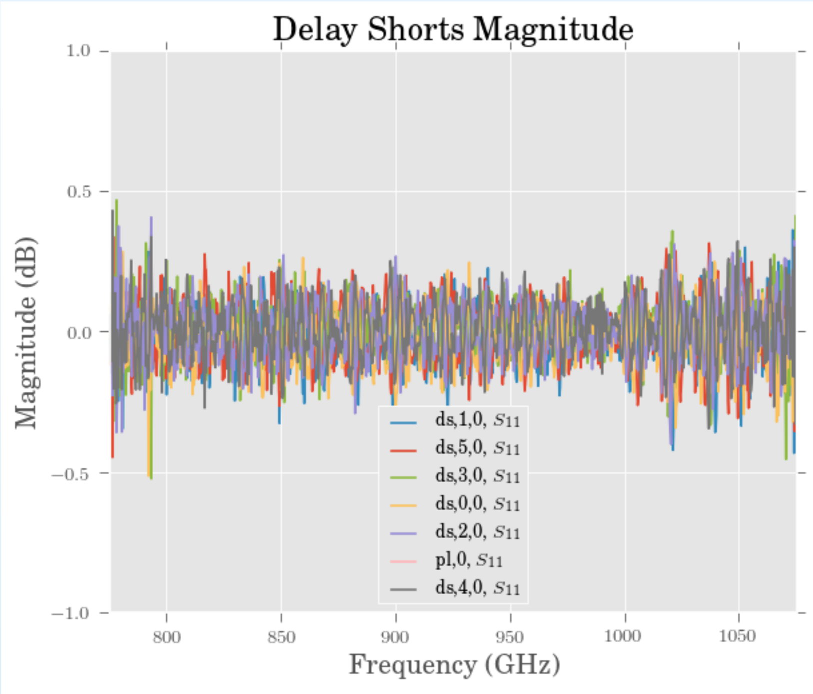


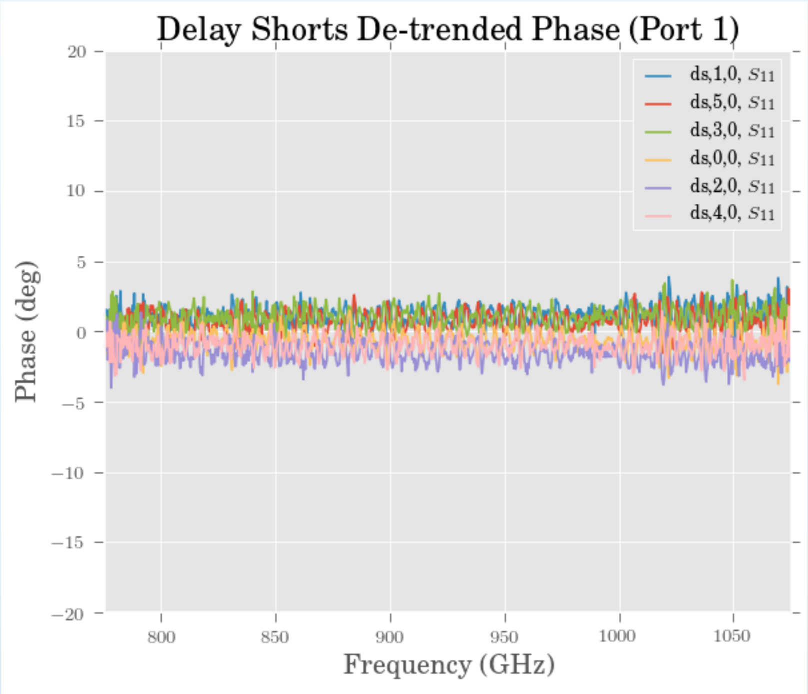
- Look at S-parameters of the calibration standards
  - Over-determined calibration → a measure of the calibration quality
- Gives an indication of the measurement quality that can be achieved

Evaluation of Calibration Quality

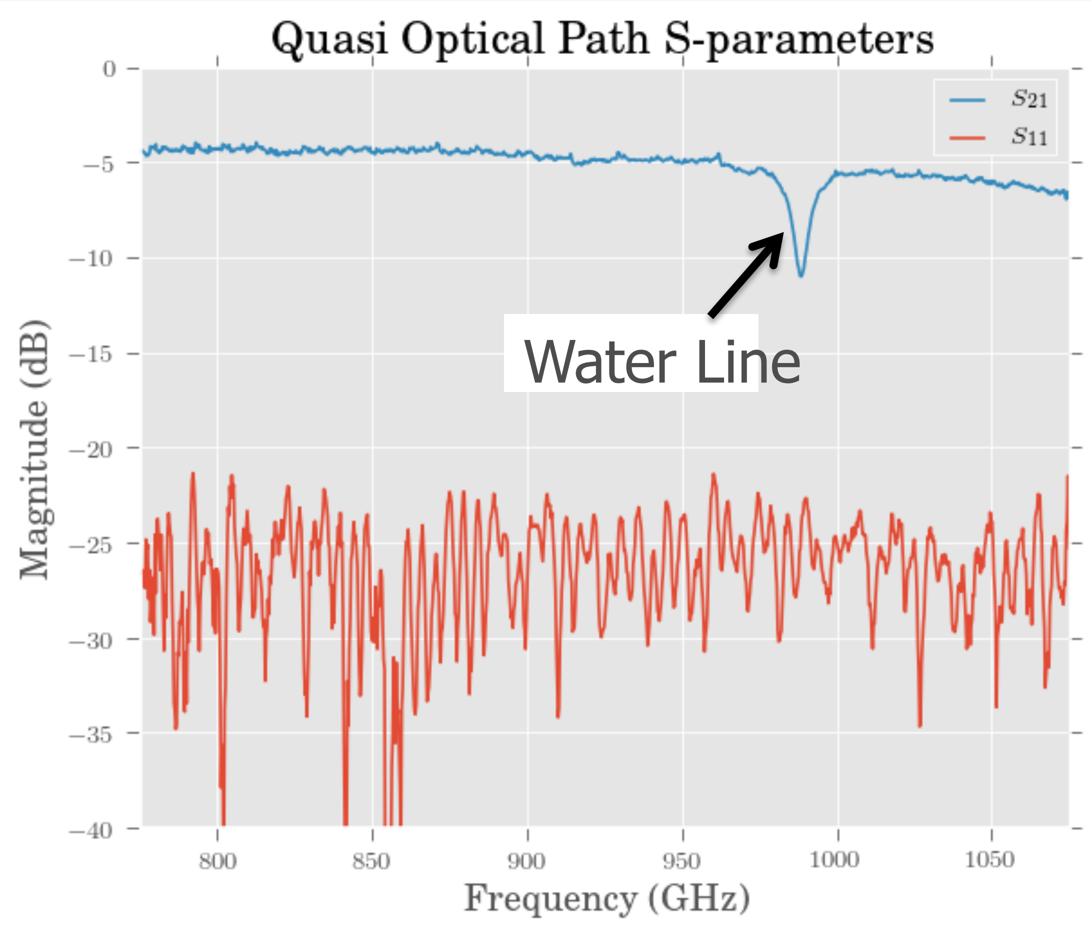


Evaluation of Calibration Quality - Shorts



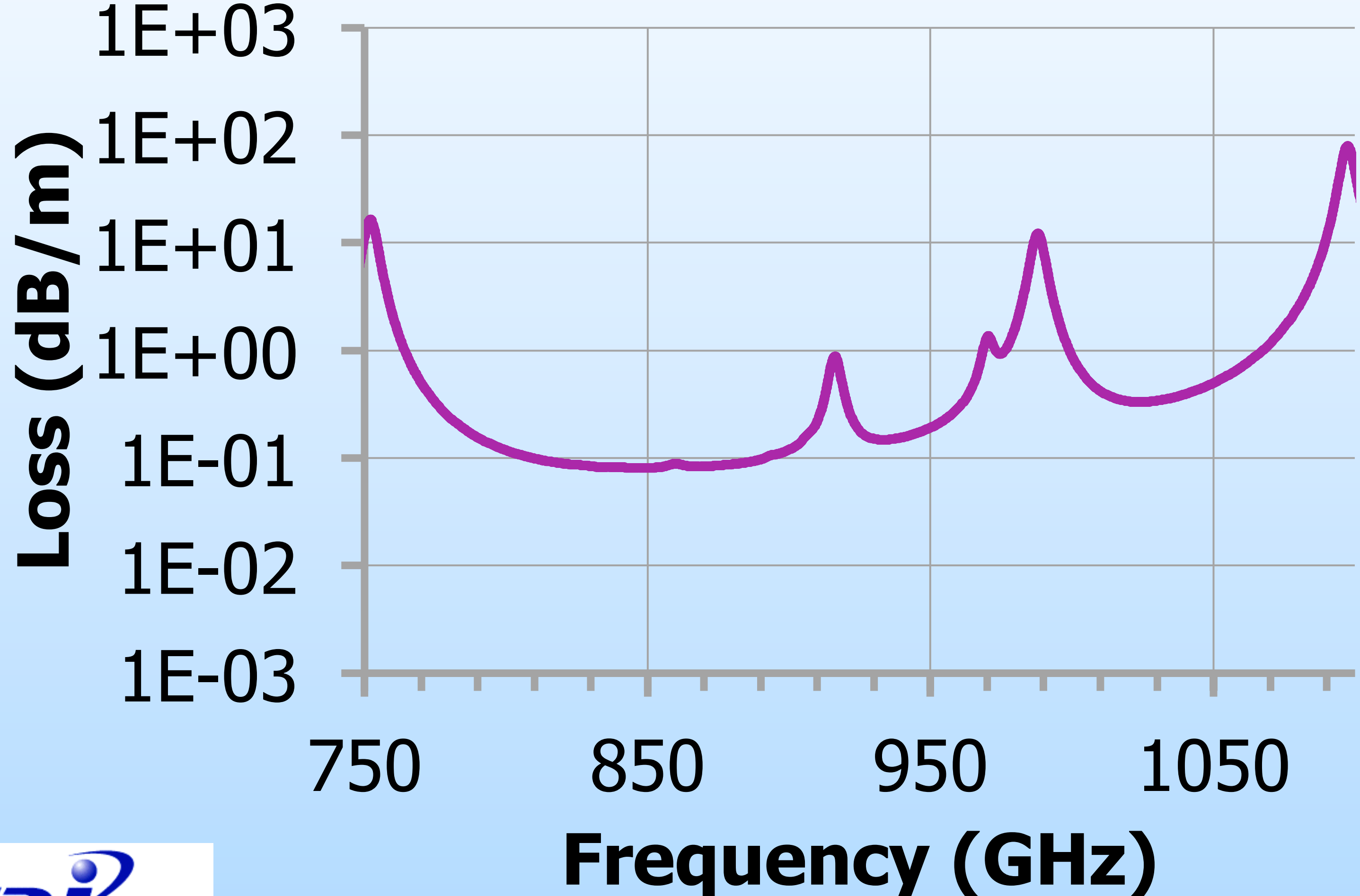


S-Parameters of Quasi-Optical System



- A measurement of the S-parameters of the Quasi-Optical system
- Measured using a two-tiered extraction method
- Uses a waveguide calibration followed by a separate QO calibration
  - See Arsenovic 2013 MTT
- Vector Star has onboard two-tiered calibration available
  - Network Extraction

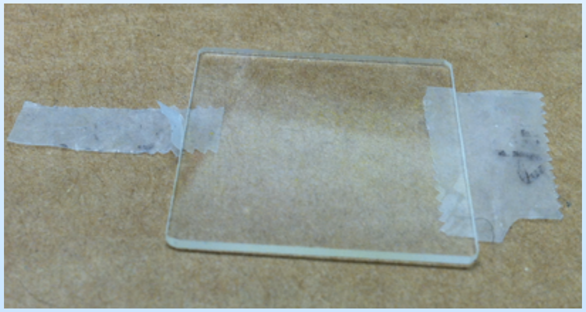
Atmospheric Transmission



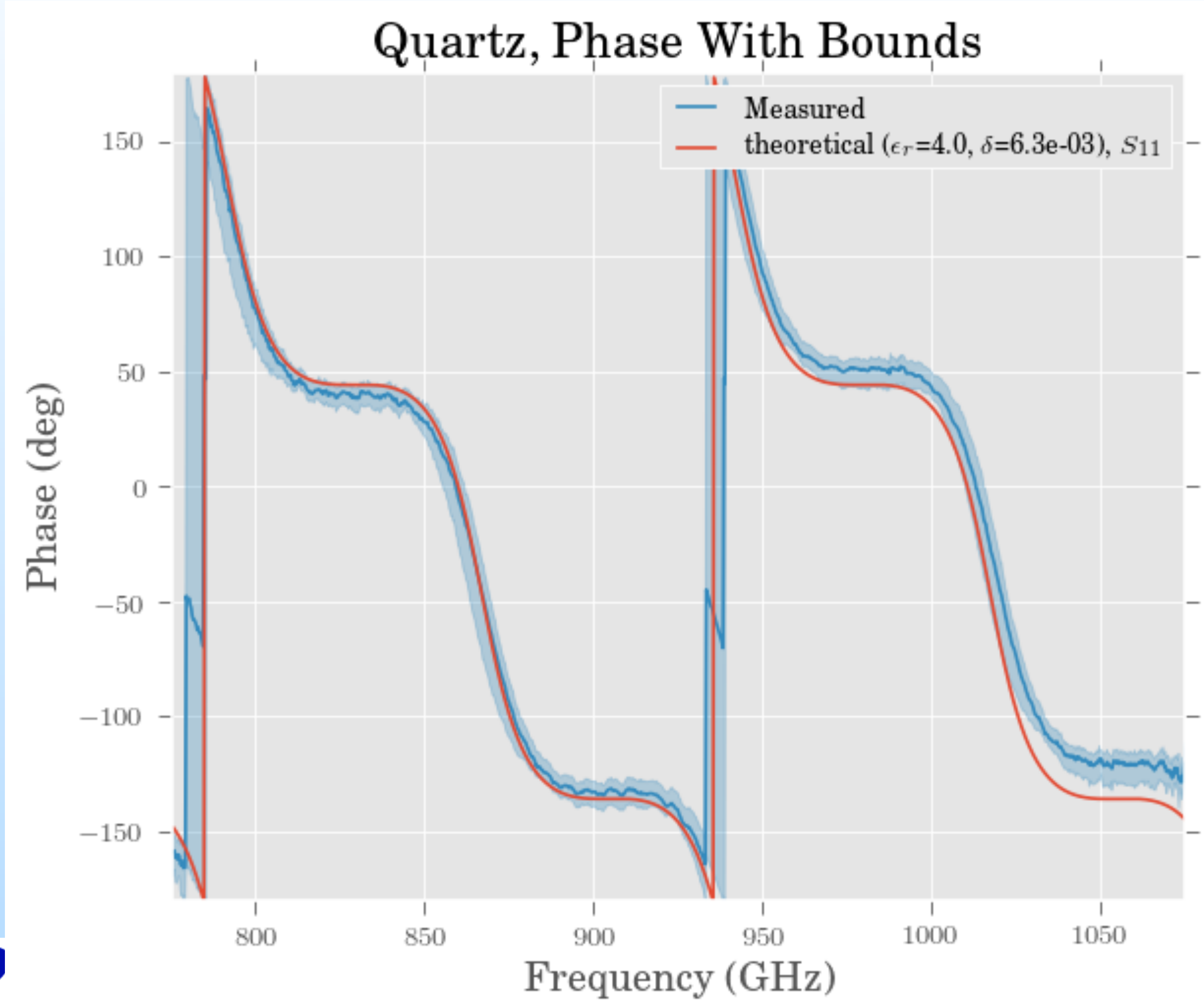
Measurements of Dielectric Samples

- Samples were taped to the metal plate at the focal point
- Repeated measurements were made of each sample
  - Sample removed from plate and re-mounted for each measurement
- Calibration using the QO method described earlier
  - Not a two-tiered calibration

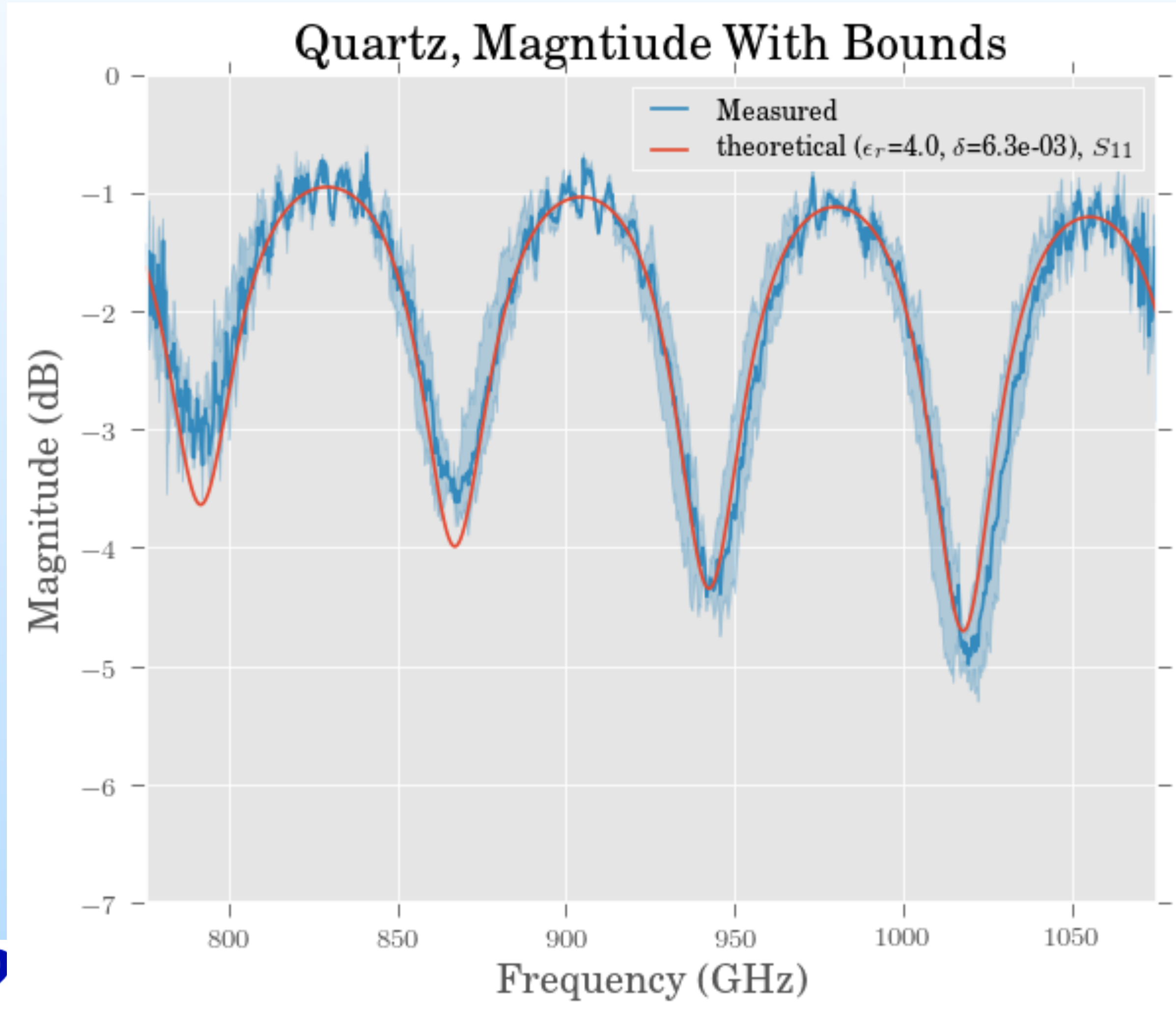
1 mm Quartz (Fused Silica)



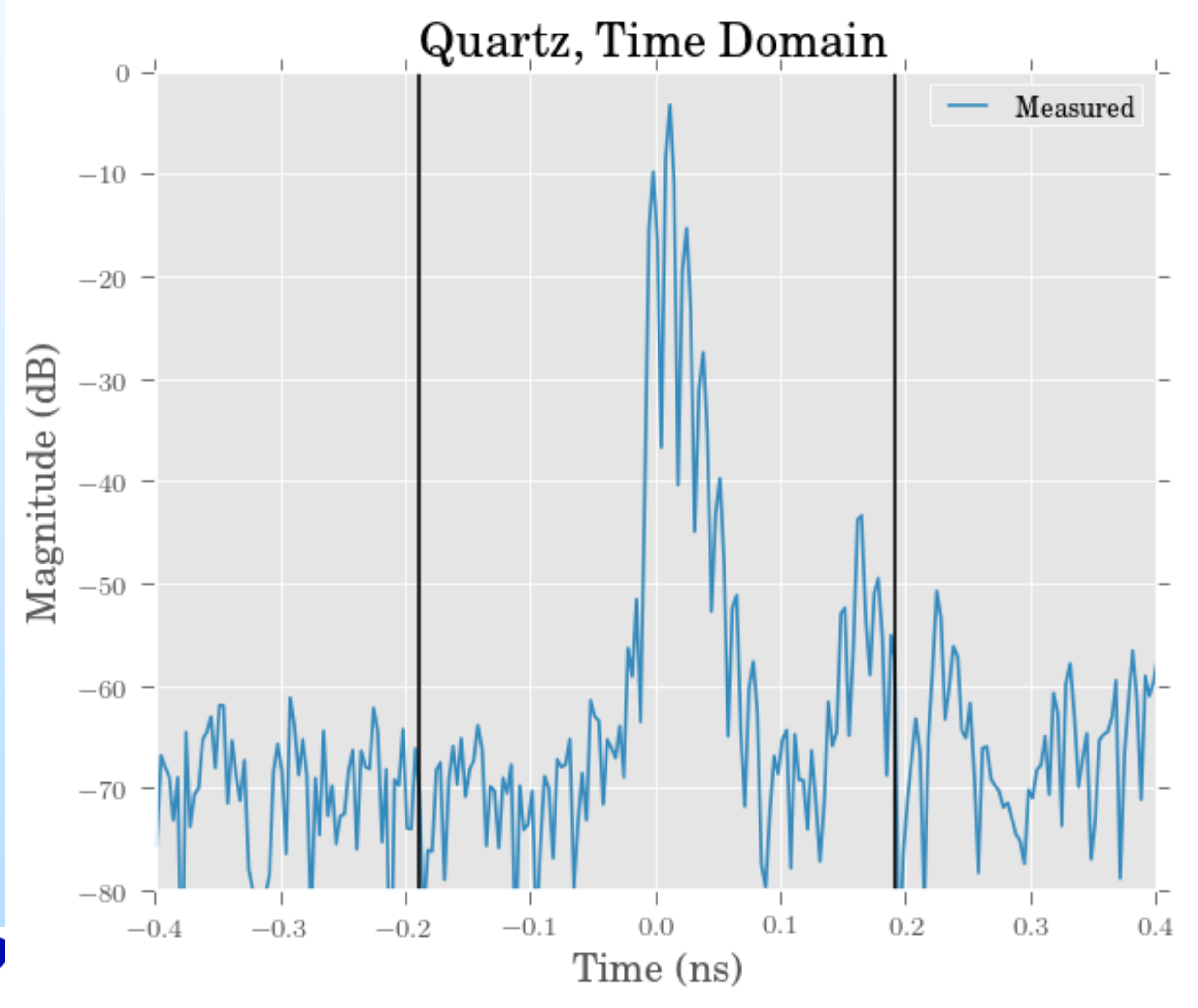
1 mm Quartz (Fused Silica)



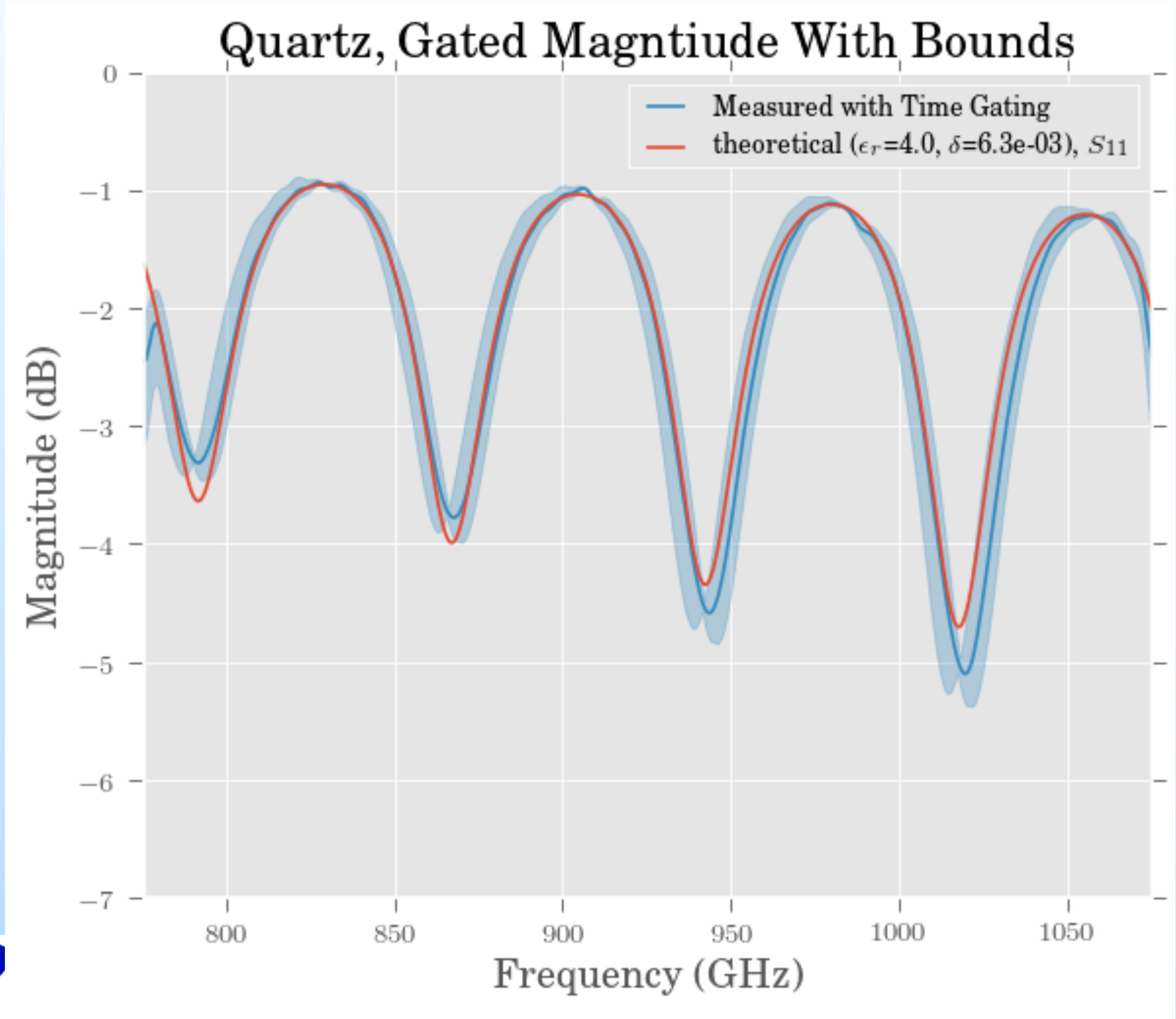
1 mm Quartz (Fused Silica)



1 mm Quartz (Fused Silica)



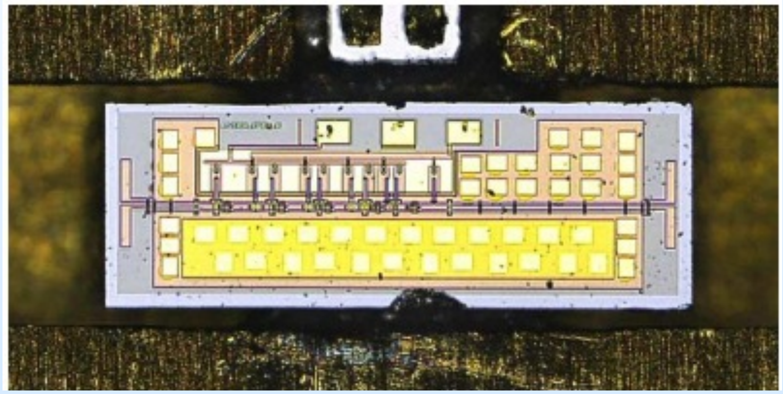
1 mm Quartz (Fused Silica)

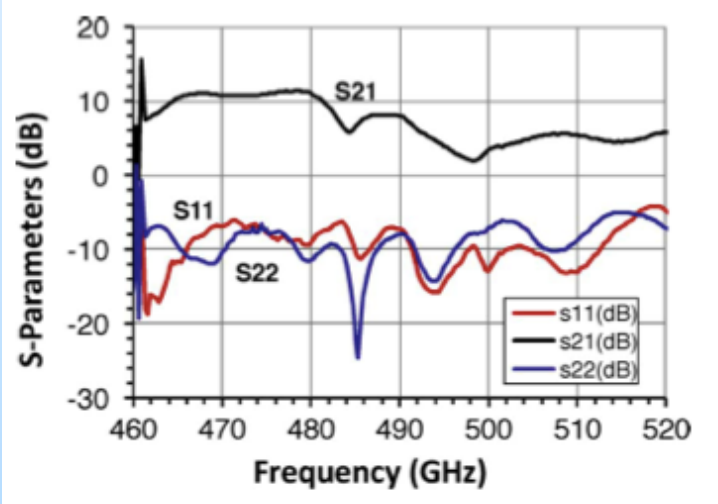


THz Wafer Probing

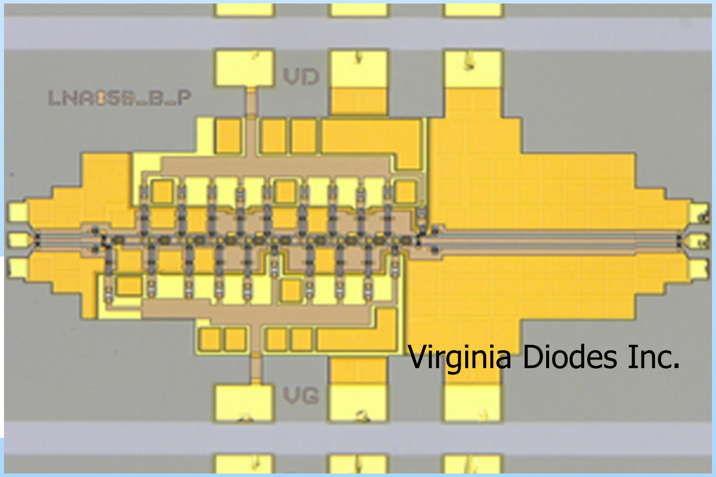
- Rapid advances in InP THz transistors
  - NGC has developed a 650 GHz amp with > 10 dB gain and P_{SAT} of 1.7 mW
    - Radisic – MTT - 2012
- The VDI THz VNA Extenders are use for on wafer probing of these THz transistors
  - Rapid device characterization (no fixture de-embedding)

480 GHz LNA (NGC, Deal – MWCL - 2010)





850 GHz Amplifier (NGC – Deal)



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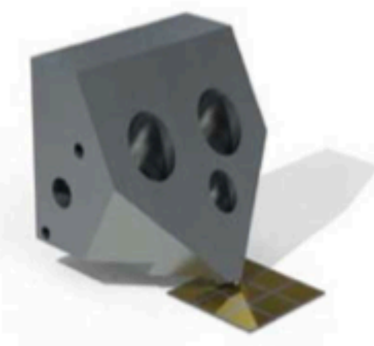
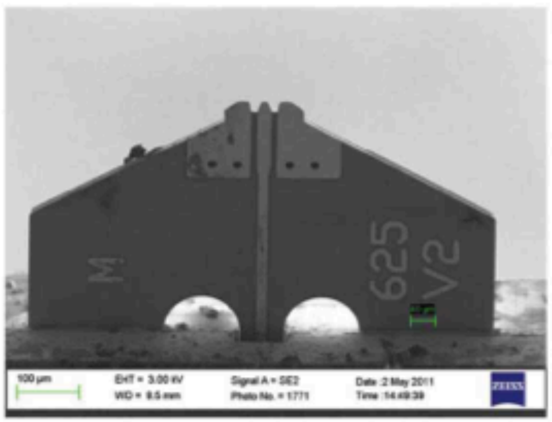
DMPI

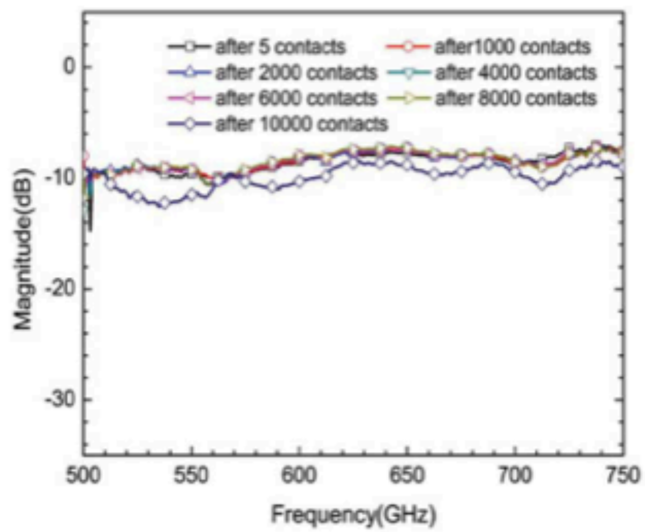
Dominion MicroProbes, Inc

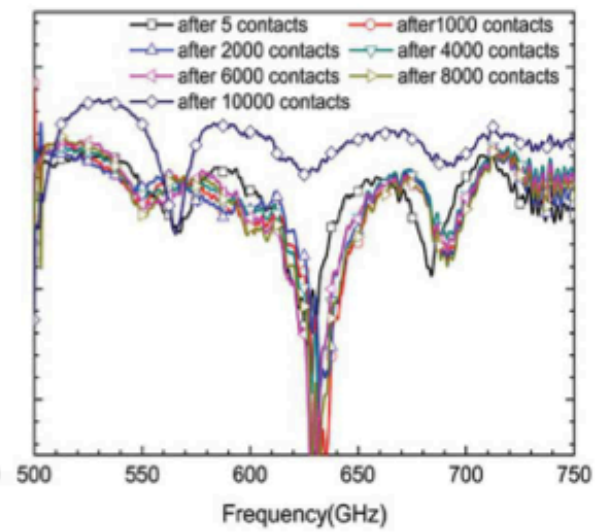
Dominion MicroProbes, Inc.
Charlottesville, VA
www.dmprobes.com
sales@dmprobes.com
(434) 962-8221

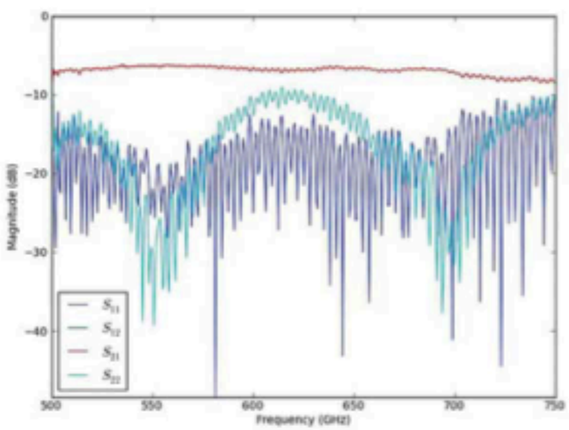


500-750 GHz Wafer Probes





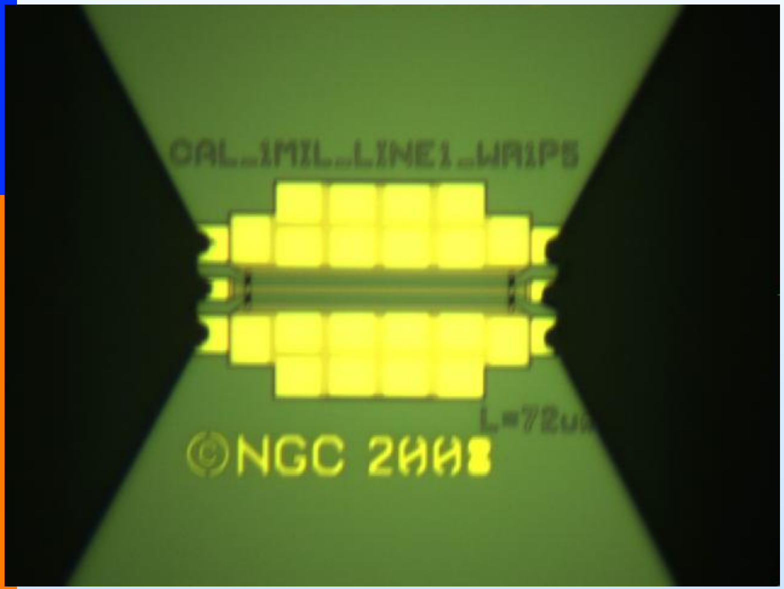




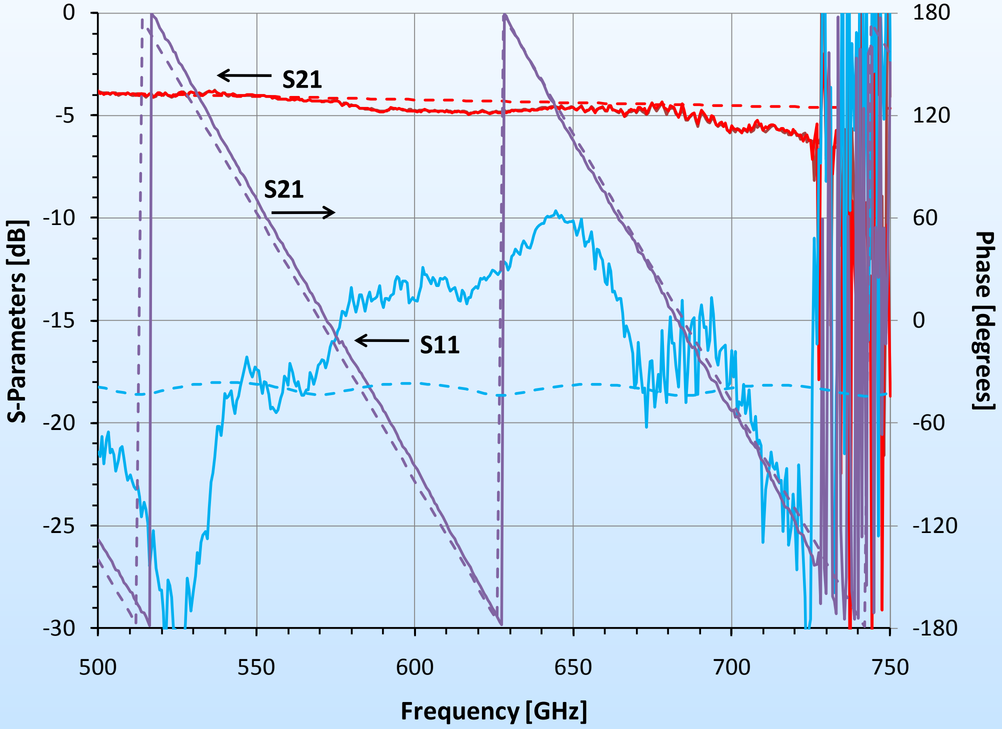
- WR1.5 Probes with replaceable single chip construction
- Average insertion loss of 7-8 dB
- Average return loss > 10 dB
- Excellent repeatability and durability
- Compatible with VDI WR-1.5 flanges

WM-380 Micromachined Probes – RF Performance

TRL Measurements from Northrup Grumman



Images courtesy of W.R. Deal



- World's first TRL calibration above 500 GHz!
  - UVa wafer probes with VDI THz Extenders
- The probe design is being extended to 1.1 THz for use with VDI 1.1 THz extenders

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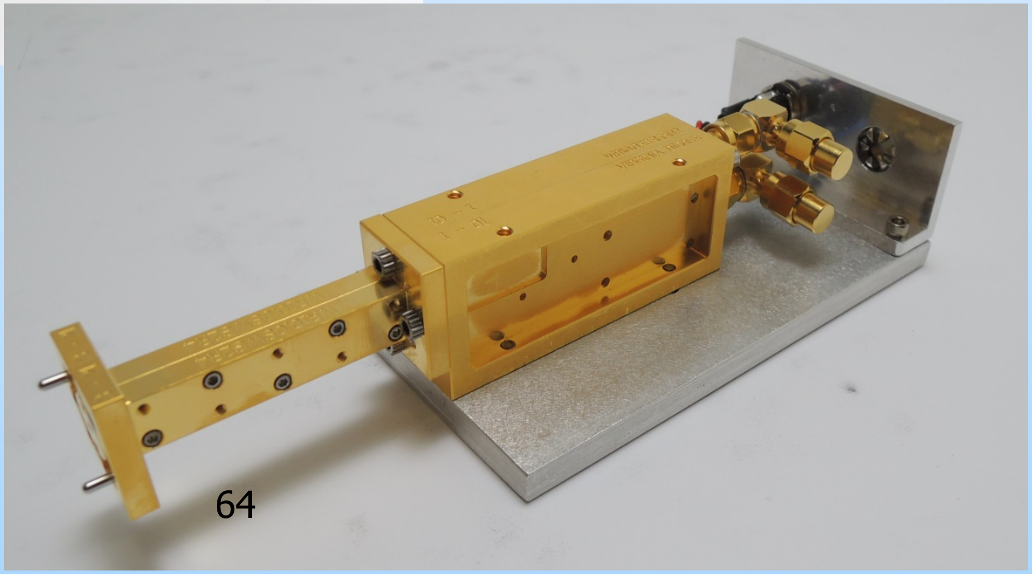
Recent Development: Mini-Modules

Full TxRx –
1.5″ x 3″ x 8.5″

Stand-alone Rx –
0.75″ x 1″ x 2.5″



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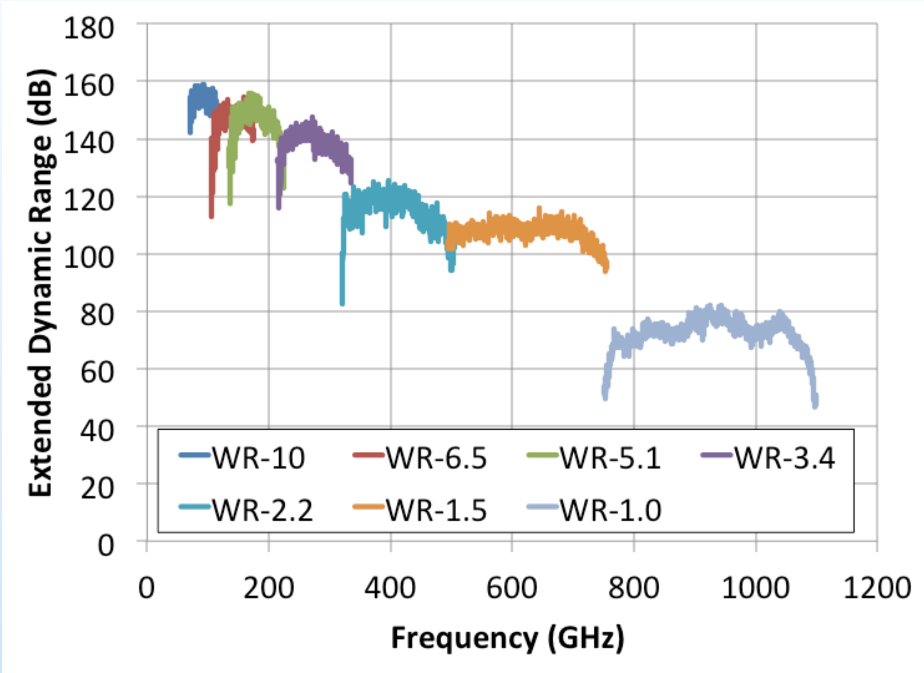
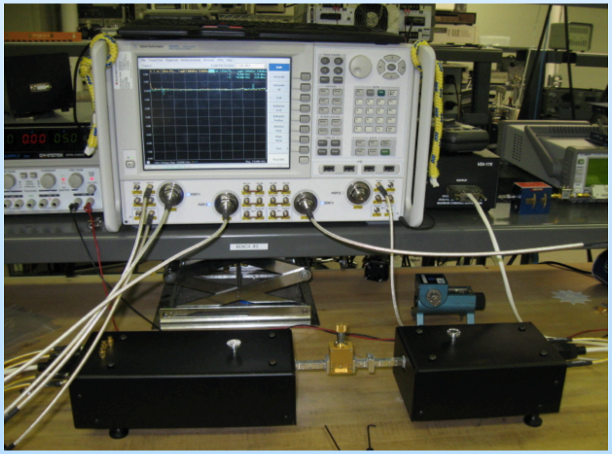
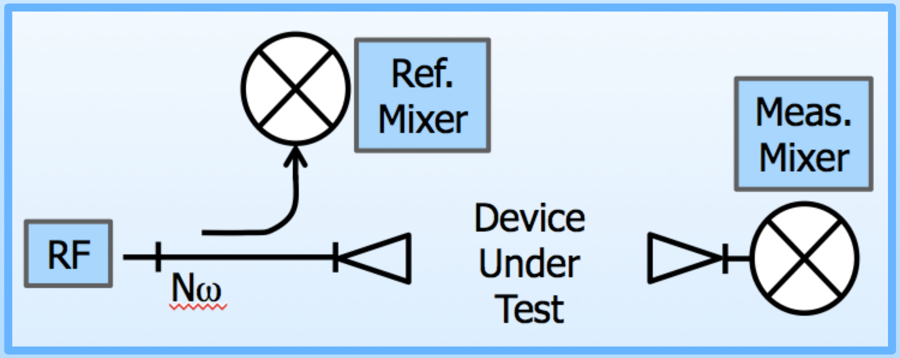
High Dynamic Range Transceivers

- VDI has developed a series of extended dynamic range transceivers
  - Customized for applications requiring high dynamic range, e.g. antenna testing
  - For use with DUTs with high loss
    - e.g. at WR-3.4 (220-330 GHz) a dynamic range of 120 dB can be achieved for DUT with 20 dB loss
    - Measurement mixer will be compressed at low bands by direct connection
- The system architecture is simplified from a typical VNA extender
  - Consists of a Source with Reference Mixer and a Measurement Mixer
    - Typical configuration for antenna testing







Conclusions

- VDI Goal: Open the THz window for routine technological use
- Technology based on Schottky diodes.
- Keys to success include innovative circuit designs, modern CAD, and advanced fabrication technology.
- Source power and frequency continues to increase.
- High performance, manufacturable systems have been developed
  - Custom sources and receivers are available at any frequency from 50 GHz through 3.1 THz
  - Full-waveguide band frequency extenders for
    - Signal generators
    - Spectrum analyzers
    - Network analyzers
- Higher levels of integration are allowing the development of more compact systems.