Solid State Sources and Transceivers for High Dynamic Range THz Measurements

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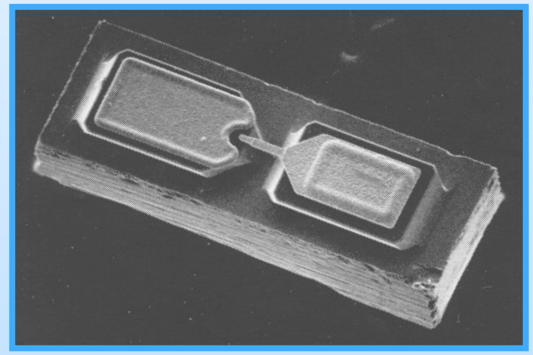
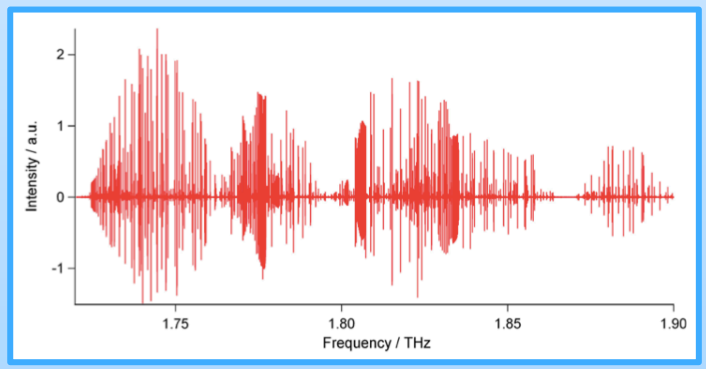
ALMA (NRAO)





De Lucia (OSU)

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www.vadiodes.com

Outline

- General Introduction
- Introduction to Schottky Diode Technology
- Solid-State THz Sources
- Solid-State THz Receivers
- THz Transceiver Systems and Applications
  - FMCW Radar
  - Gas Spectroscopy
  - THz Vector Network Analysis
- Schottky Detectors for Communication Systems
- Conclusions

Virginia Diodes - A Timeline

- 1980 – Initial work at UVa SDL
  - GaAs, Schottky Diodes, and Radio Astronomy above 100GHz
  - Developed diode technology for up to 5THz, used for radio astronomy up to 5THz
  - Many other emerging scientific applications….
- 1996 – VDI was formed
  - Goal – to make diode technology more widely available
- 2001 – VDI Restructured – we saw something was happening
  - Two new principles added
  - Began marketing components and then subsystems
  - Received first SBIR grants
- 2008 – First Vector Network Analyzer Extender Prototype Developed for ESA/ESTEC
- 2011 – First Fullband Extenders for 1.1 THz

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VDI in 2012

- 54 Employees – including 8 PhDs active in R&D
- A leader in Terahertz sources and receivers
- Most customers are involved in scientific research
- A significant player in test & measurement above 110GHz
- Experiencing rapid growth as the market for THz technology continues to expand
- Key Personnel :
  - Thomas W. Crowe – CEO, Crowe@VADiodes.com
  - Jeffrey L. Hesler – CTO
  - Stephen H. Jones – COO
  - Gerhard S. Schoenthal – Microfabrication
  - David S. Kurtz – Electronics, Reliability
  - Cliff Rowland – Marketing and Quotes

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VDI's Competitive Advantages

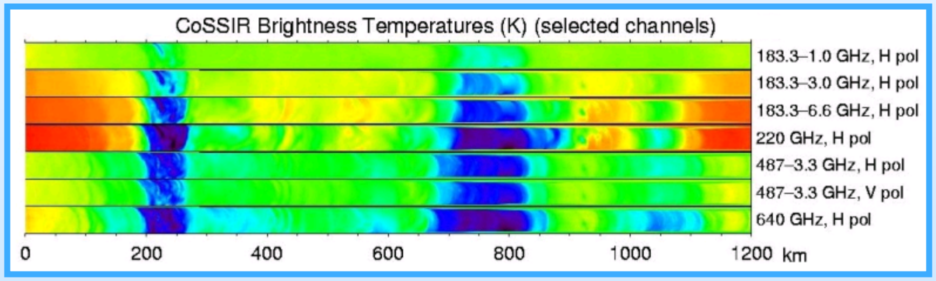
- VDI has a relatively long history in the field
  - Knowledge of the technology & applications
  - The best core technology base
    - – diodes, circuits, components, sub-systems…
  - We know the market, and are known by the market
    - 100's of customers around the world

- VDI is fully invested in THz technology
  - Continued investment in improved technology and productivity
  - Willing to take risks – 1.1THz VNA-extender, 2.7THz source…
  - But, remain focused on practical solutions

Applications Above 100GHz

Radio Astronomy

Weather Monitoring



Wang et al (NASA-GSFC)

- Basic Science – the primary driver
  - Astronomy
  - Gas Spectroscopy
  - Plasma Diagnostics for Fusion
  - EPR/ESR/PELDOR
  - Weather Monitoring (Ice Clouds)

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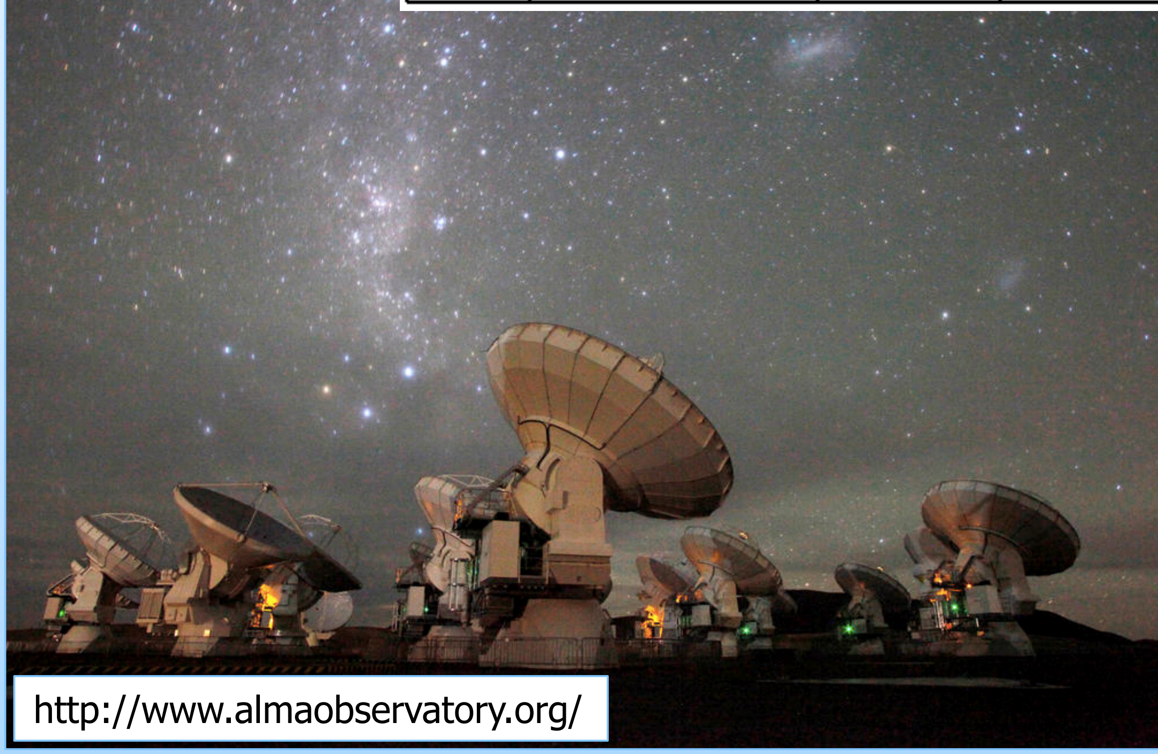
ALMA Project

- 66 Antennas on a high desert plateau in Chile
  - 54 12m and 12 7m antennas
- 2 Receivers for each band
- 12 VDI THz multiplier chains in each antenna

Table 1: Waveguides for ALMA bands

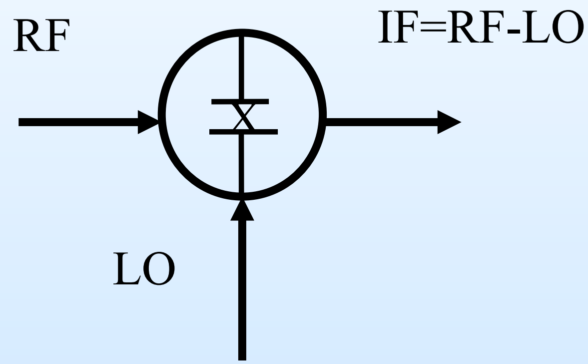
Band	from - to (GHz)	f_0 (GHz)	Δf (GHz)	$\frac{\Delta f}{f_0}$
3	84 - 116	100	32	32.0%
4	125 - 163	144	38	26.4%
5	163 - 211	187	48	25.7%
6	211 - 275	243	64	26.3%
7	275 - 370	322.5	95	29.5%
8	385 - 500	442.5	115	26.0%
9	602 - 720	661	118	17.9%
10	787 - 950	868.5	163	18.8%

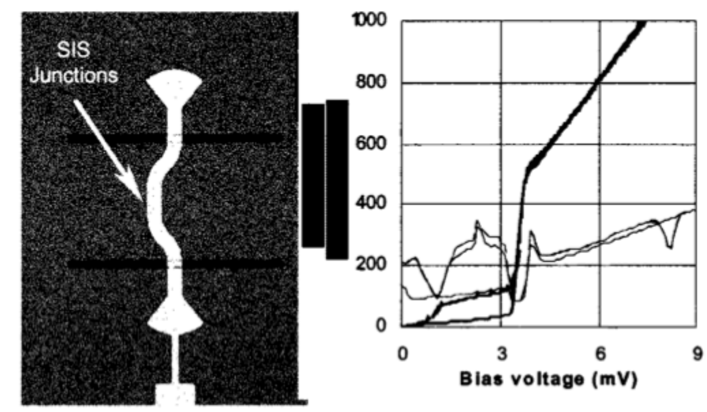


Astronomical Heterodyne Receivers

- Radio astronomers use cryogenic superconducting mixers to detect signals
  - Superconductor-Insulator-Superconductor (SIS) technology
  - State-of-the-art sensitivity
  - Requires liquid-helium dewar
    - Bulky and expensive
- Receiver uses nonlinear mixing of strong Local Oscillator (LO) with RF signal
- The Local Oscillator (LO) signal is provided by solid-state THz multiplier chain

Fundamental SIS Mixer





(a) (b)

A. Karpov, D. Miller, F. Rice, J. Zmuidzinas, J. A. Stern, B. Bumble, and H. G. Leduc, "Low noise 1.2 THz SIS receiver," in *8th Int. Superconduct. Electron. Conf.*, Osaka, Japan, June 19–22, 2001, pp. 521–522.

ALMA Band 6 (221-265 GHz) LO Chain

Phase-locked Synthesizer

Pre-multipliers

MMIC Amps

VDI THz Multipliers

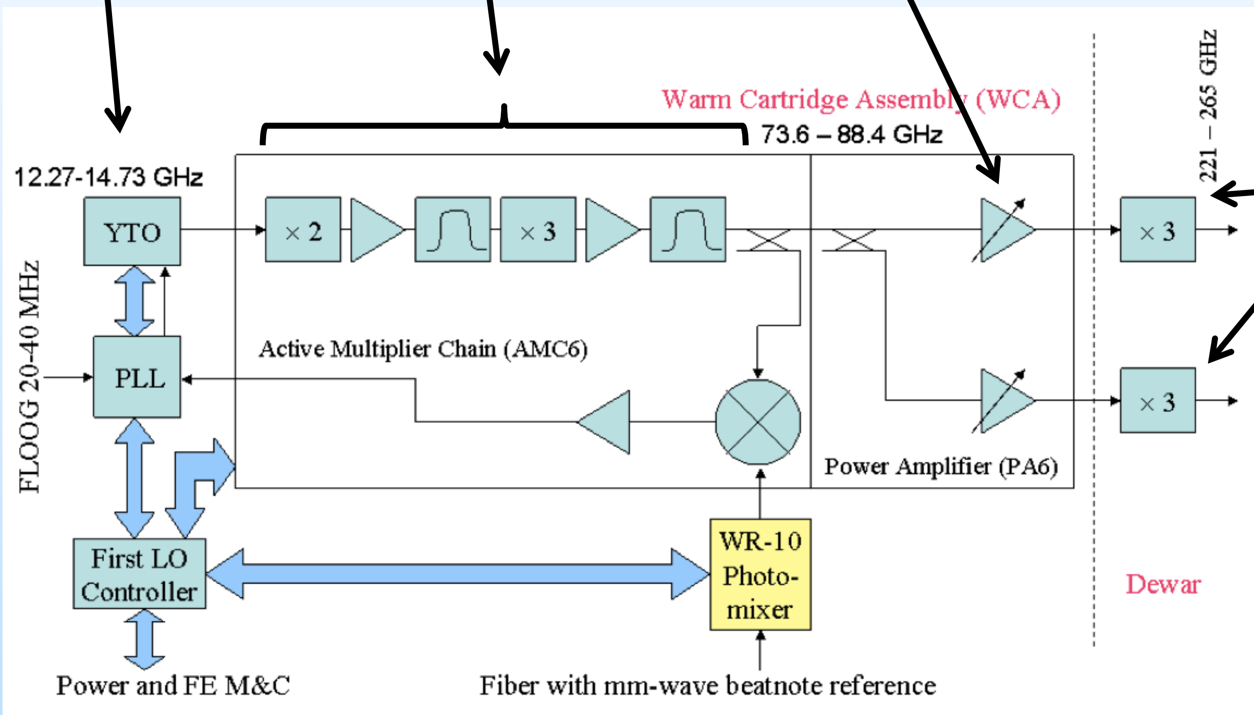
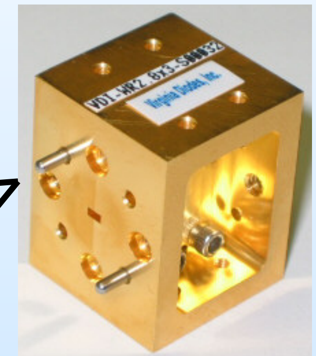


Fig. 1 Block diagram of local oscillator (LO) for ALMA Band 6 (211-275 GHz).



Bryerton 2007 ISSTT

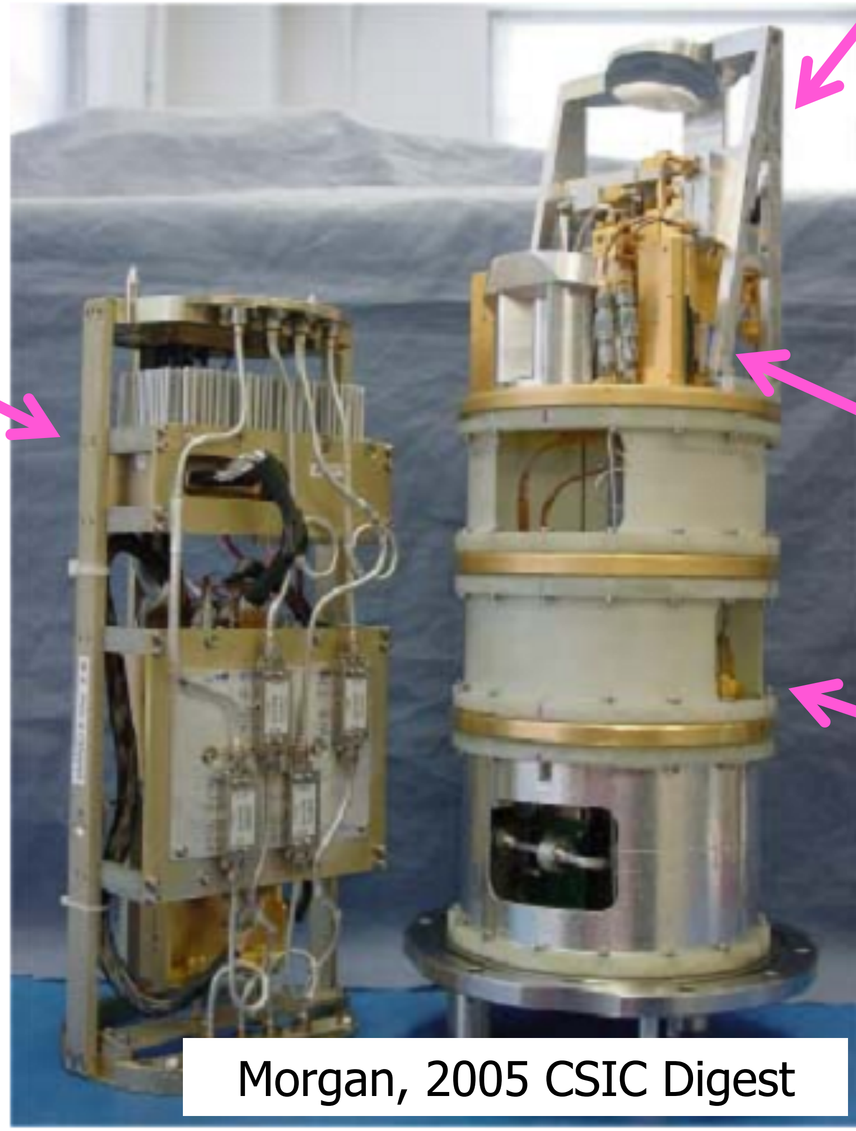
ALMA Front End

Warm Cartridge Assembly

Cryogenic Front End

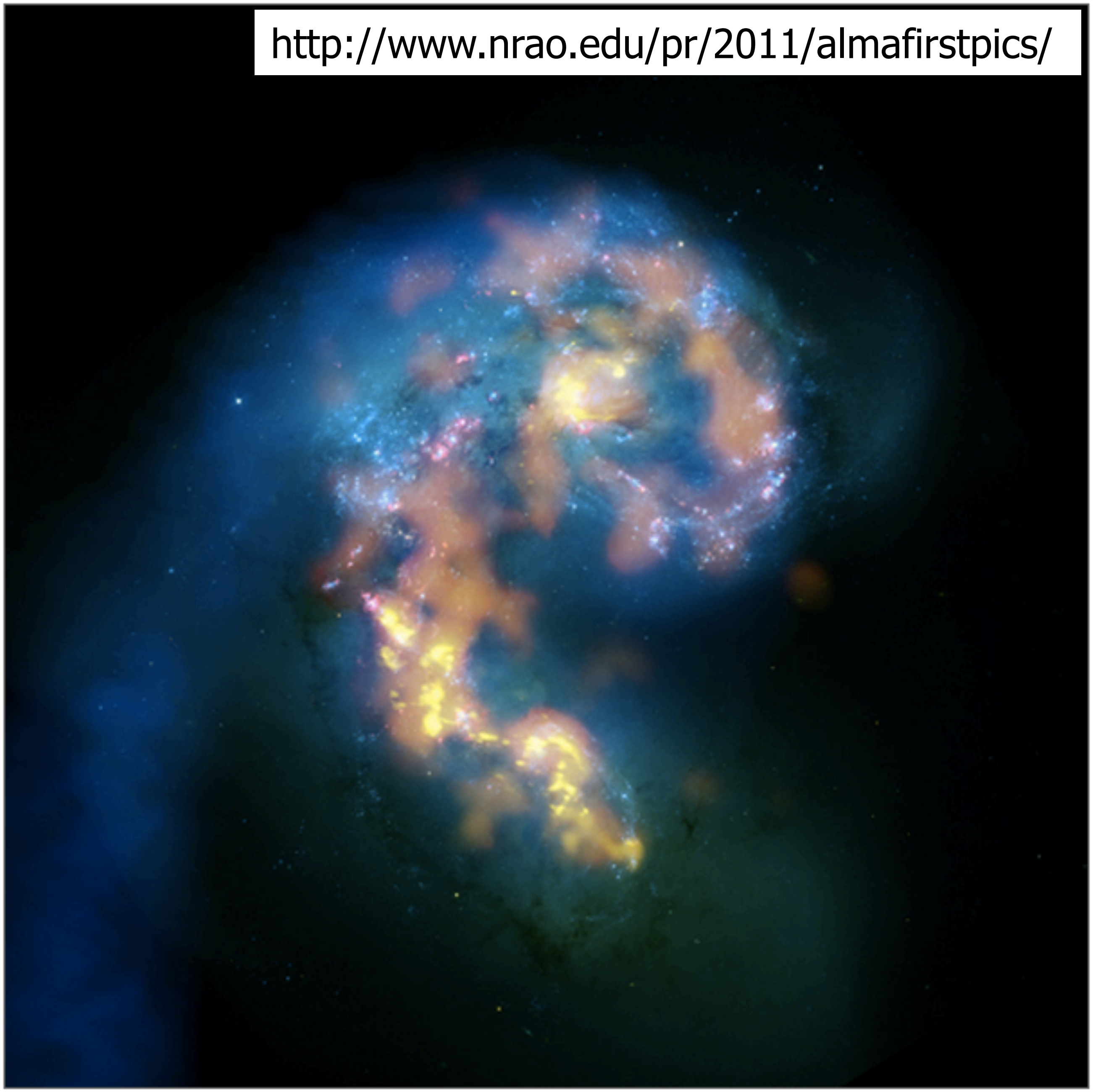
4K Stage with Mixers

VDI Multipliers on 78K Stage



Morgan, 2005 CSIC Digest

Fig. 3. Photograph of the receiver cartridge for ALMA Band 6. The warm cartridge assembly is on the left, while the cryogenic portion is on the right.

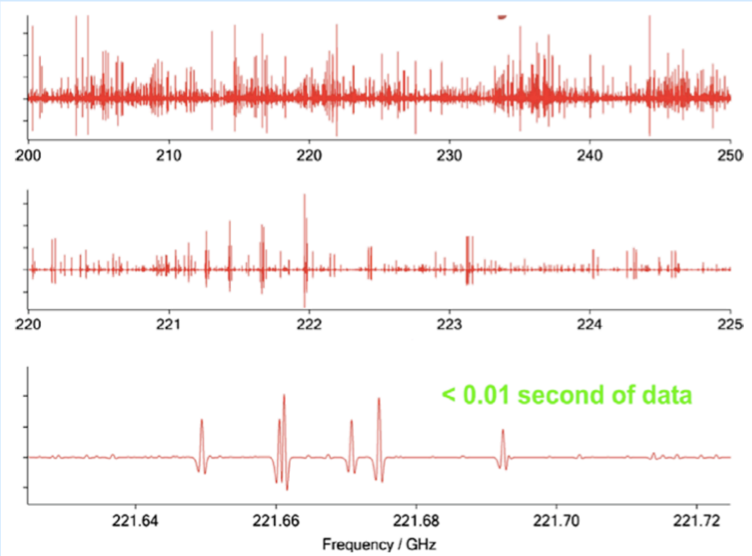


Multiwavelength composite of interacting galaxies NGC 4038/4039, the Antennae, showing VLA radio (blues), past and recent starbirths in HST and CTIO optical (whites and pinks), and a selection of current star-forming regions in ALMA's mm/submm (orange and yellows) showing detail surpassing all other views in these wavelengths.

Applications Above 100GHz

- THz Field moving from Basic Science to Applications
  - Concealed Weapons Detection
  - Collision Avoidance Radar
  - Detection of Chem./Bio. Hazards
  - Wideband & Secure Communications
  - Medical Diagnostics
  - General Test & Measurement

Chem/Bio Detection



De Lucia (OSU) – 2010 JMS

Concealed Weapons Detection

Cooper (JPL) – 2010 SPIE

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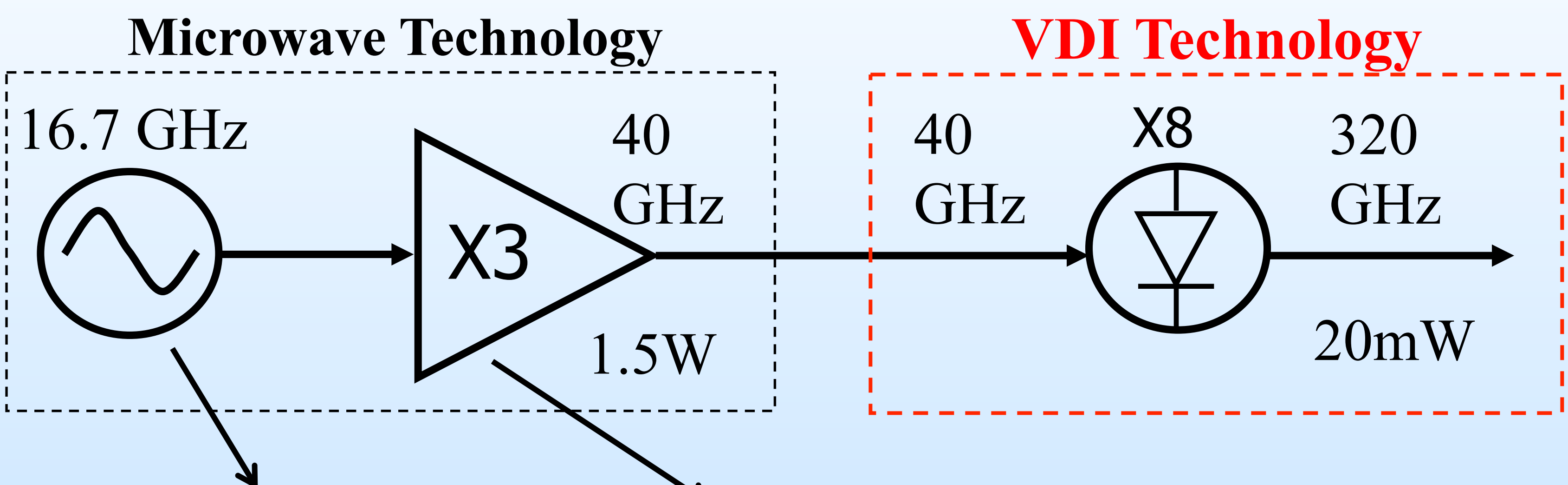
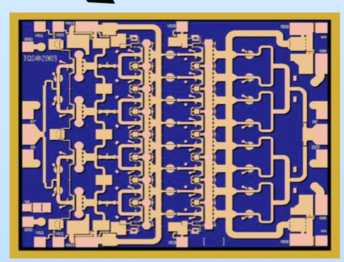
Core Technology: Use nonlinear devices to extend the frequency range of traditional microwave electronics



Herley-CTI



Triquint

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

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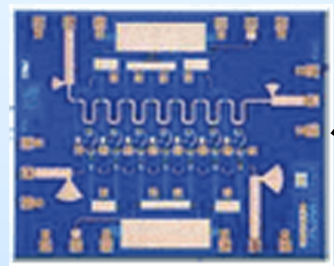
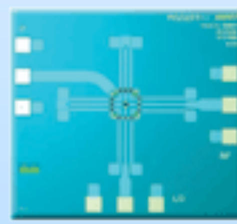
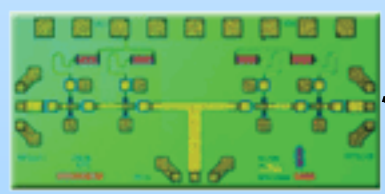
MMIC Technology

- Microwave systems are based upon Si and GaAs MMIC technology
- Wide variety of MMIC chips available
  - Mixers & Multipliers
  - Amplifiers (Power and Low Noise)
  - Switches
  - …
- Developed for commercial & military use

Hittite
MICROWAVE CORPORATION







ICs ▾

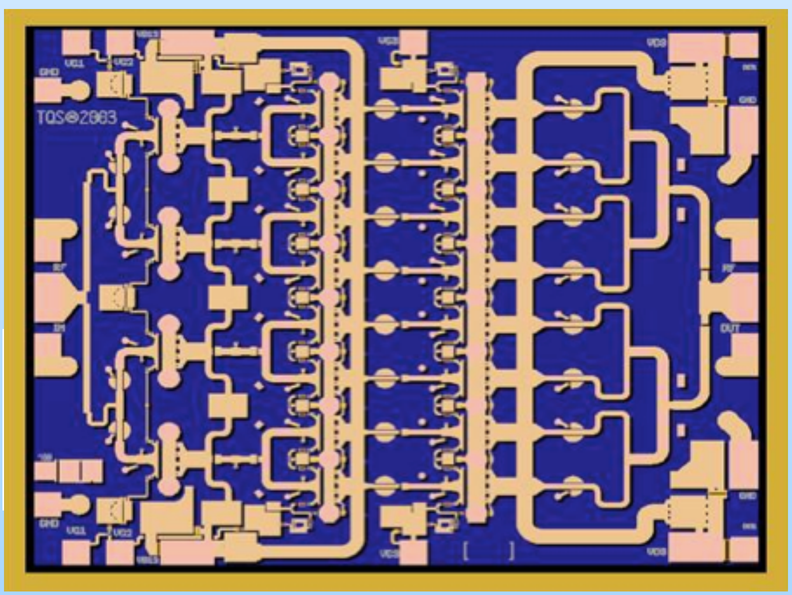
Amplifiers
Attenuators
Automatic Gain Control
Broadband Time Delay
Clocks & Timing
Comparators
Crosspoint Switch
Data Converters
DC Power Conditioning
DC Power Management
Filters - Tunable
Freq. Dividers & Detectors
Freq. Multipliers
High Speed Digital Logic
IF/Baseband Processing
Interface
Limiting Amplifiers
Mixers
Mods & Demodulators
Mux & Demux
Optical Modulator Drivers
Passives
Phase Shifters
PLLs
PLLs with Integrated VCOs
Power Detectors
SDLVAs
Signal Conditioners
Switches
Transceivers
Transimpedance Amplifiers
Variable Gain Amplifiers
VCOs & PLOs
Velocium

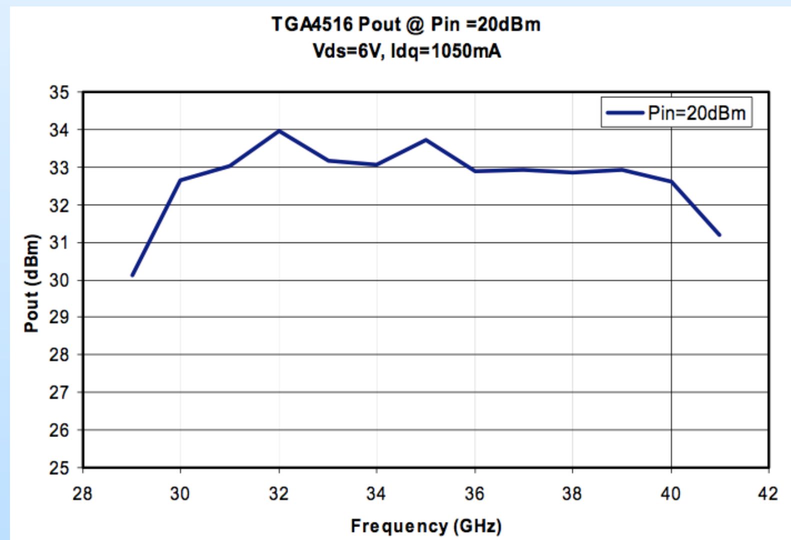
Example: Triquint 2W 30-40 GHz Amp

- 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

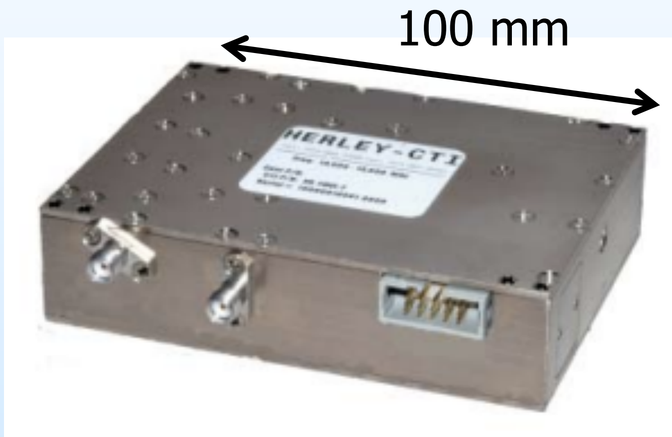




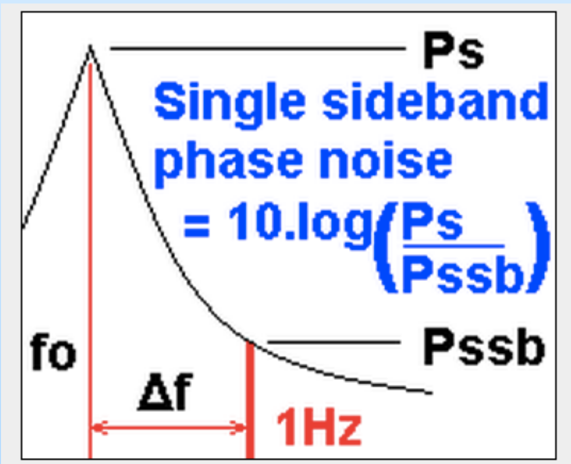
http://www.triquint.com/products/p/TGA4516-TS

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



Single sideband phase noise

www.telestrian.co.uk/phasenoise.html

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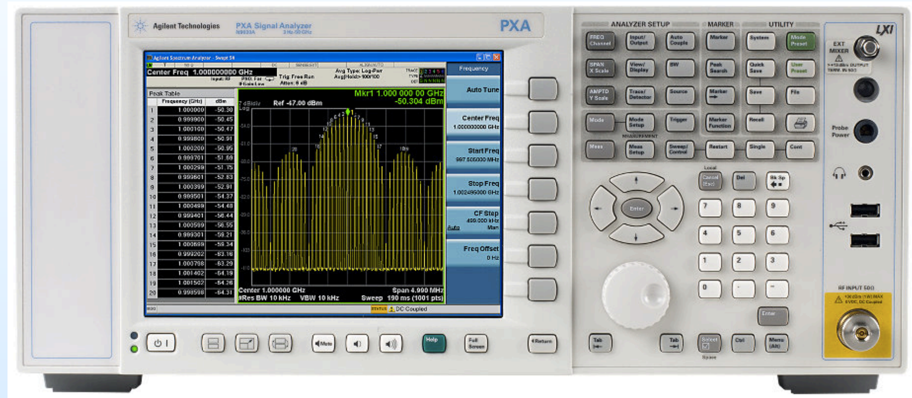
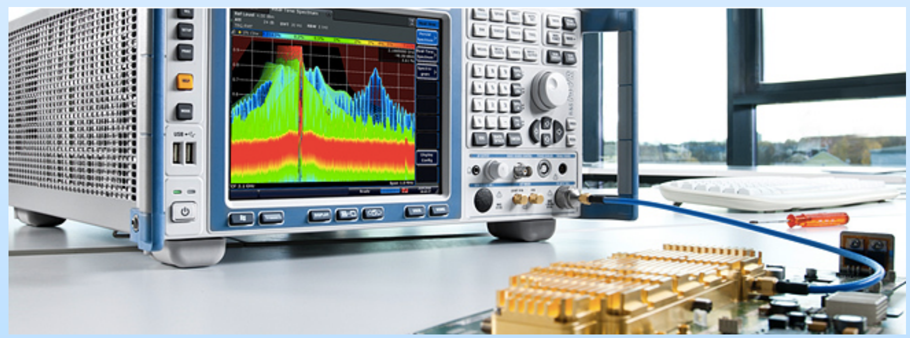
Spectrum Analyzers

- 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

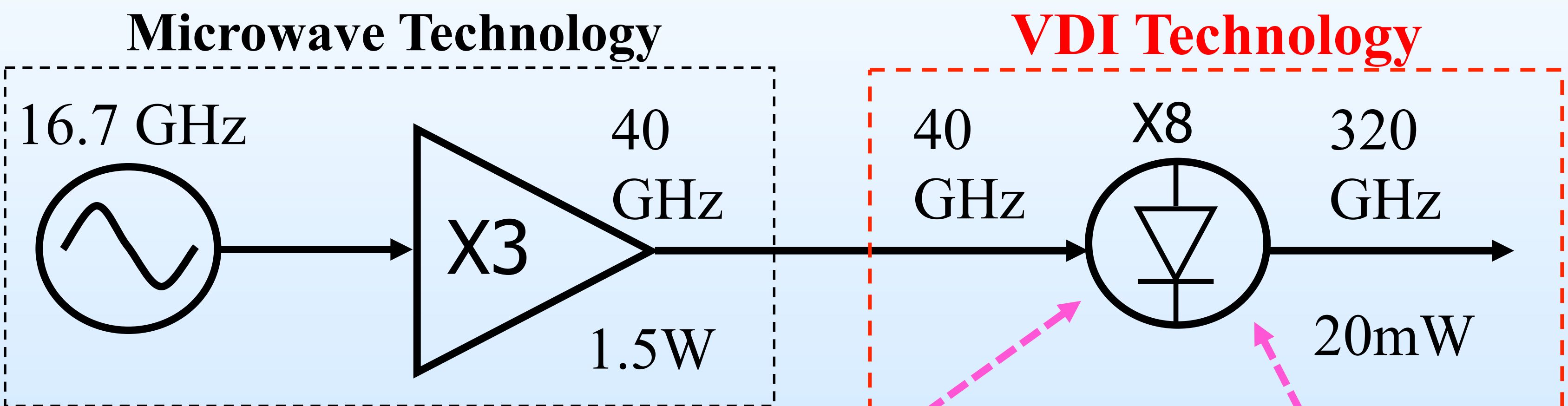


Agilent PXA



Rohde & Schwarz FSU

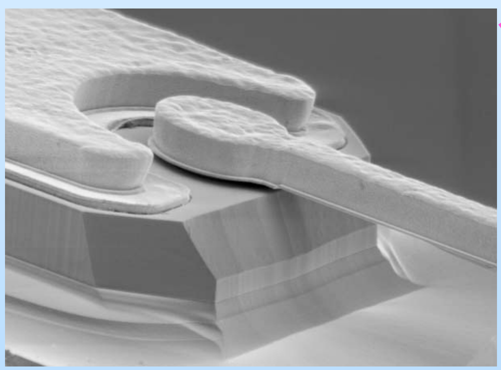
Core Technology: Use nonlinear devices to extend the frequency range of traditional microwave electronics



Schottky Diodes

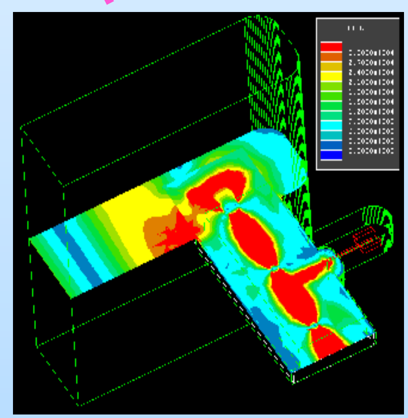
Planar

Advanced fabrication technology

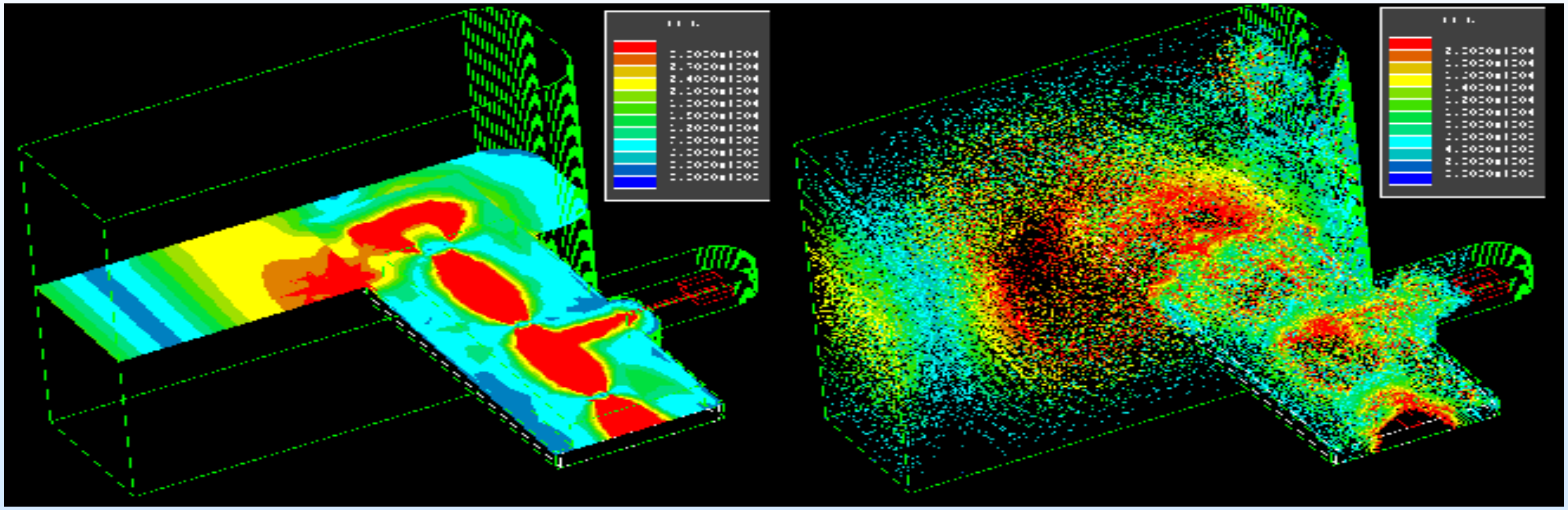


CAD Design

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



THz Technology - Computer Aided Design and Simulation

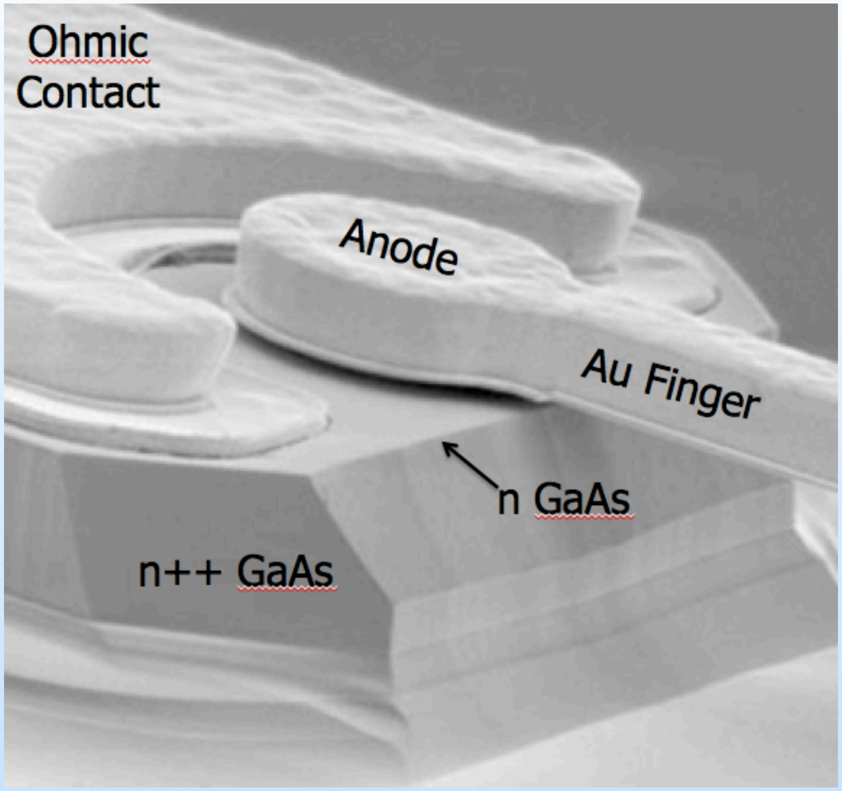


HFSS Simulation of Waveguide to Microstrip Transition

- Benefits:
  - Accurate designs, the first time, without the need for scale models.
  - E&M simulations give a “physical feel” for how the circuit behaves and how to optimize performance.
  - More complicated circuit designs can now be attempted, yielding improved performance and bandwidth.

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



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

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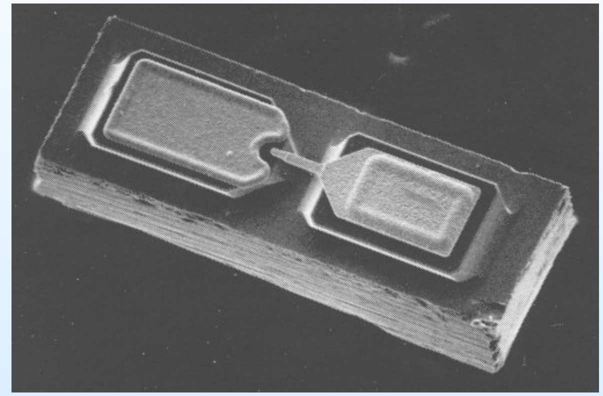
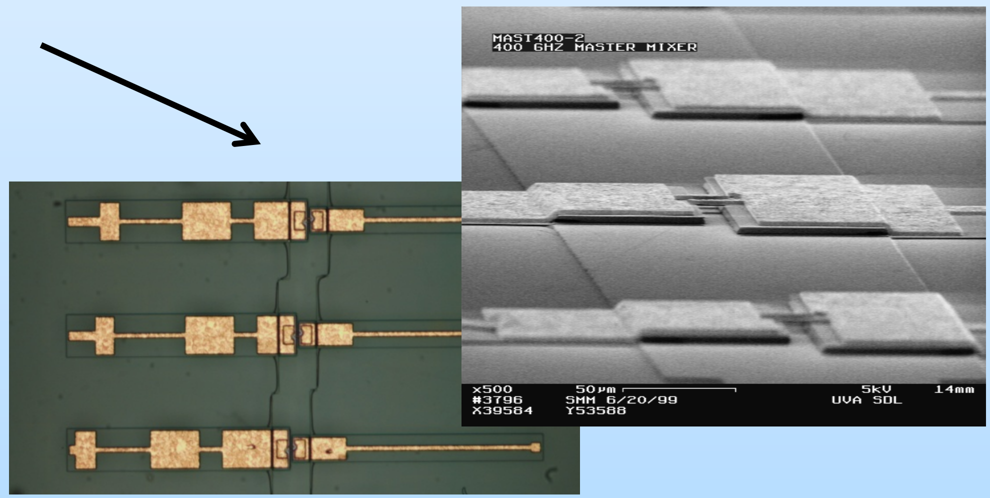
VDI Planar Diode Fabrication Technology

- Planar Schottky Diodes
  - Mechanically rugged
  - Photolithographic reproducibility
- Integration of Diode with Coupling Circuitry
  - Operation to higher frequencies (>3 THz)
  - More repeatable assembly



Flip-chip Planar Diode



Integrated Planar Diodes

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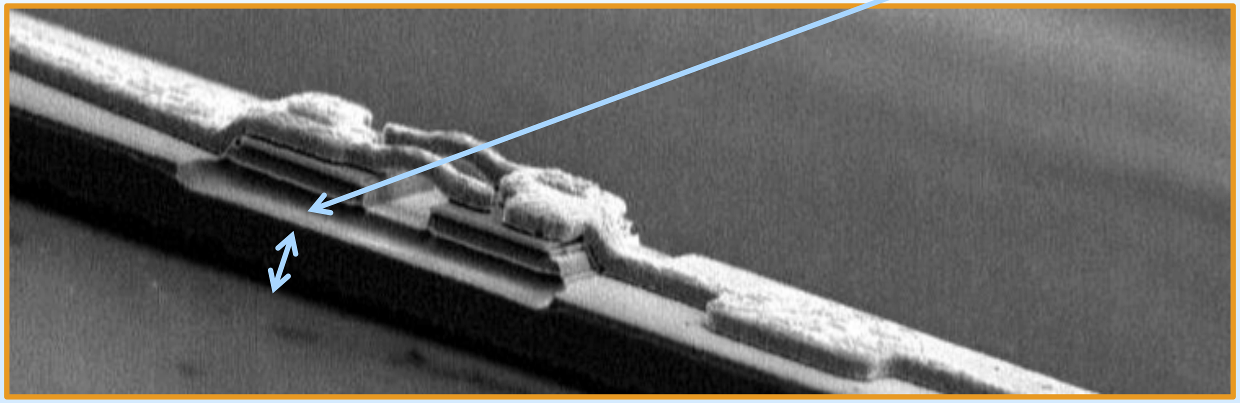
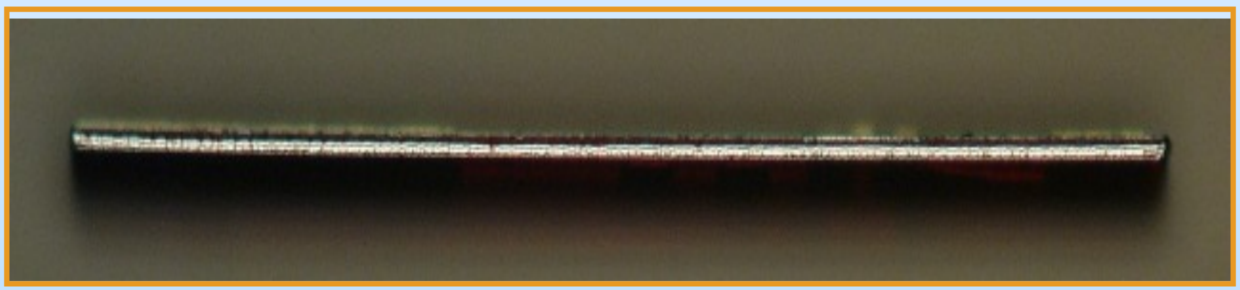
THz Diode Integrated Circuit

Thickness ~5 um (for size scale, red blood cells 5-10 um!)





THz circuits are very small, but surprisingly robust!

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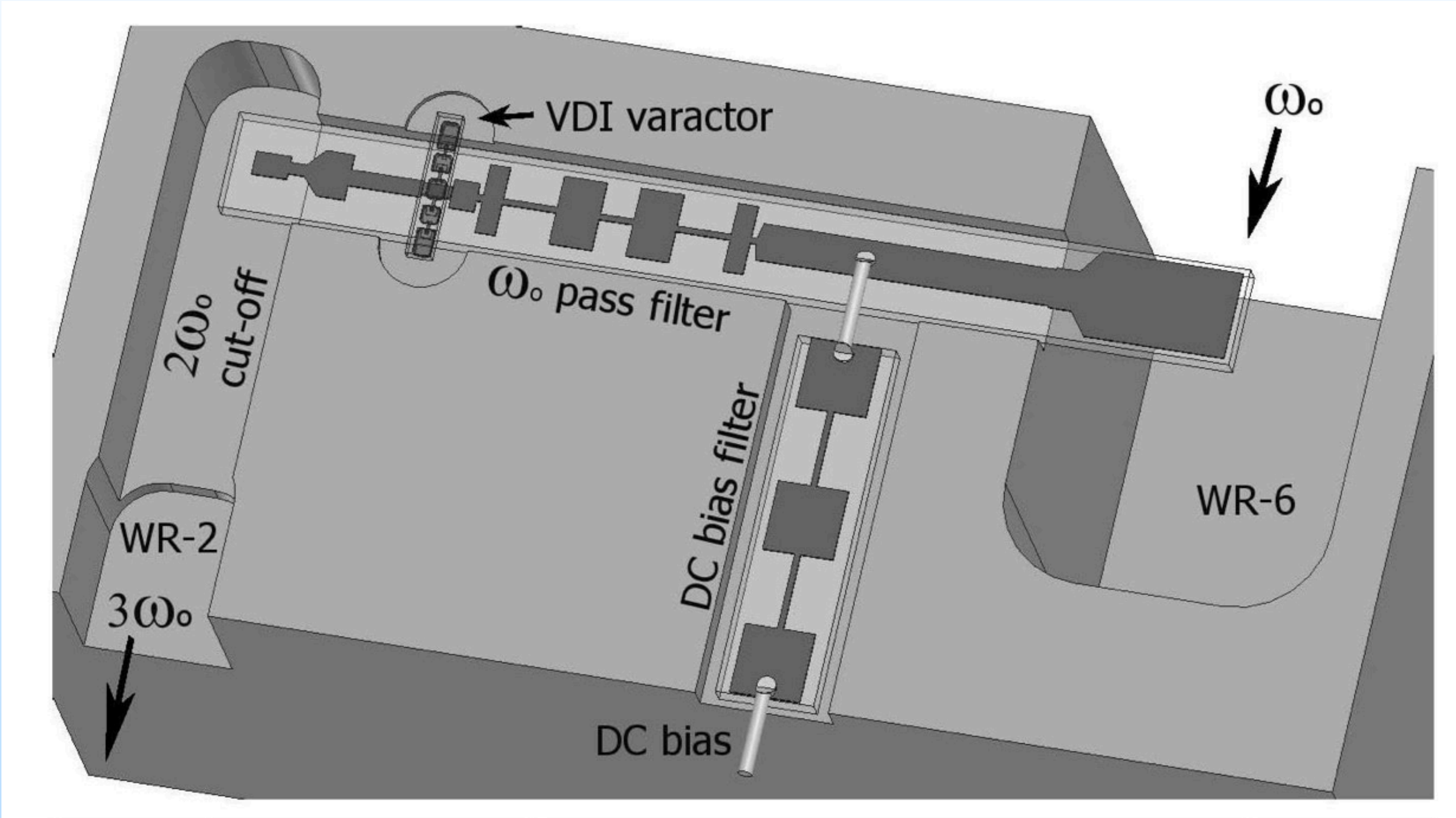
Waveguide Based Components - Varactor Frequency Tripler



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

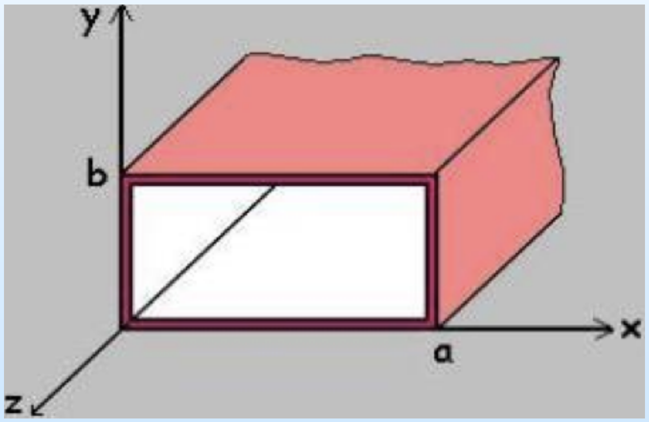


Figure from www.ee.bilkent.edu.tr

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

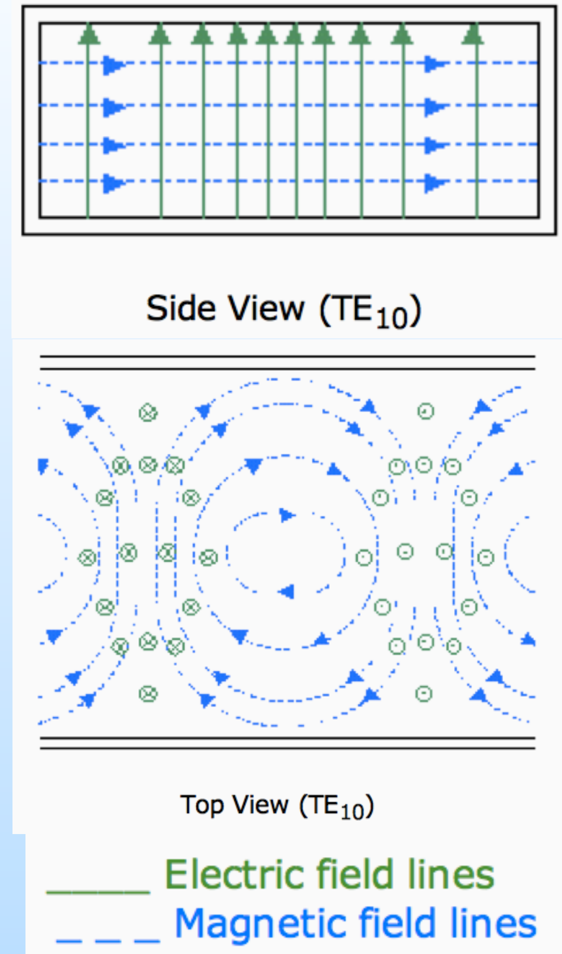


Figure from www.rfcafe.com

Waveguide Sizes and Frequency Ranges

Name	Width (µm)	Height (µm)	Cut-off frequency (GHz)	Suggested minimum frequency (GHz)	Suggested maximum frequency (GHz)
WM-2540	2540	1270	59.014	75	110
WM-2032	2032	1016	73.768	90	140
WM-1651	1651	825.5	90.791	110	170
WM-1295	1295	647.5	115.75	140	220
WM-1092	1092	546	137.27	170	260
WM-864	864	432	173.49	220	330
WM-710	710	355	211.12	260	400
WM-570	570	285	262.98	330	500
WM-470	470	235	318.93	400	600
WM-380	380	190	394.46	500	750
WM-310	310	155	483.54	600	900
WM-250	250	125	599.58	750	1100

http://grouper.ieee.org/groups/1785/

THz Waveguide Interface Standards

IEEE P1785: A New Standard for Waveguide Above 110 GHz

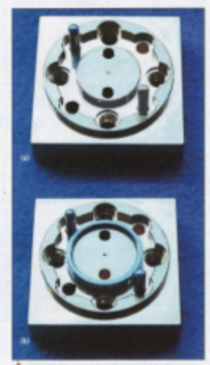
The Microwave Theory and Techniques Society (MTT-S) of the IEEE has recently launched an activity to develop an international standard to define waveguides used at frequencies of 110 GHz and above—specifically, rectangular metallic waveguides. The standard's Working Group (P1785) has already met several 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 was recently approved
- Parts 2 & 3 still under development
- See http://grouper.ieee.org/groups/1785/

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

▲ *Fig. 1 A precision version of the so-called "UG-387" flange, showing the two additional dowel holes, immediately above and below the rectangular waveguide aperture.*



▲ *Fig. 2 Ring-centered waveguide flange: (a) with dowel holes and pins and (b) with the coupling ring in place.*

"flanges". The Working Group is keen to ensure that it considered all flange designs that are used regularly at these frequencies (that is at 110 GHz and above). Therefore, a subgroup is being set up to investigate this matter further. Advice is also being sought from the entire millimeter- and submillimeter-wave communities to help identify any such candidate flange designs. *If you are aware of any flange design that you consider should be included in this standard, please contact the authors of this article.* The plan is that the standard, when published, will contain all appropriate flanges that will be used routinely in this frequency region.

For example, one such flange that is likely to be considered for inclusion in the standard is a precision version of the MIL-F-3922-67D flange (often called UG-387) that has been described[5] and is shown in **Figure 1**. Compared to the conventional UG-387 flange,[6] this precision version contains two additional alignment dowel holes immediately above and below the waveguide aperture. These additional holes (and the associated dowel pins) are specified to a tighter dimensional tolerance than the dowel holes and pins found on the conventional UG-387 flange. This leads to better mechanical alignment of the waveguide interfaces and hence lower electrical reflection from a mated pair of flanges.

Another type of flange that is likely to be considered for inclusion in the standard is a newer design—a ring-centered flange,[7] as shown in **Figure 2**. This design is compatible with both the UG-387 and precision UG-387 flange designs, but also uses a coupling ring to significantly improve the alignment of the flange interfaces.

It is expected that the IEEE standard, when published, will contain several flange designs, allowing end-users (such as customers, suppliers, etc.) to chose a design that best meets their given requirements. The role of the standard, in this context, is to provide the information needed for this choice to be made reliably.

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.[8] Therefore, the publication of this standard is timely, and should serve our industry well for many years to come. ■

Nick Ridler and Ron Ginley are chair and vice-chair, respectively, of the IEEE P1785 working group (http://grouper.ieee.org/groups/1785).

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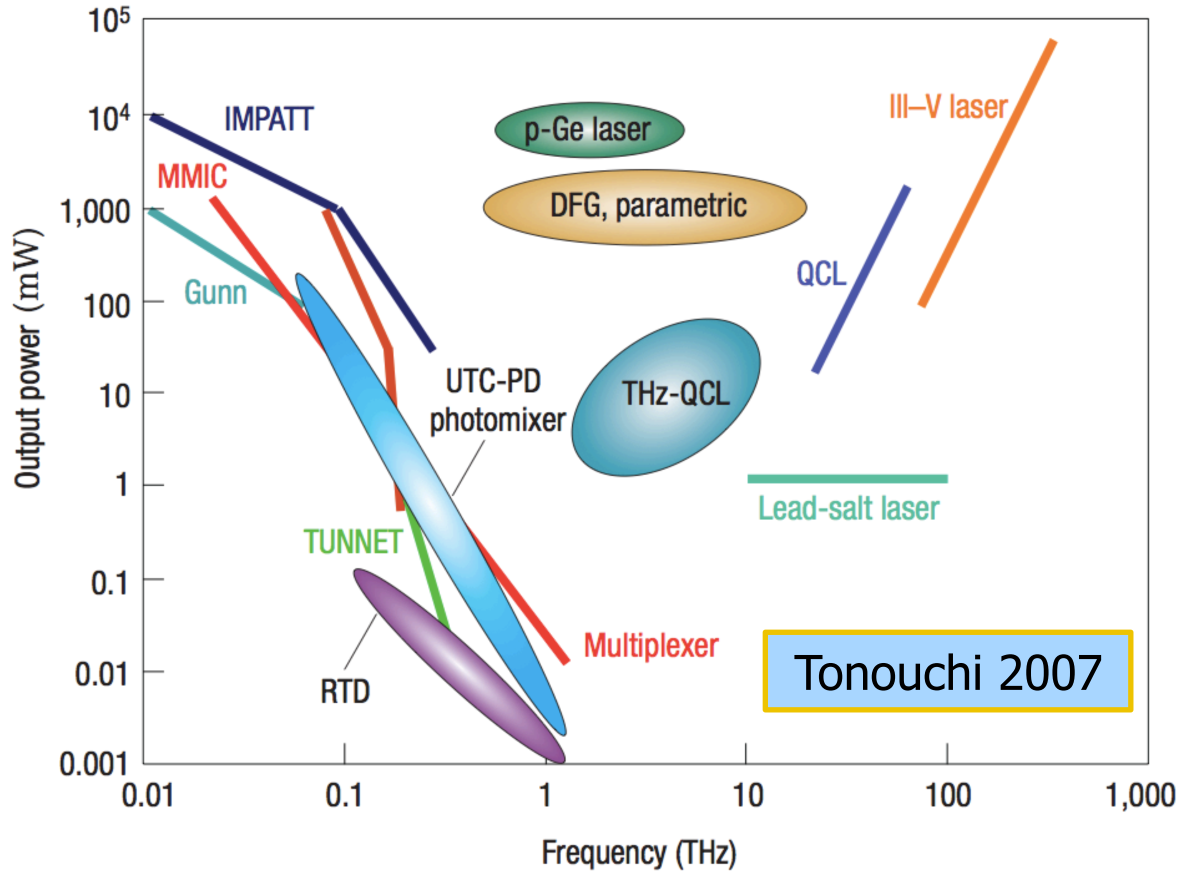
Ridler et al., Microwave Journal Cables & Connectors Supplement, Mar. 2011, pp. 20-24.

Virginia Diodes, Inc.

www.vadiodes.com

Challenges Above 100 GHz

- The transition from electronics to optics
  - No transistors, semiconductor lasers, isolators, switches, tunable attenuators



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Challenges Above 100GHz

- No broadly accepted standards – power, flanges, connectors
- High transmission line losses
  - Microstrip ~ 1 dB/mm @ 600 GHz
  - Waveguide ~0.08 dB/mm @ 600 GHz
  - Atmospheric losses 0.0002 dB/mm (typ.) at 600 GHz
    - 0.02 dB/mm at 557 GHz Water line
- Machining challenges
  - 3 THz operation requires channel width < 25 um!

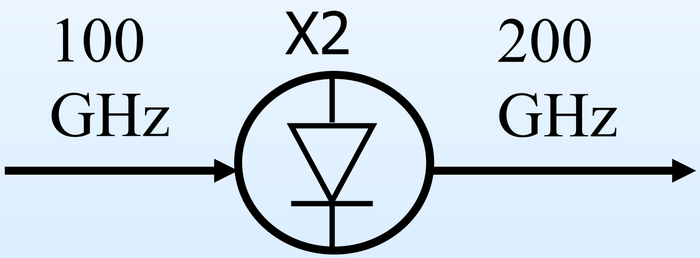
Outline

- General Introduction
- Introduction to Schottky Diode Technology
- **Solid-State THz Sources**
- Solid-State THz Receivers
- THz Transceiver Systems and Applications
  - FMCW Radar
  - Gas Spectroscopy
  - THz Vector Network Analysis
- Schottky Detectors for Communication Systems
- Conclusions

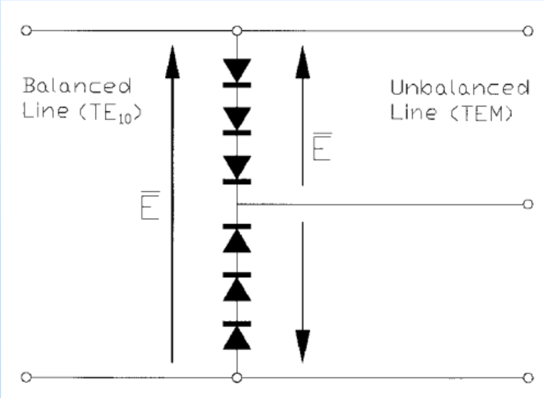
Schottky Diode Frequency Multipliers

- 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

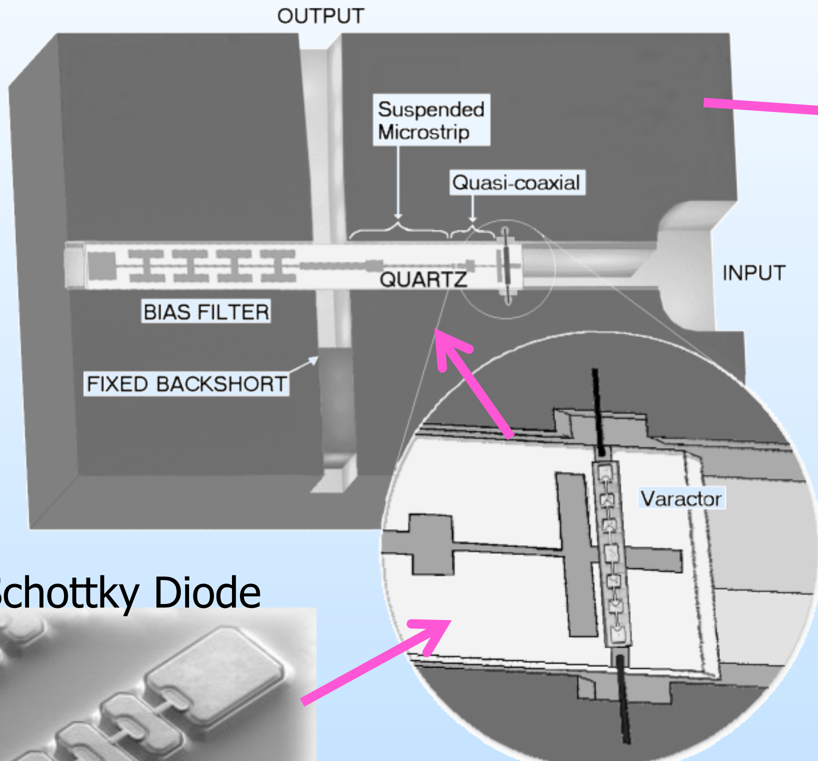


Balanced Circuit Topology

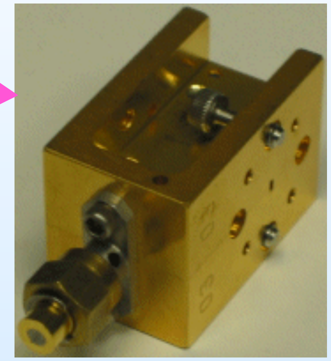


Porterfield et al (MTT, 1999)

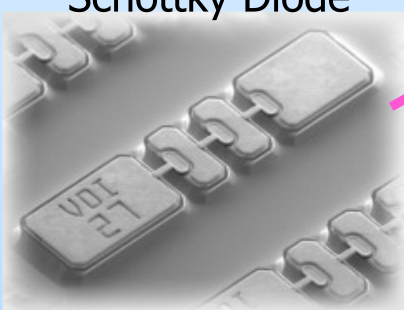
THz Sources: Balanced Varactor Doublers

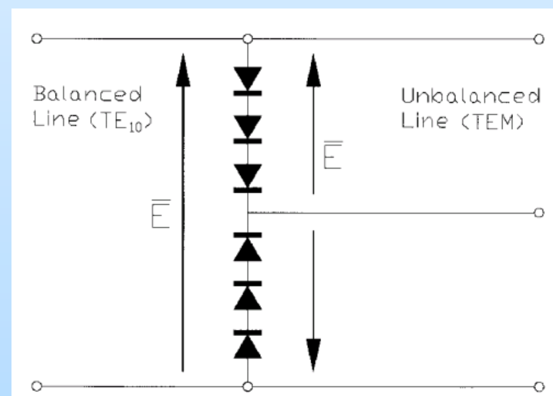


Frequency Doubler



Schottky Diode





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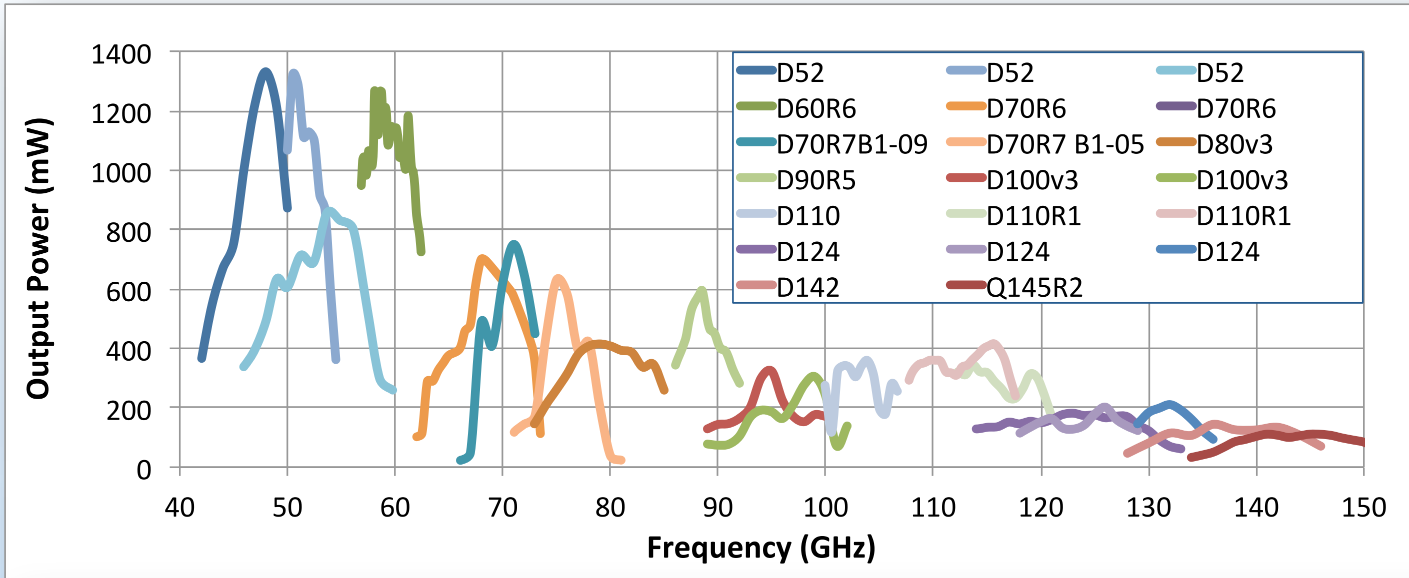
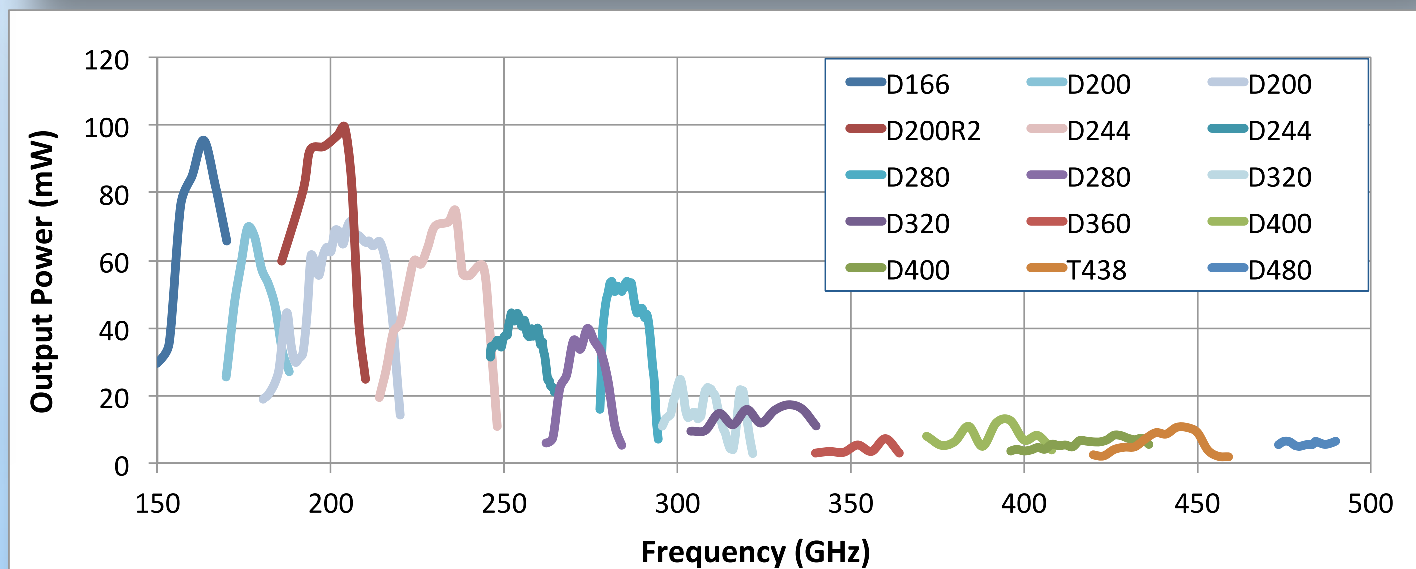
2/21/13

VDI High-Power High-Efficiency Varactor Multipliers





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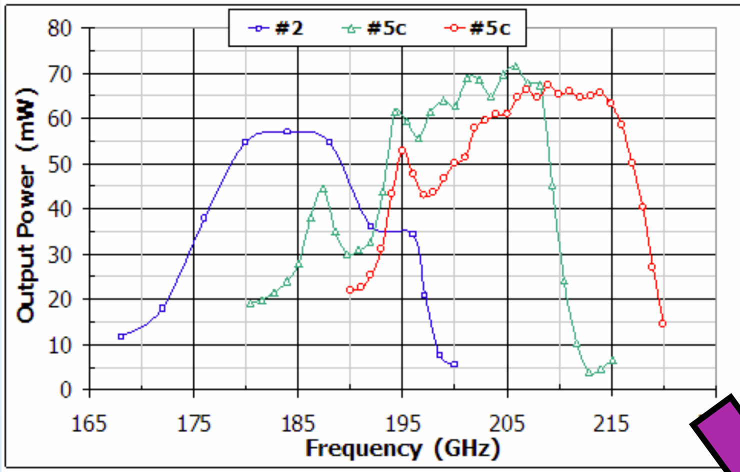
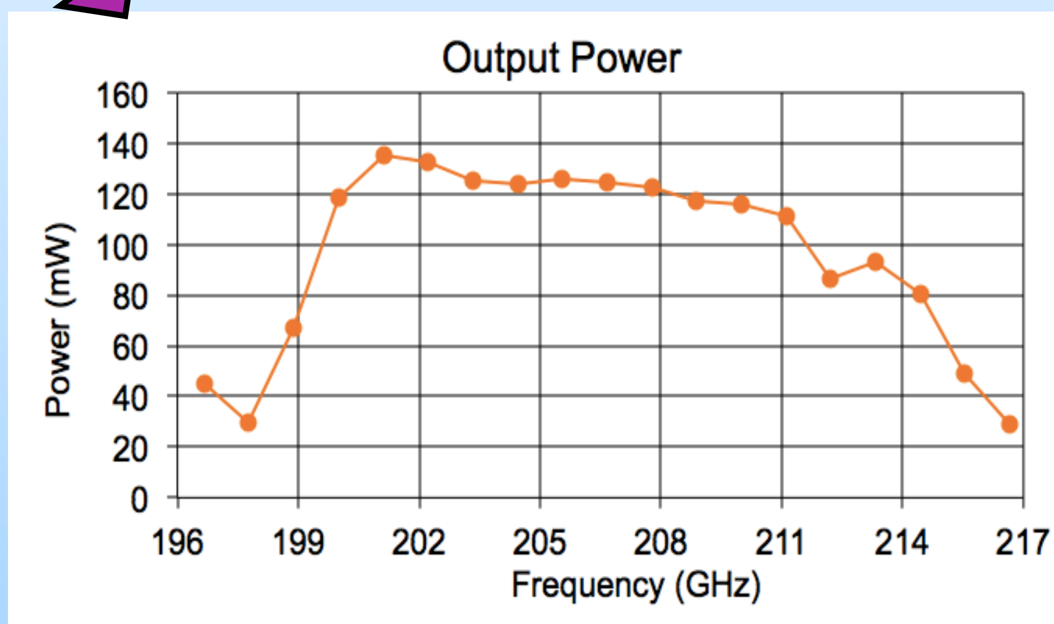
Recent 200 GHz Varactor Multiplier Results



- Previous version had maximum power ~60 mW
- Recent development of diamond heat spreaders
  - Thermal issues are key for multiplier design
- Diamond design ran cooler and has much higher efficiency
- In addition VDI has a technology to power combine two varactor doublers in one block
  - Combining efficiency near 100%
- Diamond+Combining → > 200 mW at 200 GHz

D200

Latest Result



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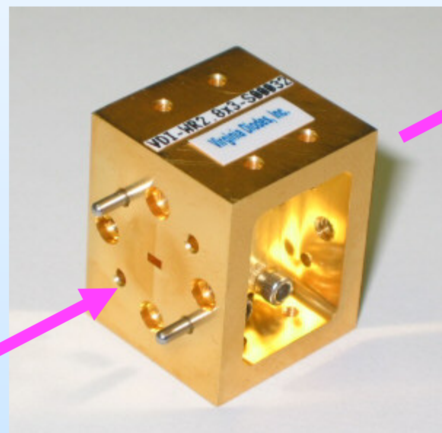
Broadband Frequency Multipliers

WR-2.8X3
(265-400 GHz)



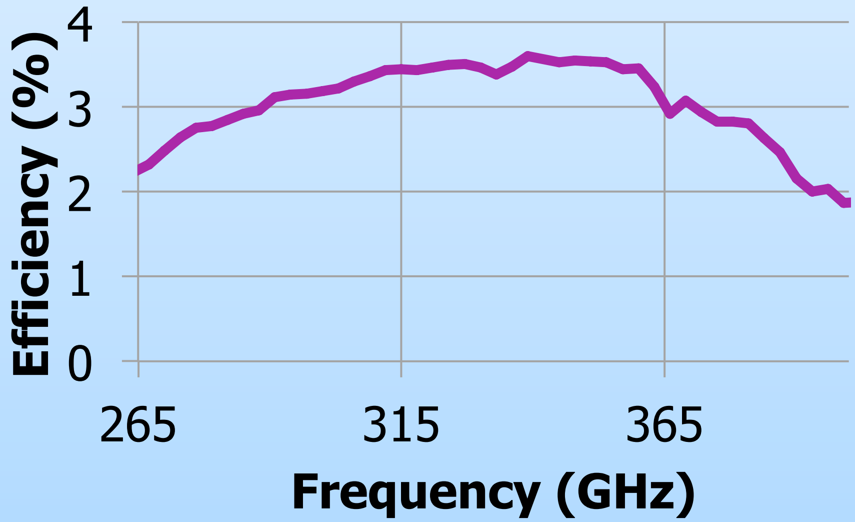
Input

88-133 GHz

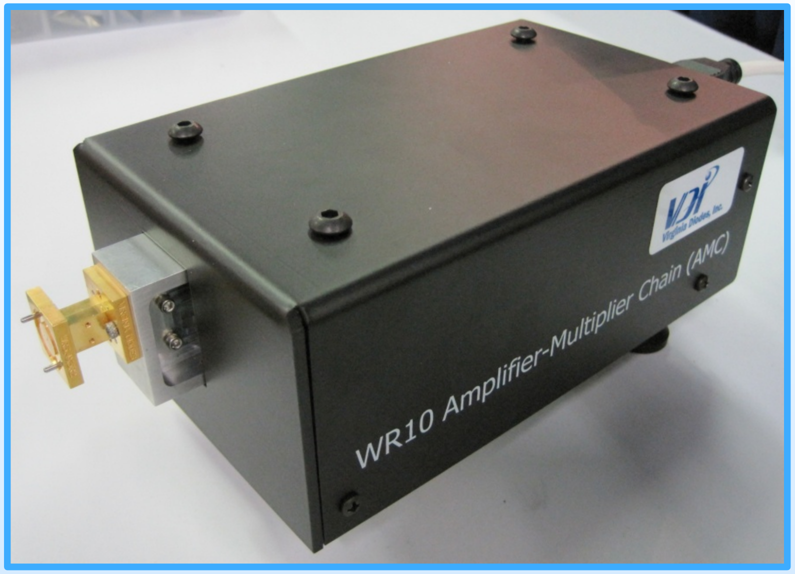
Output

265-400 GHz

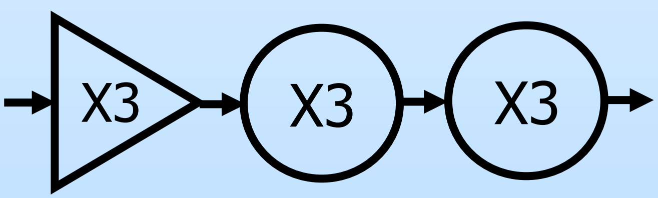
- Tunerless
- Ambient operation
- Rugged and repeatable



Broadband Sources : VDI WR3.4AMC Tx Extender



- 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



Input
< 20 GHz

Output
220-330
GHz

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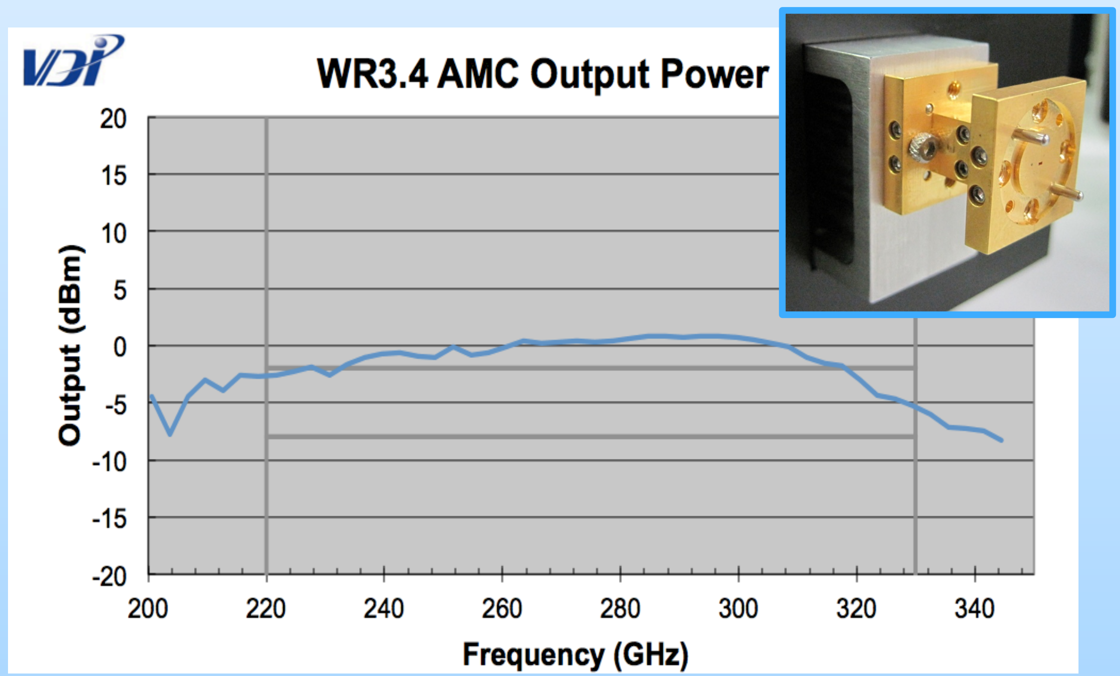
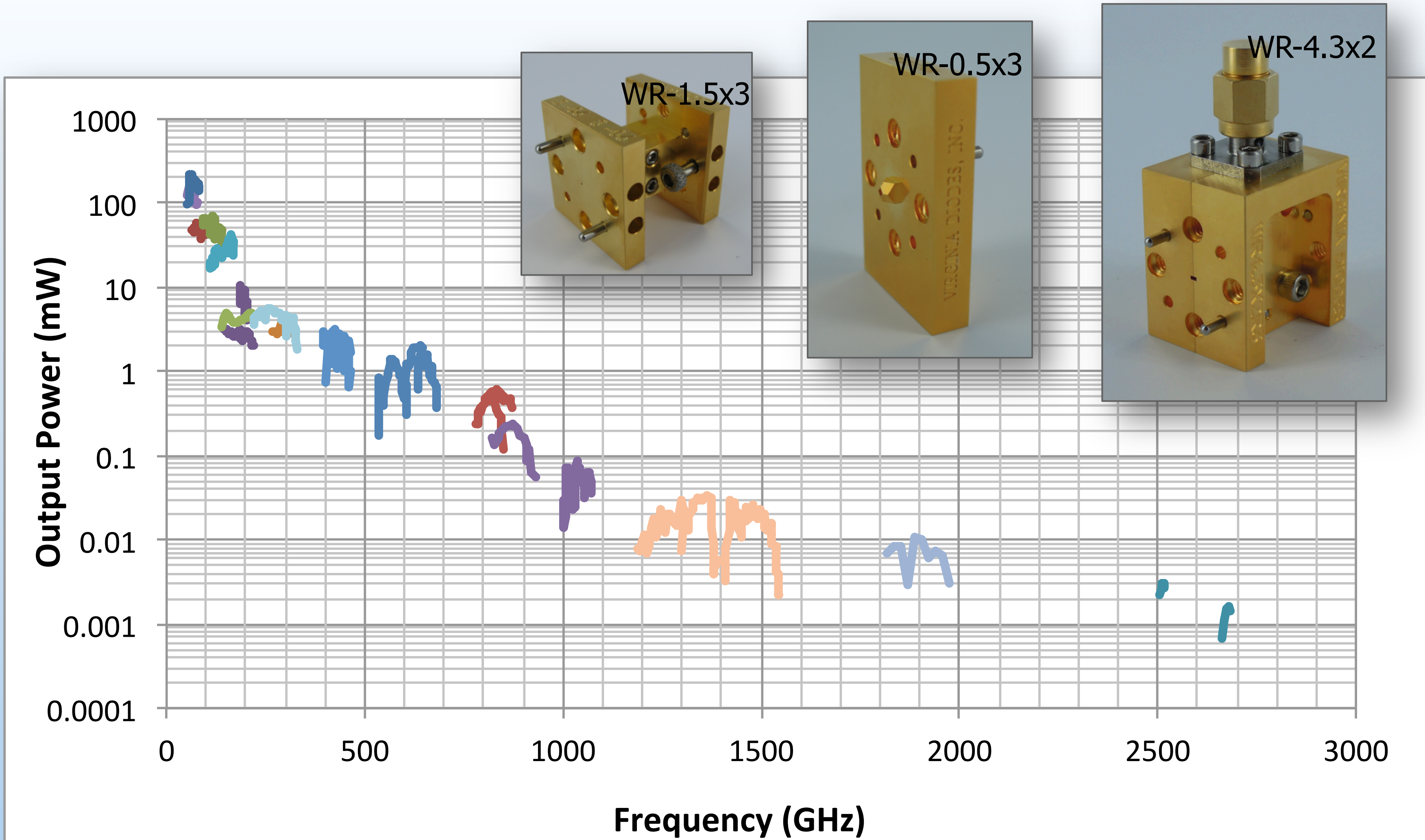
Virginia Diodes



VDI Broadband Varistor Multipliers



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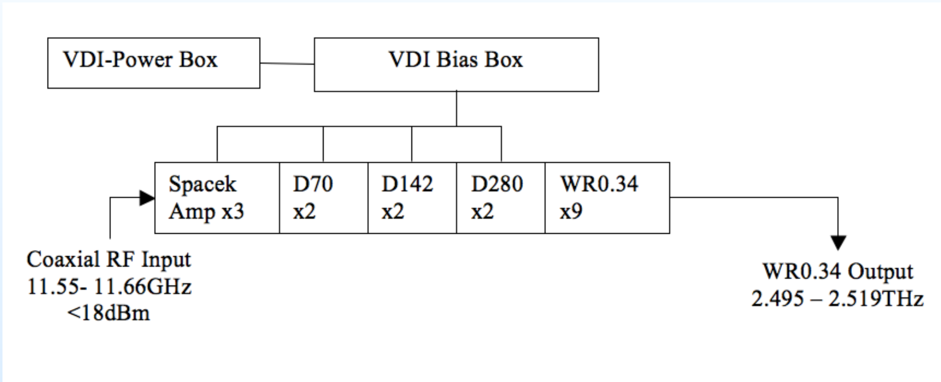
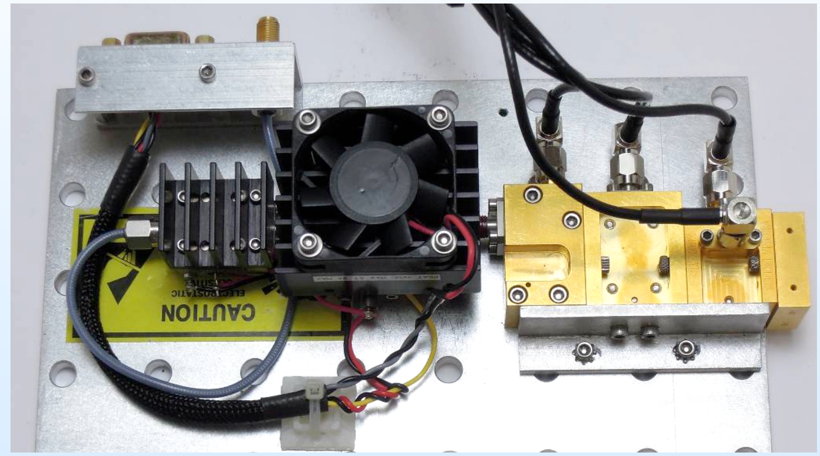
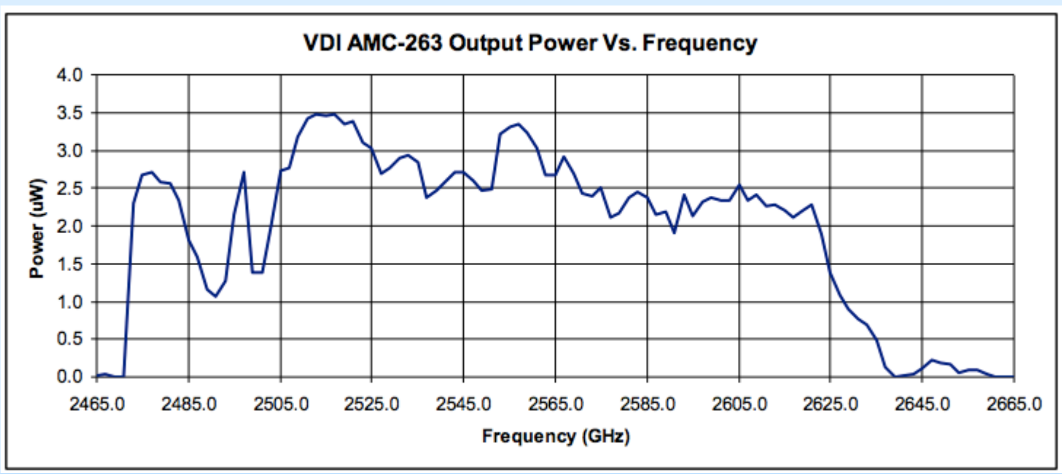
2/21/13

2.5 THz Source for Astronomy







Channel		Frequencies [THz]	Lines of interest
low-frequency	L1 a,b	1.25 – 1.50	[NII], CO series, OD, HCN, H_2D^+
low-frequency	L2 a,b	1.81 – 1.91	NH_3, OH, CO(16-15), [CII]
mid-frequency	M a,b	2.5, 2.7	OH($^2\Pi_{3/2}$), HD
high-frequency	H	4.7	[OI]

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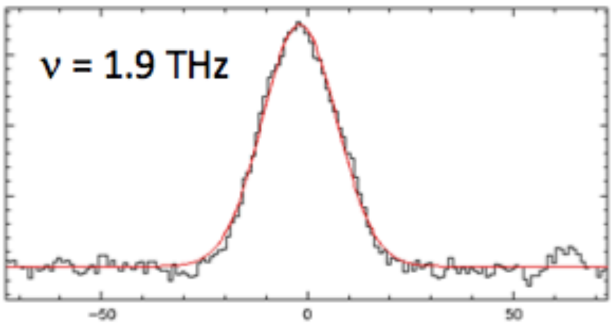
R.Güsten 02.04.11

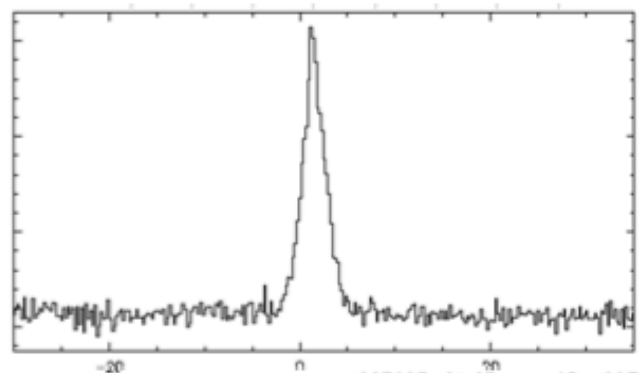
GREAT detects first photons from space

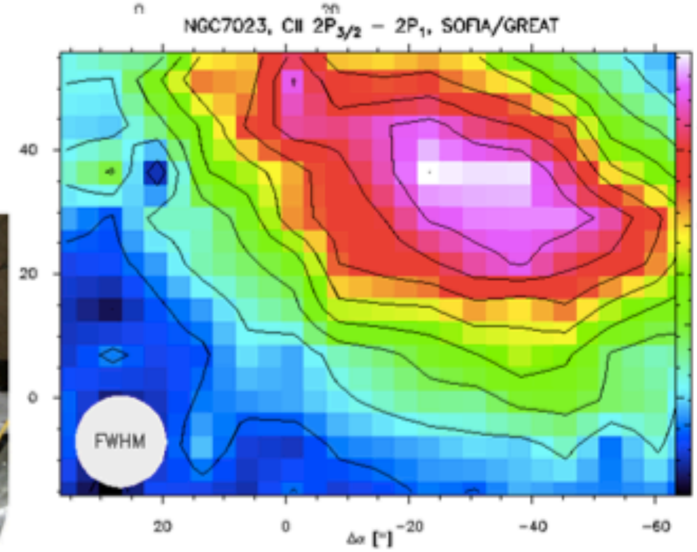
On 1st April 2011, GREAT successfully concluded its commissioning flight

Total power scan across Saturn



[CII] 1.9 THz towards NGC 7023





GREAT team on board of OCF4: R.Güsten, J.Stutzki, S.Heyminck, U.Graf, A.Bell, O.Ricken, H.Wiesemeyer

GREAT is developed by the MPI for Radio Astronomy and the Universität zu Köln,
in collaboration with the MPI for Solar System Research and the DLR Institute of Planetary Research

Outline

- General Introduction
- Introduction to Schottky Diode Technology
- Solid-State THz Sources
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  - THz Vector Network Analysis
- Schottky Detectors for Communication Systems
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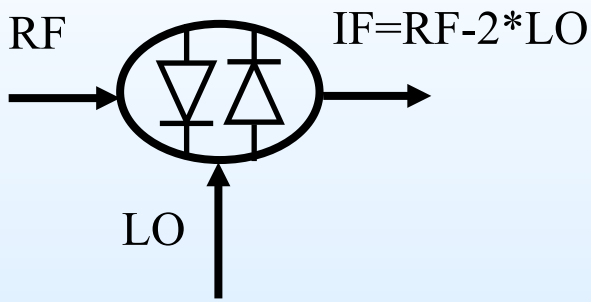
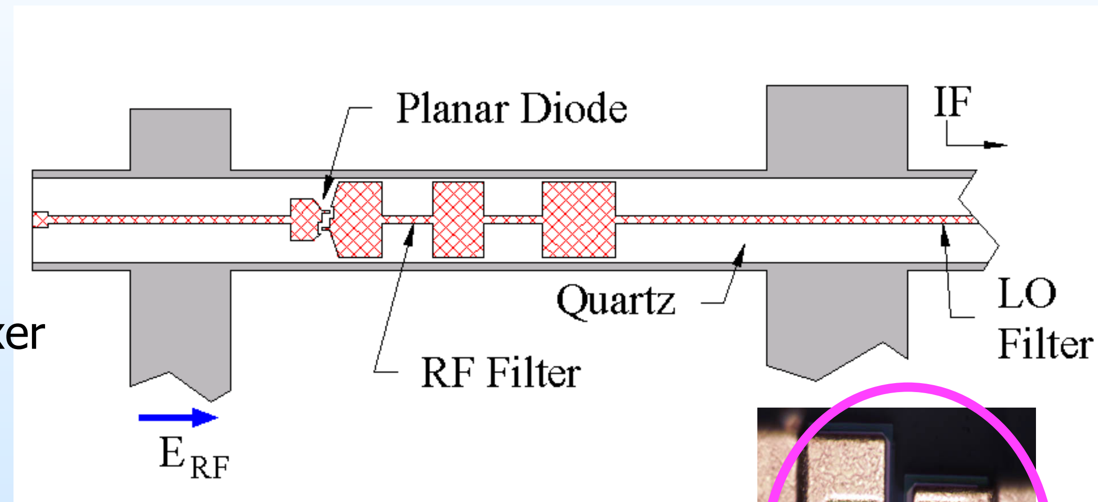
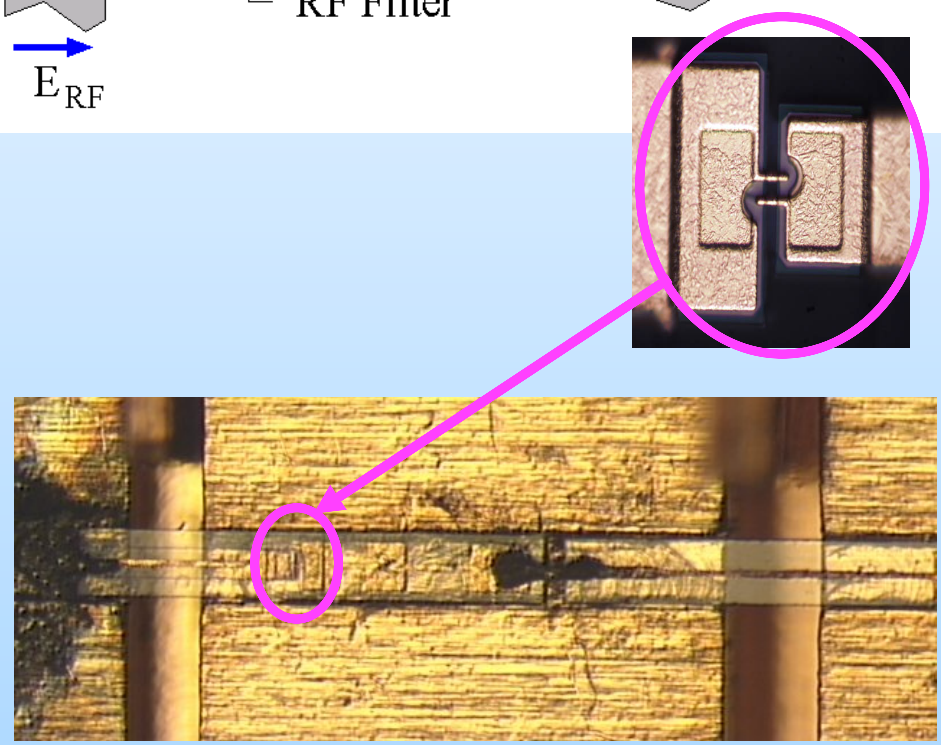
Heterodyne Subharmonic Mixers





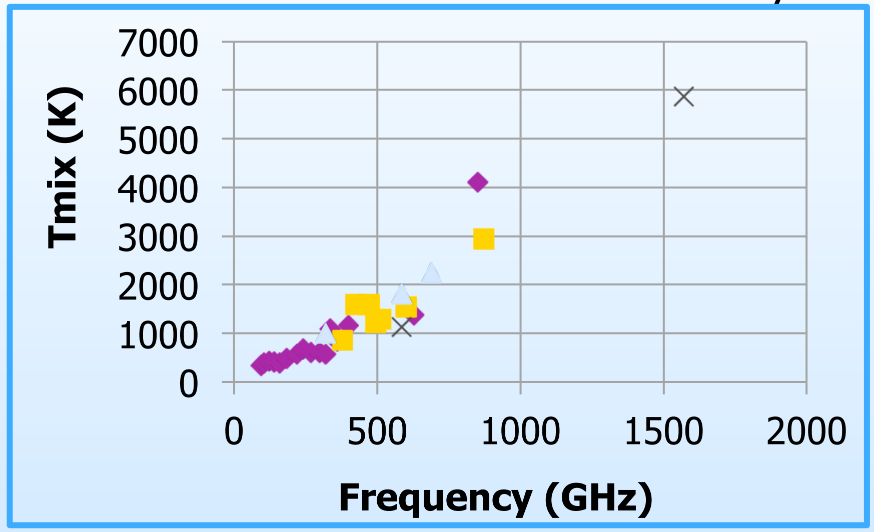


- Anti-parallel Subharmonic Mixer
  - LO at ½ RF
  - No external diplexer needed
  - LO noise suppression
  - Relatively low IF impedance
- Use Tunerless Broadband Mixer Design
  - Broadband
- Disadvantages
  - requires larger LO power
  - difficult to bias diodes

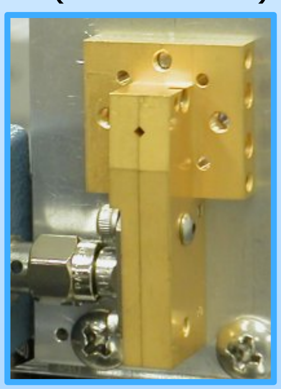
VDI Heterodyne Mixers

- Mixers available from WR-10 (75-110 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

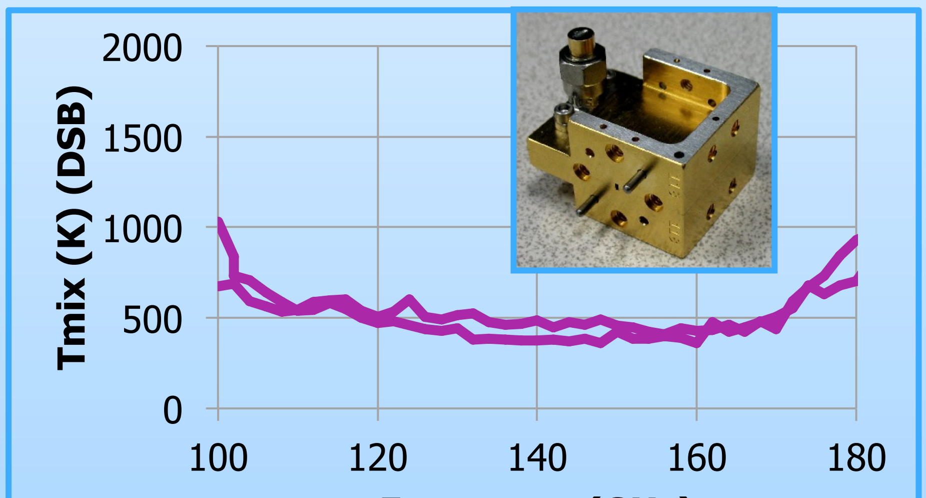
VDI Mixer Performance Summary



WR-0.65SHM
(1.1-1.7 THz)



Measured Performance of WR-6.5SHM



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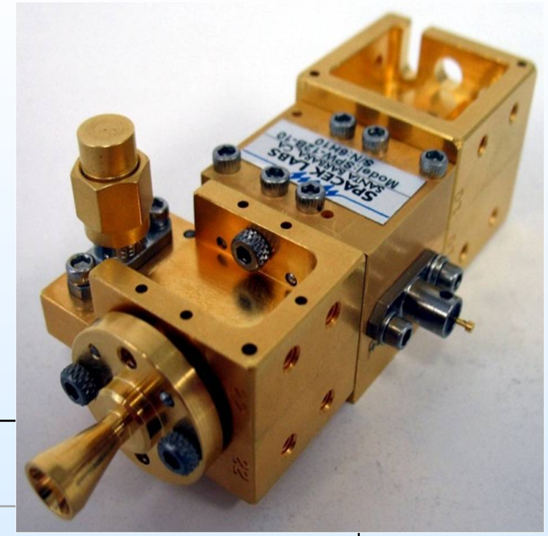
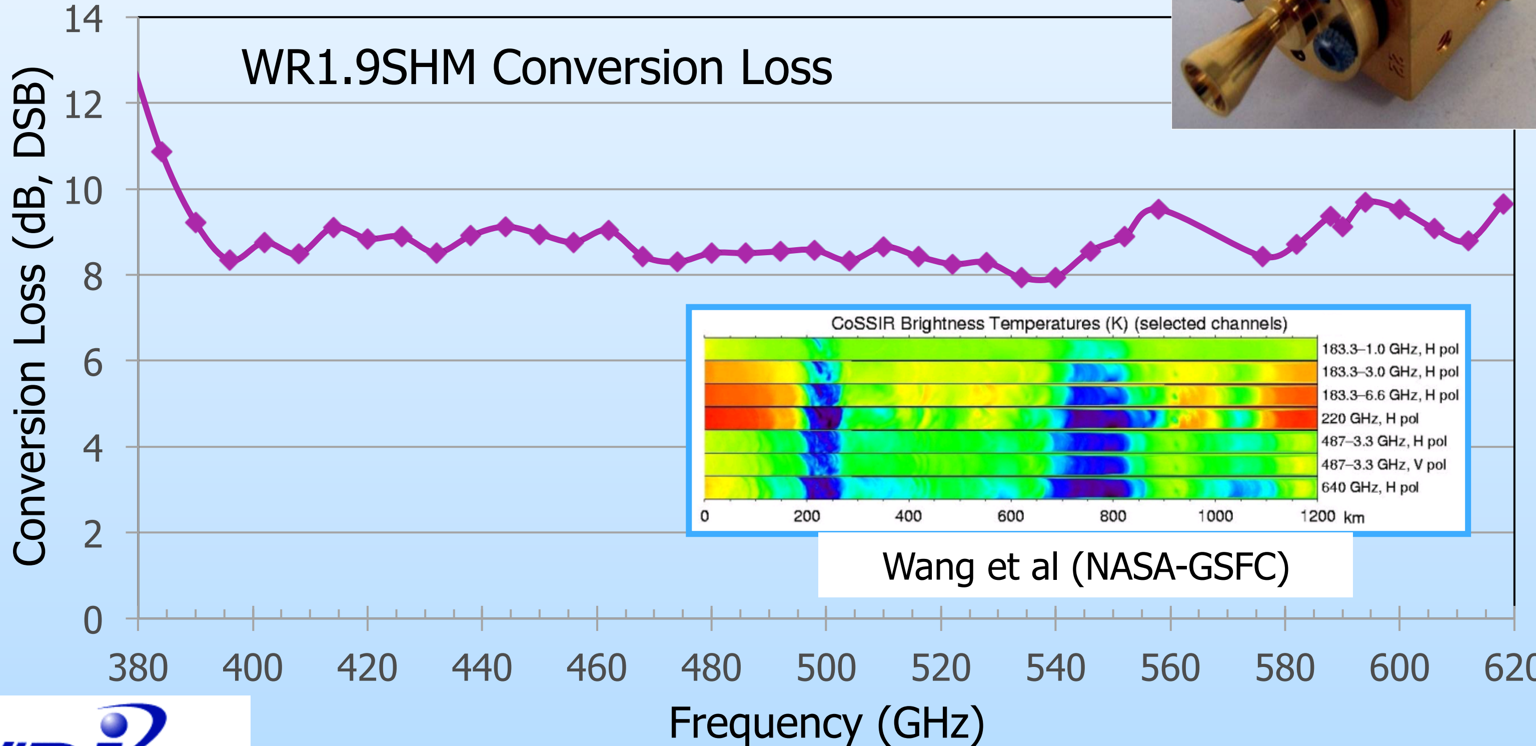
400-600 GHz Radiometer

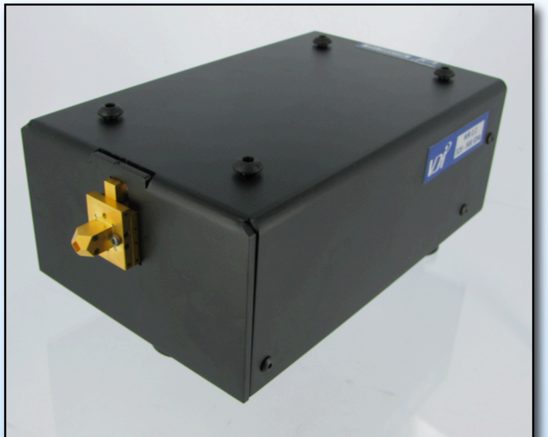
- Developed for use as a radiometer for limb sounding and ice cloud measurements
  - State-of-the-art sensitivity



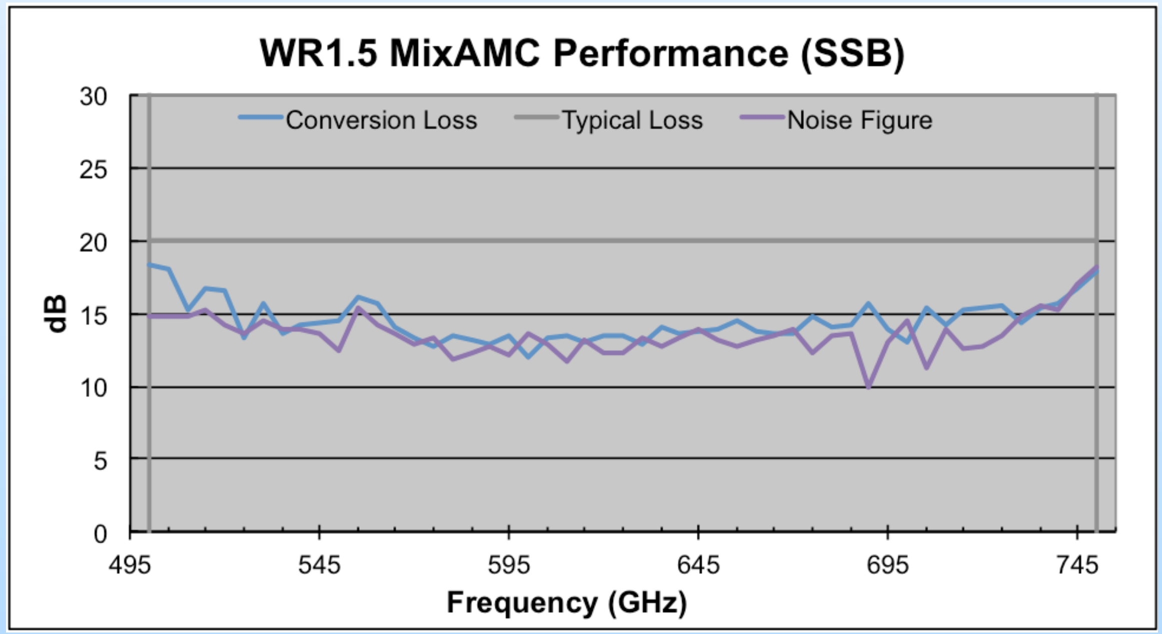


Wang et al (NASA-GSFC)

VDI Mixer/Amplifier/Multiplier Chains (MixAMCs)

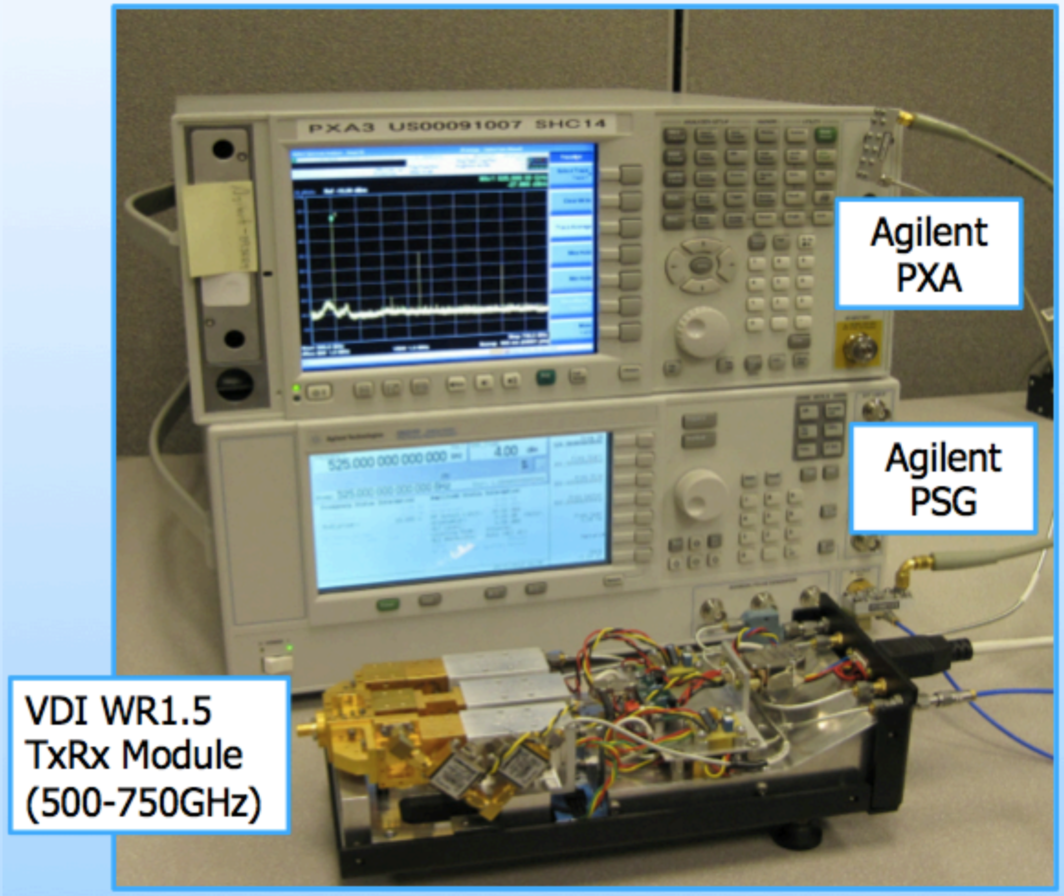


- Fullband down-conversion and frequency extension of microwave spectrum analyzers into the THz range
  - Banded coverage from 75GHz-1,100GHz
  - IF Bandwidth to 40 GHz
  - Turnkey operation



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



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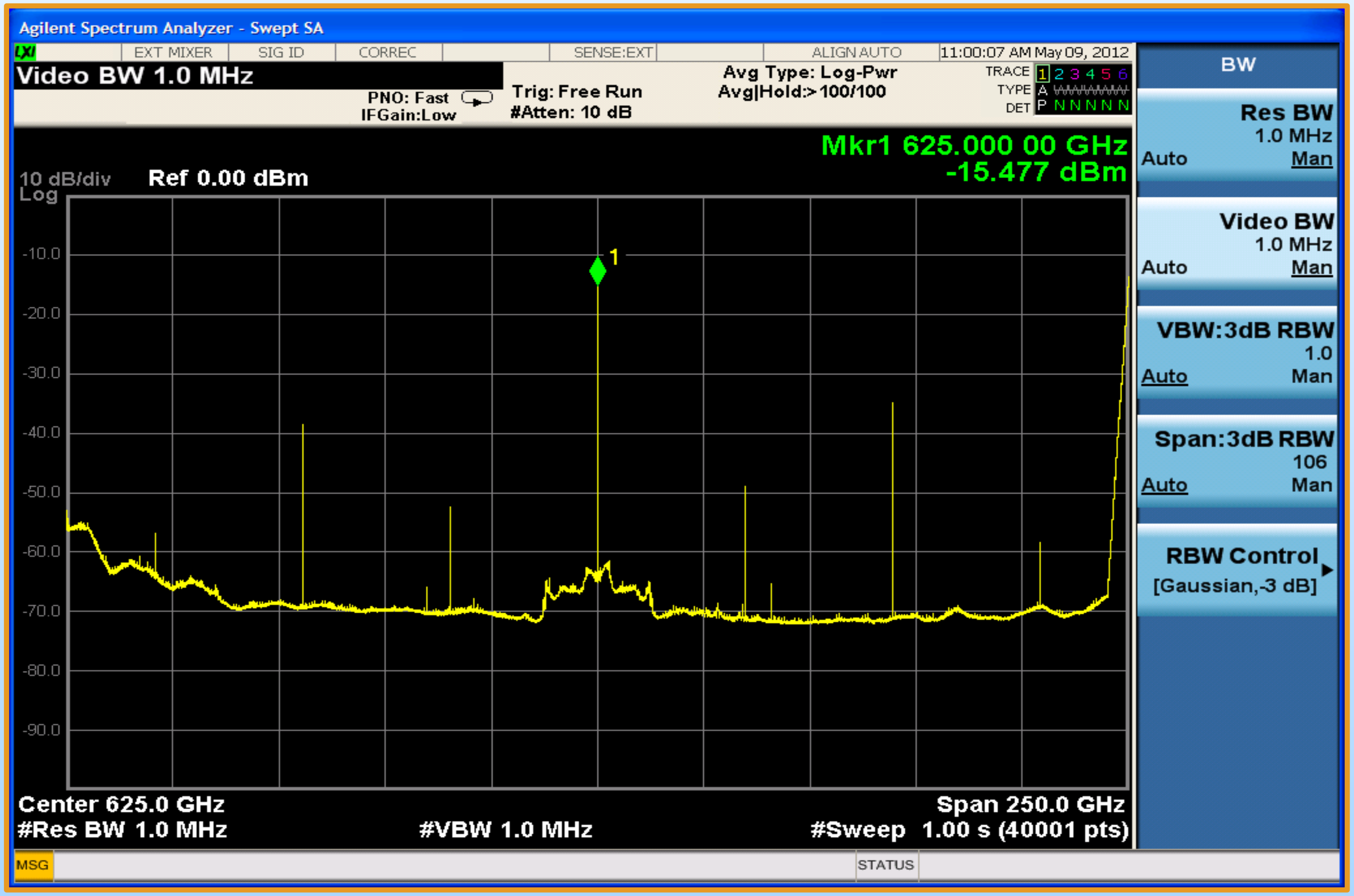
Spectral purity of a 625 GHz Signal

- 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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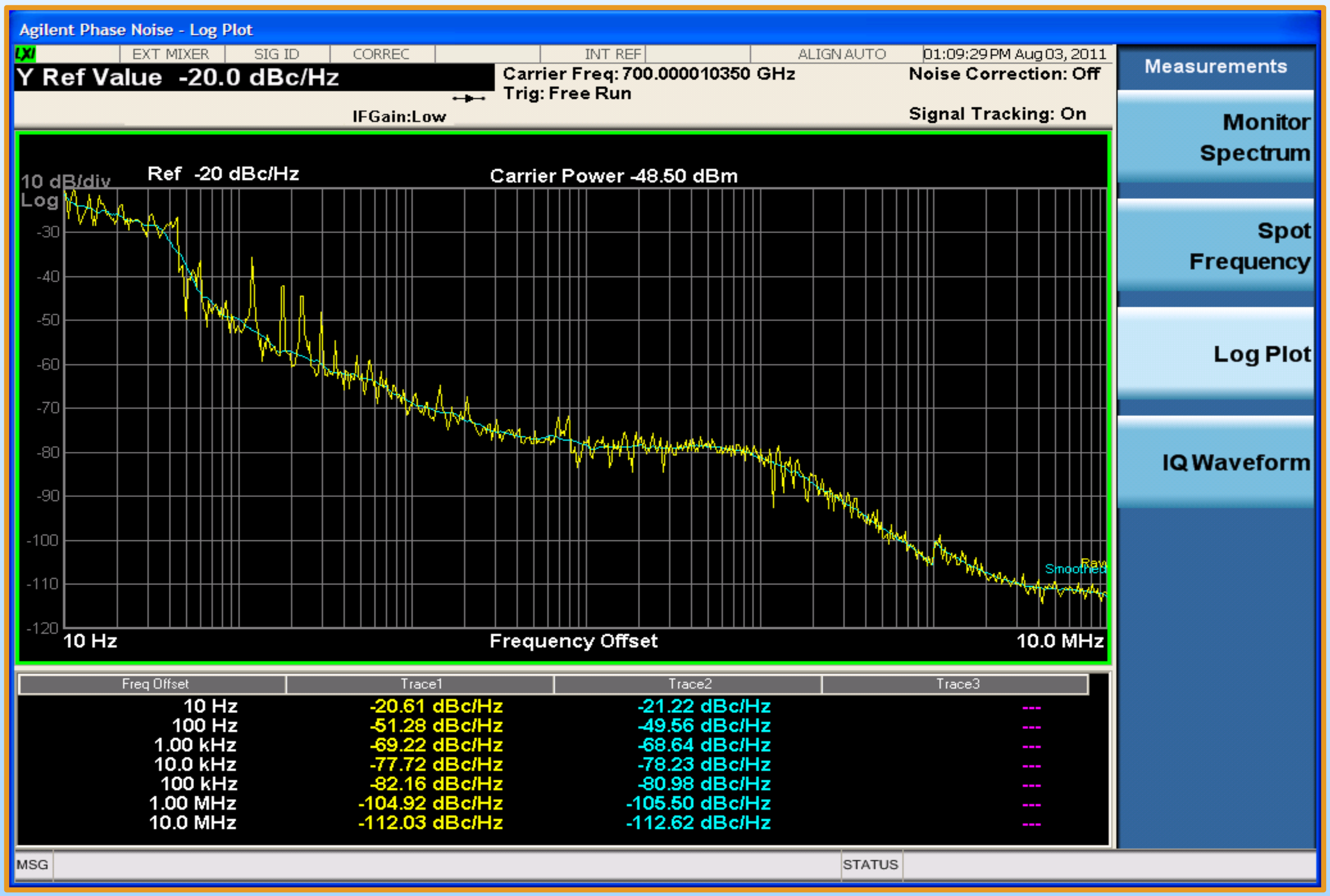
Phase Noise Measurement at 700 GHz

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



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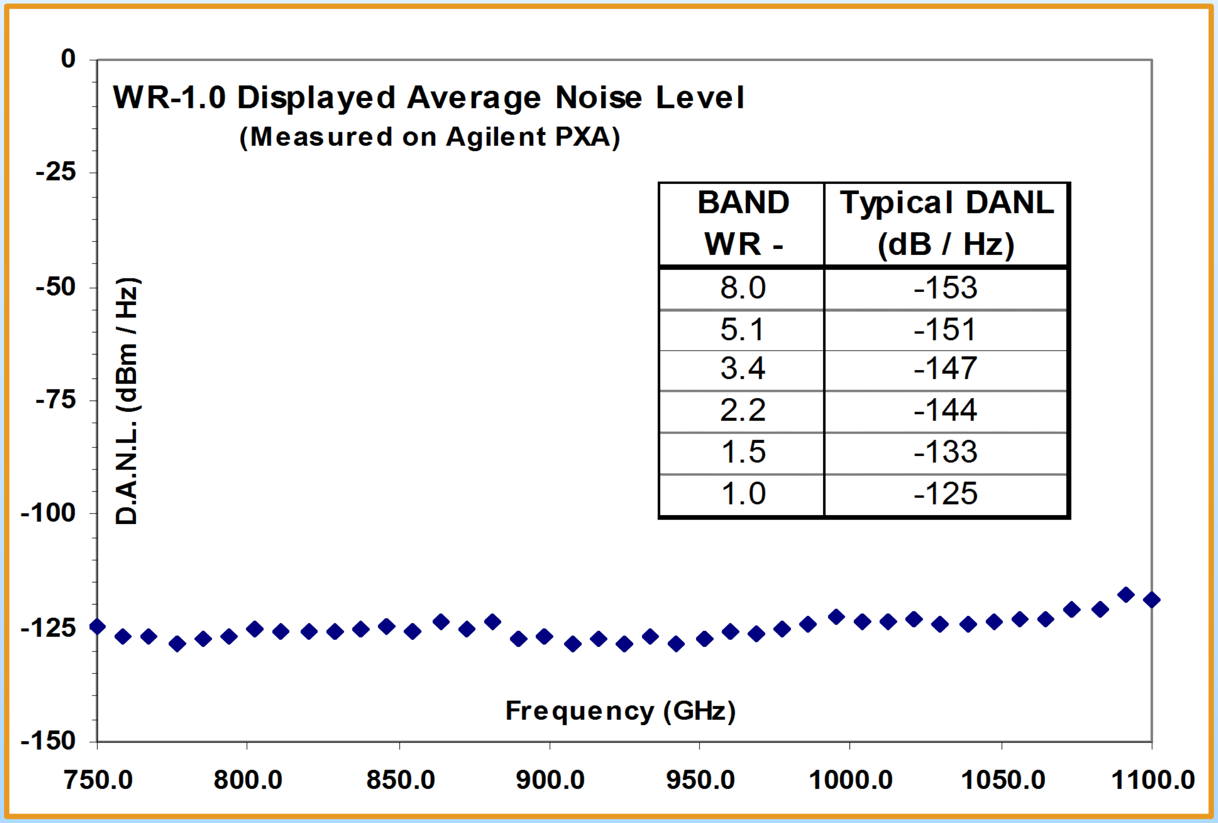
Displayed Average Noise Level (DANL) measured in the WM-250 band – 750-1,100GHz

- A measure of the minimum detectable signal with 1 Hz bandwidth



BAND WR -	Typical DANL (dB / Hz)
8.0	-153
5.1	-151
3.4	-147
2.2	-144
1.5	-133
1.0	-125

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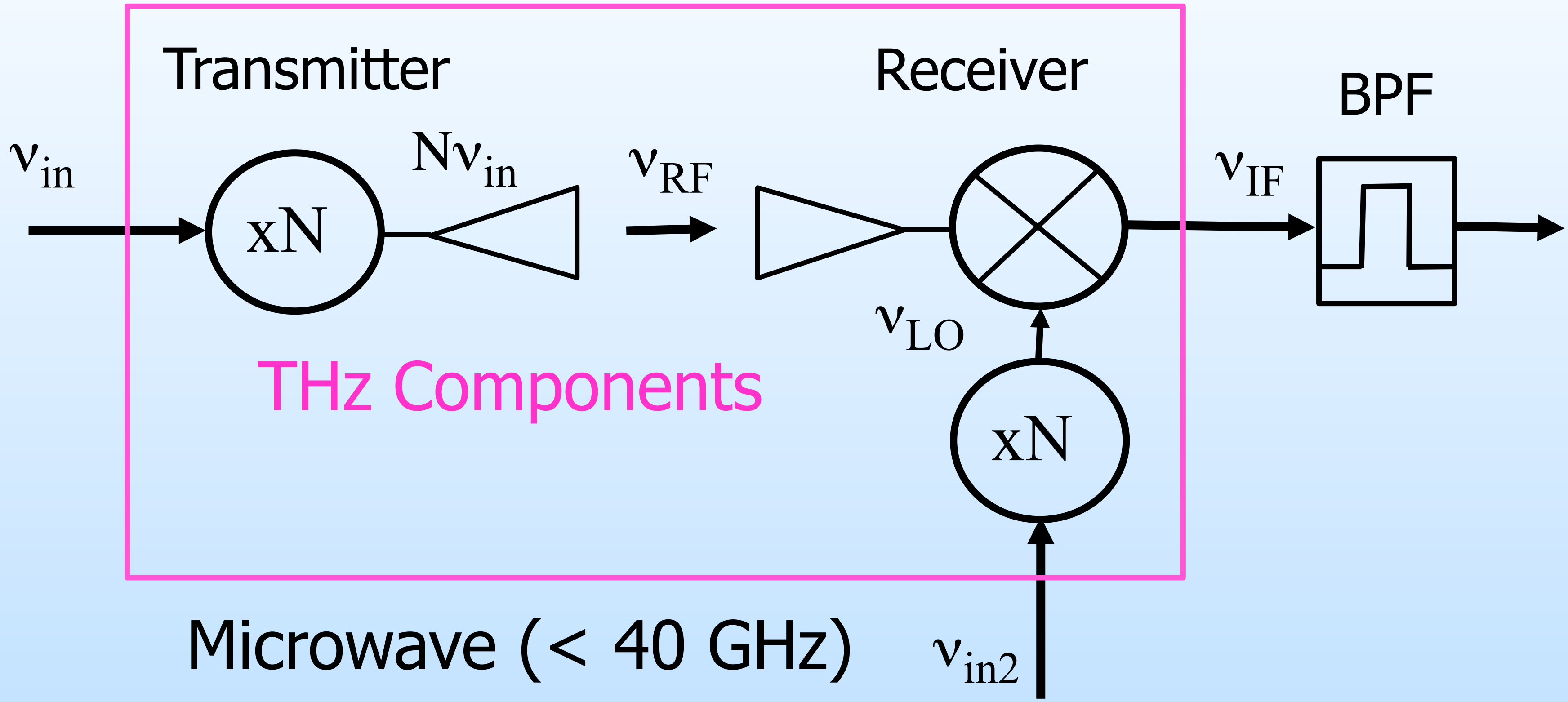
THz Heterodyne Transceivers



- Dynamic range up to 150 dB can be achieved
  - Sensitivity dominated by thermal noise – kTB
  - Narrowband filtering at IF to achieve high signal to noise
- Both amplitude and phase can be measured

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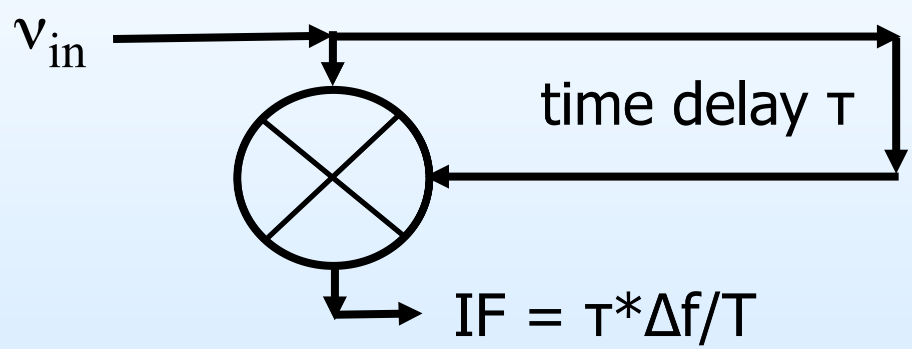
FMCW Radar

- Frequency Modulated Continuous Wave Radar
  - Add frequency modulation to CW source
- Source is split
  - One arm feeds a mixer directly
  - The other arm is time delayed before hitting the mixer
- The IF from the mixer is proportional to the delay time (and thus distance)



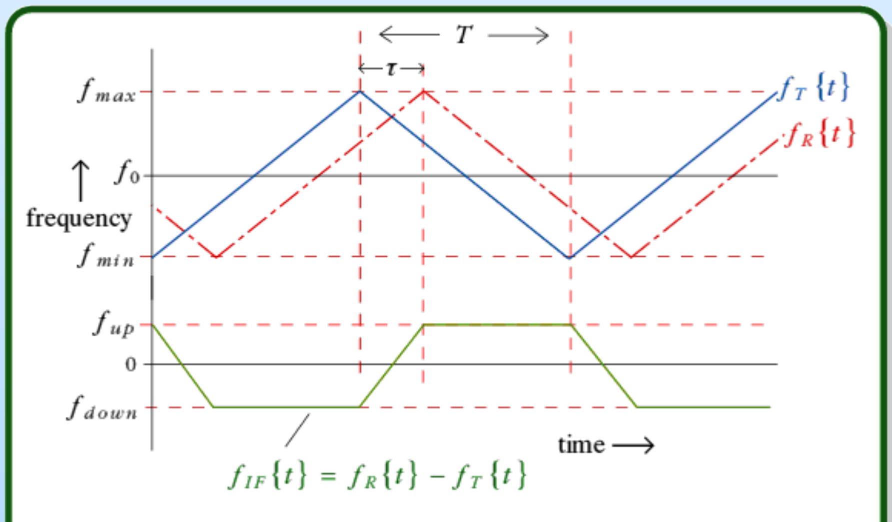


Figure 15.3 CWFM Signal frequencies.

http://www.st-andrews.ac.uk/~www_pa/Scots_Guide/intro/electron.htm

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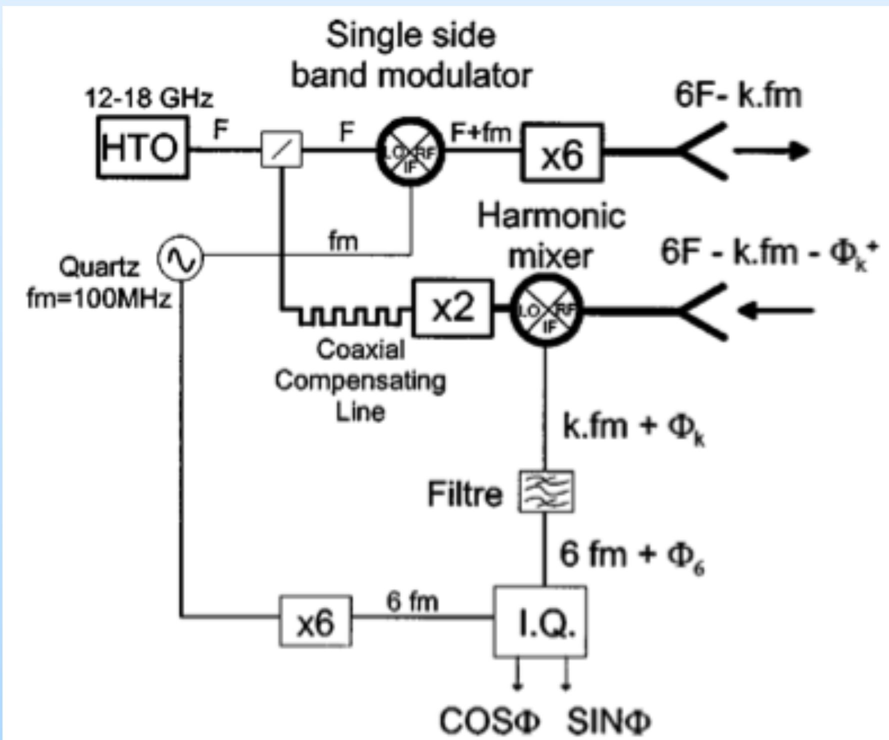
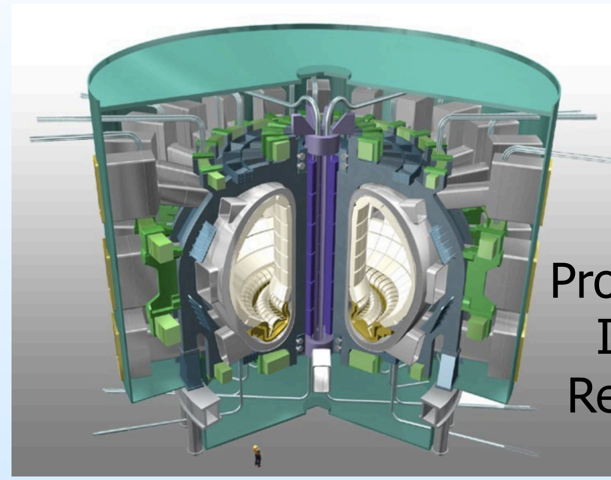
FMCW Radar for Fusion Plasma Diagnostics

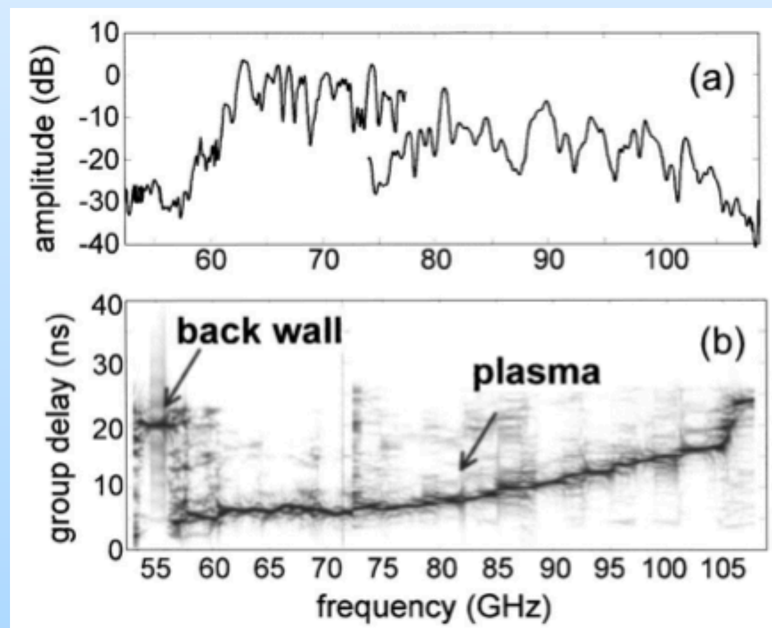
- Radar used to rapidly measure position of plasma boundary over a wide frequency range
- Key diagnostic tool
  - Measures plasma density versus distance into the plasma



Clairet - Rec. Sci. Instr. 2003

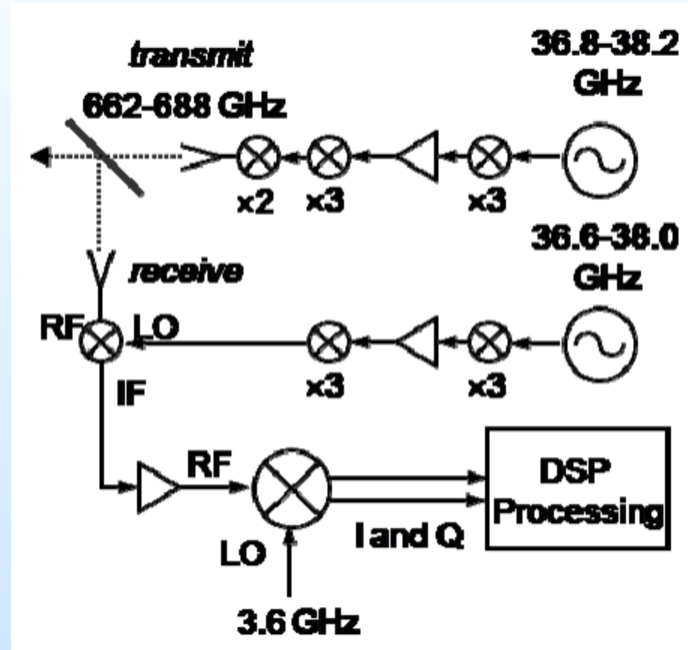


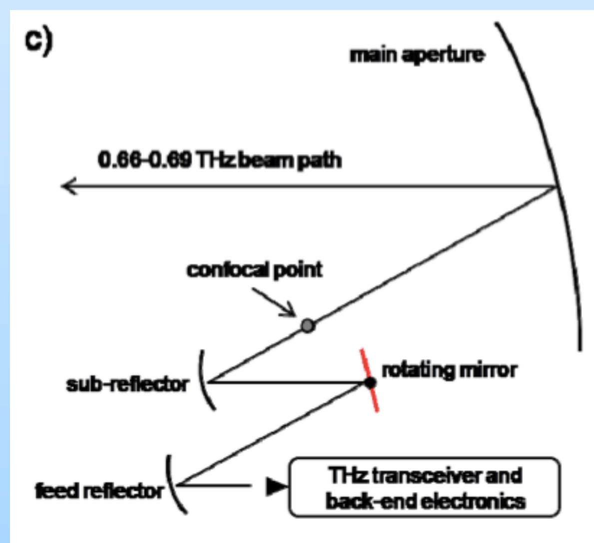
Proposed ITER Reactor



FMCW Radar for Imaging - JPL

- Goal – real time security imaging at 25m standoff with 2cm depth resolution
- Single transceiver with mechanically scanned optics
  - VDI components were used for the THz transceiver
- Prototype system achieved 0.2 Hz frame rate
  - Video rates can be achieved by improving the scanning speed and moving to a transceiver array





Cooper (JPL) 2010 SPIE

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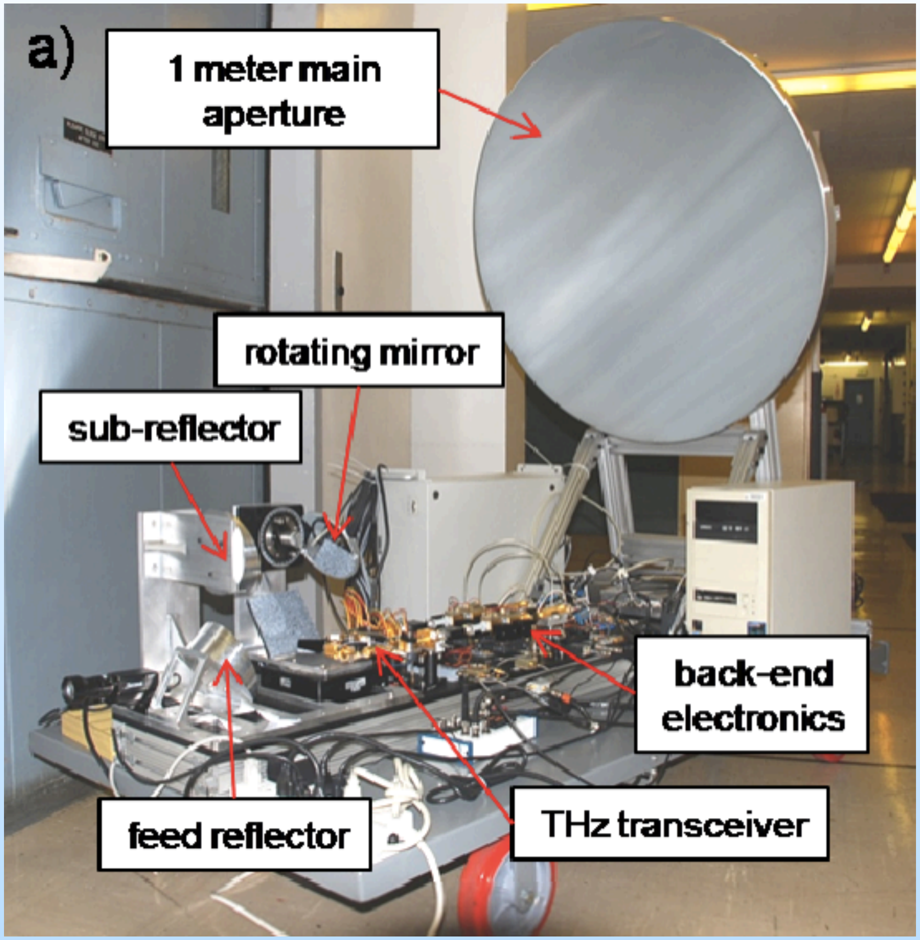
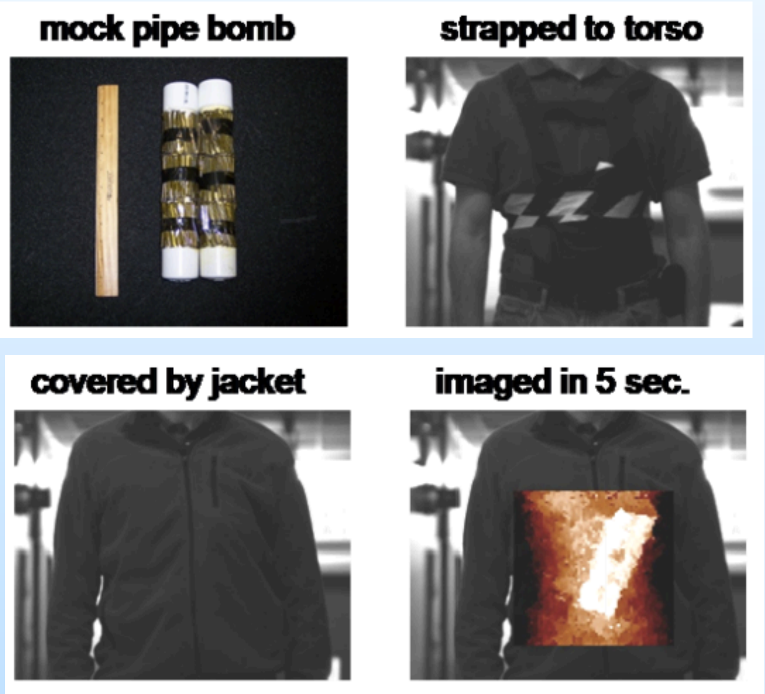
FMCW Radar for Imaging - JPL





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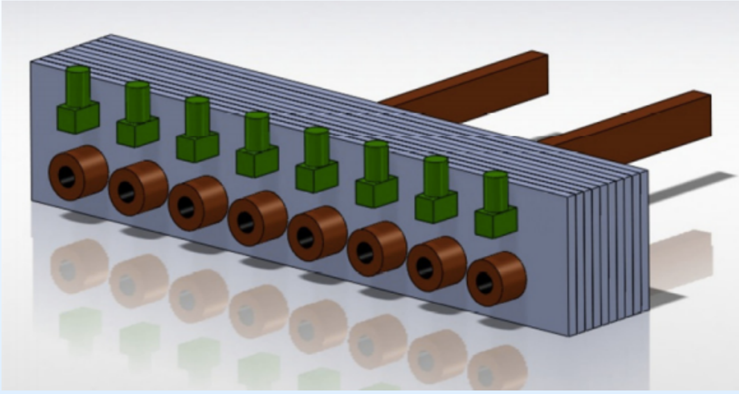
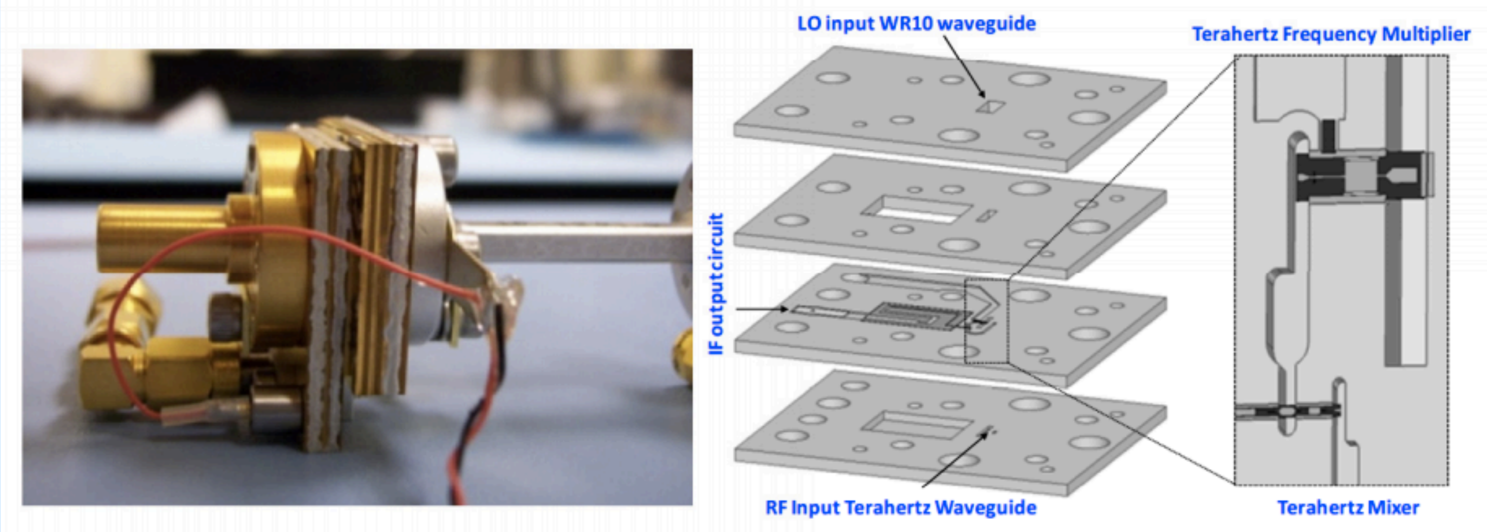
JPL – THz Array Receivers

- Silicon micromachined arrays
- Integrated LO multipliers

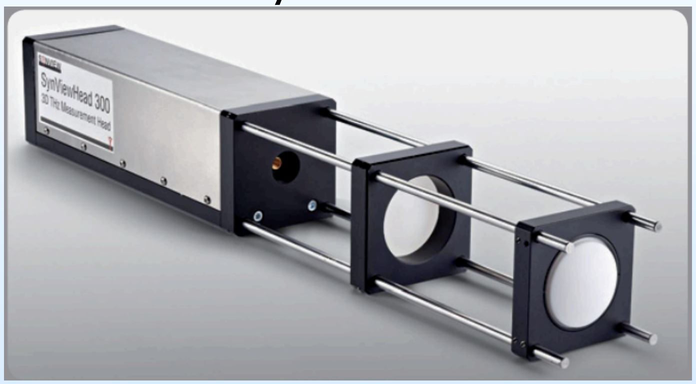




Chattopadhyay – JPL – 2011 (trs-new.jpl.nasa.gov)

FMCW Radar - Synview

THz SynView Head



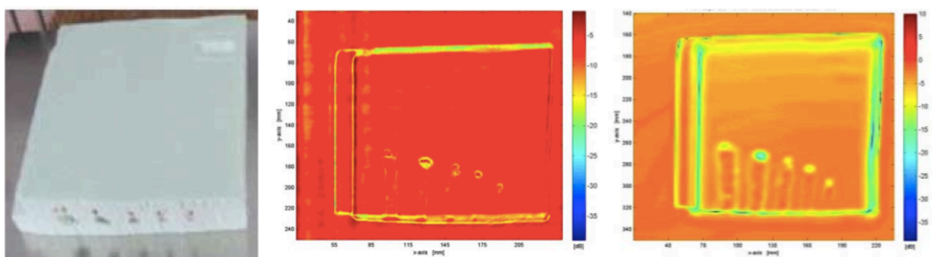


Fig. 6 Styrodur sample with defects. Left: picture of sample, center: synthetic reconstructed image, right measured image with focusing optics

Keil 2011 IRMMW

	SynViewHead 450 *)	SynViewHead 700 *)
Operation mode	coherent FMCW	
Frequency range	0.33 THz – 0.50 THz	0.50 THz – 0.75 THz
Measurement time per range profile	; - 1 sec	
Dynamic range for a measurement time of 100 µs / 10 ms / 100 ms	> 30 dB / > 40 dB / > 50 dB	> 30 dB / > 40 dB / > 50 dB
Output power	10 µW	5 µW
Spatial resolution	0.7 mm	0.5 mm
Depth resolution (layer separation) in typical materials	1.5 mm	1.2 mm
	< 1 mm (If both Heads are used simultaneously e.g. in the SynViewScan TRMF)	
Depth resolution in air	2.25 mm	1.8 mm
Range-, depth- and thickness precision	at least 20 µm (typ.) for any single interface within the depth resolution window	at least 20 µm (typ.) for any single interface within the depth resolution window

http://www.synview.com/

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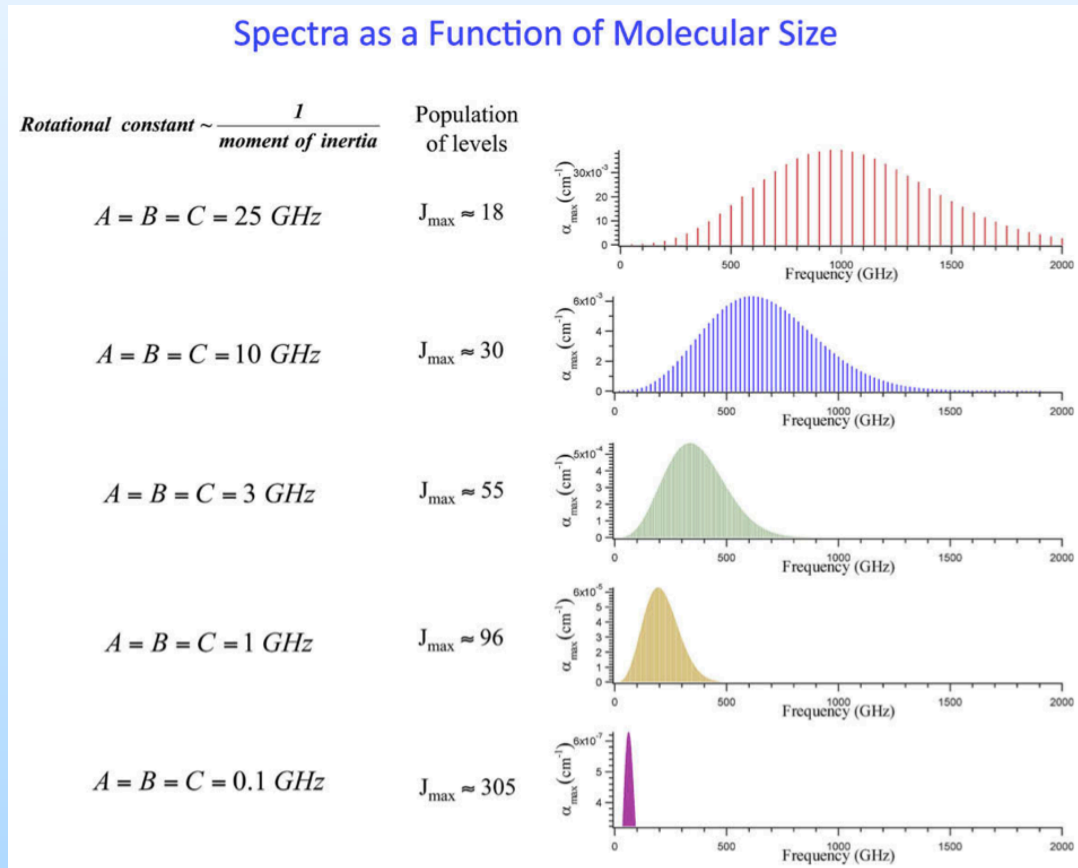
Molecular Gas Spectroscopy

- Molecular resonances occur periodically throughout the THz region
  - Peak of distribution determined by the size of the molecule
  - Spectral fingerprint can be used to determine presence of a gas with very low false positives
- Potential of gas spectroscopy as an analytical tool was understood as early as the 1950's
  - However, the technology wasn't mature enough to allow commercial system development
- Technological advances have changed this
  - THz component development
  - Modern computing speed
  - General improvement in spectroscopic techniques



De Lucia – J. Molec. Spect 2010

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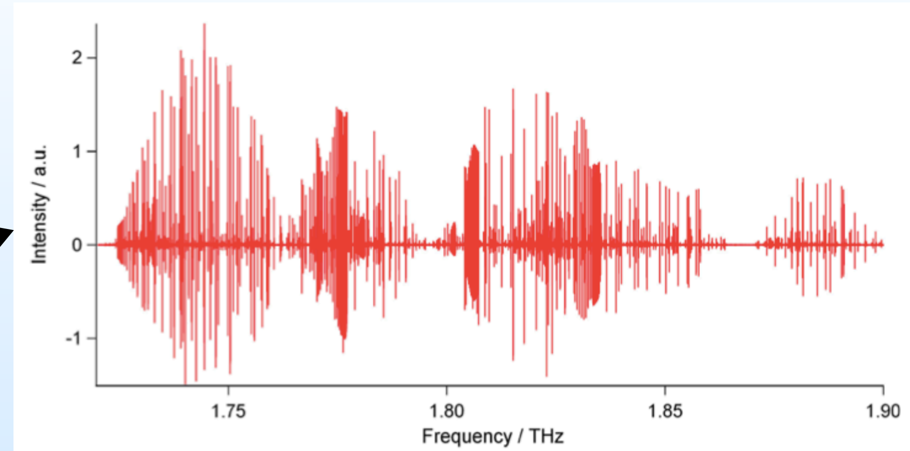
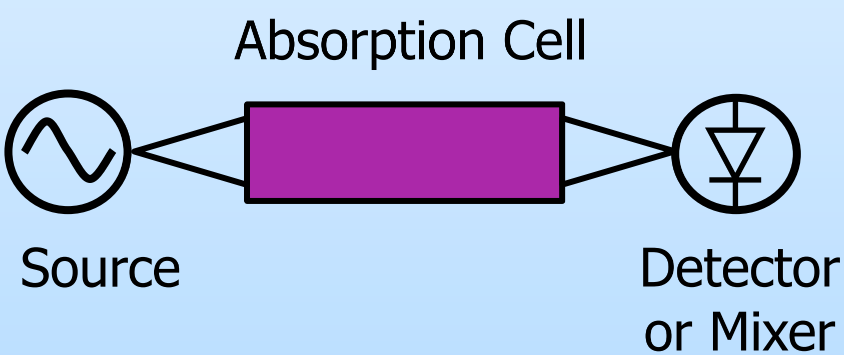
Molecular Gas Spectroscopy

- High resolution CW spectroscopy
  - Frequency resolution ~10 kHz
- Spectrum of Methanol (CH3OH) measured using a VDI 1.7-1.9 THz Source



De Lucia – J. Molec. Spect 2010



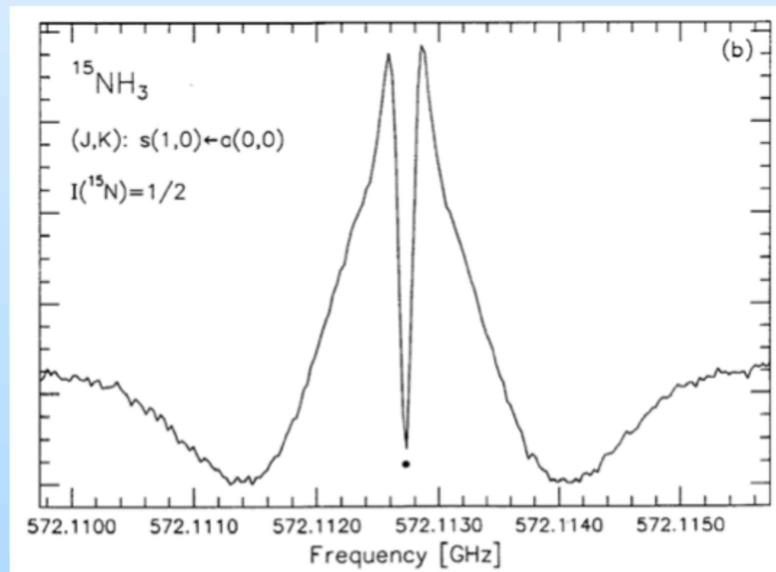


Fig. 7. The lamb-dip spectrum of ammonia.

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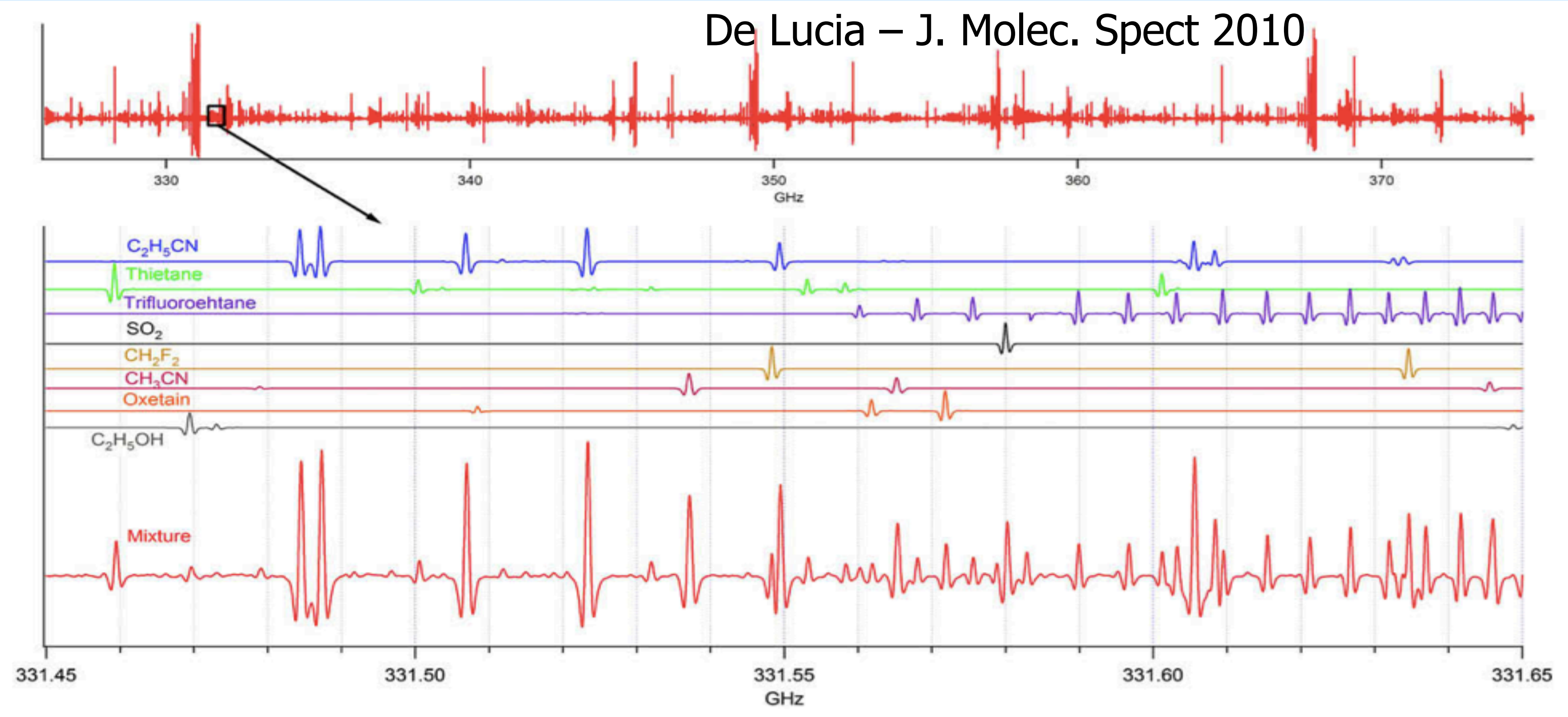
OSU (De Lucia) FASST Spectrometer

- Measurement of a mixture of 20 gases
  - 3 seconds to scan 50 GHz bandwidth
  - 10 msec to scan 200 MHz bandwidth (lower curve)
- The large amount of information can be used to accurately determine the gases present in the mixture

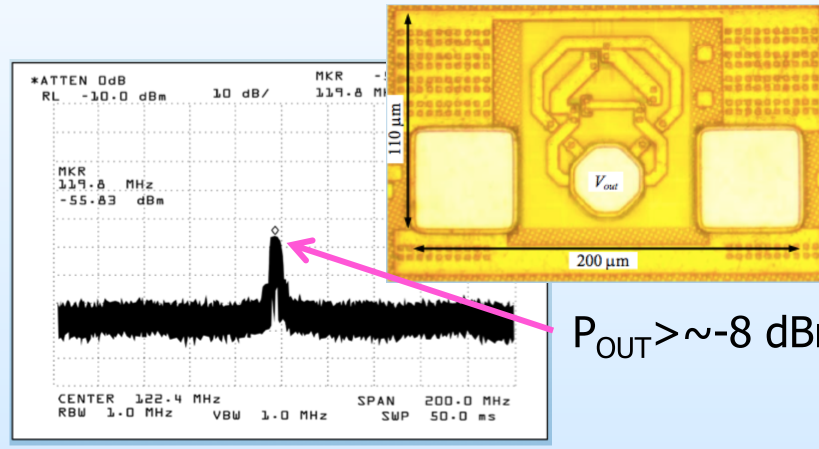
De Lucia – J. Molec. Spect 2010



Spectrometer Using Si CMOS

- Gas spectroscopy doesn't require high power
  - ~100 uW is enough
- Si CMOS is a realistic base for a THz gas spectrometer
  - Greatly reduced cost and size
  - Still many technical challenges to be overcome

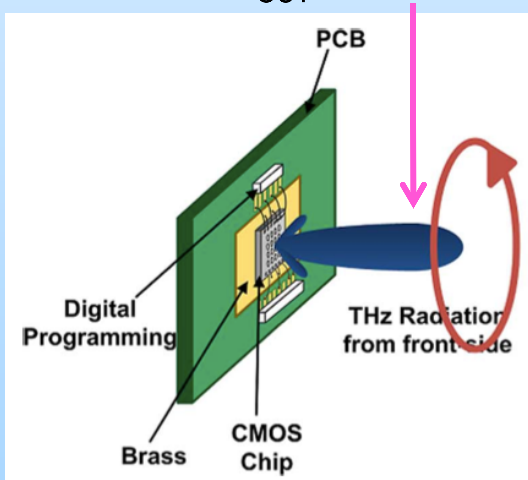
480 GHz Third Harmonic Oscillator



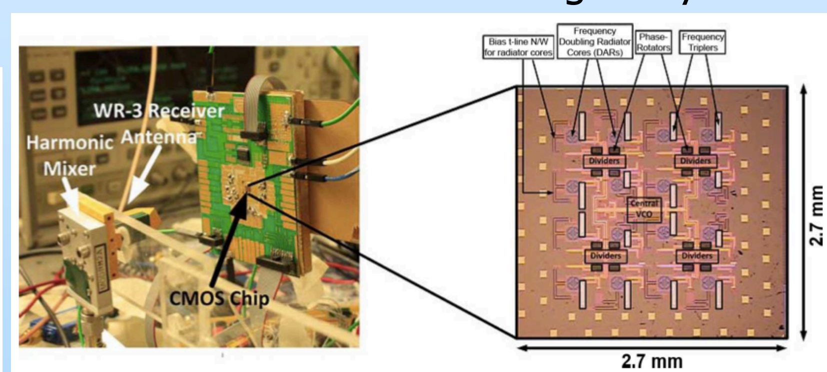
P_{OUT}>~-8 dBm

Cornell (Afshari) IEEE 802.11 - 2012

P_{OUT} -7 dBm



280 GHz Beam Steering Array



CalTech (Sengupta) IEEE SSC - 2012

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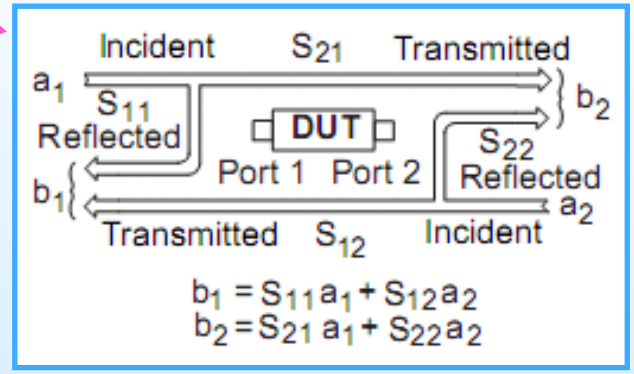
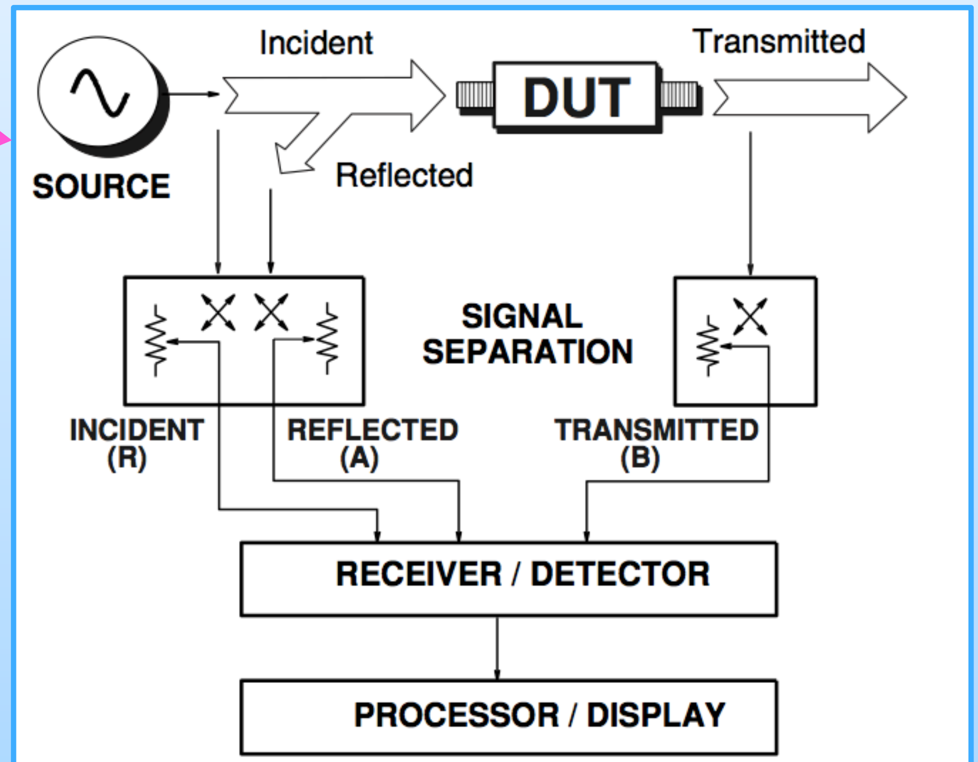
Vector Network Analyzers

- VNA are used to measure the complex scattering parameters of a DUT
  - Why is complex important?
    - Needed to fully characterize a device
    - Needed to transform to time domain
    - Enables advanced calibration routines



- VNA Configuration
  - Incident wave sampled by reference mixer (R)
  - Scattered waves sampled by measurement mixers (A & B)
  - Measured vector ratios A/R and B/R of calibration standards and DUT are used to determine the DUT response



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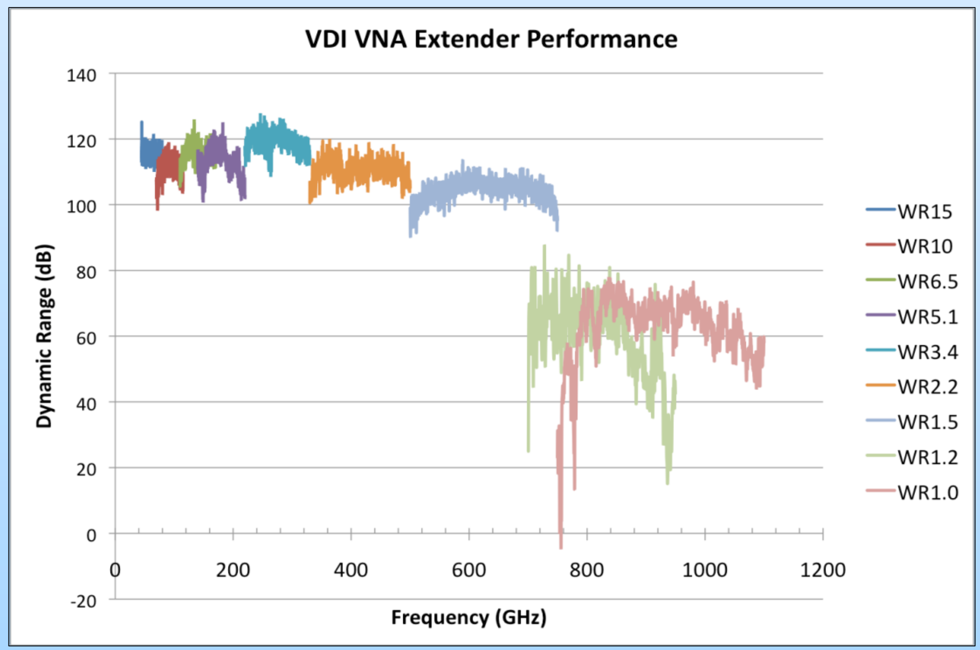
Virginia Diodes VNA Extenders

- Extend VNA's to THz
- VDI Extenders available from WR-10 (75-110 GHz) thru WR-1.0 (750-1050GHz)
  - 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 WR-1.5 (500-750 GHz)
    - 70 dB (typ.) at WR-1.2 (600-900 GHz)
    - 60 dB (typ.) at WR-1.0 (750-1050 GHz)
  - Excellent amplitude and phase stability
- Compatible with Agilent, R&S & Anritsu VNAs
- Modular Research-grade versions also available
  - Reconfigurable between different frequency bands
    - e.g. same drivers used to cover WR-2.2 and WR-1.5 bands



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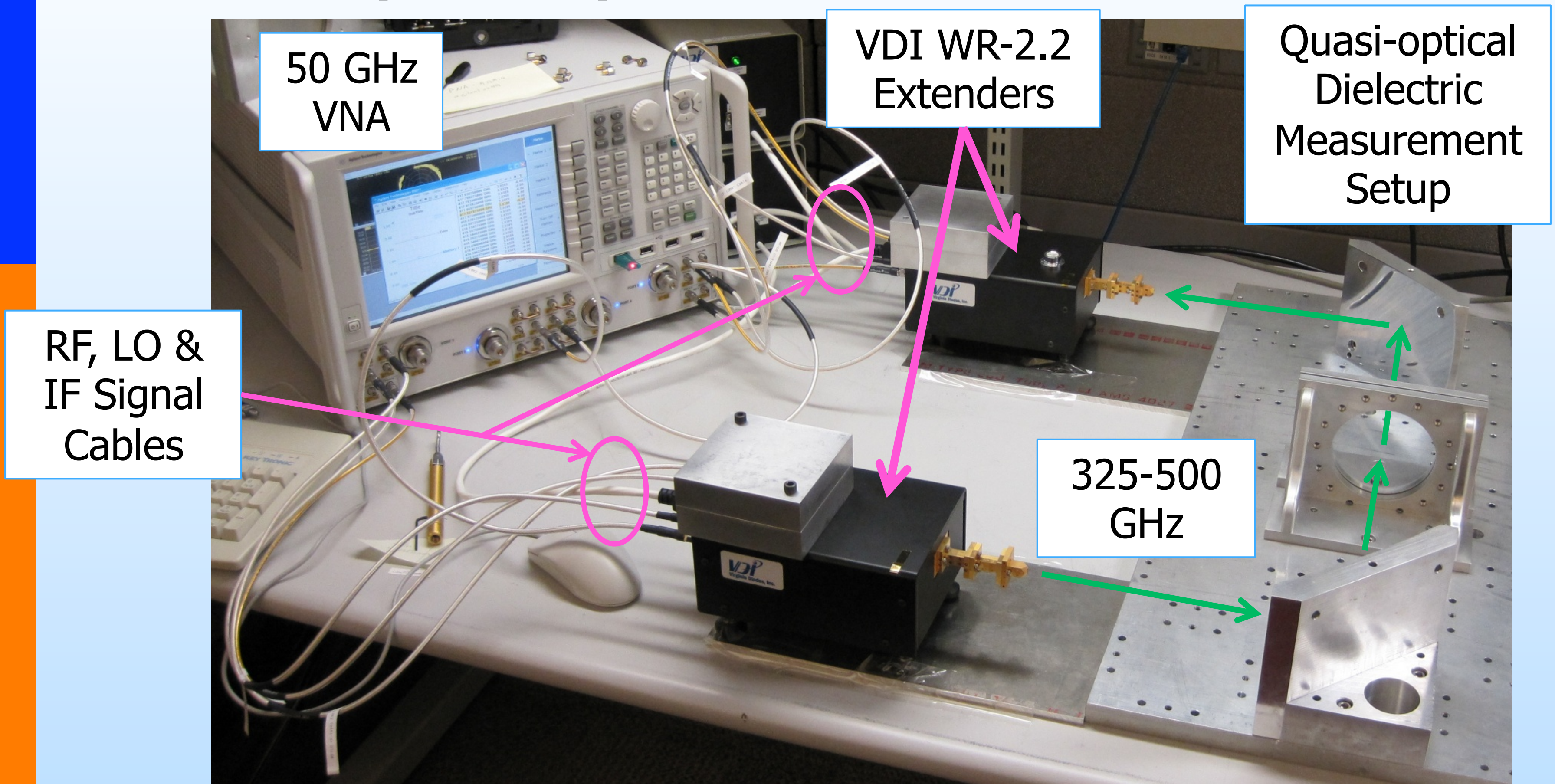
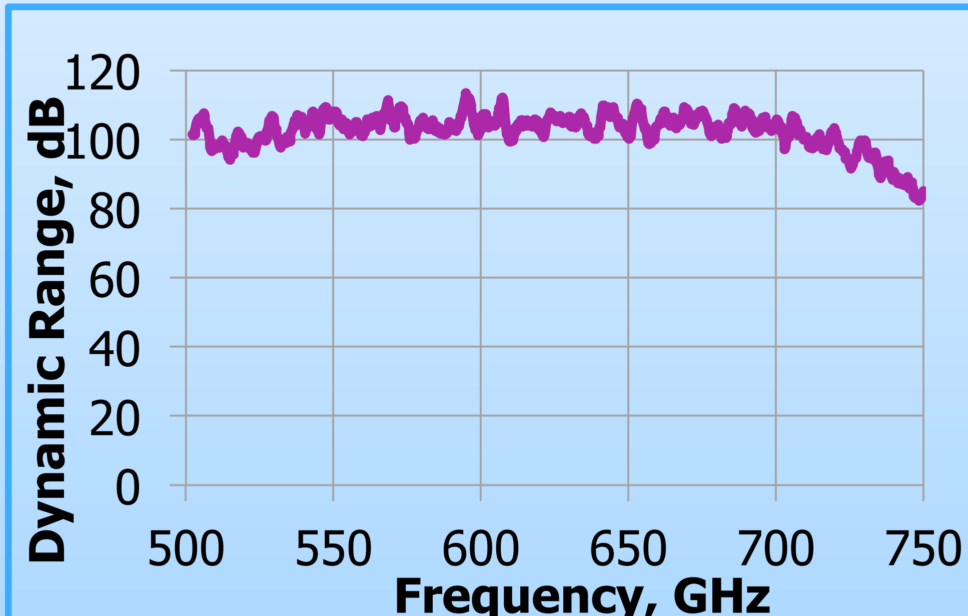
Frequency Extension of a VNA



- Quasi-optical dielectric measurements performed at Agilent (Santa Rosa)
  - In this case the extender is used in “front-panel” mode of operation (no controller Test Set needed)

WR-1.5 VDI VNA Extender

- Dynamic range 100 dB typical
  - With 10 Hz IF Bandwidth
- Excellent amplitude and phase stability
  - +/-10 degrees and +/-0.8dB, under normal operating conditions
- Coupler Directivity: >30dB, typical
- ***VDI is shipping extenders throughout the WR10 - WR1.2 waveguide bands***



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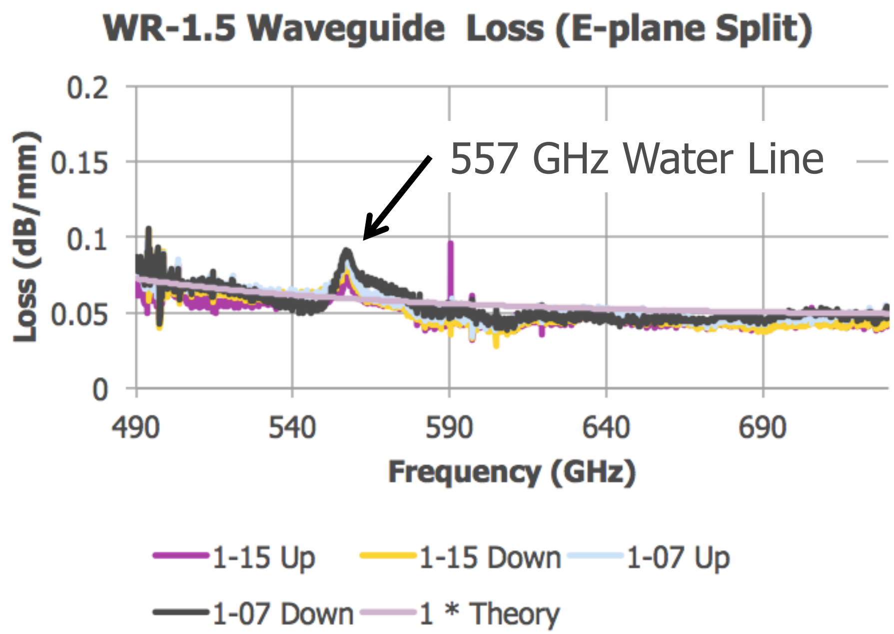
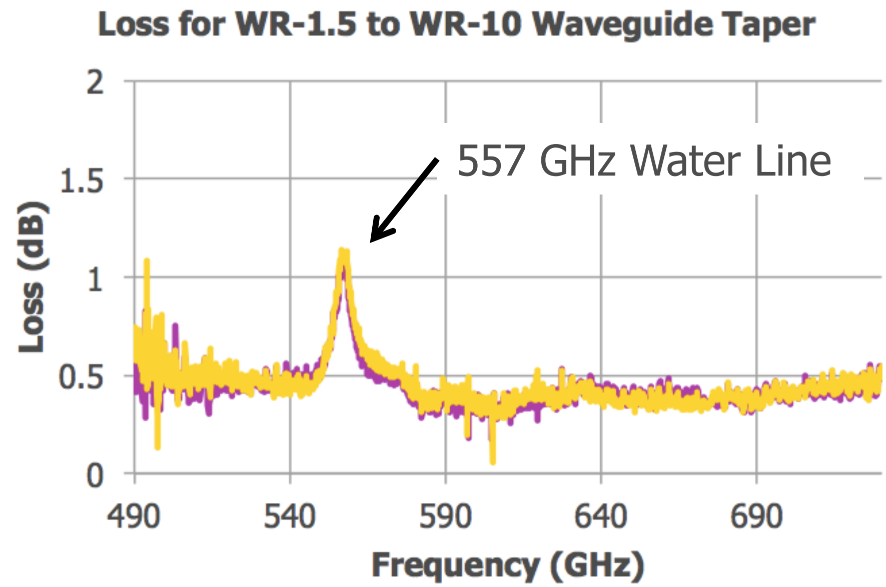
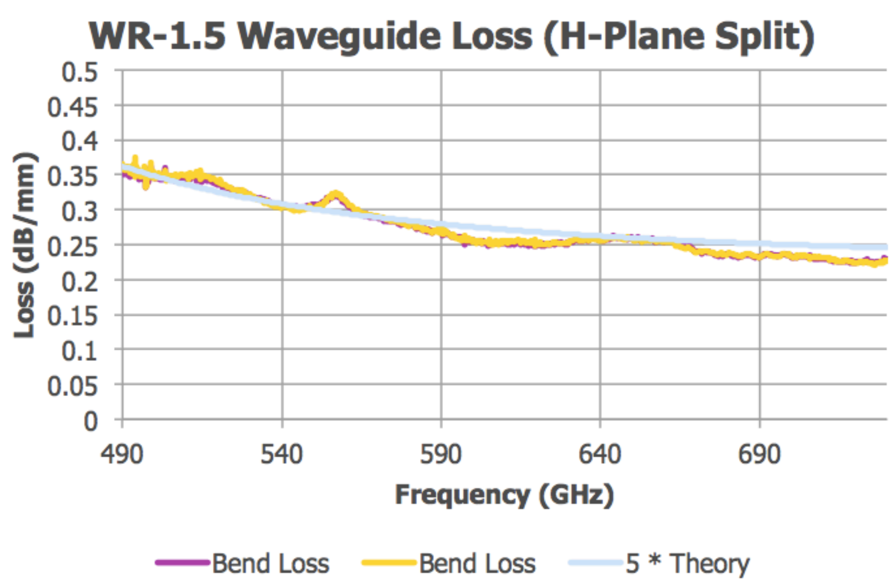
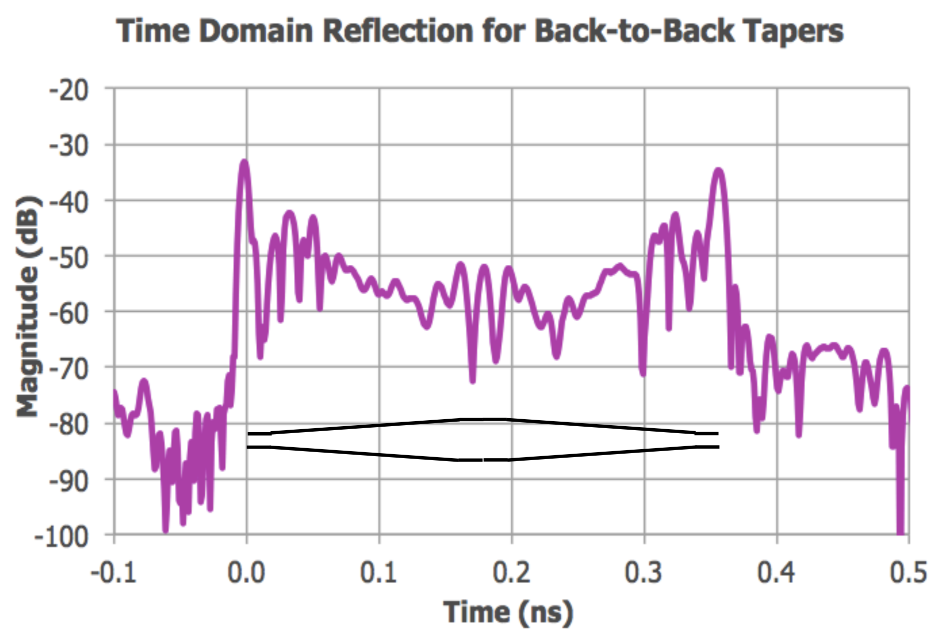
WR-1.5 Measurements





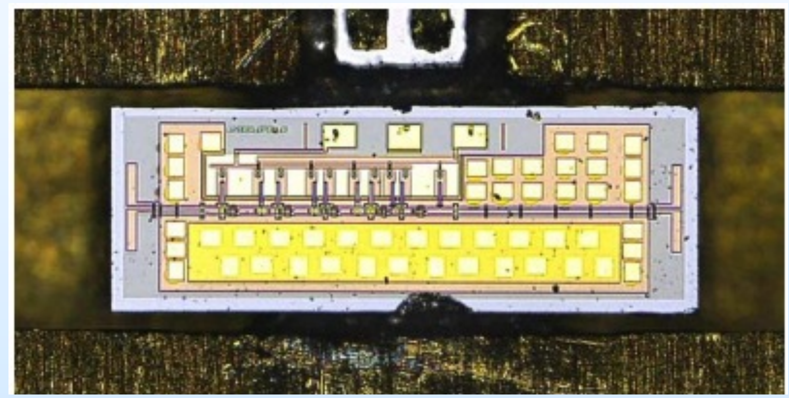


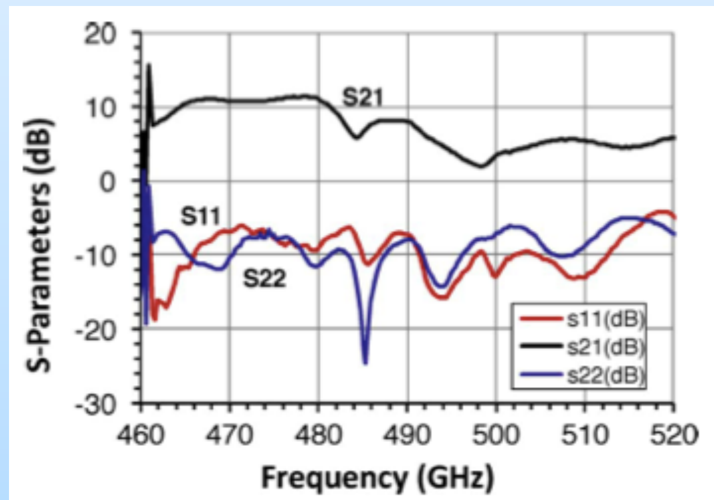


THz Wafer Probing

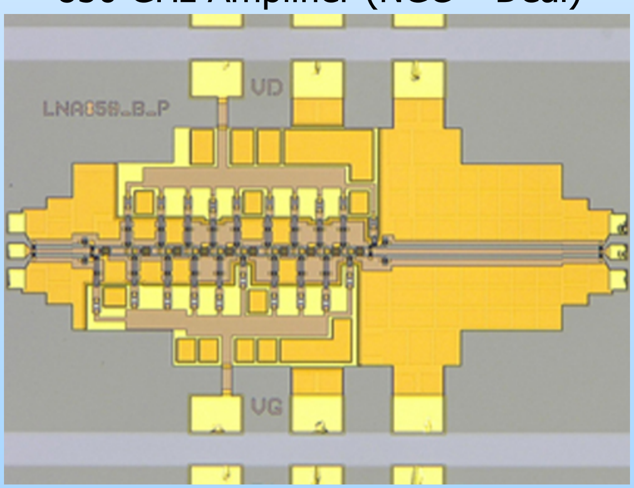
- Rapid advances in InP THz transistors
  - NGC has developed a 650 GHz amp with > 10 dB gain and P_{SAT} of 1.7 mW
    - Radisic – MTT - 2012
- The VDI THz VNA Extenders are use for on wafer probing of these THz transistors
  - Rapid device characterization (no fixture de-embedding)

480 GHz LNA (NGC, Deal – MWCL - 2010)





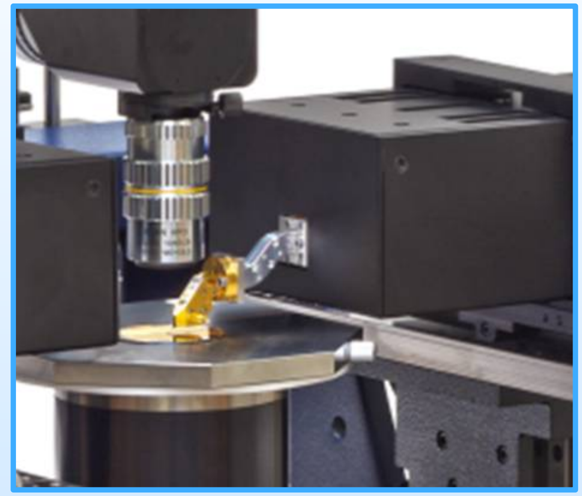
850 GHz Amplifier (NGC – Deal)



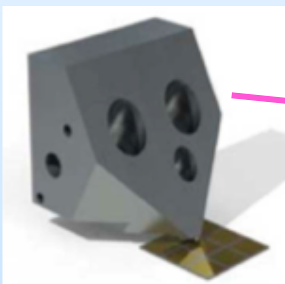
THz Wafer Probing

- First on-wafer TRL calibration >500 GHz!
  - Work in progress on 1 THz on wafer calibration

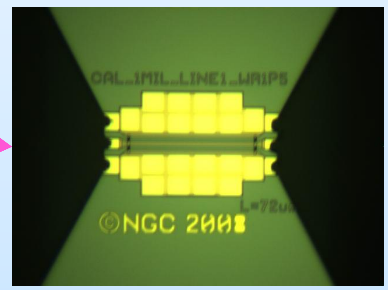
THz Wafer Probe Station (Cascade)



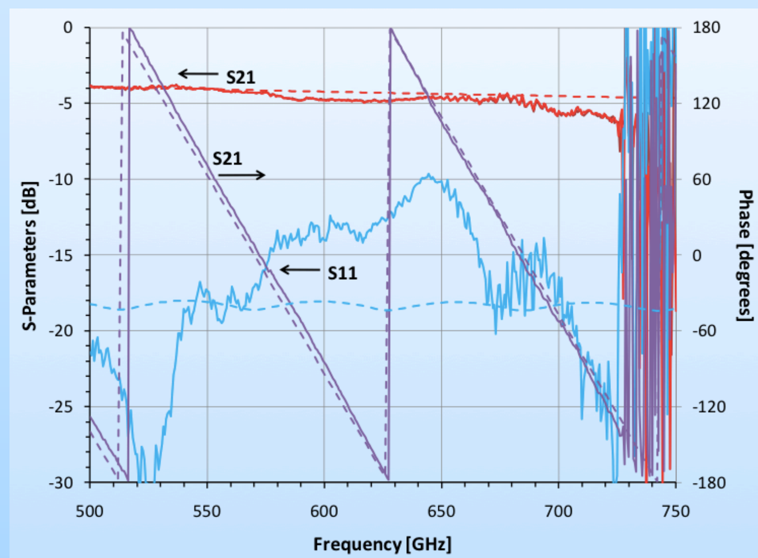
THz Wafer Probe (DMPI)



Probing a CPW Thru Line



On Wafer TRL Calibration



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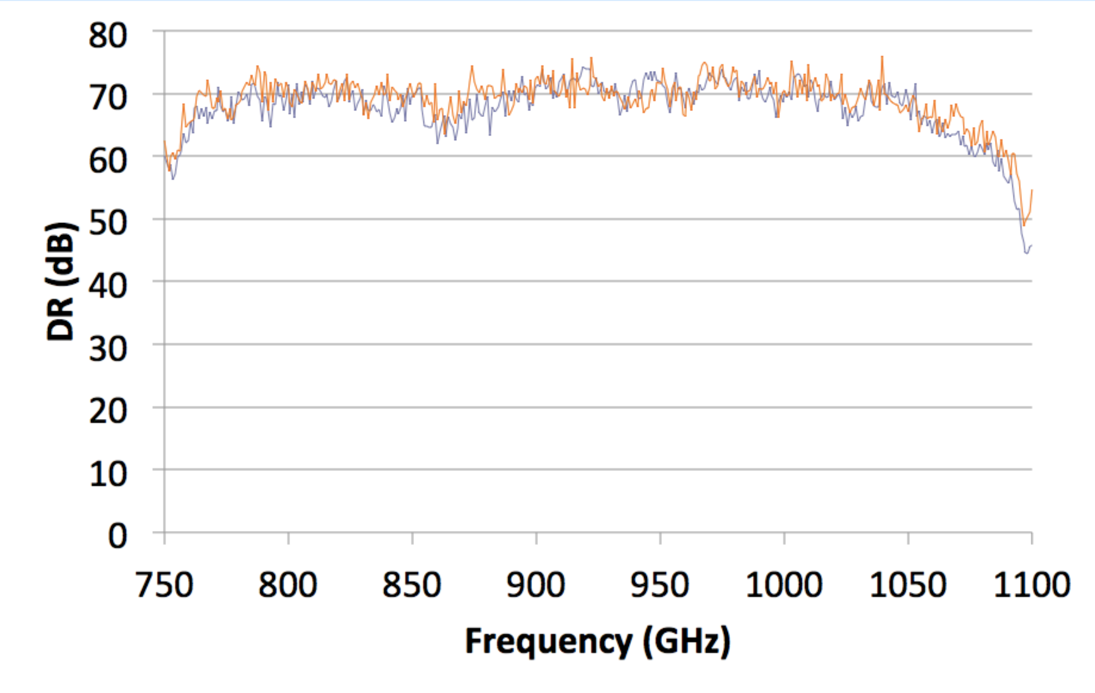
WR-1.0 VDI VNA Extender

- Dynamic range 60 dB typical
  - With 10 Hz IF Bandwidth
- Excellent amplitude and phase stability
  - +/-10 degrees and +/-0.8dB, under normal operating conditions
- THz Measurements using SOLT calibration



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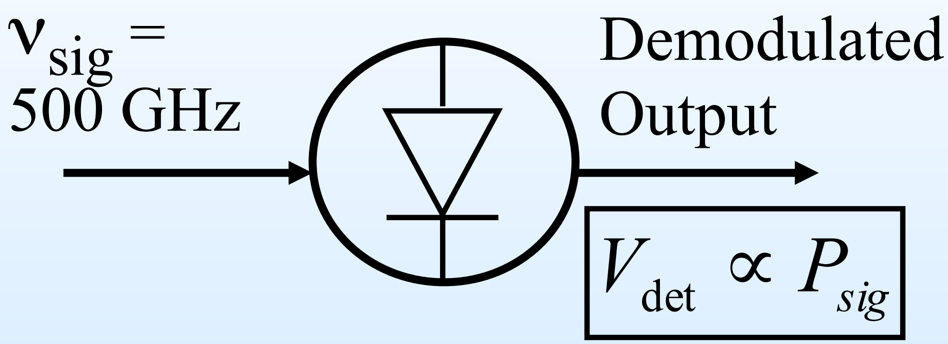
Outline

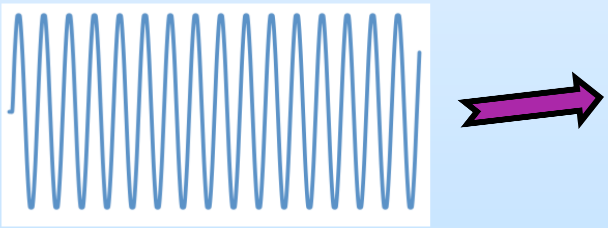
- General Introduction
- Introduction to Schottky Diode Technology
- Solid-State THz Sources
- Solid-State THz Receivers
- THz Transceiver Systems and Applications
  - FMCW Radar
  - Gas Spectroscopy
  - THz Vector Network Analysis
- **Schottky Detectors for Communication Systems**
- Conclusions

Detectors

- Used to convert an applied high frequency signal to baseband
- Wide range of applications
  - Power measurement
  - Spectroscopy
  - Pulse Detection
  - Imaging
  - Communications

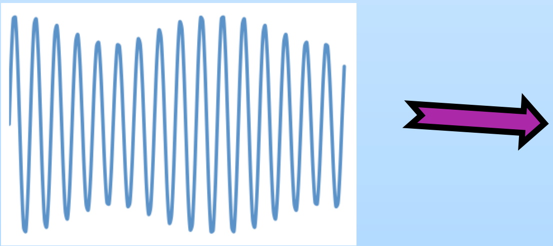


Input ω_1



Output @ DC

Input ω_1 & ω_2



Output @ ω_2-ω_1

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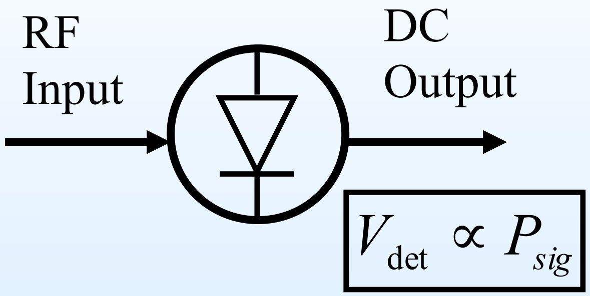
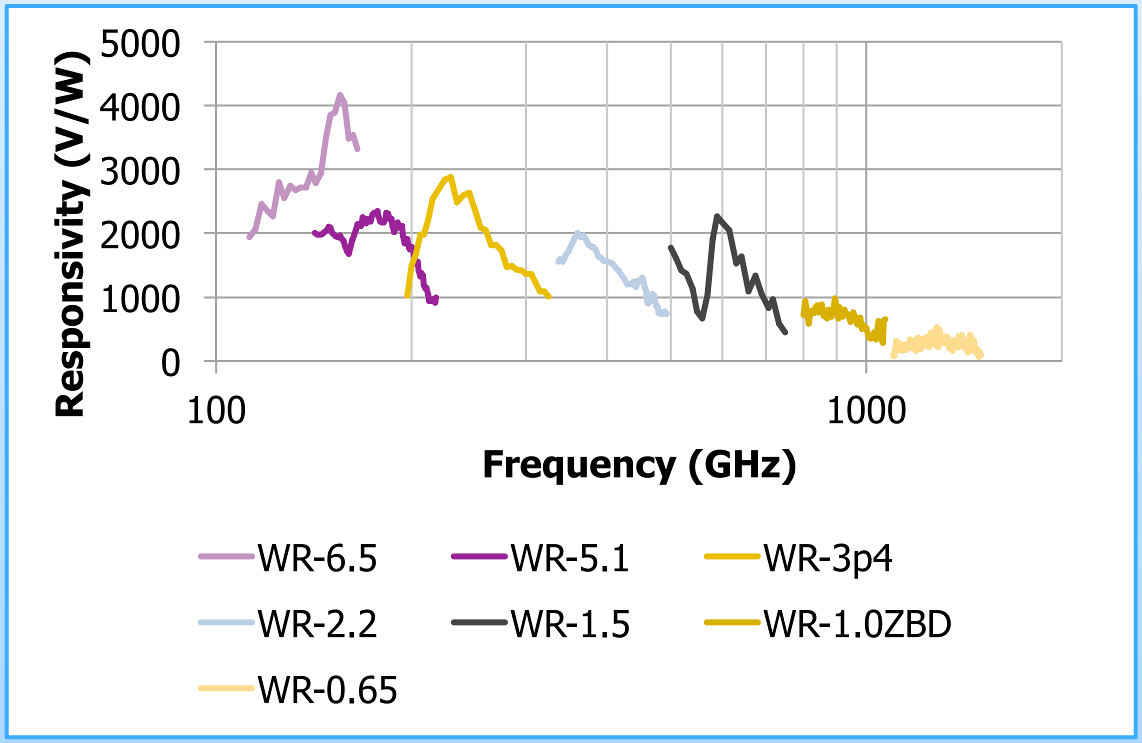
VDI Schottky Detectors



WR-3.4ZBD

Quasi-optical Detector

- Biased or Zero-bias diodes available
- Waveguide-based detectors
  - High Sensitivity
    - 3000 V/W @ 100 GHz
    - 300 V/W @ 1.5 THz
  - Bandwidth limited to 40-50%
- Quasi-optical Detector
  - Bandwidth 100 GHz to > 1 THz
  - Responsivity 500 V/W typ.
- Sub-ns Response time



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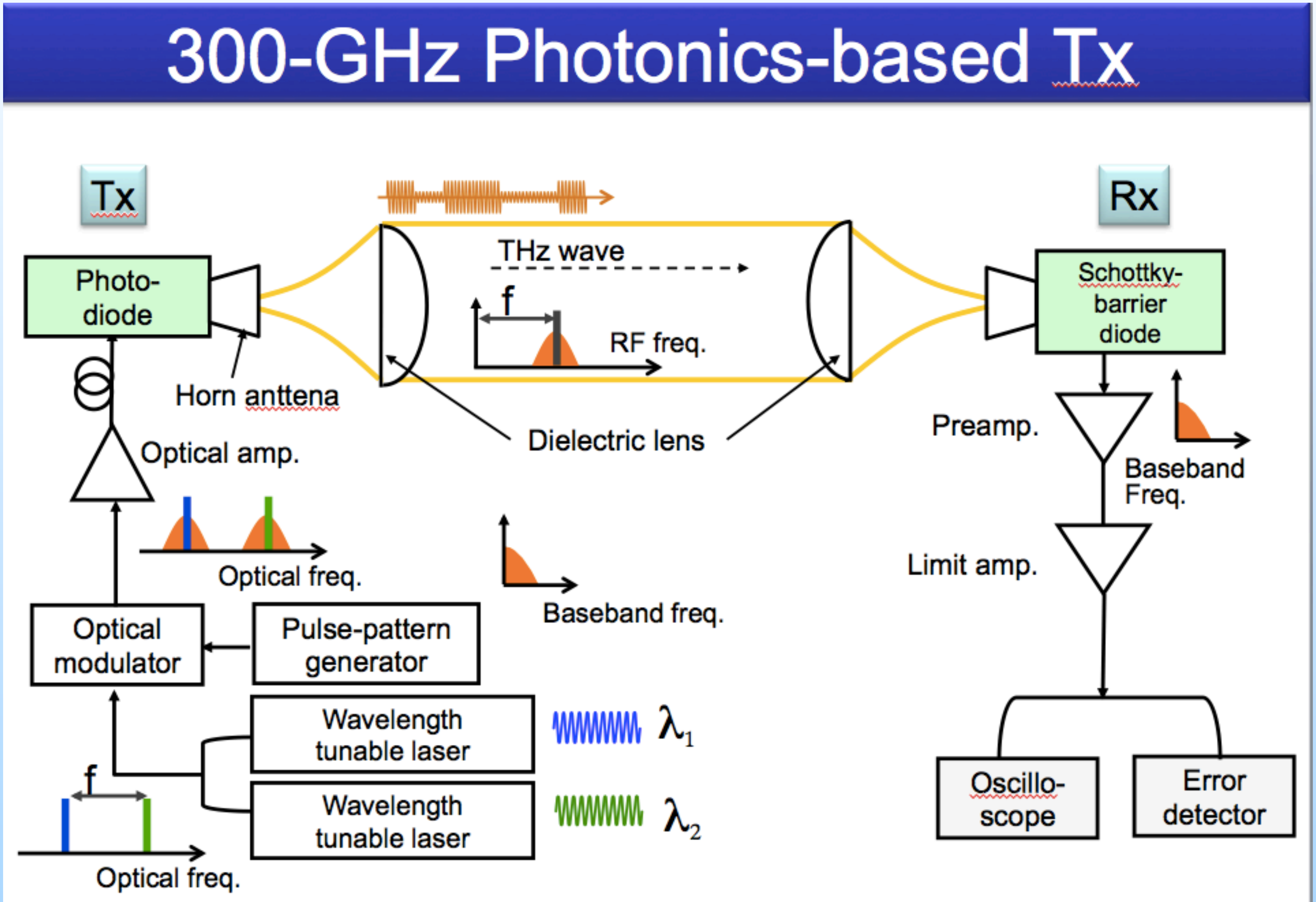
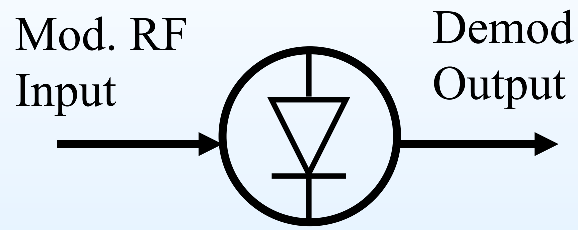
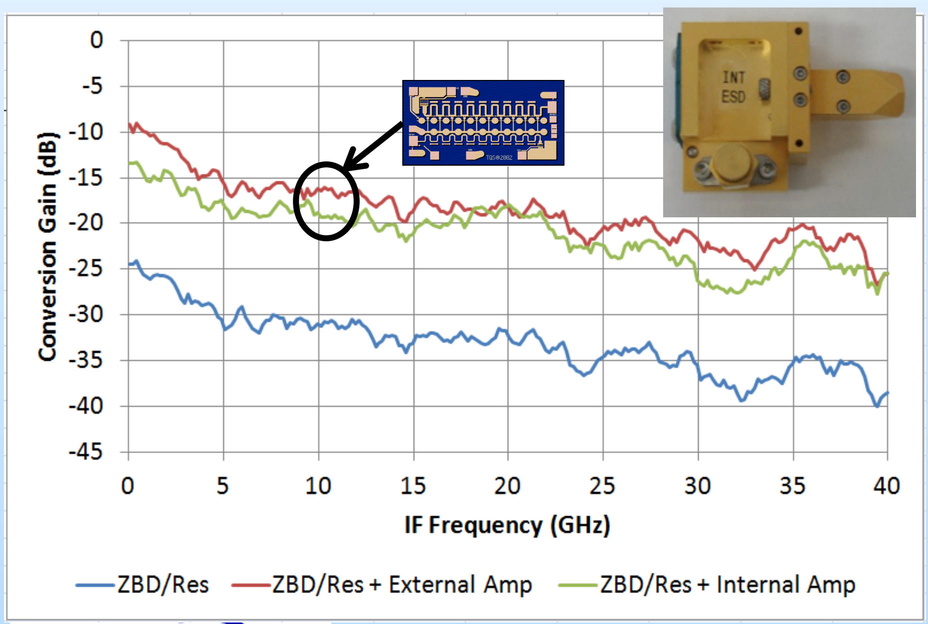
Photonics-based Communications – Nagatsuma (Osaka University)



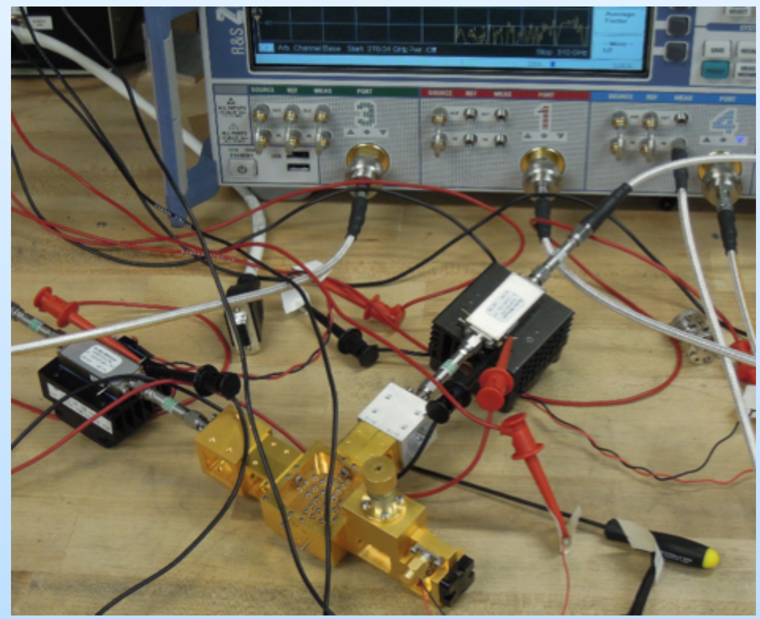
Wideband Demodulation using Schottky Detectors

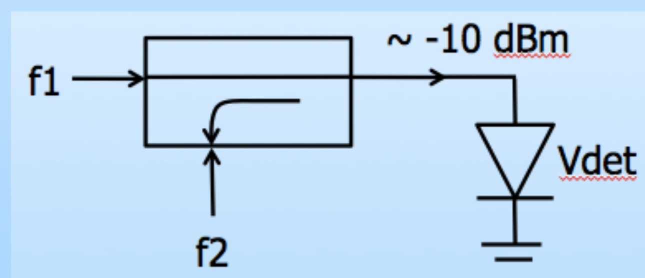
- Used for Communications systems
  - Goal 100 GB/s communication
- Redesign VDI detectors to achieve wide demodulation bandwidth
  - 40+ GHz bandwidth at 300 GHz
  - 35 GHz bandwidth at 100 GHz
- Integrated amplifiers to improve flatness





300 GHz Detector during testing





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Conclusions

- Goal: Open the THz window for routine technological use
  - Broad range of high performance, manufacturable components have been developed
- VDI components are an enabling technology for many THz application
  - Imaging, Spectroscopy, Communication…
- THz Vector Network Analyzers to 1.1 THz
  - High sensitivity, accurate calibration
- Keys are circuit integration, modern CAD, circuit designs and advanced fabrication technology

Useful References

- P.H. Siegel, Terahertz Technology. IEEE Trans. Microwave Theory Tech. 50, 910–928 (2002).
- M. Tonouchi, Cutting-edge Terahertz Technology. Nature Photonics 1, 97-105 (2007)
- F. De Lucia, The Submillimeter: A Spectroscopist's View, Journal of Molecular Spectroscopy 261, 1-17 (2010)

VDI WR9.0 THz Starter Kit: 82-1100 GHz

- Series of cascaded multipliers and detectors
  - Tunerless, instantaneous sweeping over > 40% bandwidth
- Rapidly interchangeable components
  - Turn-key operation
- Built-in AM modulation and Power Control capability
  - For use with detectors
- Detectors are available for all bands
  - Responsivity 2500 V/W at WR-10, 500 V/W at WR-1.0

•WR-9 – 82-125 GHz
•Pout ~ 25 mW

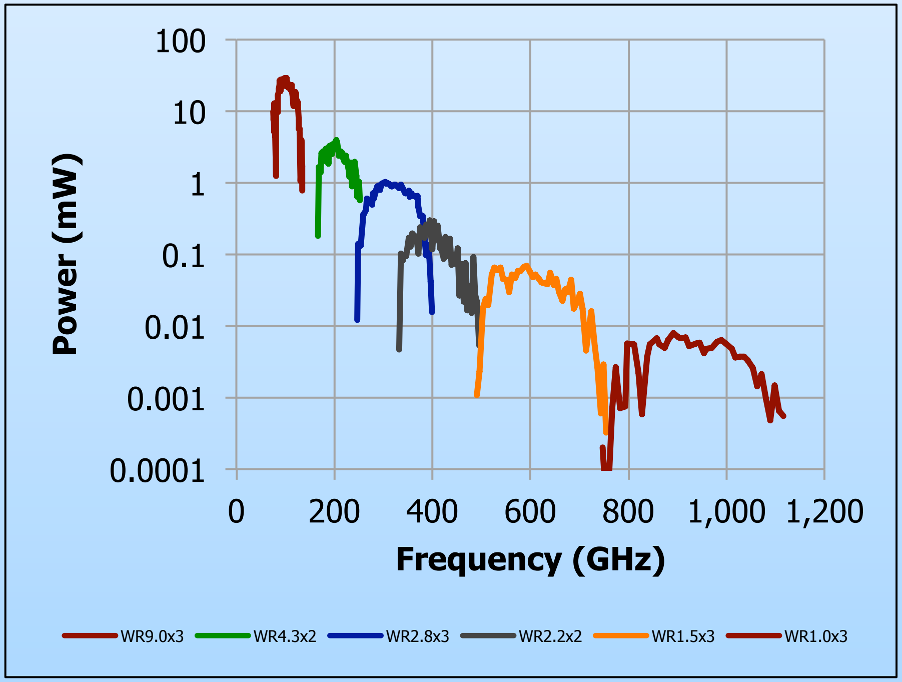
•WR-4.3 – 170-250 GHz
•Pout ~ 3 mW

•WR-2.8 – 265-375 GHz
•Pout ~ 0.7 mW

•WR-2.2 – 340-500 GHz
•Pout ~ 0.18 mW

•WR-1.5 – 510-750 GHz
•Pout ~ 30 uW

•WR-1.0 – 795-1100 GHz
•Pout ~ 4 uW



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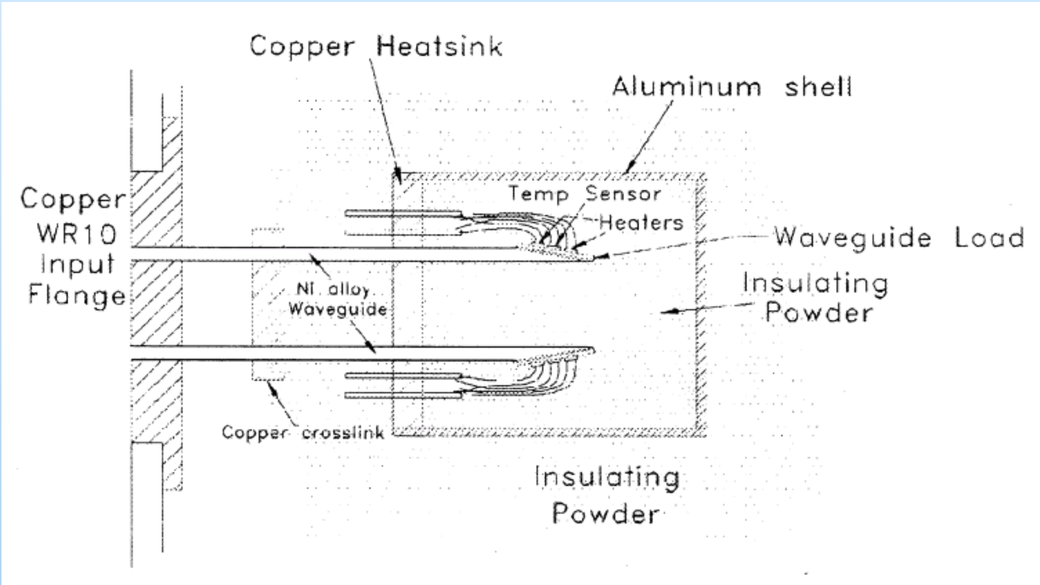
Power Measurements at THz

- No power standard defined above 110 GHz
  - Below 110 GHz NIST/NPL/… provide traceable calibrations
- THz Community has used a variety of power detection methods
  - Direct Detection (Schottky, Bolometer, Golay Cell…)
    - Very sensitive, difficult to calibrate (& limited accuracy)
  - Photo-acoustic (Golay, Keating Power Meter)
    - Quasi-optical coupling, calibrated, slow
  - Pyroelectric
    - Quasi-optical coupling, difficult to calibrate (& limited accuracy), slow
  - Calorimeter
    - Thermal, flat response to THz, well matched, calibrated, slow

Calorimeter



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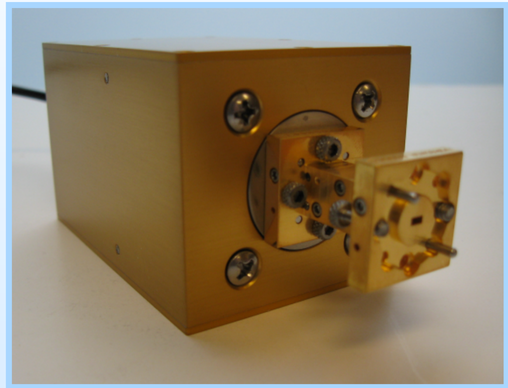
VDI Erickson PM4 Power Meter

- *Calibrated power meter for mm-Wave measurements*
- *Waveguide dry calorimeter*
- *75 GHz to > 2 THz frequency response*
- *1 µW to 200 mW range*
- *Excellent input match (better than -25dB IRL > 80 GHz)*



Scale	90% Response Time	RMS Noise
200 mW	0.1 sec	~3 uW
20 mW	0.15 sec	~0.3 uW
2 mW	1.3 sec	0.1 uW
200 uW	15 sec	0.01 uW

- *WR-10 waveguide input*
- *Sensor size is 5.1 x 4.8 x 7.6 cm.*
- *1 meter cable connects to sensor*
- *0-10 V analog output*
- *RS232 Interface*
- *Full line of waveguide transitions available*
- *Vacuum operation optional*

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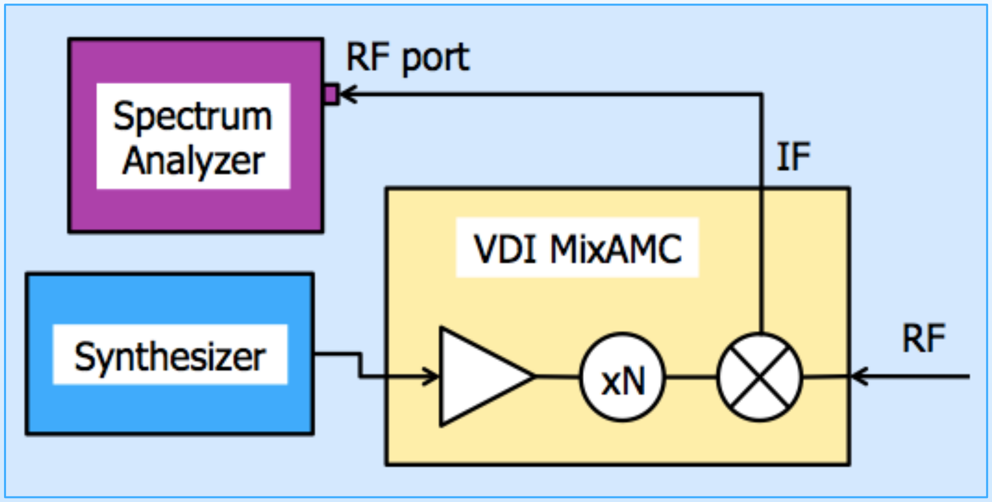
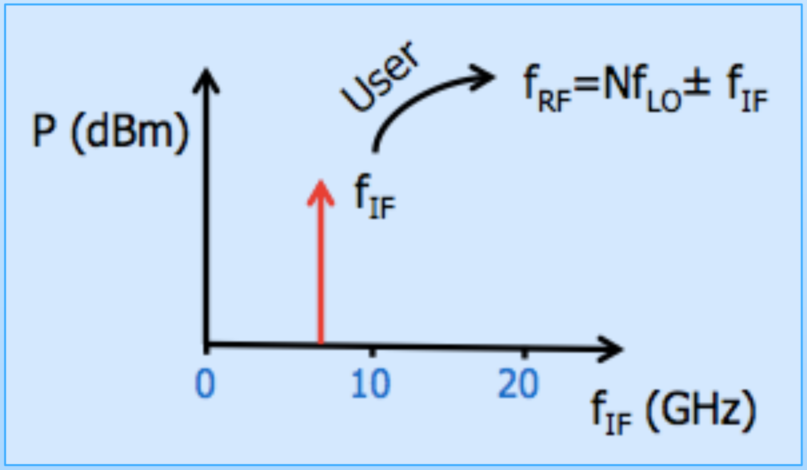
MixAMC & Spectrum Analyzers: Block Downconversion

- General principle 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 15 GHz up to > 40 GHz, depending upon the waveguide band
- Uses of block downconversion
  - General analysis of THz signals
    - Requires User analysis, see below
  - 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
- User must determine where the signals are coming from
  - Spurious mixing products can be weeded out by by varying the synthesizer slightly to determine the mixing order
    - Similar to signal identification
  - Conversion loss of MixAMC can be used to determine RF power



Spectrum Analyzer Display



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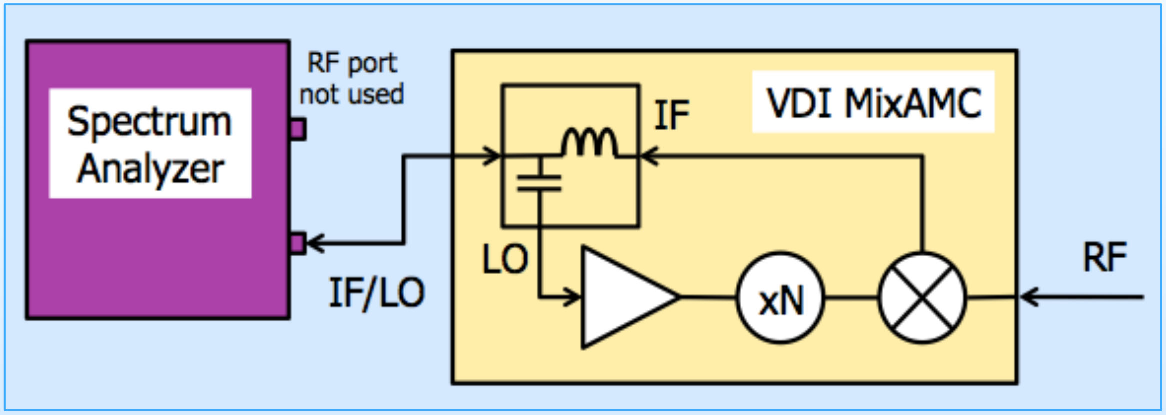
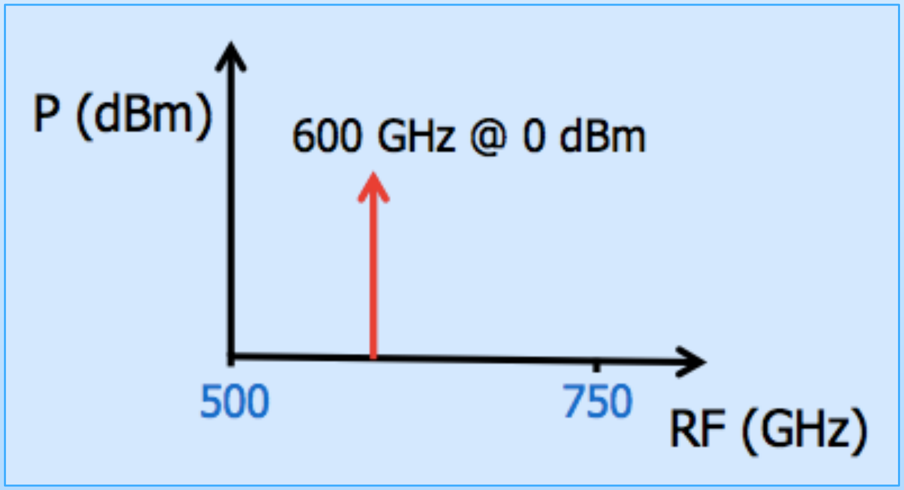
MixAMC & Spectrum Analyzers: Frequency Analyzer Extension

- General principle of Frequency 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)
- Spectrum analyzer performs signal analysis
  - Signal identification used to determine the actual frequency of the RF signal and remove spurious signals
  - Conversion loss table used to adjust power level
- Uses of Frequency Analyzer Extension
  - General signal analysis
  - 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



Spectrum Analyzer Display



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