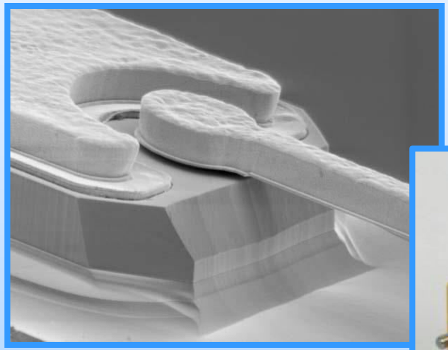
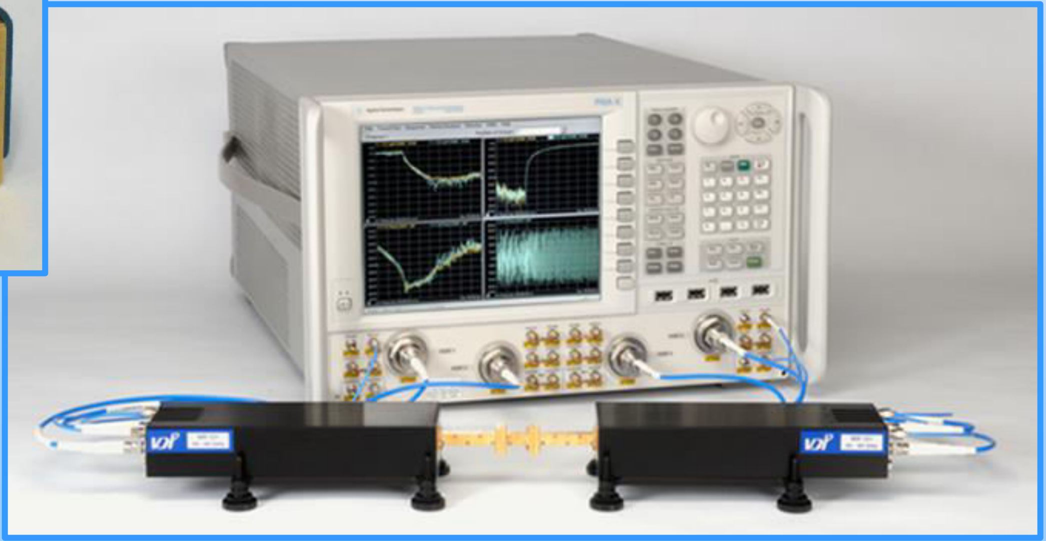
Solid-State Signal Generation and Detection at mm-Waves & THz

Dr. Jeffrey L. Hesler

CTO
Virginia Diodes Inc.,
Charlottesville, VA, USA





Virginia Diodes, Inc.

www.vadiodes.com

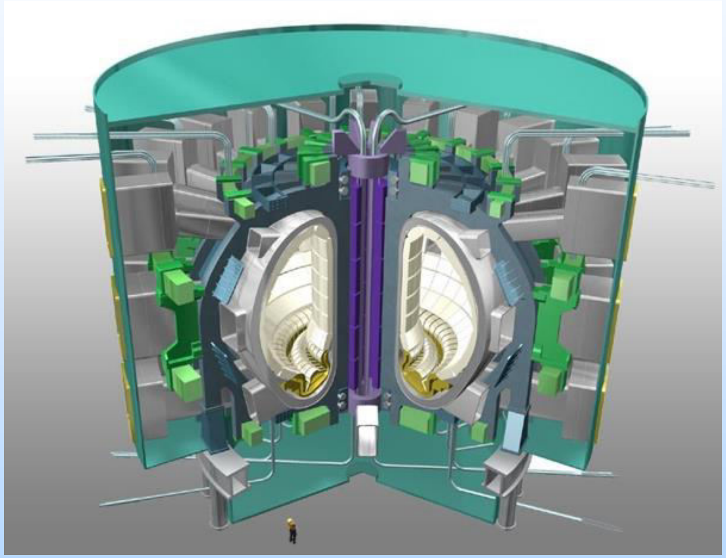
This Presentation

- Introduction
  - THz Applications
  - Schottky Diode Technology
- Schottky-Based THz Heterodyne Transceiver Components
  - THz Signal Generation
  - Waveguide Interfaces
  - THz Signal Detection
    - Generation of Wideband Modulated Signals at THz
- THz Transceivers
  - Chirped Transform Spectroscopy
- Solid-State Sources & DNP
- Conclusions

Applications Above 100GHz

Radio Astronomy

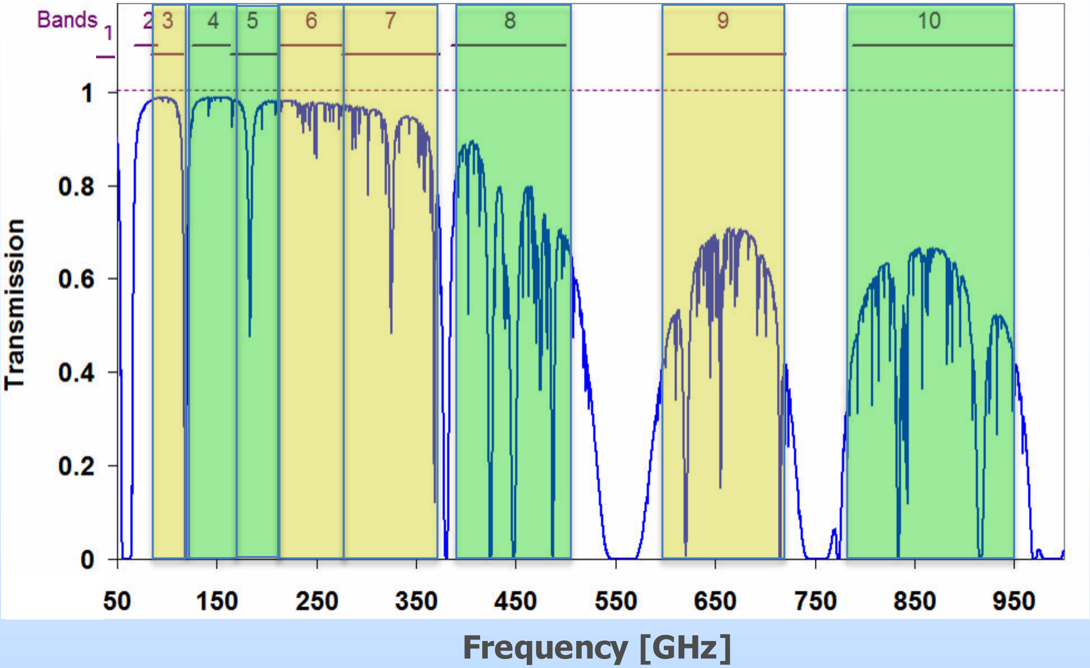
Fusion Plasma (e.g. ITER)



- Basic Science – the primary driver
  - Astronomy, Physics, Chemistry, Fusion Plasma, …

ALMA Chajnantor Site (5000m)

ALMA Development (~1998-2007)



- 66 Antennas
  - 12 m & 7 m diameter dishes
- 2 Receivers for each band
- 12 VDI THz multiplier chains in each antenna

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%

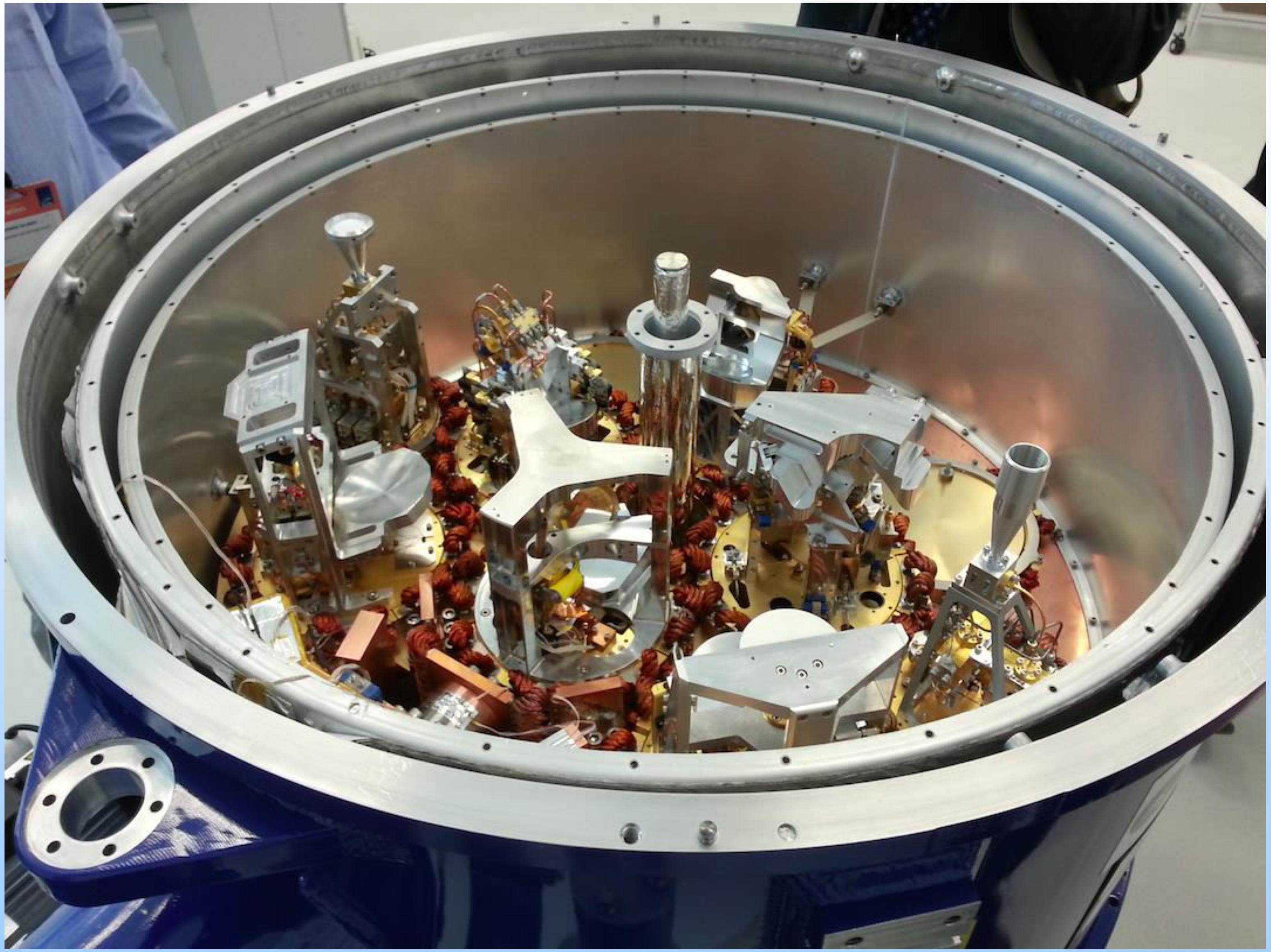
VDI (bands 4–10)

Virginia Diodes, Inc.

www.vadiodes.com

ALMA Chajnantor Site (5000m)

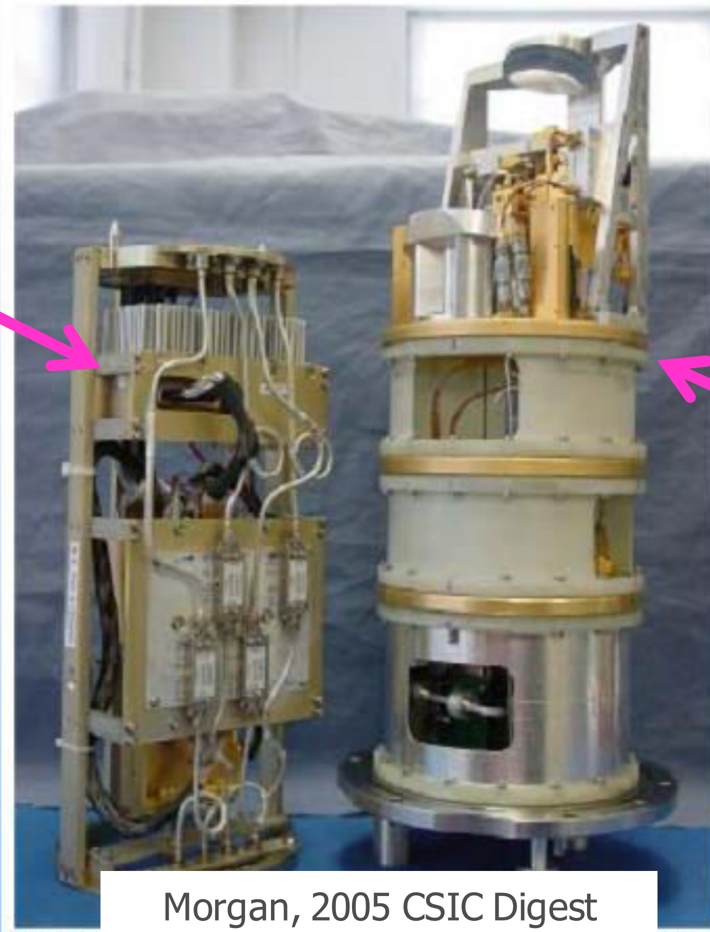
ALMA Front End Cryostat



ALMA Front End

Warm Cartridge Assembly with LO YIG Tuned Oscillator and Driver Stage (up to ~120 GHz)

Driver contains integrated multi-chip modules taking ~12-24 GHz YTO output to 65-122 GHz output



Morgan, 2005 CSIC Digest

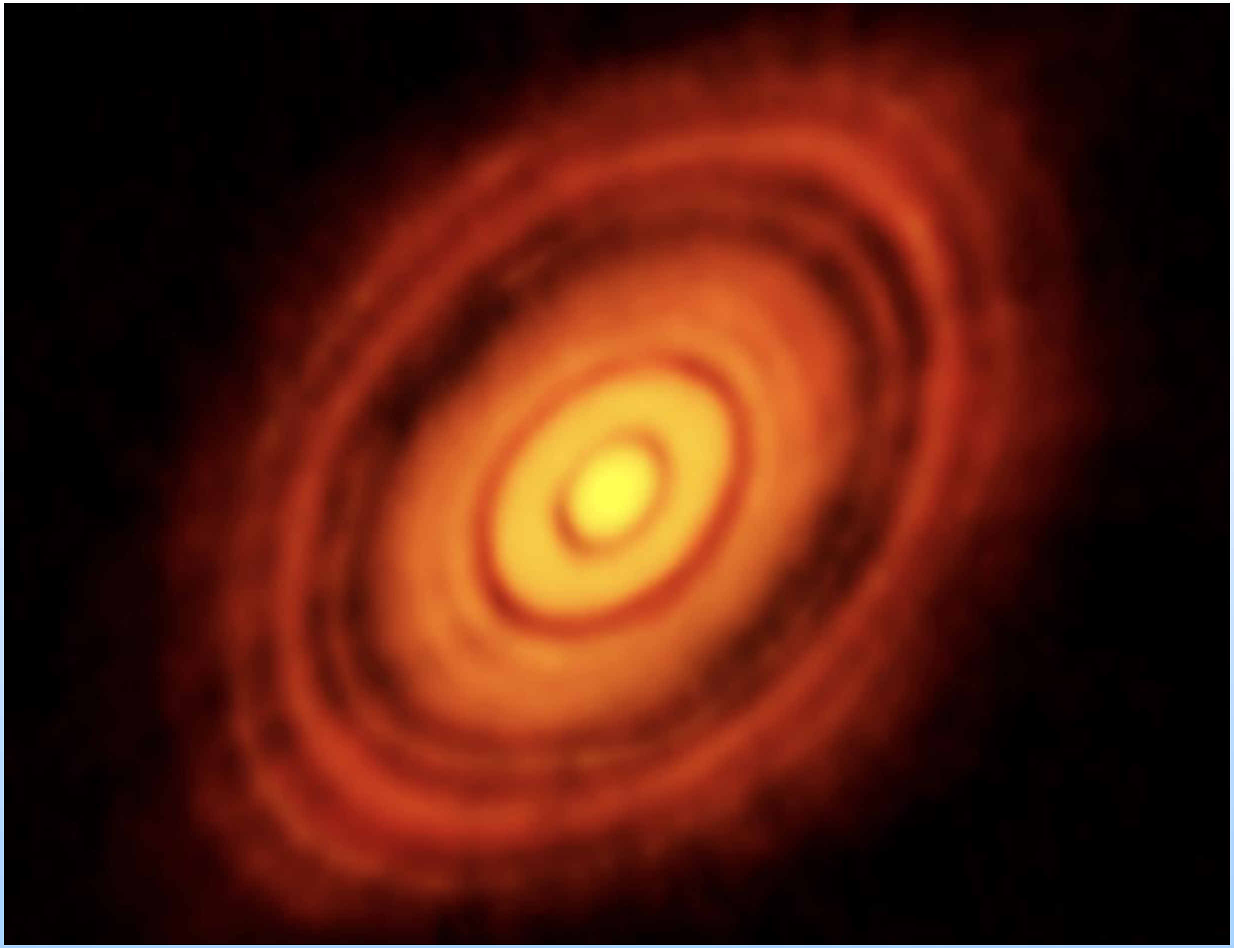
Fig. 3. Photograph of the receiver cartridge for ALMA Band 6. The warm cartridge assembly is on the left, while the cryogenic portion is on the right.

Cryogenic Front End

4K Stage with SIS Mixers

VDI Multipliers on 77K Stage

ALMA Science

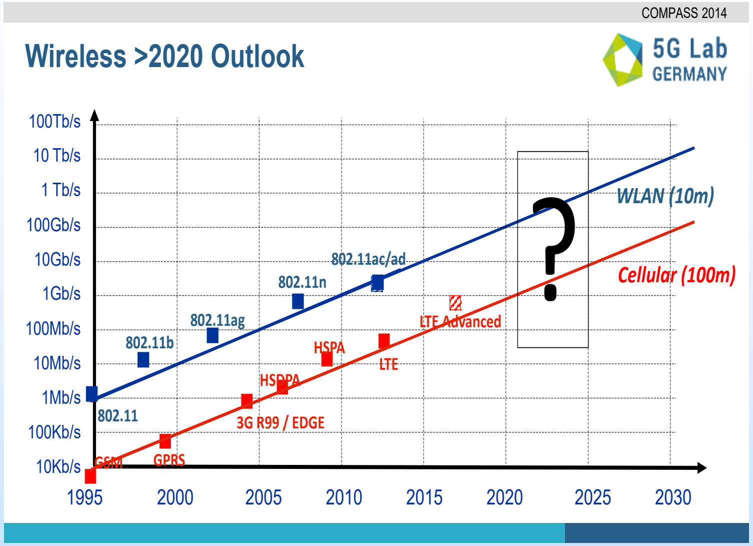


- ALMA image of the young star HL Tau and its protoplanetary disk. This best image ever of planet formation reveals multiple rings and gaps that herald the presence of emerging planets as they sweep their orbits clear of dust and gas. Credit: ALMA (NRAO/ESO/NAOJ); C. Brogan, B. Saxton (NRAO/AUI/NSF)

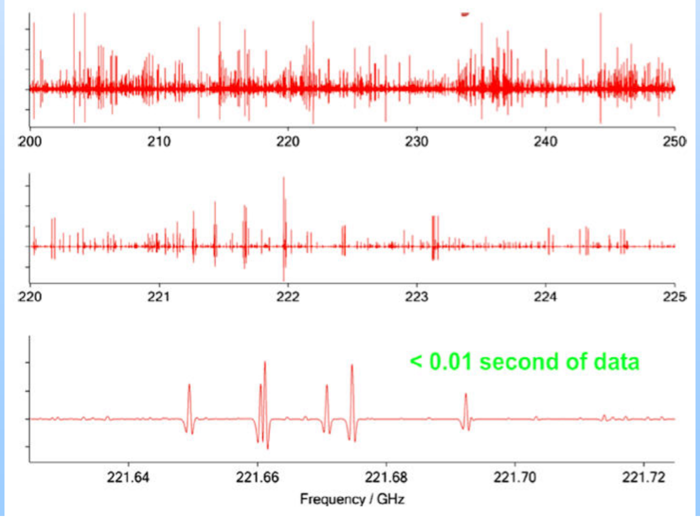
Applications Above 100 GHz

- Field moving from Basic Science to Applications
  - Concealed Weapons Detection
  - Collision Avoidance Radar
  - Detection of Chemical/Biological Hazards
  - Wideband & Secure Communications
  - Medical Diagnostics
- Also a strong interest in basic Test & Measurement capabilities at THz

Communications



Chem/Bio Detection



De Lucia (OSU) – 2010 JMS

Concealed Weapons Detection

Thruvision – Knife Detection

https://www.gov.uk/government/news/new-technology-to-detect-knives-in-public-places

This Presentation

- Introduction
  - THz Applications
  - **Schottky Diode Technology**
- Schottky-Based THz Heterodyne Transceiver Components
  - THz Signal Generation
  - Waveguide Interfaces
  - THz Signal Detection
    - Generation of Wideband Modulated Signals at THz
- THz Transceivers
  - Chirped Transform Spectroscopy
- Solid-State Sources & DNP
- Conclusions

Virginia Diodes Inc.

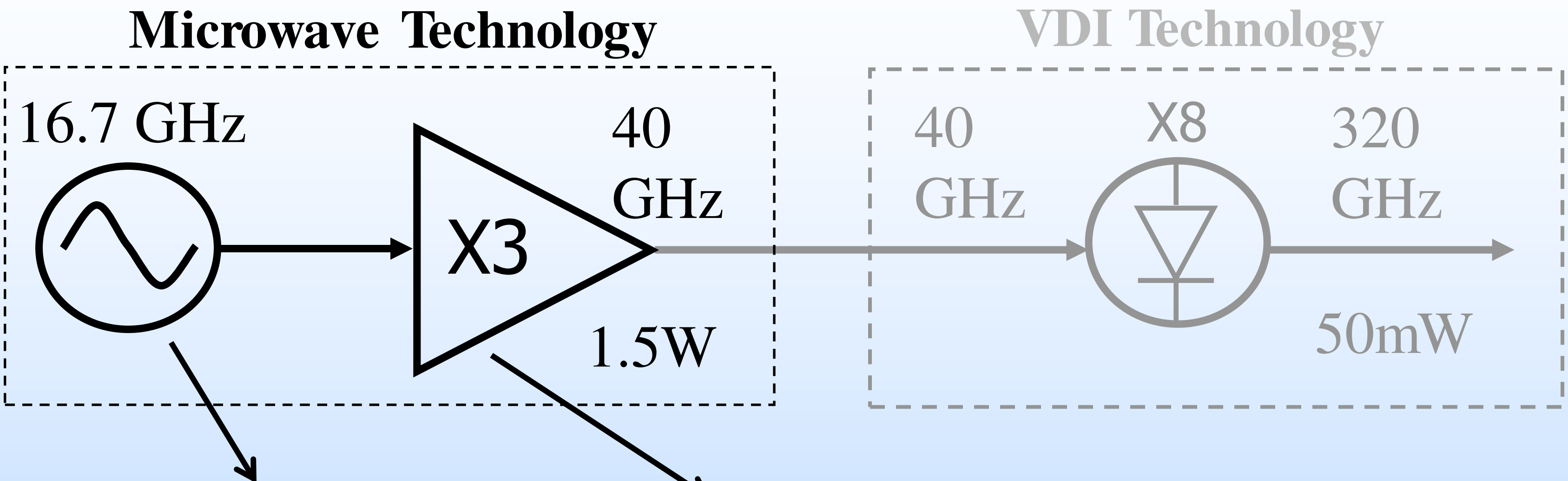
- VDI is a small, high technology company focused on the emerging field of Terahertz Technology
  - Advanced scientific base, emerging new applications, and THz Test & Measurement…

- Look at the core technology behind VDI

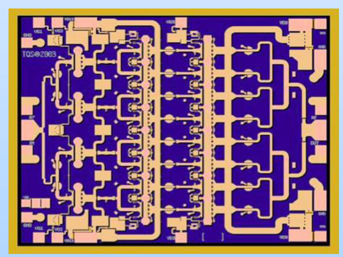
Virginia Diodes, Inc.

www.vadiodes.com

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



Herley-CTI

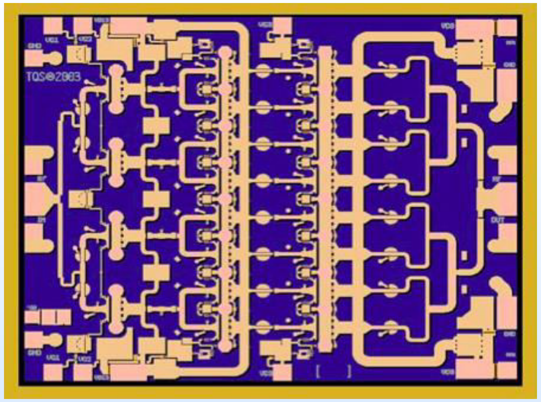

Triquint

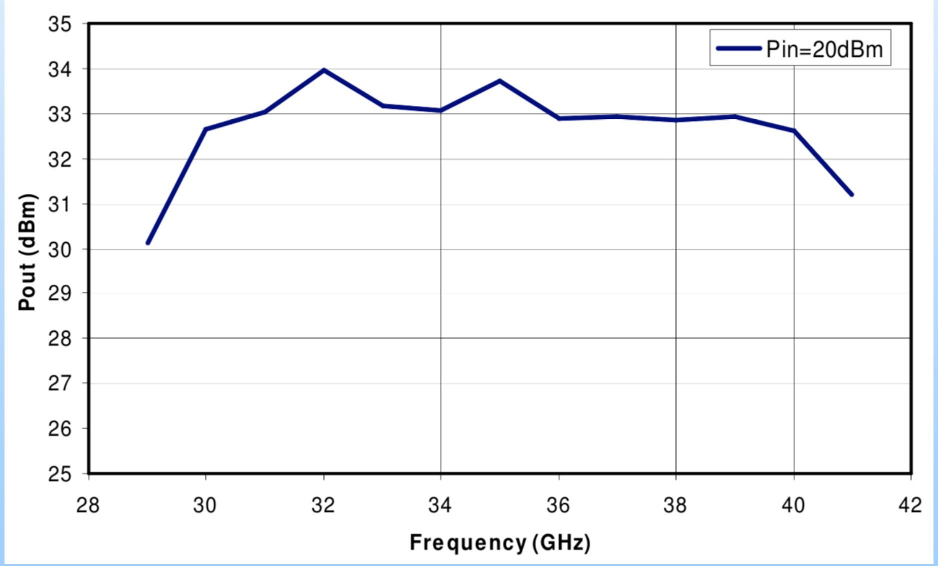
- Microwave technology developed for large scale commercial applications
  - Communications (Satellite, Point-to-Point, Personal)
  - Radar

Virginia Diodes, Inc.

Example: mmWave Base Technology

- Qorvo 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…

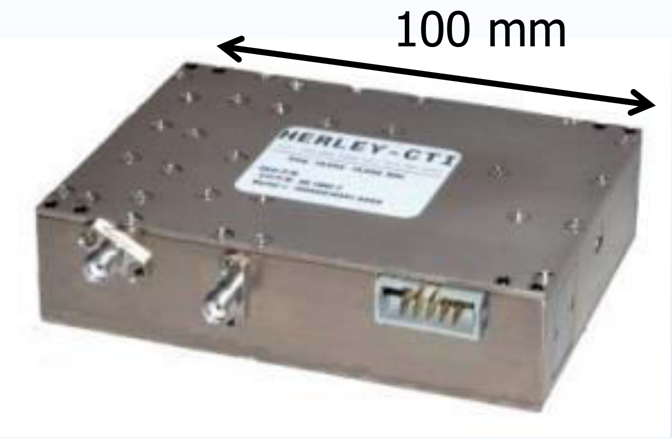




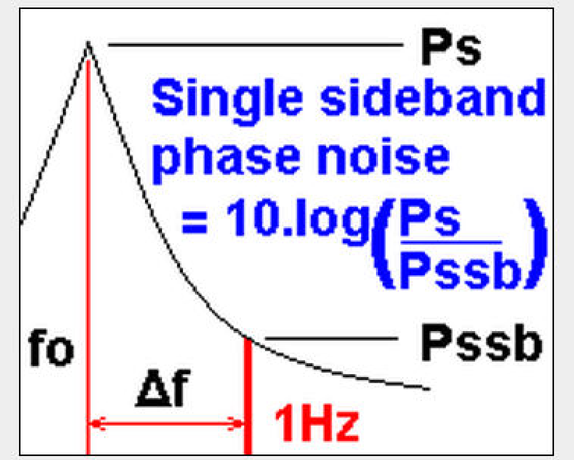
Virginia Diodes, Inc.

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



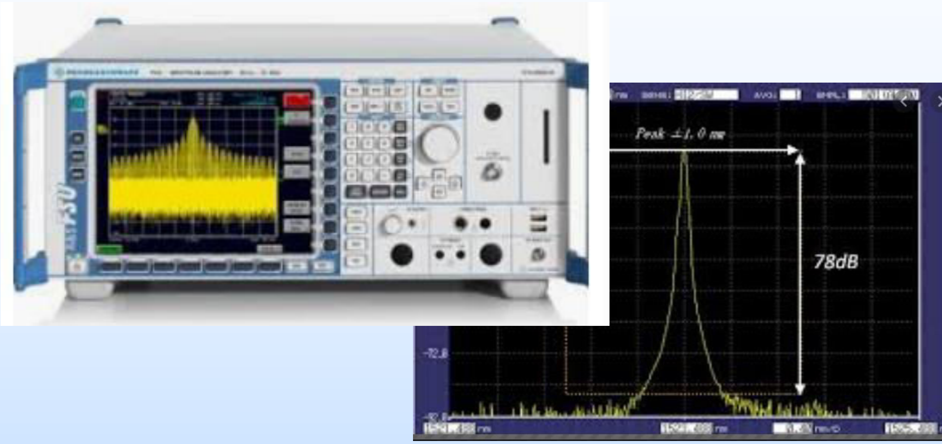
Single sideband phase noise

www.telestrian.co.uk/phasenoise.html

Microwave Test & Measurement

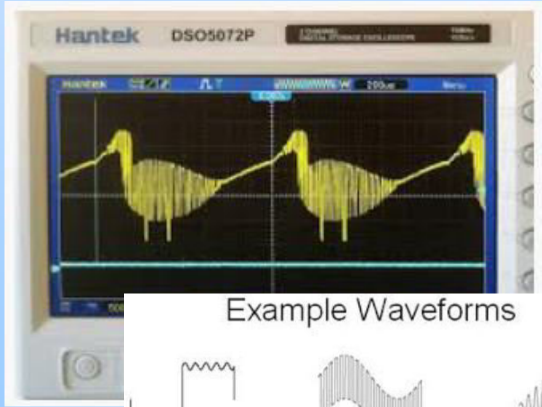
Signal Generator

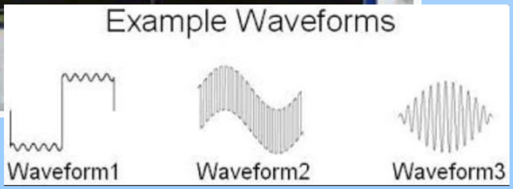
Spectrum Analyzer



Highspeed Oscilloscopes

Arbitrary Waveform Generator

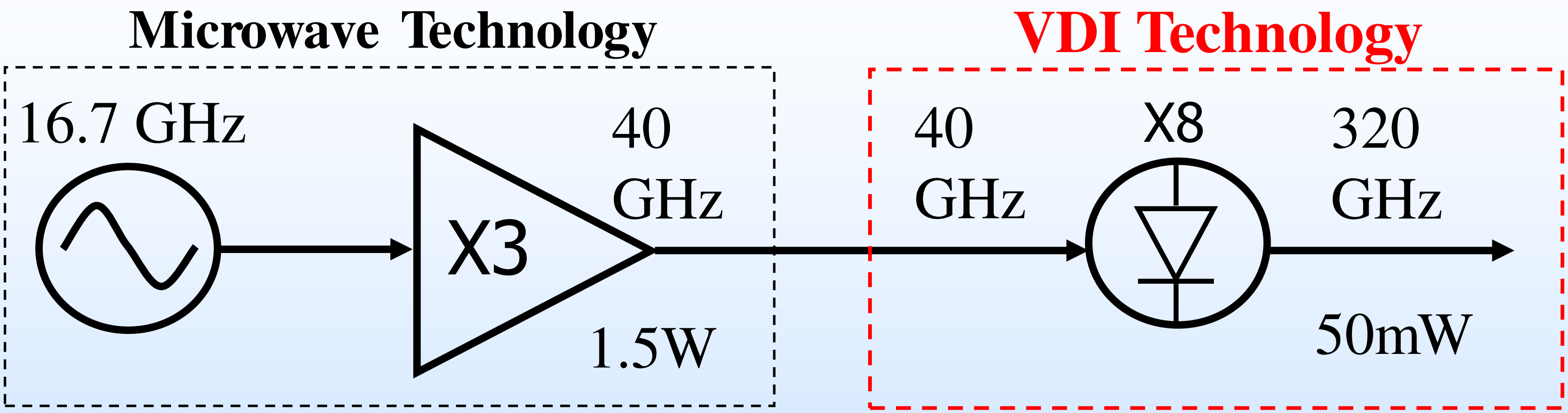




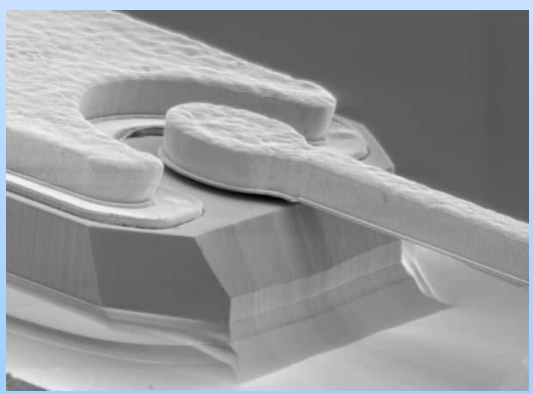
Vector Network Analyzer

Virginia Diodes, Inc.

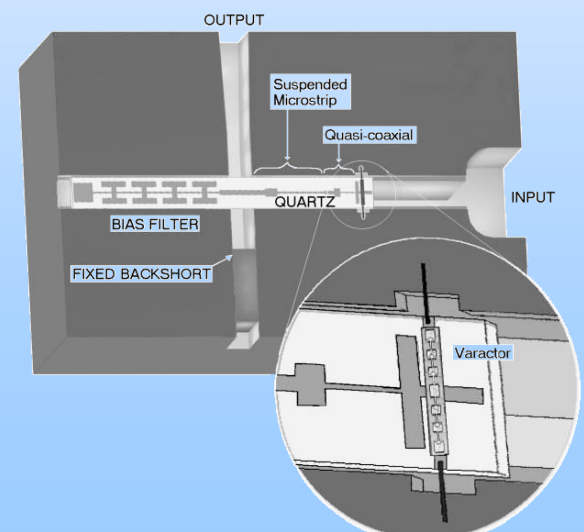
VDI Core Technology: Use nonlinear devices to extend the frequency range of traditional microwave electronics



Schottky Diode



Frequency Doubler

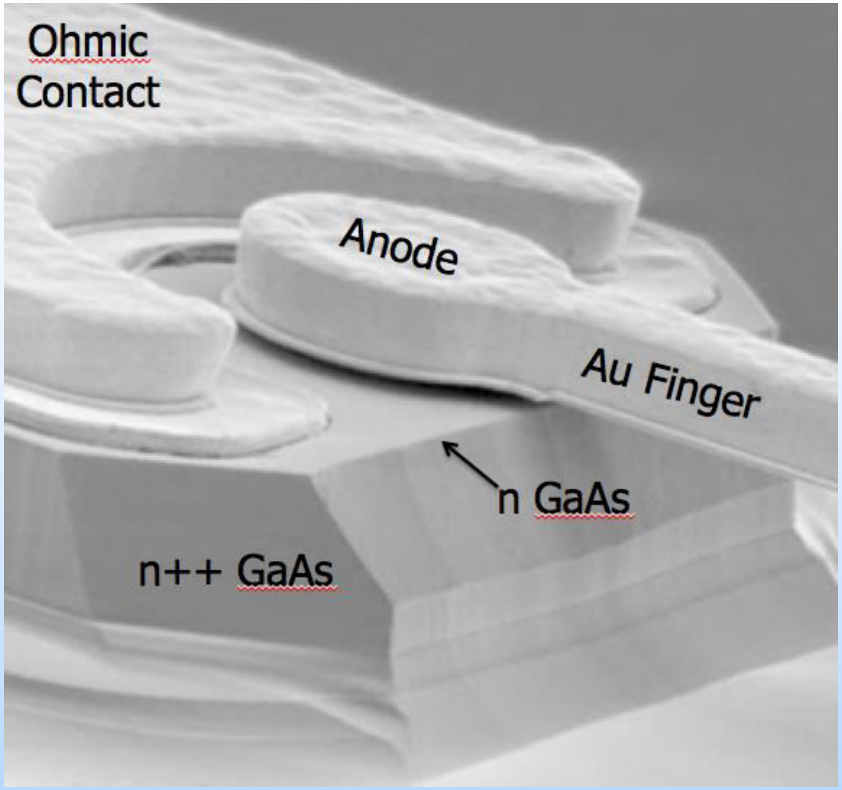


Virginia Diodes, Inc.

www.vadiodes.com

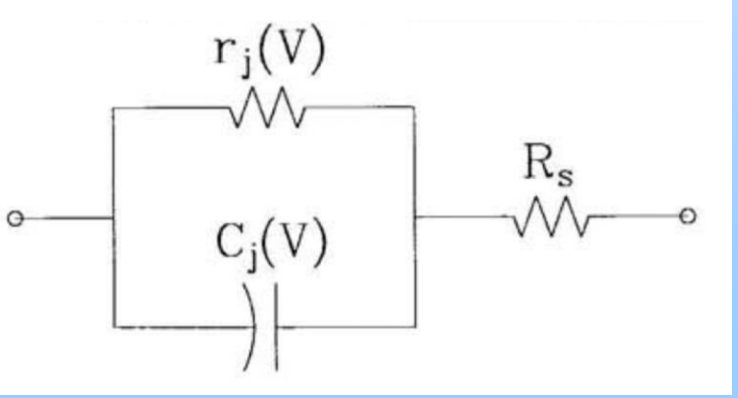
Schottky Diodes

- 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 key for THz**



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

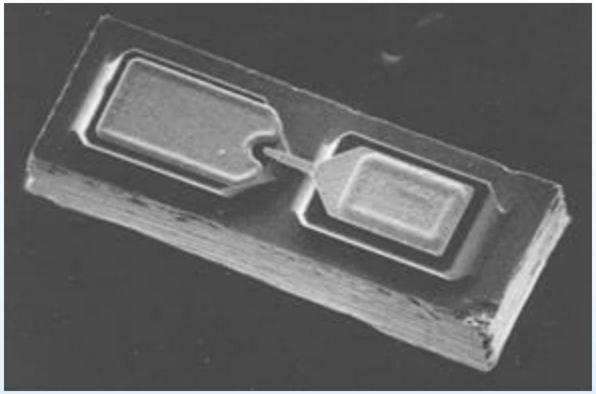
$$C_j = \frac{C_{j0}}{\sqrt{1 - V_j/V_{bi}}}$$



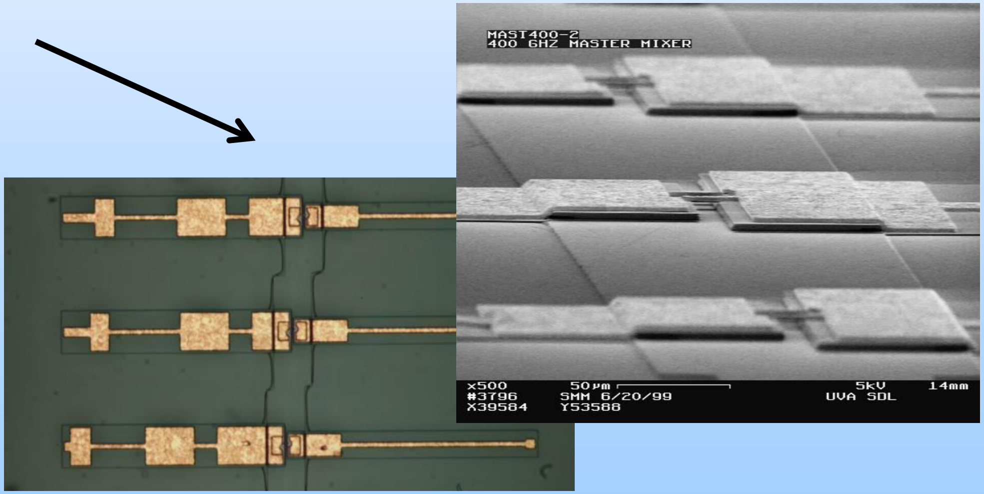
Virginia Diodes, Inc.

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

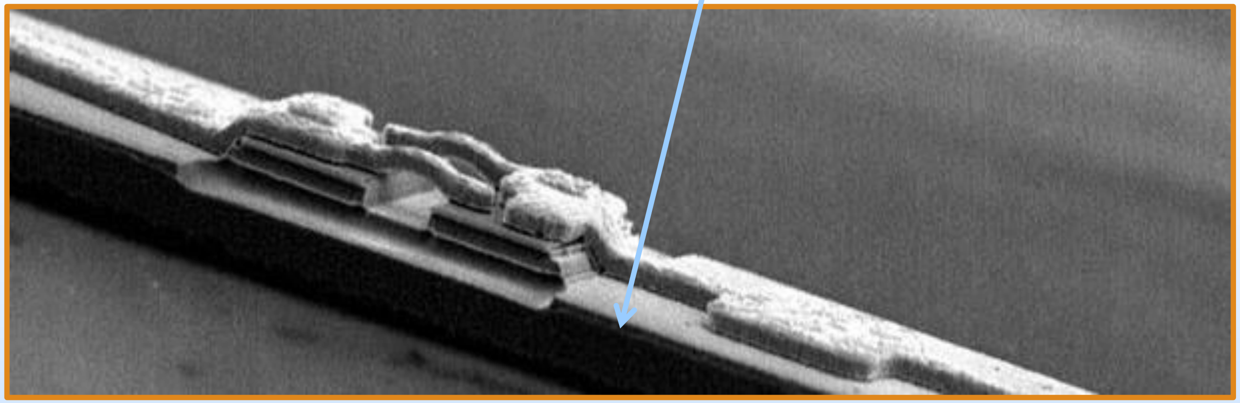


Integrated Planar Diodes

Virginia Diodes, Inc.

THz Diode IC

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

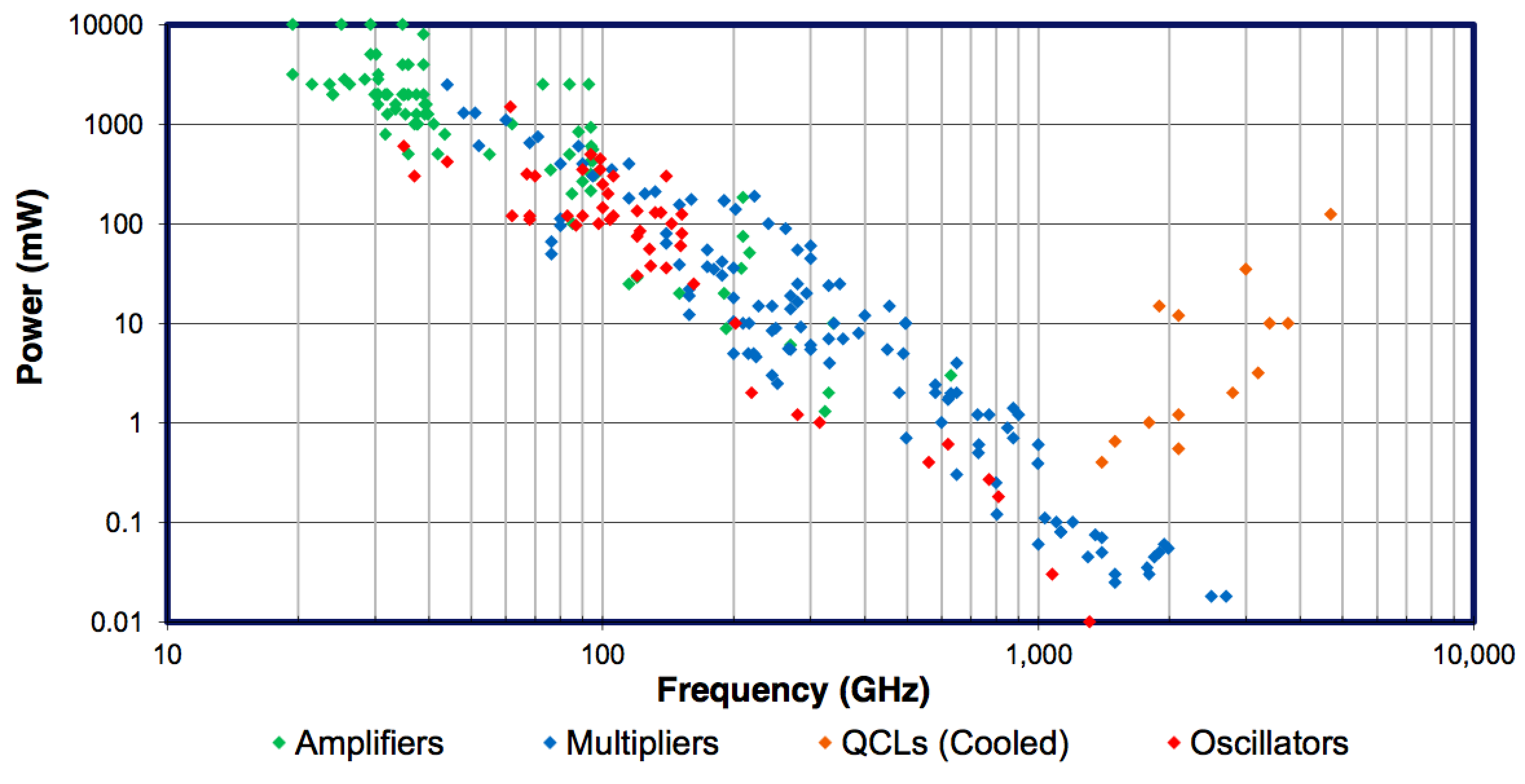


THz circuits are very small, but surprisingly robust!

This Presentation

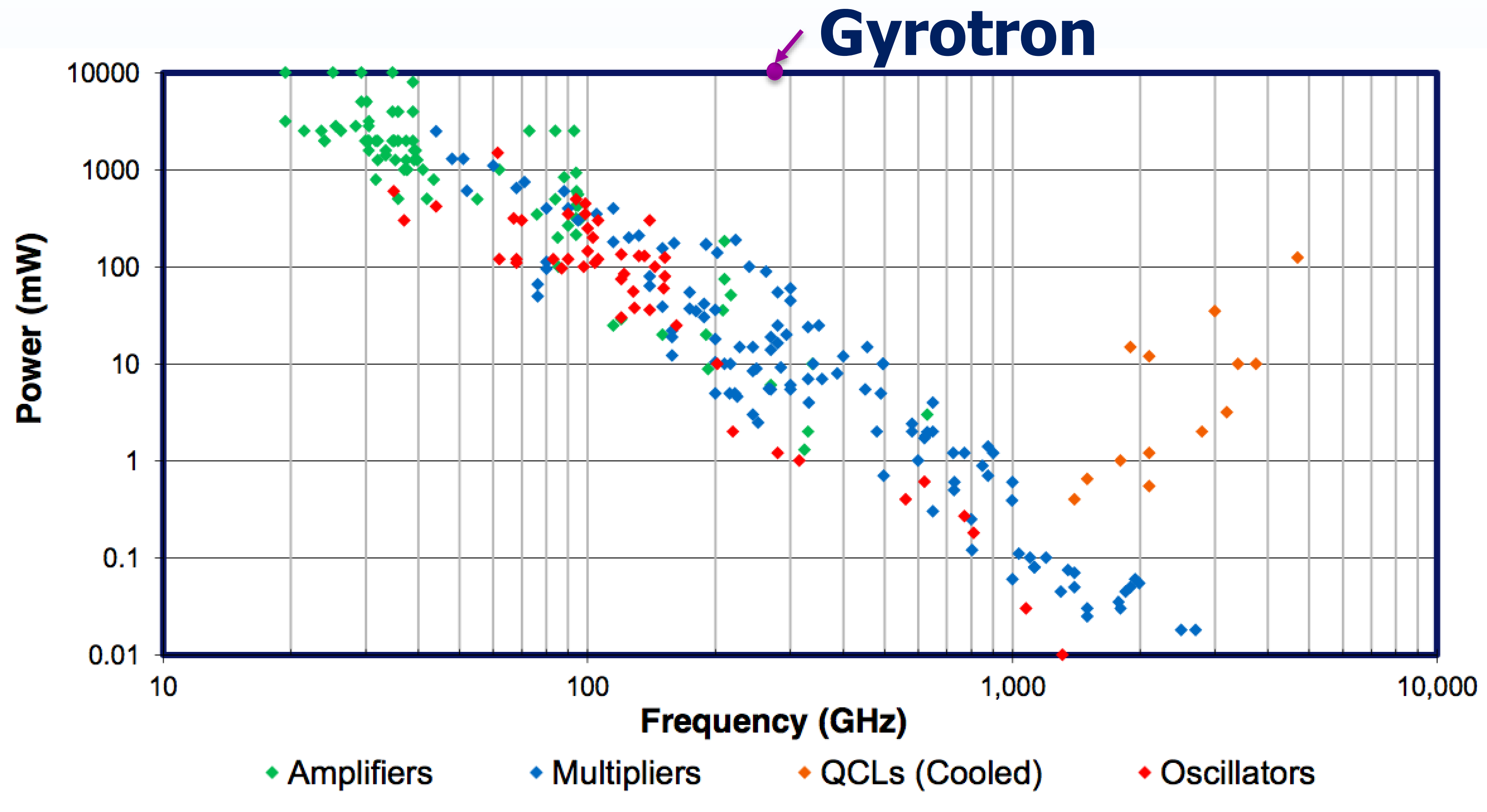
- Introduction
  - THz Applications
  - Schottky Diode Technology
- Schottky-Based THz Heterodyne Transceiver Components
  - **THz Signal Generation**
  - Waveguide Interfaces
  - THz Signal Detection
    - Generation of Wideband Modulated Signals at THz
- THz Transceivers
  - Chirped Transform Spectroscopy
- Solid-State Sources & DNP
- Conclusions

Power from Solid State Sources



http://www.vadiodes.com/images/AppNotes/ApplicationNote-SummaryofSolid-StateSources.pdf

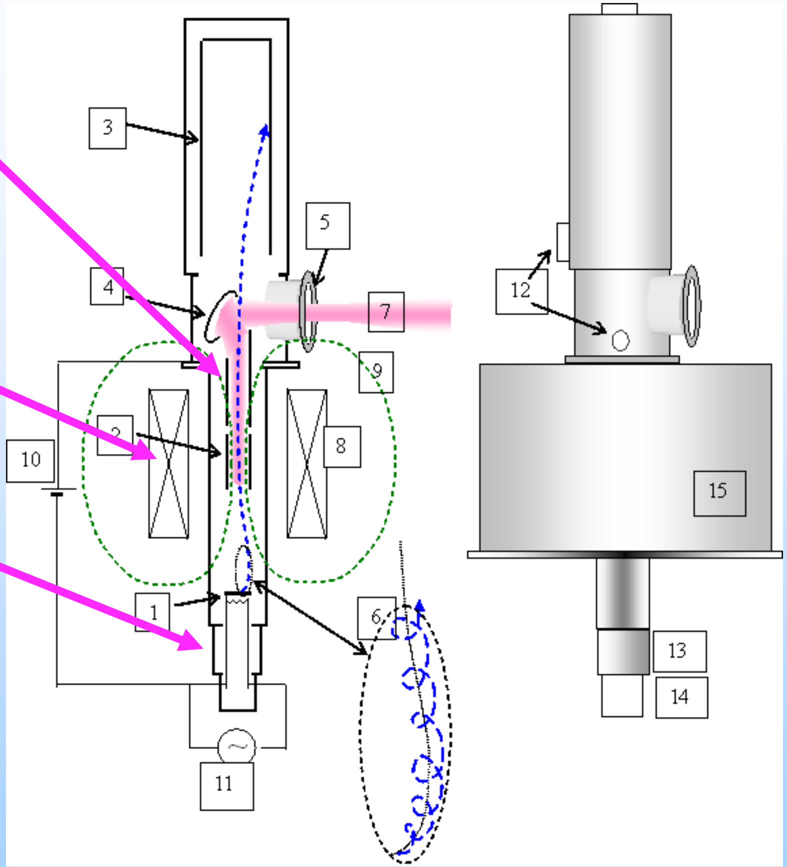
Power from Solid State Sources



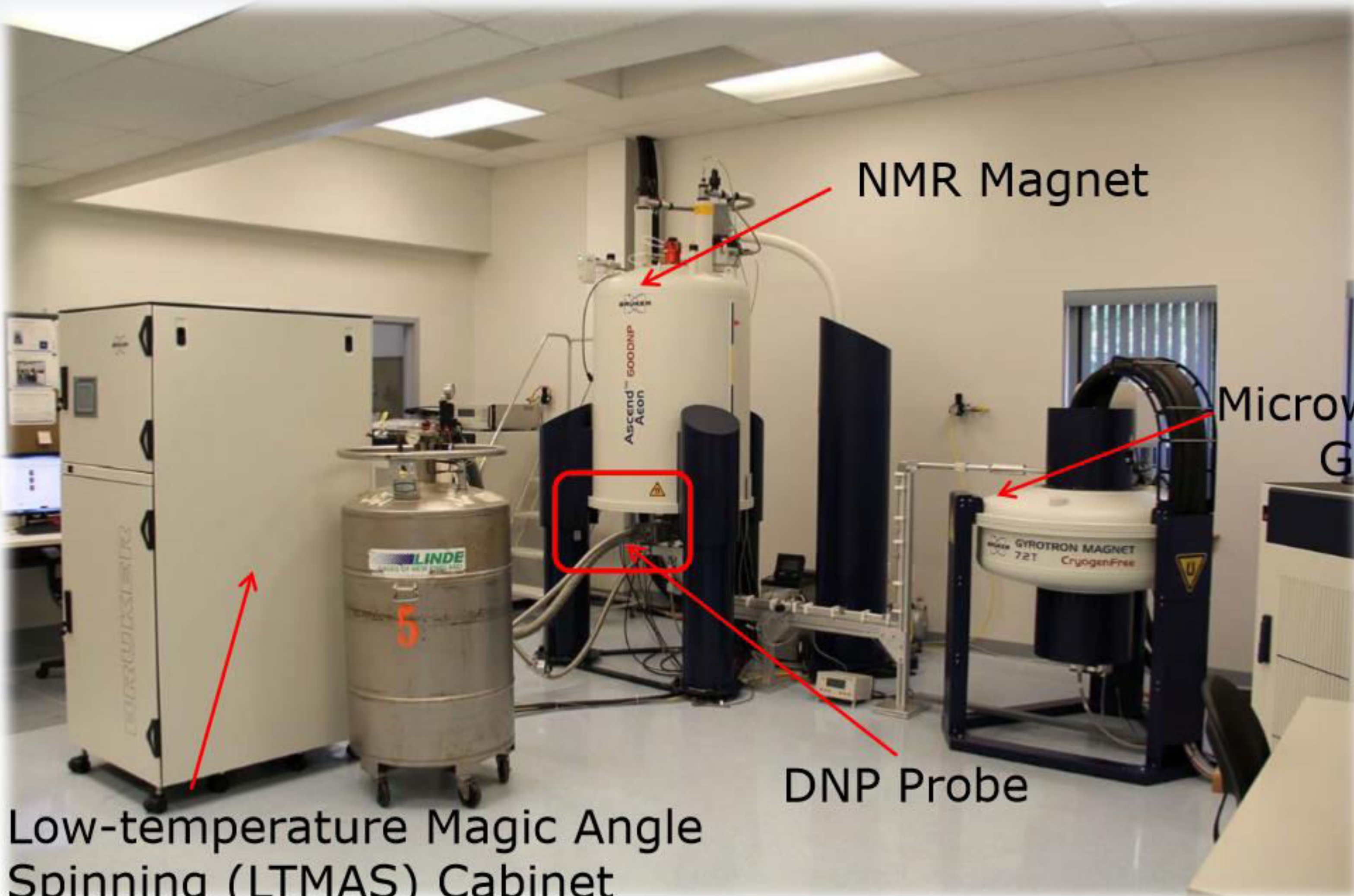
http://www.vadiodes.com/images/AppNotes/ApplicationNote-SummaryofSolid-StateSources.pdf

Gyrotron Basic Operation

- Accelerated electrons generate THz
  - Cyclotron resonance
- Superconducting magnet
- Electron gun
- Very high powers
  - 10's of kW at 94 GHz
  - kW's at 260 GHz

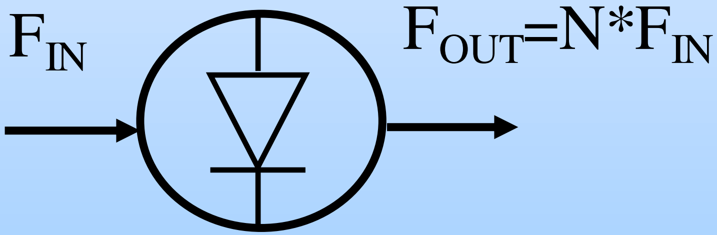


Solid-State DNP Spectrometer



Signal Generation Using Schottky Diodes

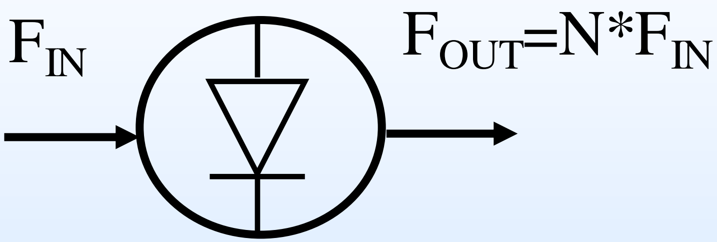
- Use the nonlinearity of the Schottky diode to generate harmonics of a lower frequency signal
  - Use either nonlinear variable capacitance or resistance



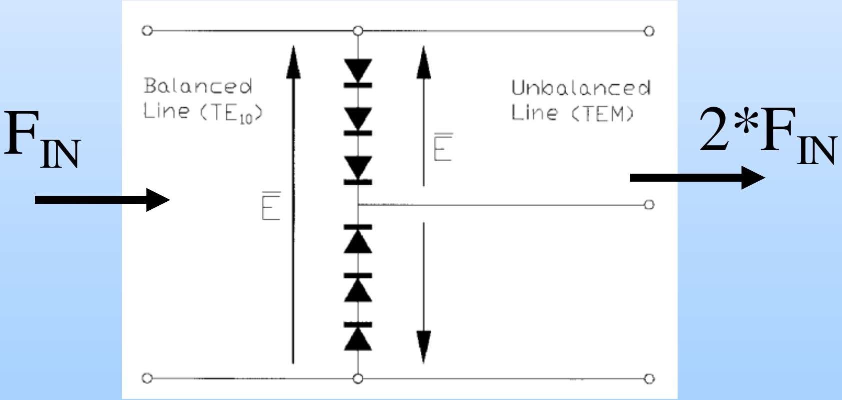
Schottky Diode Frequency Multipliers

- Careful choice of circuit configuration
  - Anti-series diode configuration
  - Balanced design allows for broad bandwidth and high efficiency
  - Spatial mode filtering between harmonics
- Multiple diodes for increased power handling

Diode Multiplier



Balanced Circuit Topology



Porterfield et al (MTT, 1999)

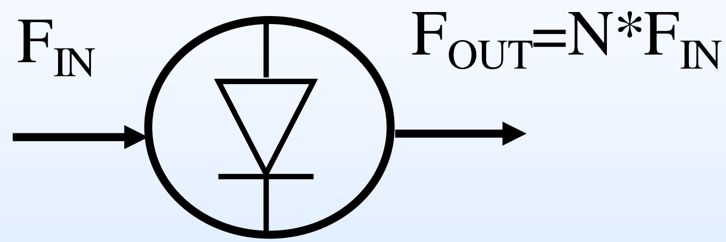
Virginia Diodes, Inc.

www.vadiodes.com

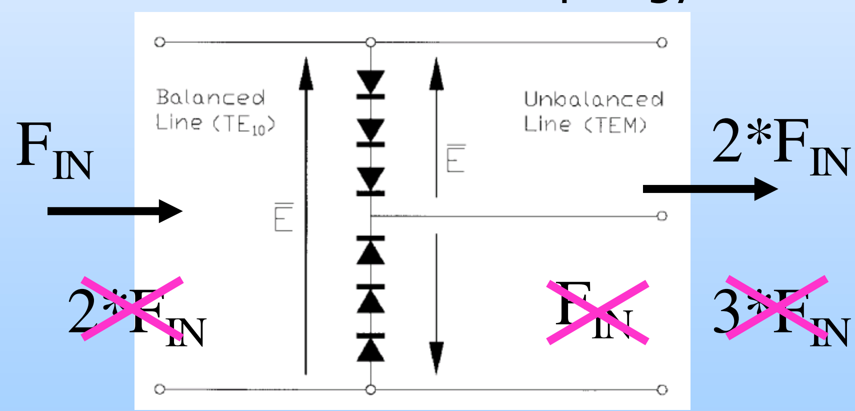
Schottky Diode Frequency Multipliers

- Careful choice of circuit configuration
  - Anti-series diode configuration
  - Balanced design allows for broad bandwidth and high efficiency
  - Spatial mode filtering between harmonics
- Multiple diodes for increased power handling

Diode Multiplier



Balanced Circuit Topology

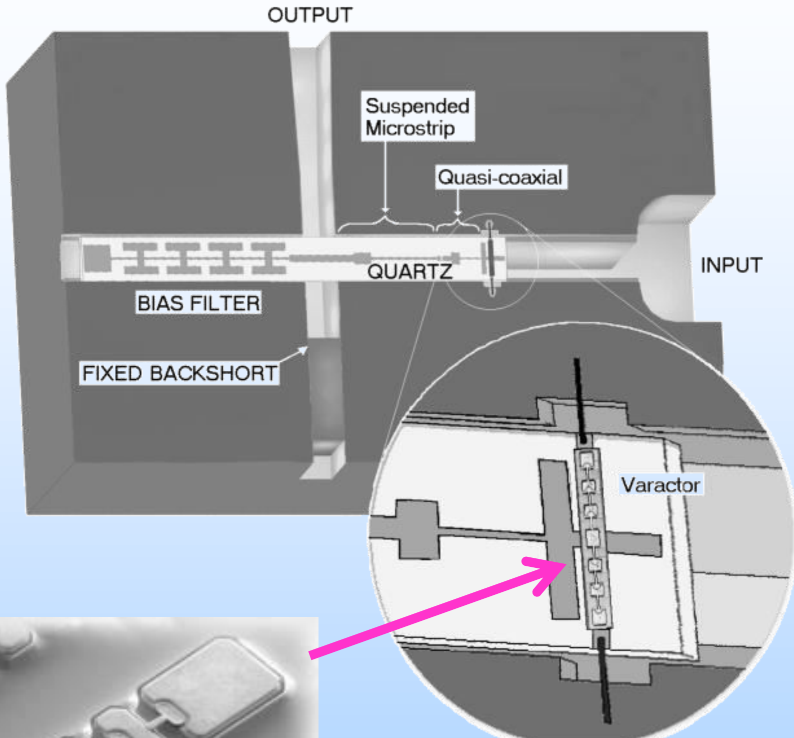


Porterfield et al (MTT, 1999)

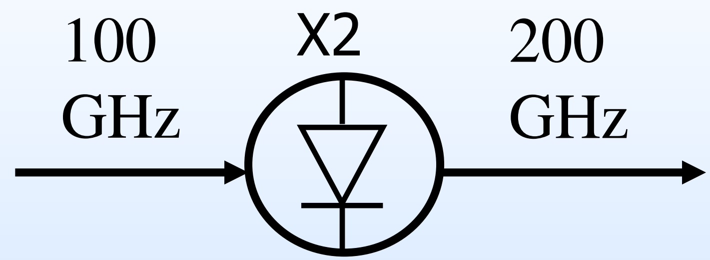
Virginia Diodes, Inc.

www.vadiodes.com

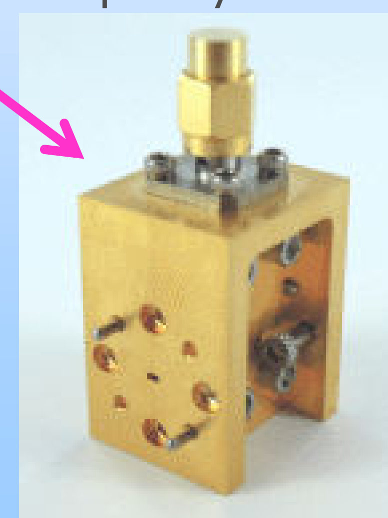
Signal Generation Using Schottky Diodes



Diode Multiplier



Frequency Doubler

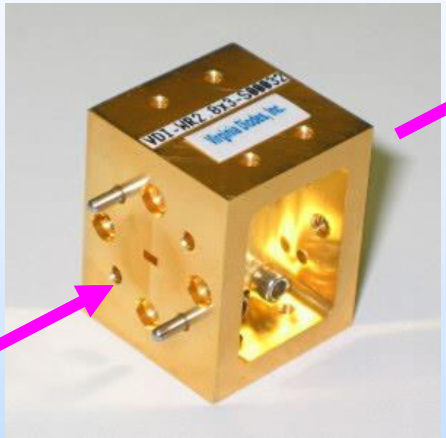


Virginia Diodes, Inc.

www.vadiodes.com

Broadband Frequency Multipliers

WR-2.8X3
(265-400 GHz)



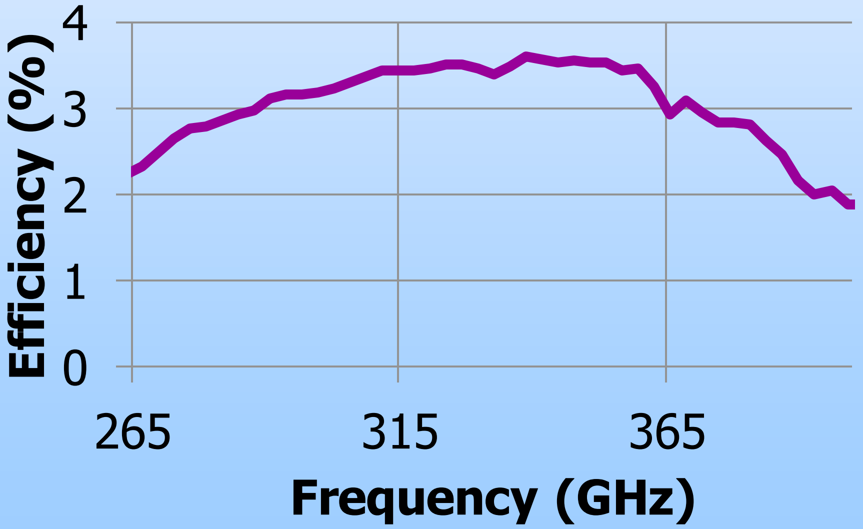
Output

265-400 GHz

Input

88-133 GHz

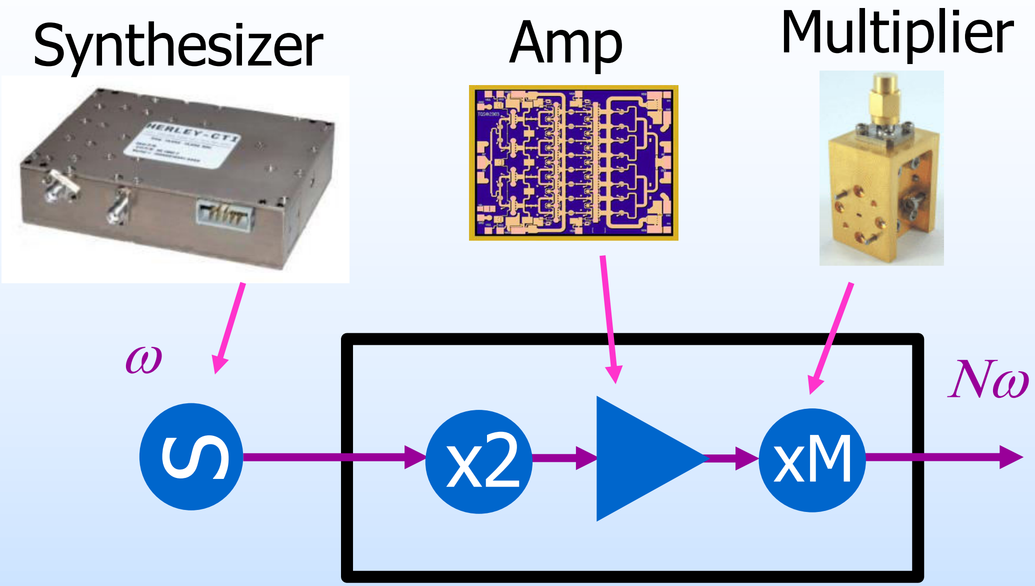
- Tunerless
- Ambient operation
- Balanced design → reduction of unwanted harmonics

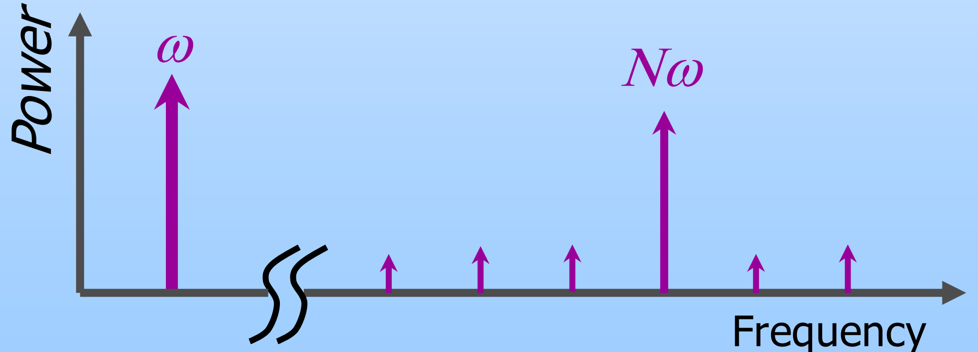


Virginia Diodes, Inc.

Amplified Multiplier Chains

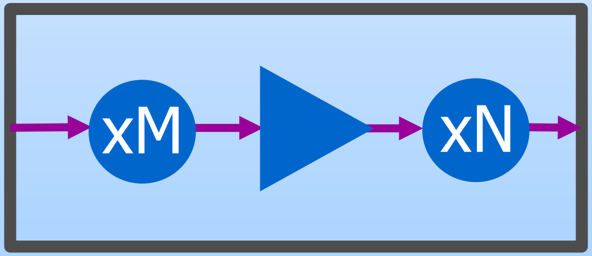
- Combination of amplifiers and multipliers
- Nearly all the power in a single tone
  - Spectral purity achieved using filtering and balanced designs

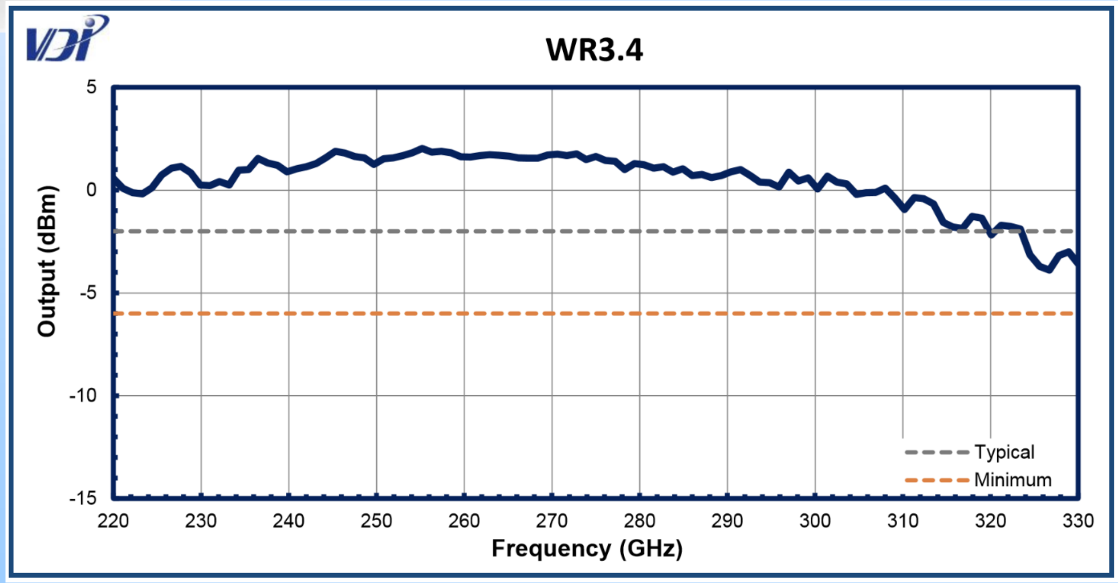




THz Signal Generator Extenders (SGX)

- Synthesizer Extender to THz
  - Turn-key Source
  - Tunerless, instantaneous sweeping over > 40% bandwidth
- State-of-the-art Output Power
  - Standard units to 1.1 THz

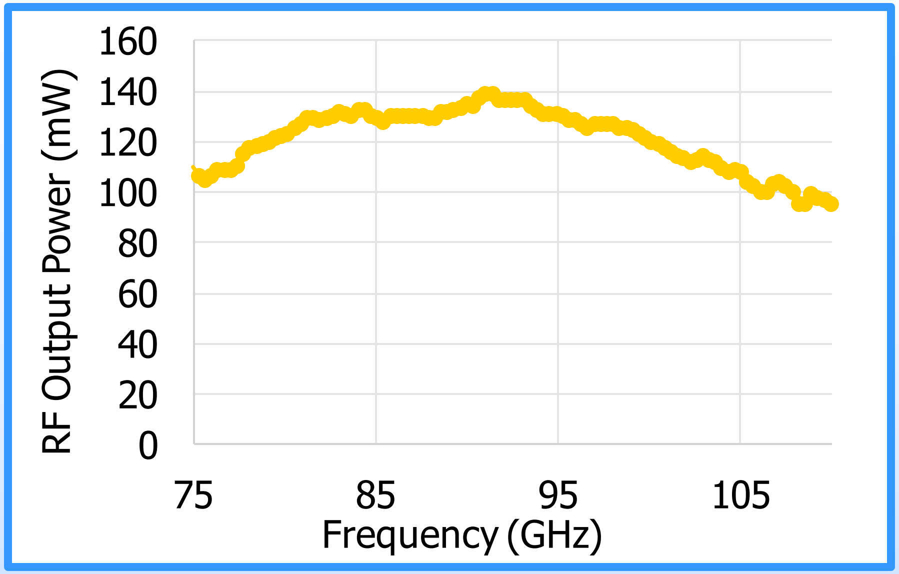


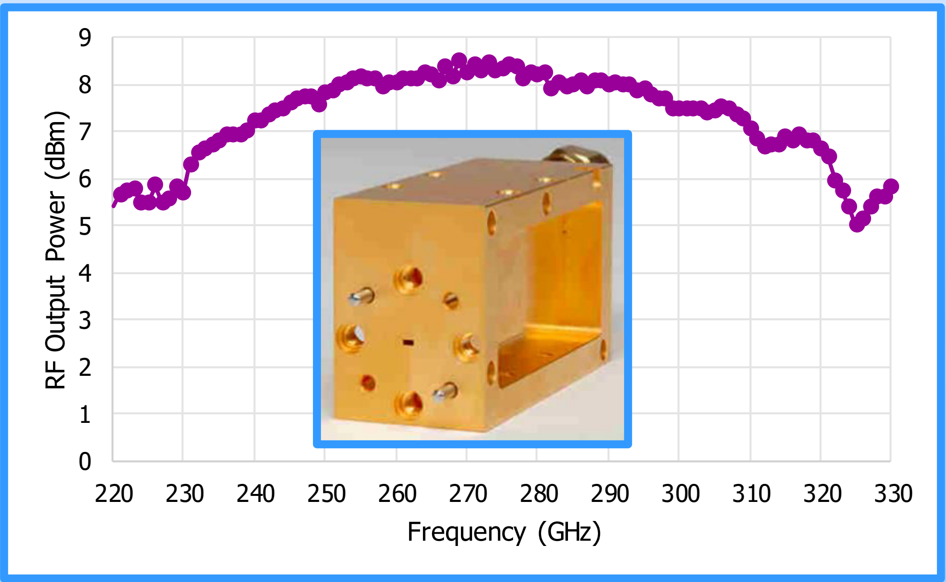


Virginia Diodes, Inc.

New mm-Wave Amplifers

- Amplifiers are moving into the mm-Wave and THz
  - e.g. WR-10 amp with > 100 mW
- This newly available drive power enables dramatic improvements in broadband THz power generation
  - e.g. using WR-3.4 tripler we achieve ~7 dB improvement in output power
- More results on the way, with similar improvements to beyond 1 THz



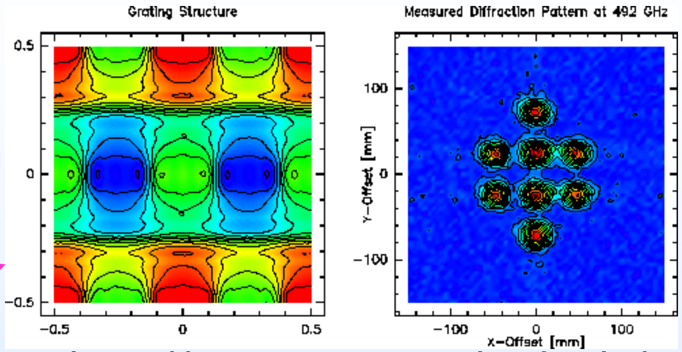


Virginia Diodes, Inc.

www.vadiodes.com

High Power Applications

- Steady need for high-powered THz sources
- Radio Astronomy
  - Focal Plane Array LO Sources

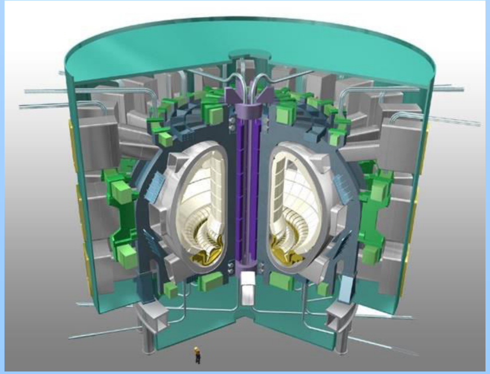


http://www.astro.uni-koeln.de/

- Spectroscopy
  - Electron Spin Resonance
  - Dynamic Nuclear Polarization

https://www.bruker.com

- Plasma Diagnostics
  - ITER

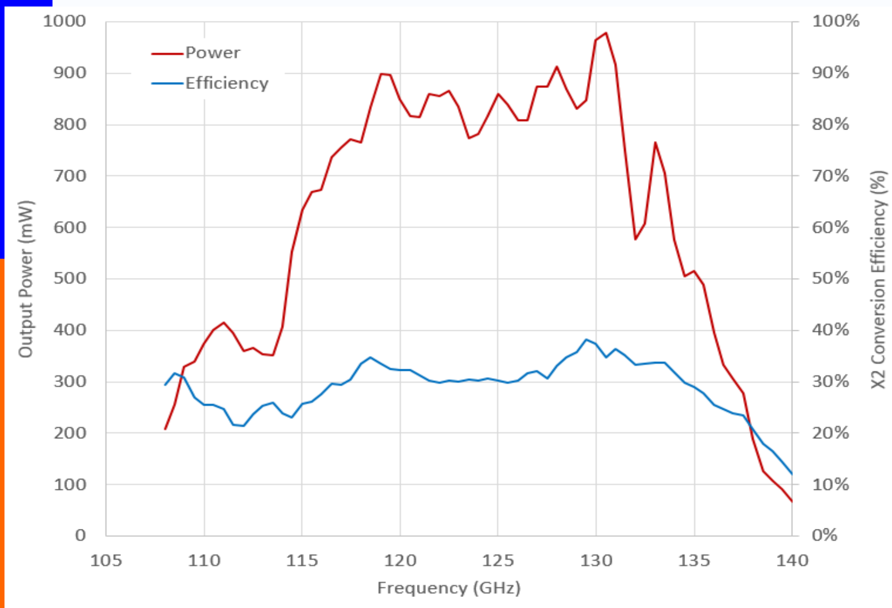


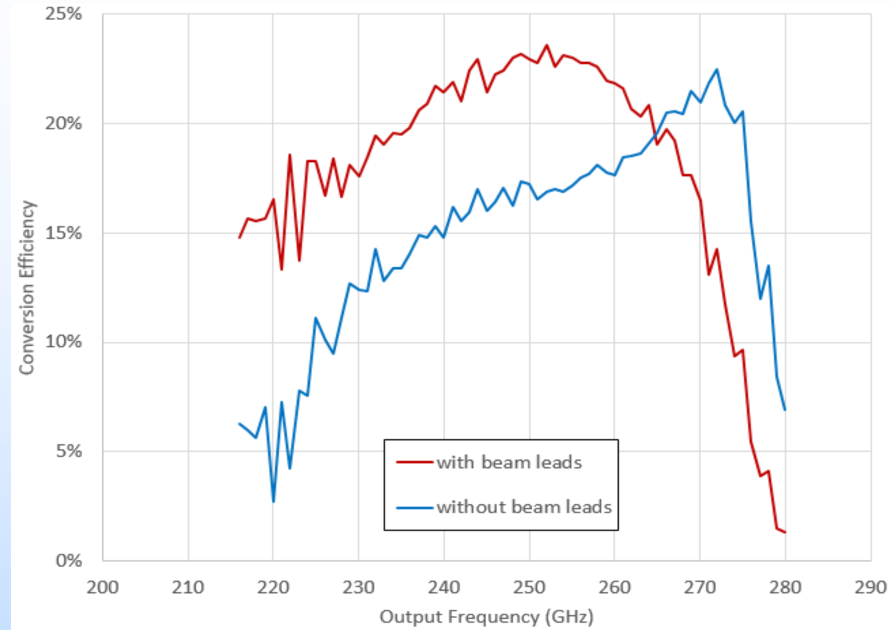
https://www.iter.org

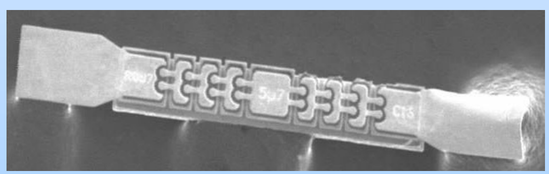
Virginia Diodes, Inc.

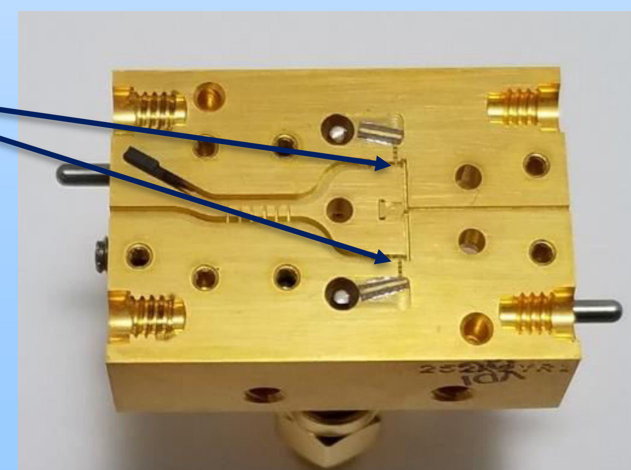
www.vadiodes.com

130 GHz and 260 GHz Frequency Doublers





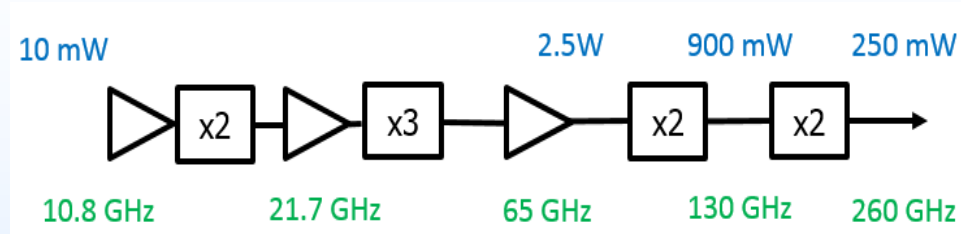


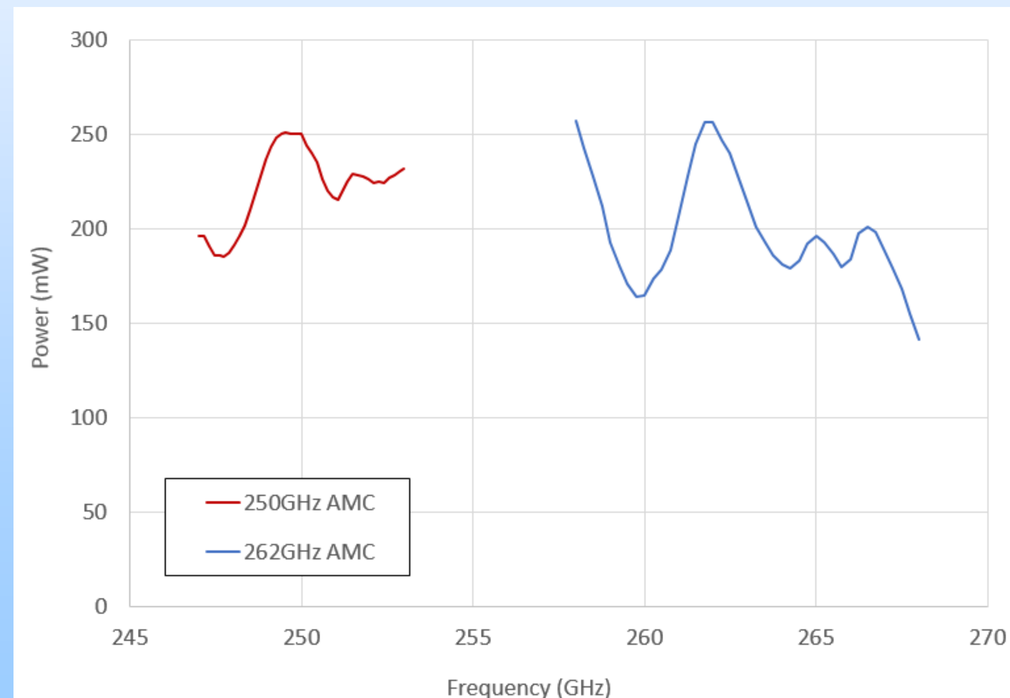


- Diode arrays
- Integrated beam leads
- Diamond embedding circuits
- Power combining

Virginia Diodes, Inc.

250 GHz and 262 GHz Sources

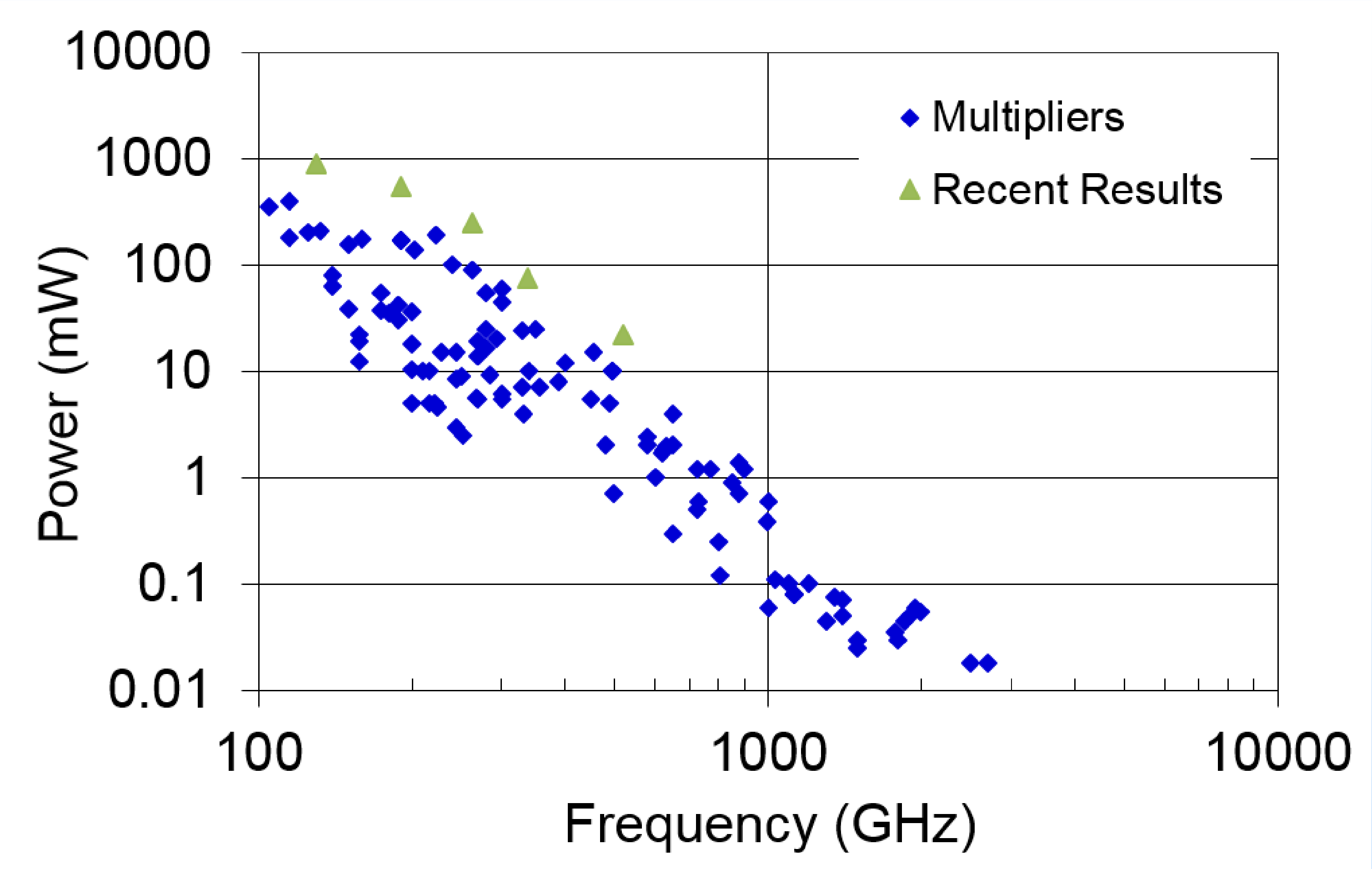




Virginia Diodes, Inc.

www.vadiodes.com

mm-Wave Sources Based on Diode Multipliers



Virginia Diodes, Inc.

www.vadiodes.com

This Presentation

- Introduction
  - THz Applications
  - Schottky Diode Technology
- Schottky-Based THz Heterodyne Transceiver Components
  - THz Signal Generation
  - **Waveguide Interfaces**
  - THz Signal Detection
    - Generation of Wideband Modulated Signals at THz
- THz Transceivers
  - Chirped Transform Spectroscopy
- Solid-State Sources & DNP
- Conclusions

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

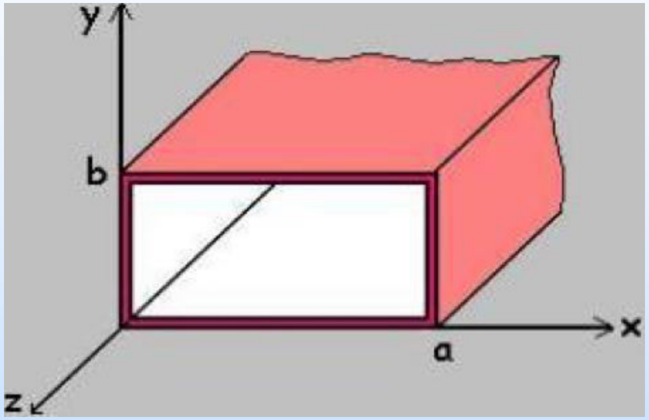


Figure from www.ee.bilkent.edu.tr

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

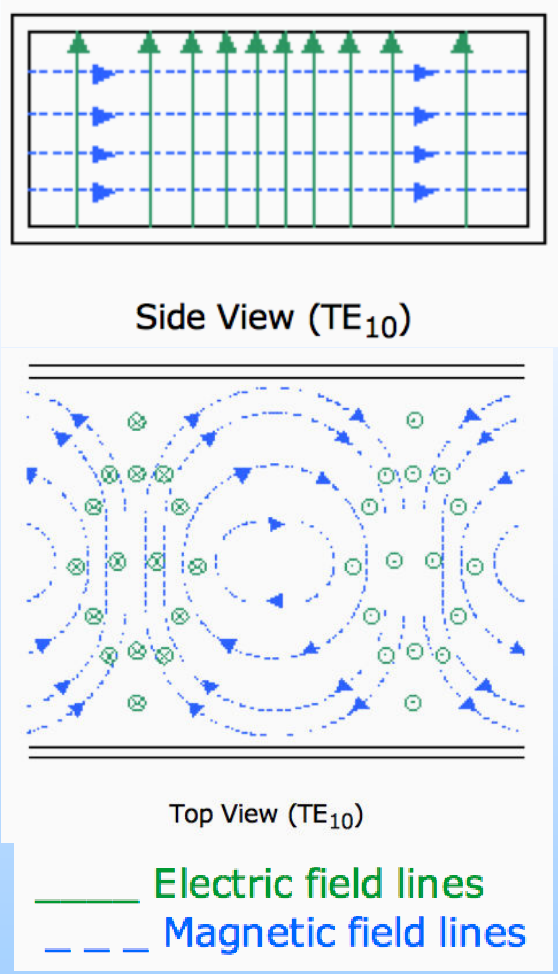


Figure from www.rfcafe.com

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	-	-

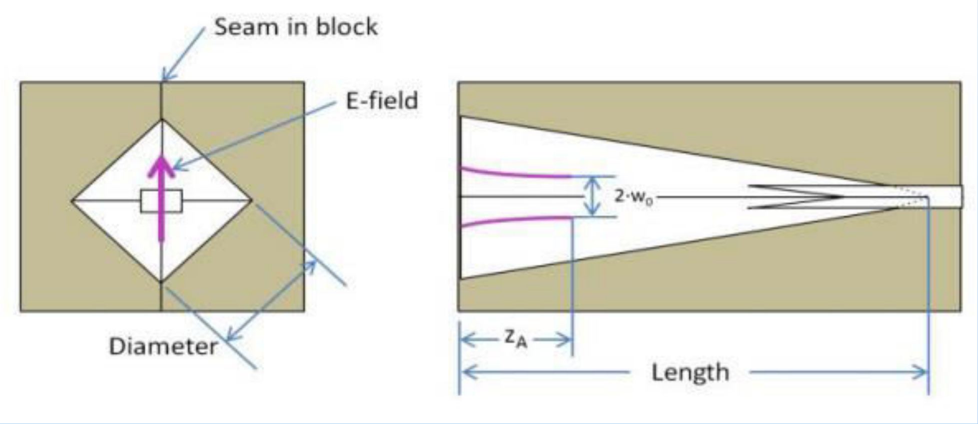
* Waveguide loss calculated according to IEEE P1785.1

Virginia Diodes, Inc.

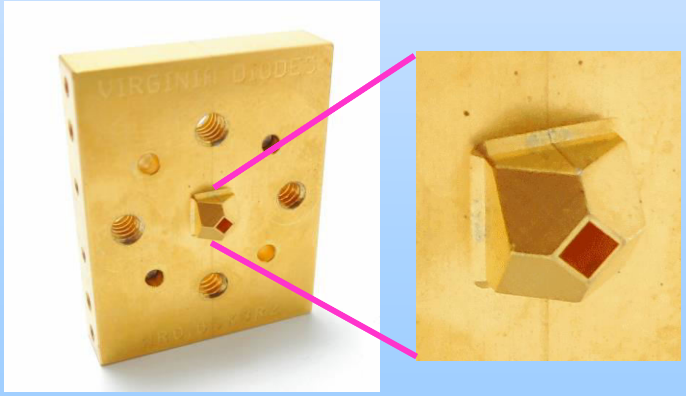
Interfaces for Waveguide-based THz Components

- VDI has sources and detectors to 3 THz
- Waveguide interface has been typically used up to 1.1 THz
- Above 1.1 THz have used horn integrated into block
  - Usually a diagonal horn
- However, there are reasons to extend interfaces higher…
  - Greater flexibility
  - Direct connection of components without quasi-optics
  - Allows more general test & measurement of THz components

220-330 GHz Tripler



1.1-1.7 THz Tripler



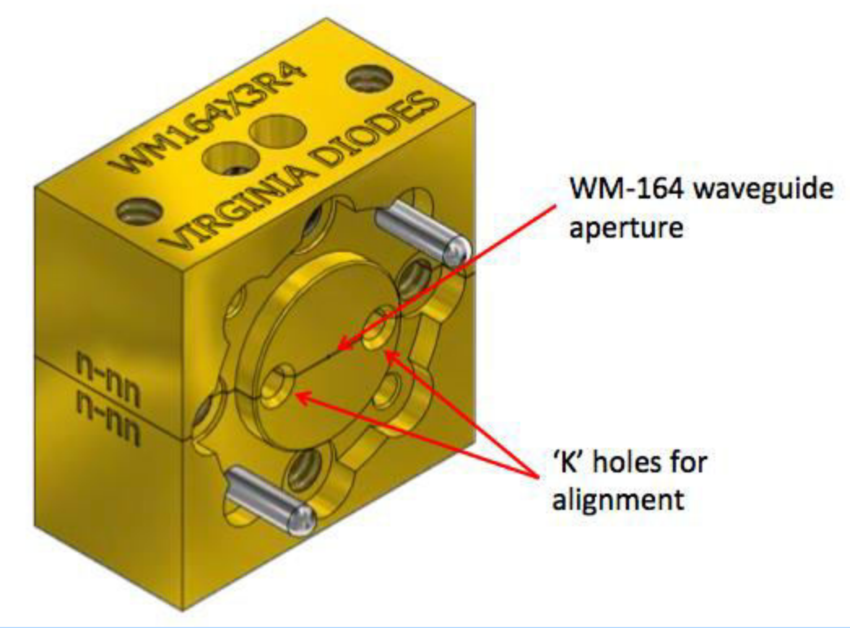
IEEE P1785 Workgroup

- P1785 – "Rectangular Metallic Waveguides and Their Interfaces for Frequencies of 110 GHz and Above"
  - Website: grouper.ieee.org/groups/1785
- Three parts to the standard
  - P1785.1: Define waveguide dimensions and associated frequency bands
  - P1785.2: Define waveguide interfaces (i.e. flanges)
  - P1785.3: Recommendations for Interface Performance and Uncertainty Specifications
- Goals: to develop a standard to allow compatibility between manufacturers & improve performance

IEEE P1785.2 Interface

- Workgroup converged on one main interface topology
  - Can be connected using 4 different methods
    - Outer dowels, inner dowels, ring, boss/socket
  - One drawing for all variants
    - Except for socket version
  - Backwards compatible
  - Improved performance

P1785.2 Interface shown for WM-164 Tripler



Virginia Diodes, Inc.

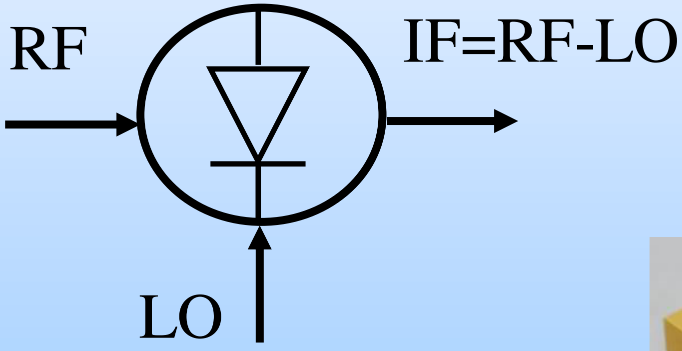
www.vadiodes.com

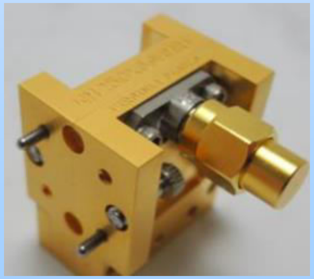
This Presentation

- Introduction
  - THz Applications
  - Schottky Diode Technology
- Schottky-Based THz Heterodyne Transceiver Components
  - THz Signal Generation
  - Waveguide Interfaces
  - **THz Signal Detection**
    - Generation of Wideband Modulated Signals at THz
- THz Transceivers
  - Chirped Transform Spectroscopy
- Solid-State Sources & DNP
- Conclusions

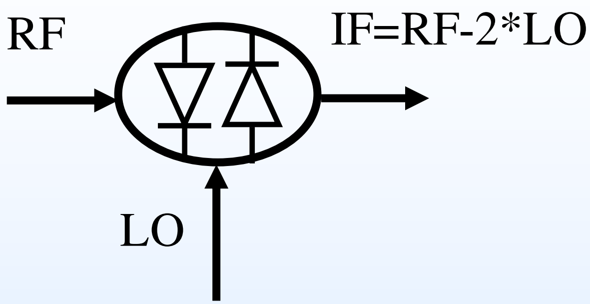
Signal Detection Using Schottky Diodes

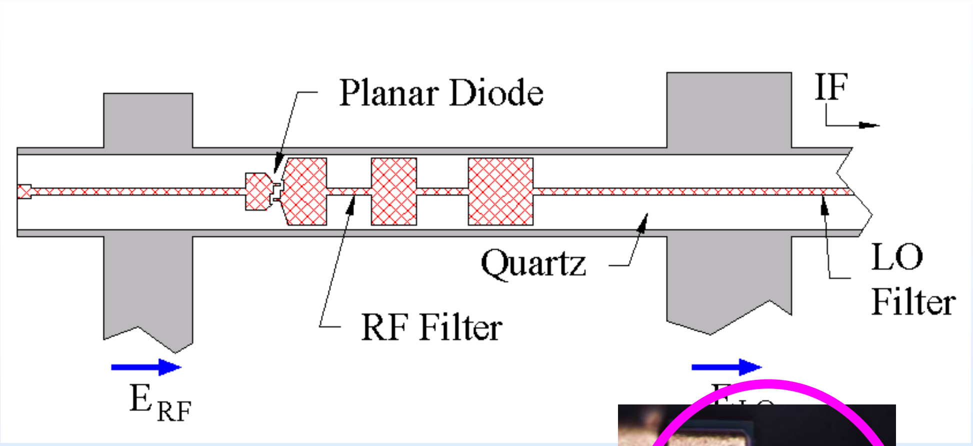
- Use the nonlinearity of the Schottky diode to mix a local oscillator signal with a THz signal



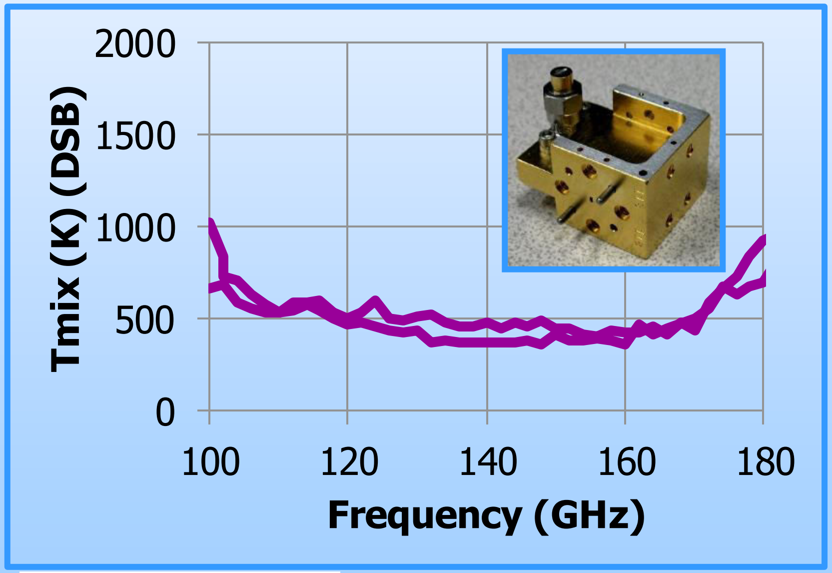


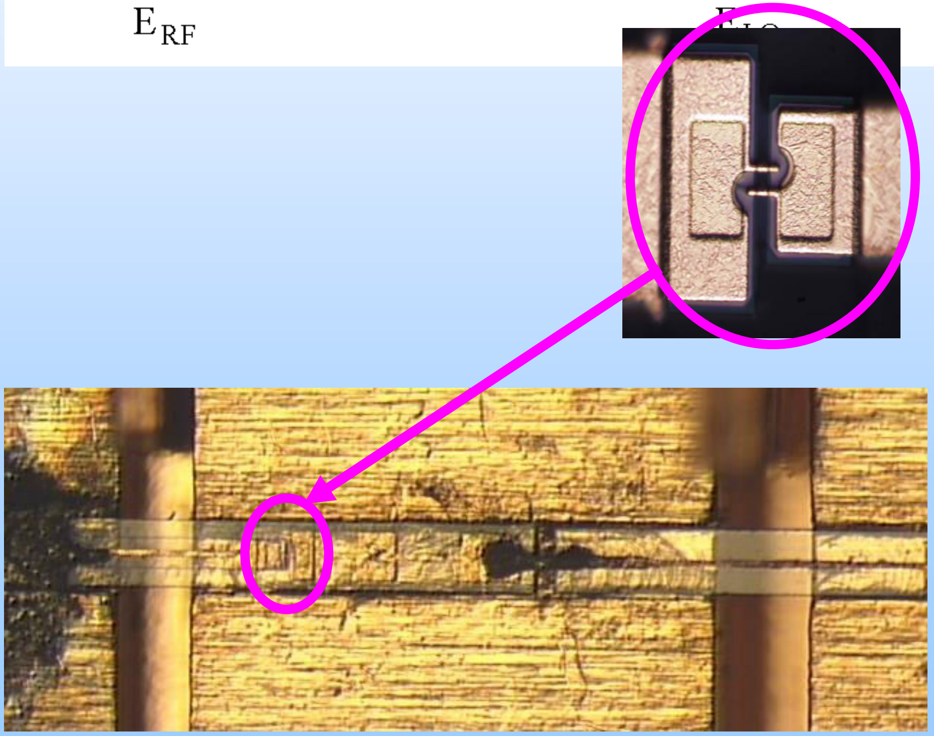
Signal Detection Using Schottky Diodes





Measured Performance of WR-6.5SHM

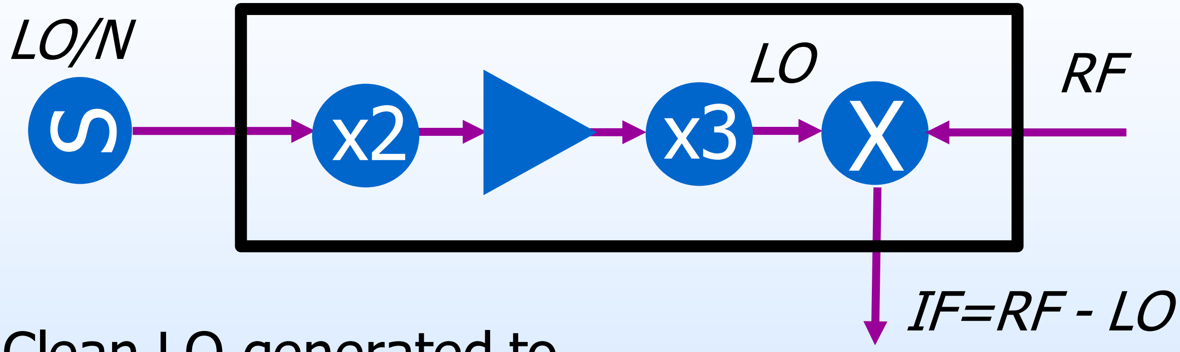




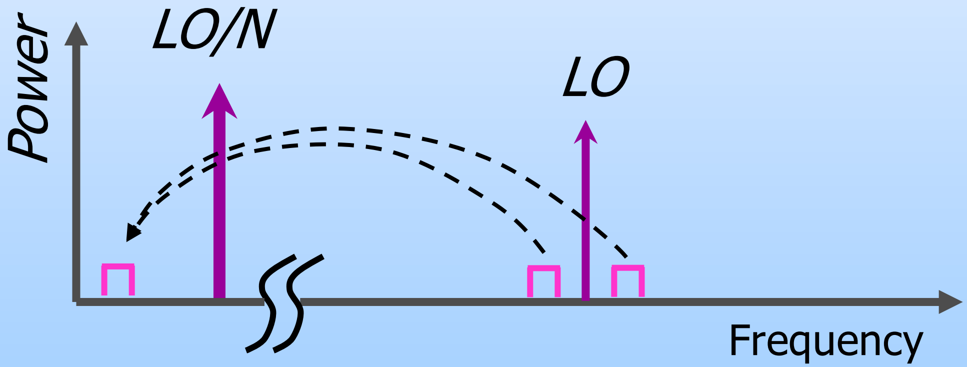
Virginia Diodes, Inc.

www.vadiodes.com

THz Spectrum Analyzer Extenders



- Clean LO generated to drive mixer – single tone
  - Filtering and balanced designs
- Mixing between high frequency LO and RF
  - IF = RF +/- LO

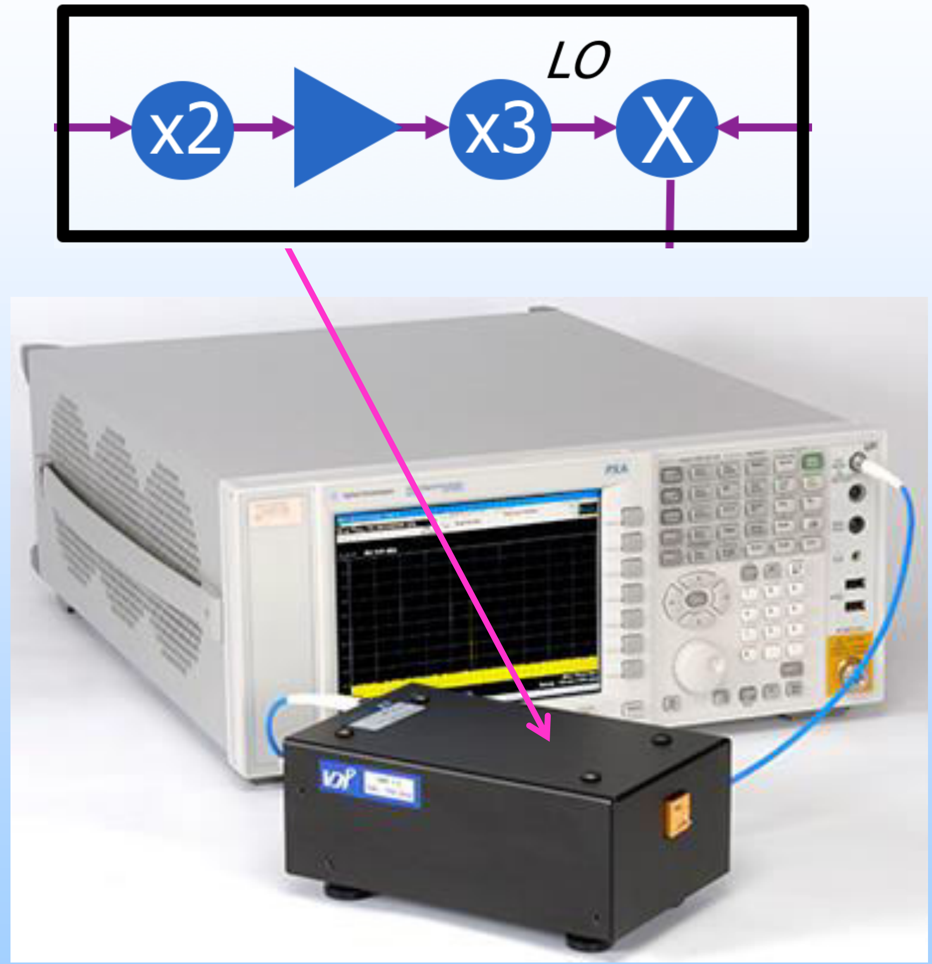


Virginia Diodes, Inc.

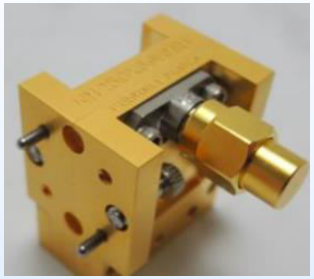
www.vadiodes.com

THz Spectrum Analyzer Extenders

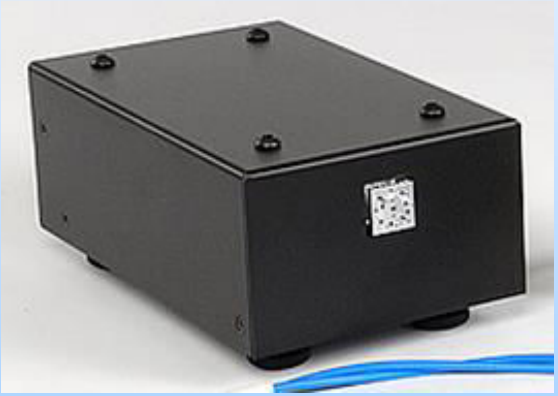
- Sophisticated instrument to analyze microwave signals
  - Spectral purity
  - Phase noise
  - Communication Signal Demodulation
  - …
- A core microwave test capability
  - Along with sources and vector network analyzers
- Can be extended to THz using the Schottky technology

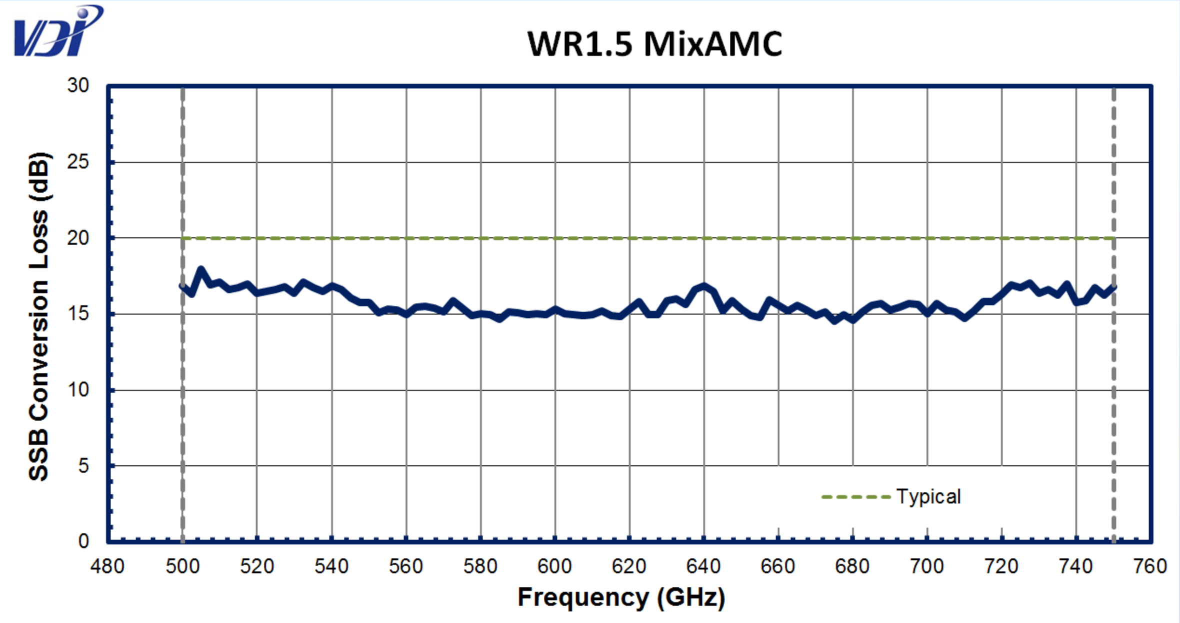


VDI Spectrum Analyzer Extenders (SAX's)



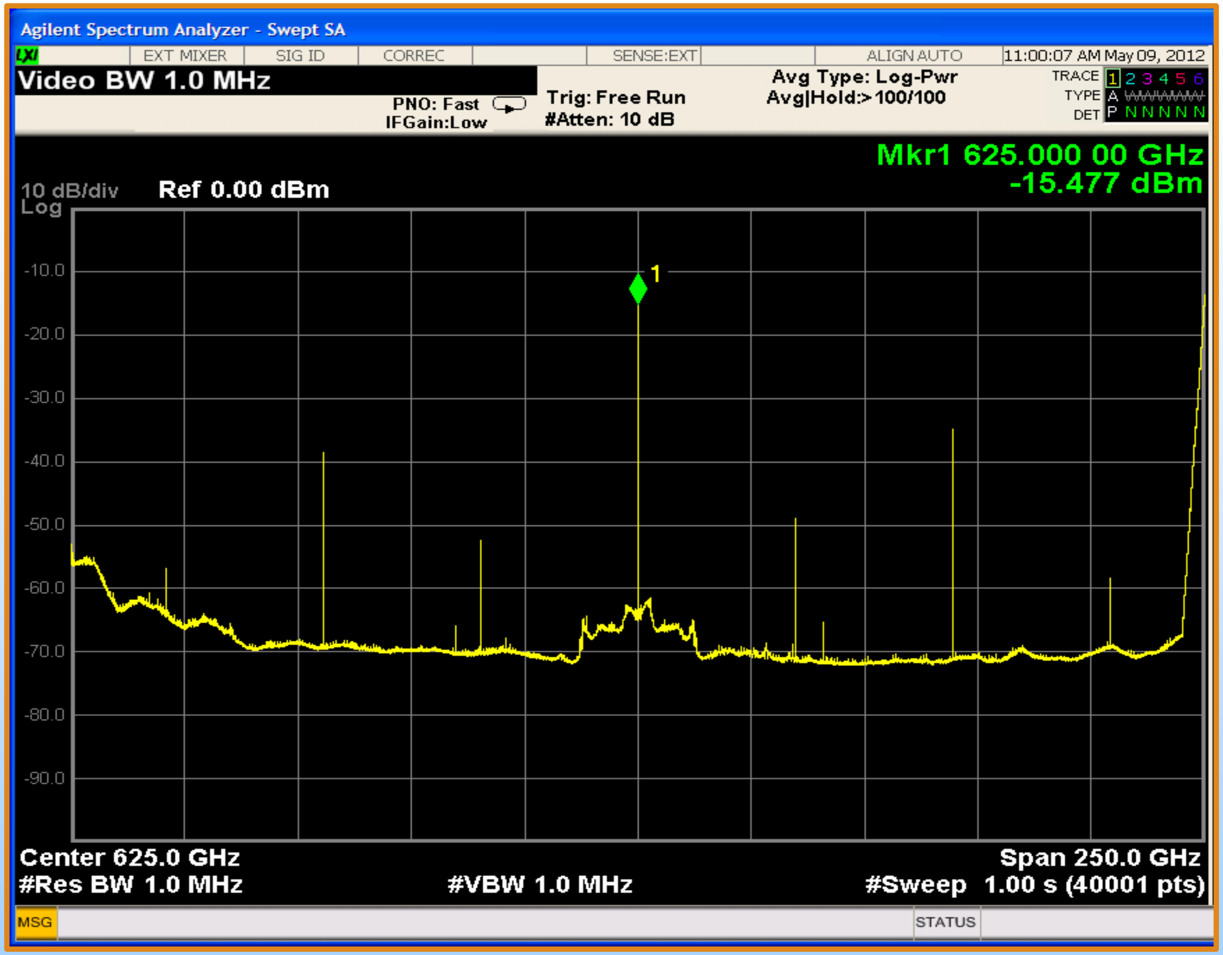
- Fullband down-conversion and frequency extension of microwave spectrum analyzers into the THz range
  - Banded coverage from 75GHz-1,100GHz
  - IF Bandwidth up to 40 GHz
  - DANL 150 dBm/Hz to 750 GHz
    - 135 dBm/Hz to 1.1 THz





Virginia Diodes, Inc.

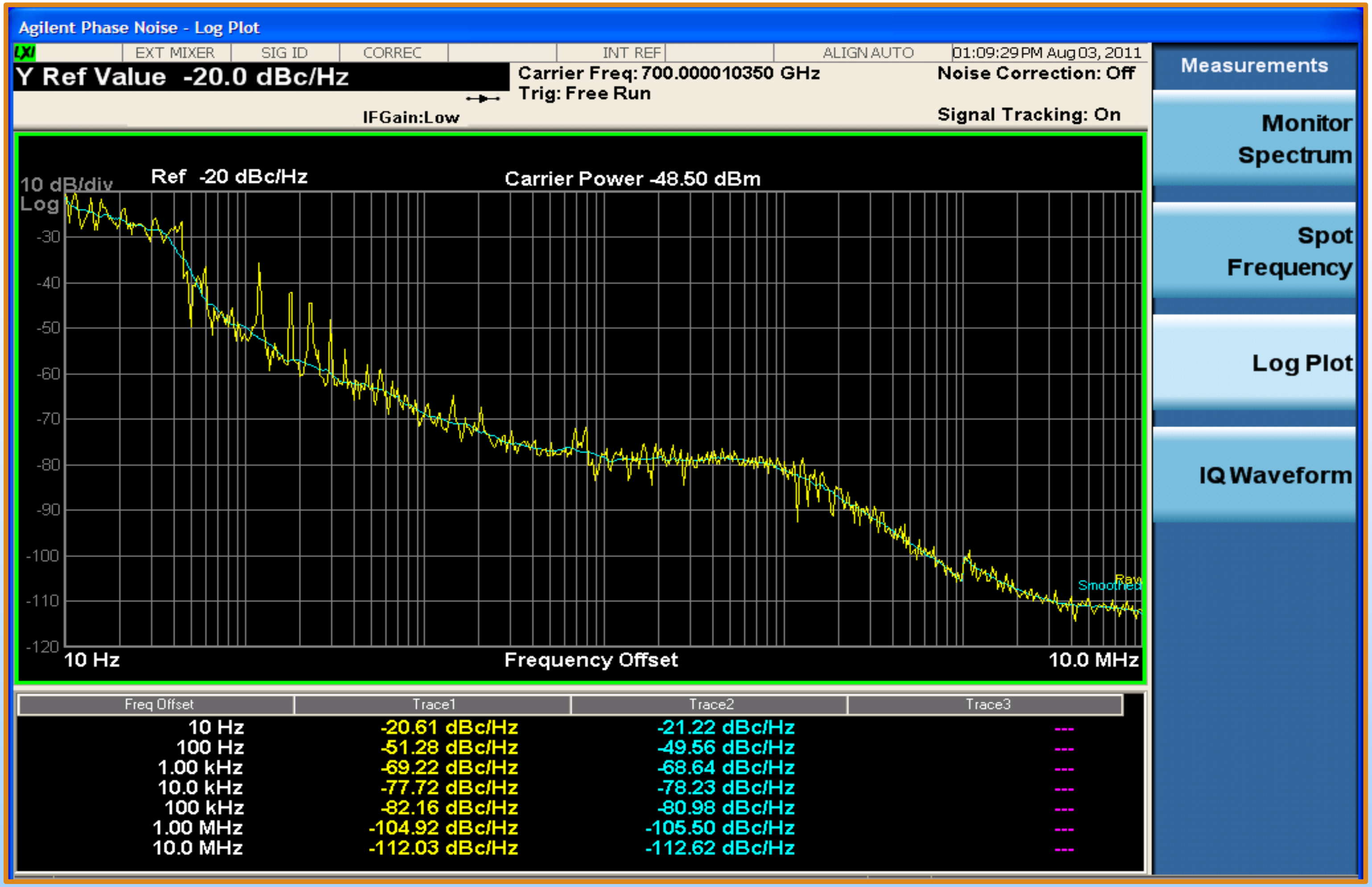
625 GHz Spectral Measurement



Virginia Diodes, Inc.

www.vadiodes.com

Phase Noise Measurement at 700 GHz



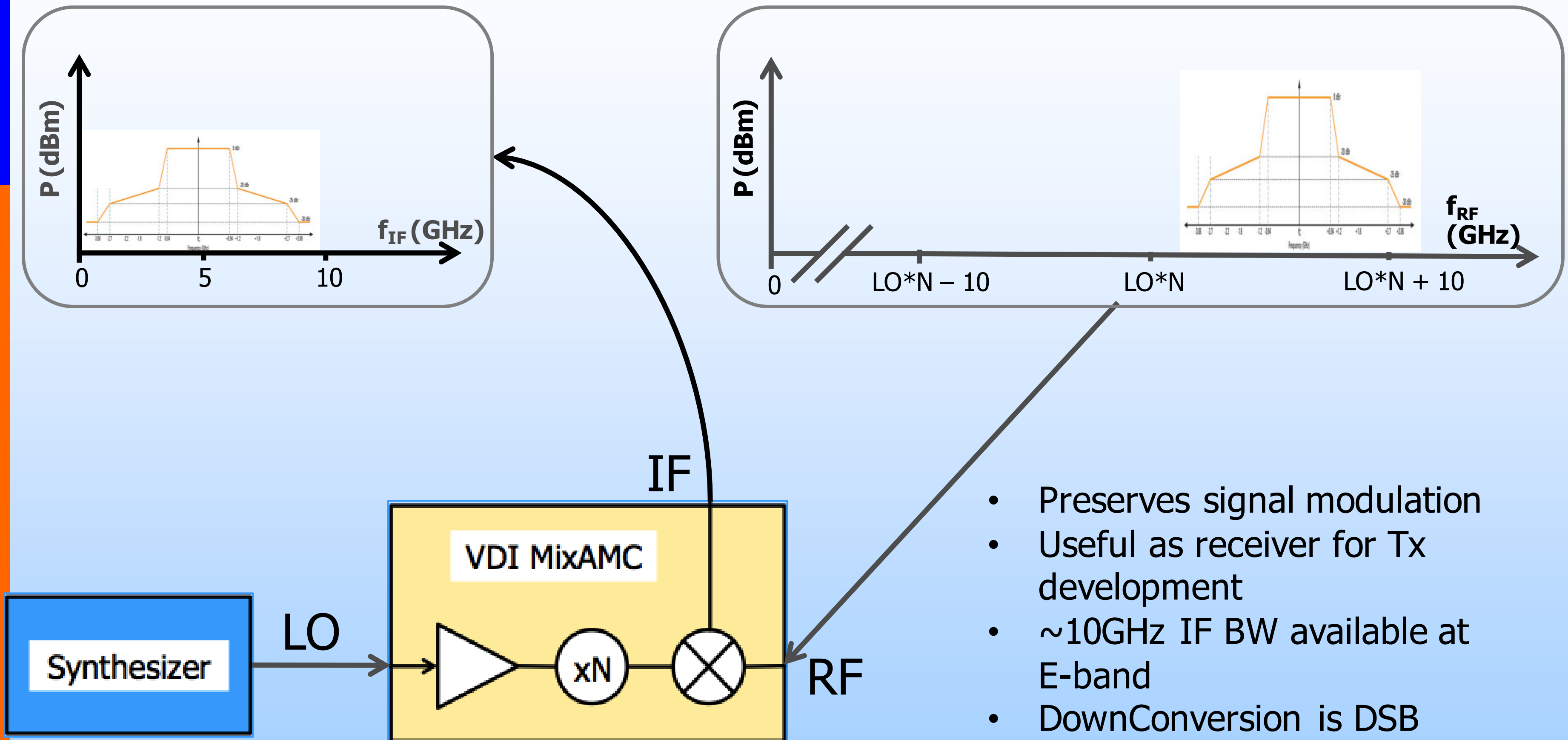
Virginia Diodes, Inc.

www.vadiodes.com

This Presentation

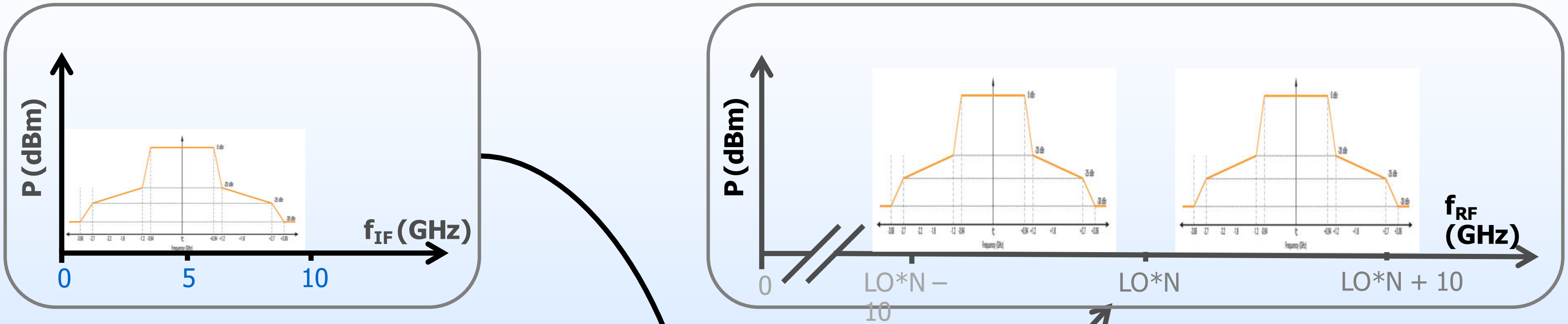
- Introduction
  - THz Applications
  - Schottky Diode Technology
- Schottky-Based THz Heterodyne Transceiver Components
  - THz Signal Generation
  - Waveguide Interfaces
  - THz Signal Detection
    - **Generation of Wideband Modulated Signals at THz**
- THz Transceivers
  - Chirped Transform Spectroscopy
- Solid-State Sources & DNP
- Conclusions

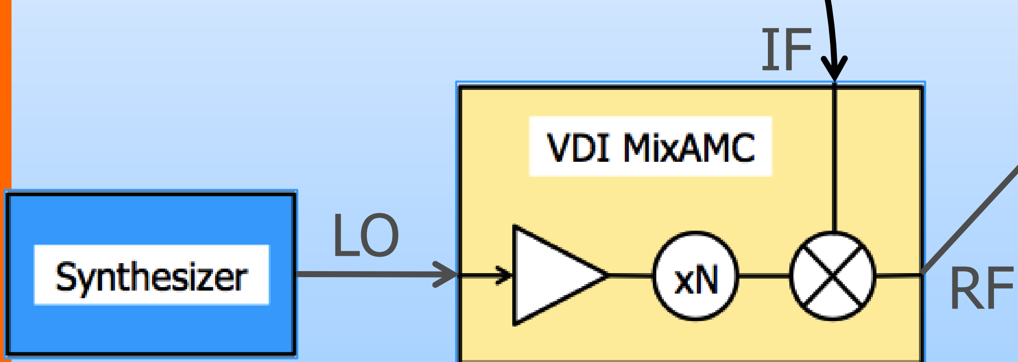
Block Downconversion



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

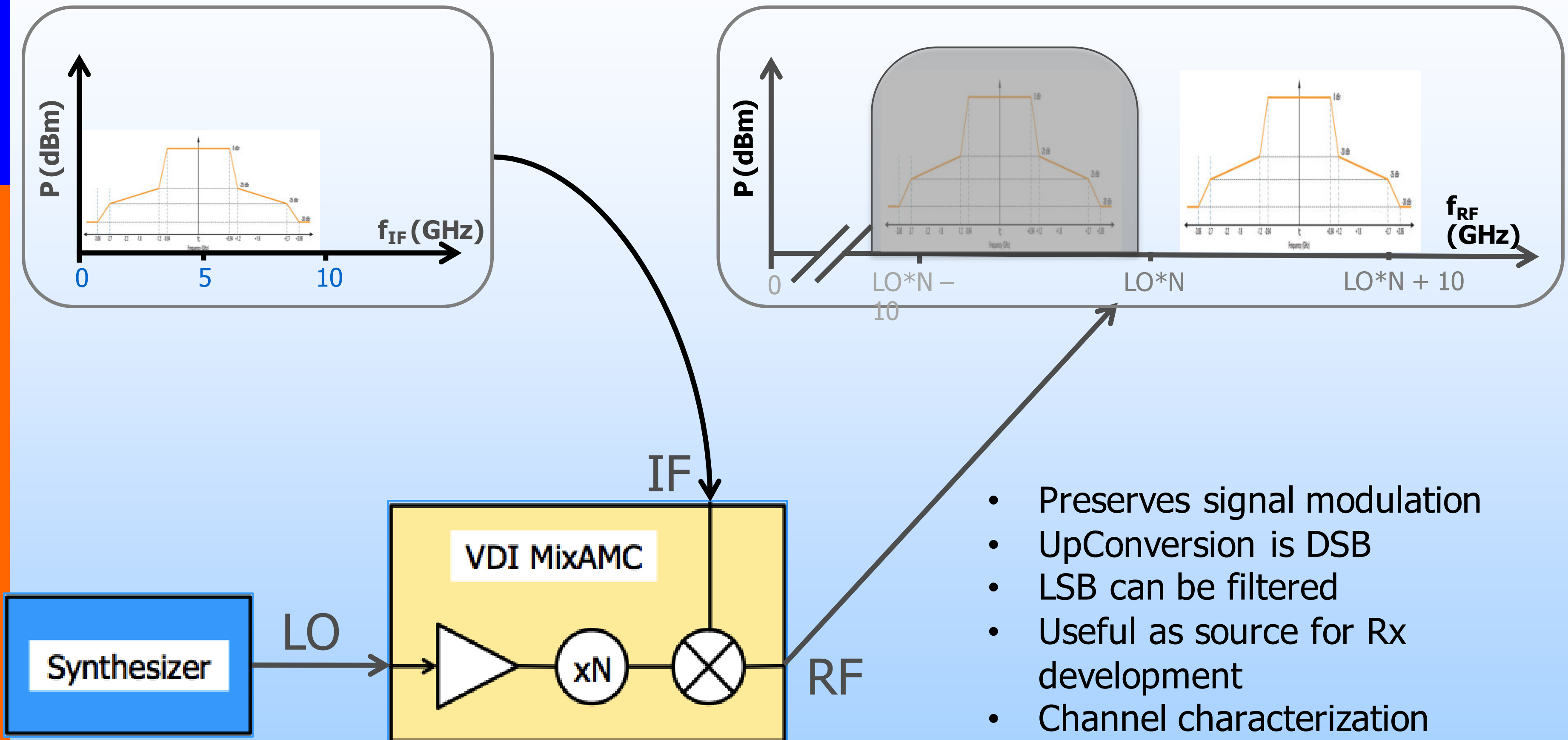
Block Upconversion





- Preserves signal modulation
- UpConversion is DSB
- LSB can be filtered
- Useful as source for Rx development
- Channel characterization

Block Upconversion

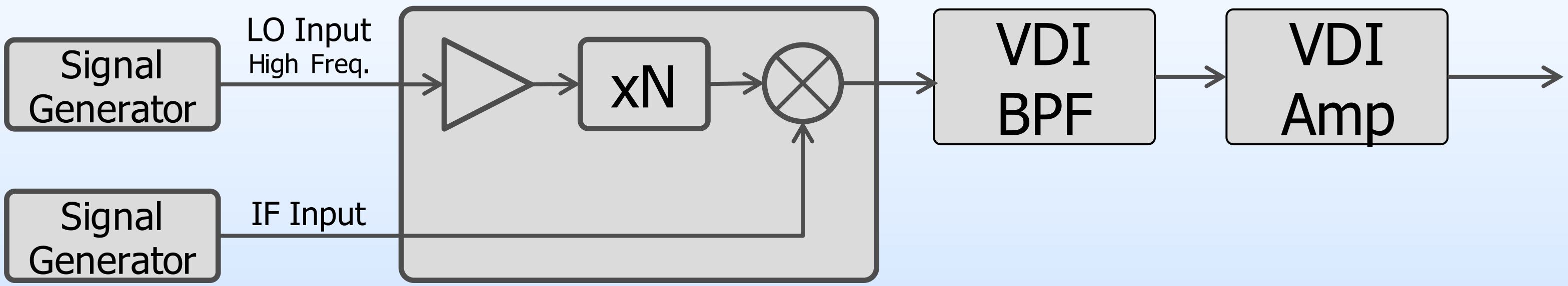


- Preserves signal modulation
- UpConversion is DSB
- LSB can be filtered
- Useful as source for Rx development
- Channel characterization

Virginia Diodes, Inc.

VDI SAX-UP for Comm Applications

Block Up-Conversion

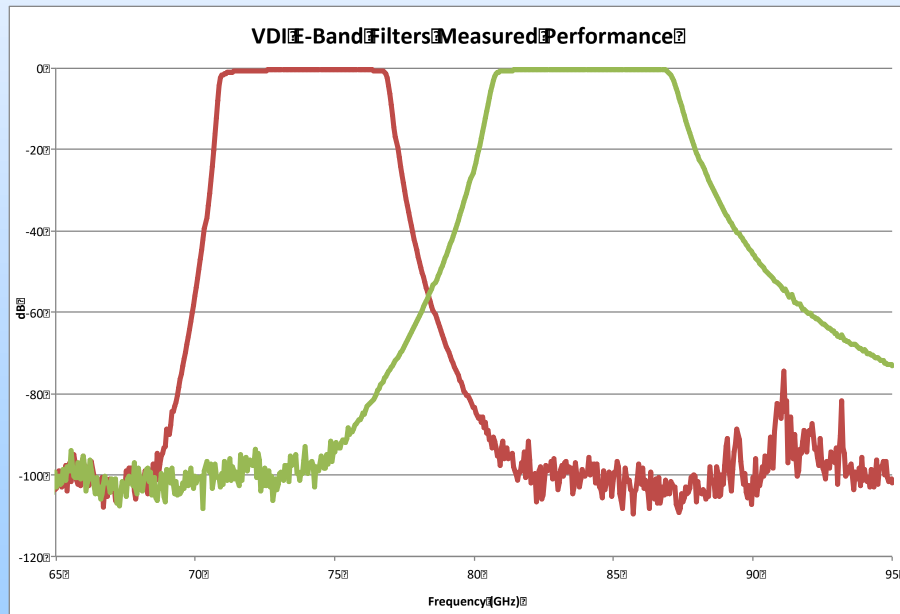


- Can be used to upconvert or downconvert wide band modulated signals
- The double side band nature of the device makes filtering necessary
- VDI has developed a set of waveguide filters and amplifiers to be used for these applications

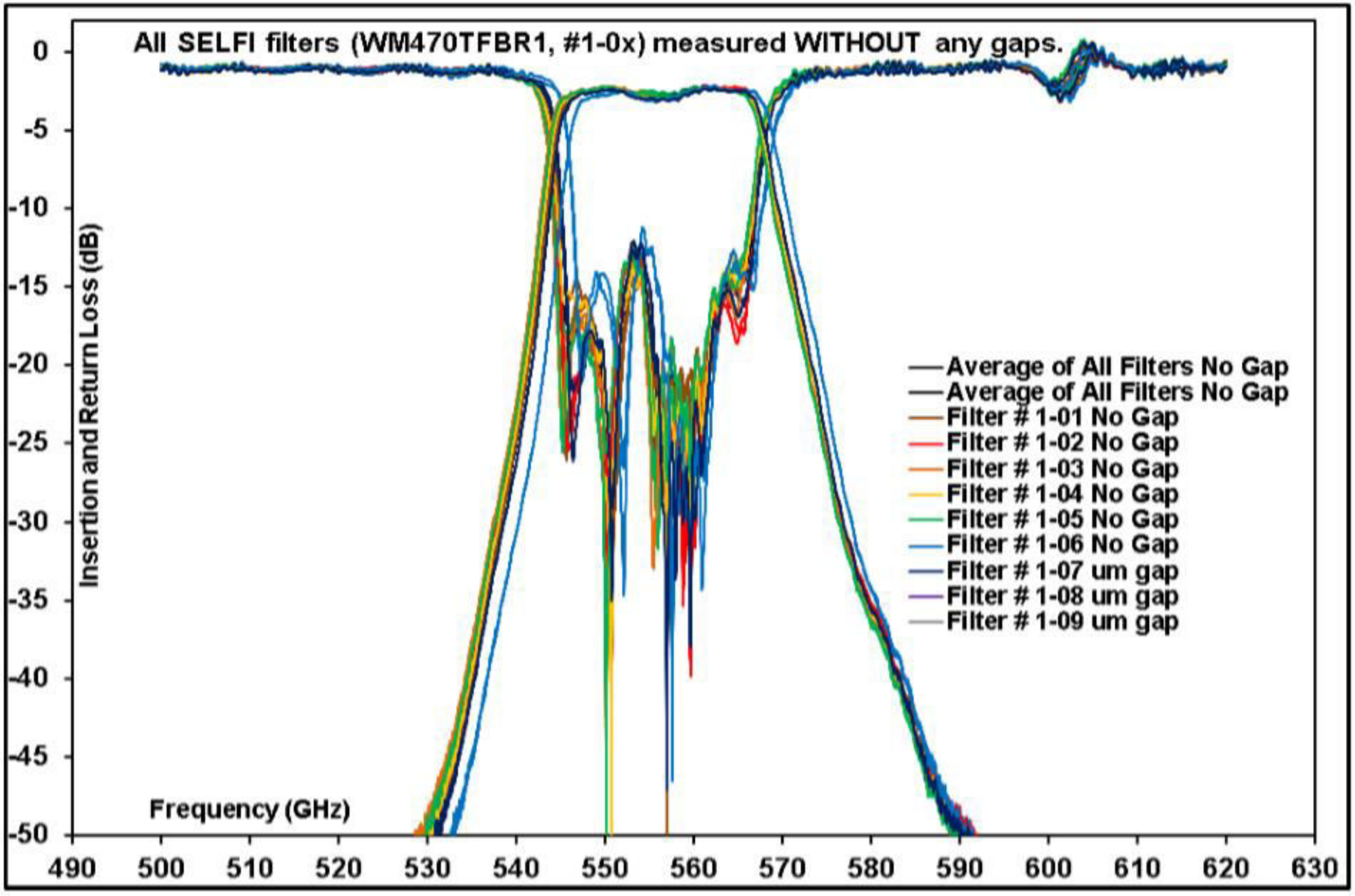
Bandpass Filters for Comm Links

P/N	Waveguide Size	Pass Band (GHz)	-40dB Points (GHz)
WR12BPF59.5-61.6	WR12	59.5-61.5	59.1 & 62.8
WR12BPF71-76	WR12	71-76	70.3 & 77.7
WR12BPF81-86	WR12	81-86	79.2 & 89.3
WR6.5BPF152-162	WR6.5	152-162	147.5 & 166.75

- Low pass band insertion loss (<1dB)
- High out of band rejection (~100dB)
- Sharp band edges
- Custom filters can be produced



560 GHz Bandpass Filter

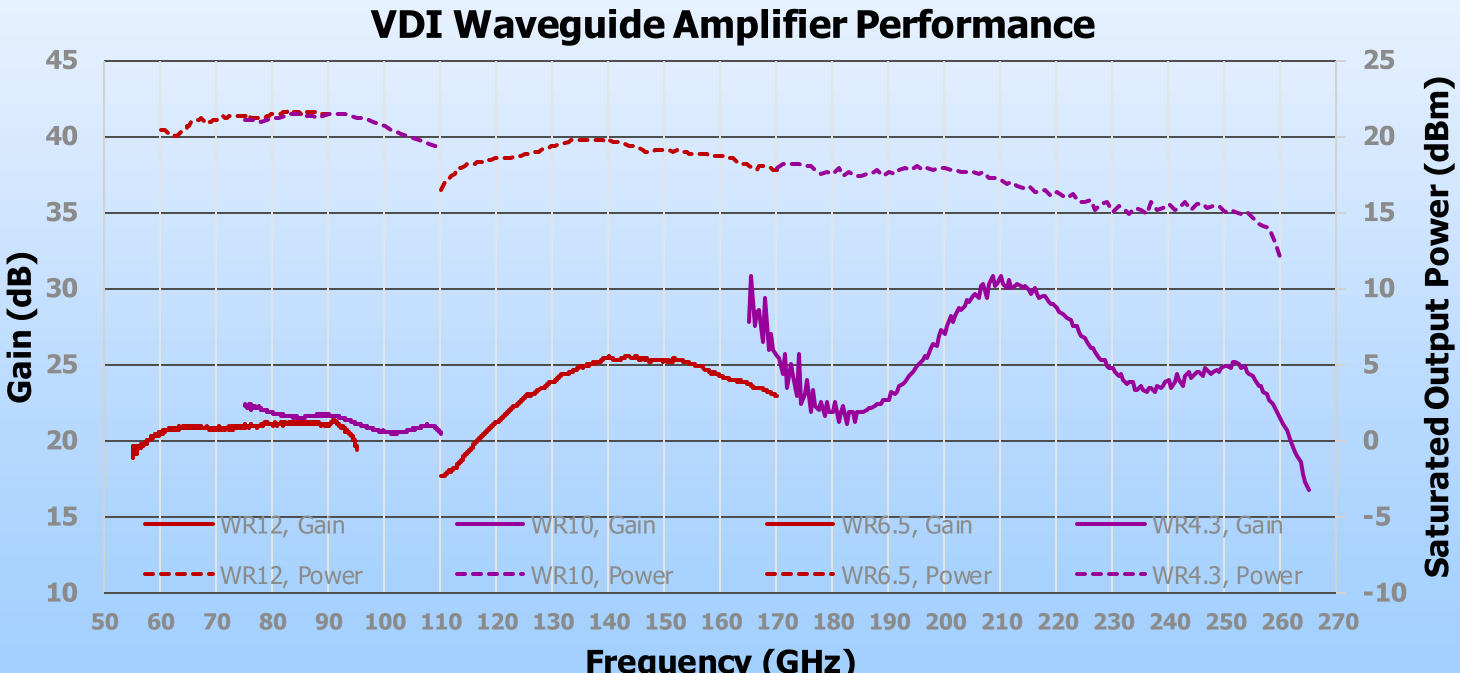


Virginia Diodes, Inc.

Medium Power Waveguide Amplifiers

Recent Development at VDI

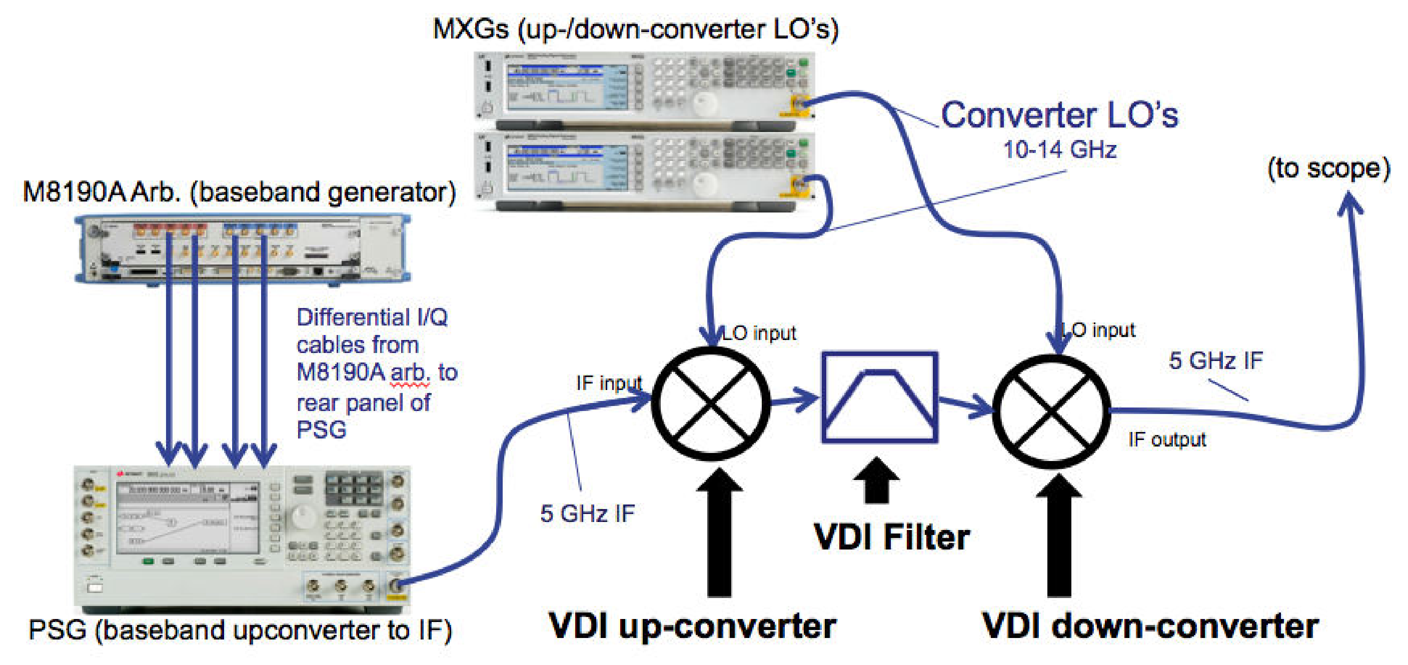
- WR12 (60-90 GHz) to WR4.3 (170-260 GHz) with WR15 (50-75 GHz) under development.
- High gain and saturated output power.
- Full waveguide band coverage.
- Single voltage bias.



Virginia Diodes, Inc.

SAX: Communications Example

- Simulated radio for signal with 2 GHz modulation bandwidth
  - Mixer IF centered at 5 GHz
    - Allows separation between upper and lower sidebands for filtering

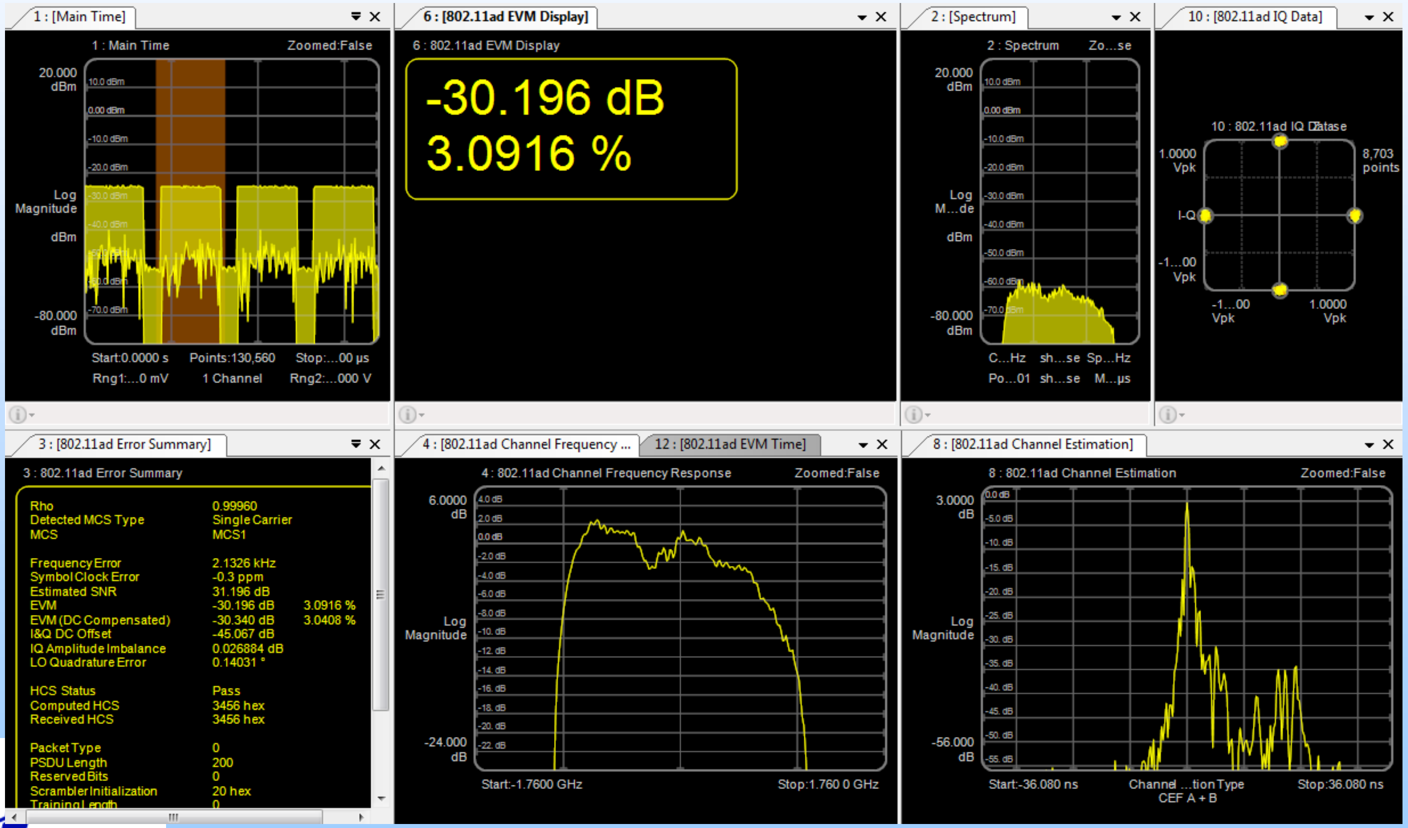


Virginia Diodes, Inc.

5 GHz Modulation Width: Filtered

Demodulation of filtered signal, measured at down-converter output:

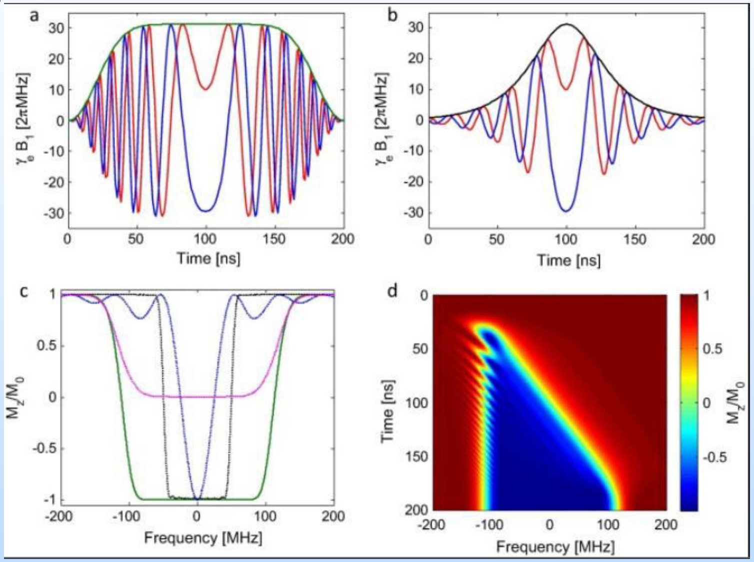
➢802.11ad MCS1 signal
2 GHz BW at 5 GHz IF carrier, π/2 shifted-BPSK modulation
➢Up-converter LO: 12.1667 GHz (**73 GHz** after mixing) at 2 dBm
➢Down-converter LO: 11.5833 GHz (**69.5 GHz** after mixing) at 2 dBm
➢Optimizations performed (including equalizer)



Virginia Diodes, Inc.

Shaped pulses for ESR/DNP

- Use these methods to generate shaped pulses at mm-Wave
  - Using a mixing based upconversion
  - Multipliers will distort the signals
- Optimal control based pulses can be used to improve sensitivity and accuracy



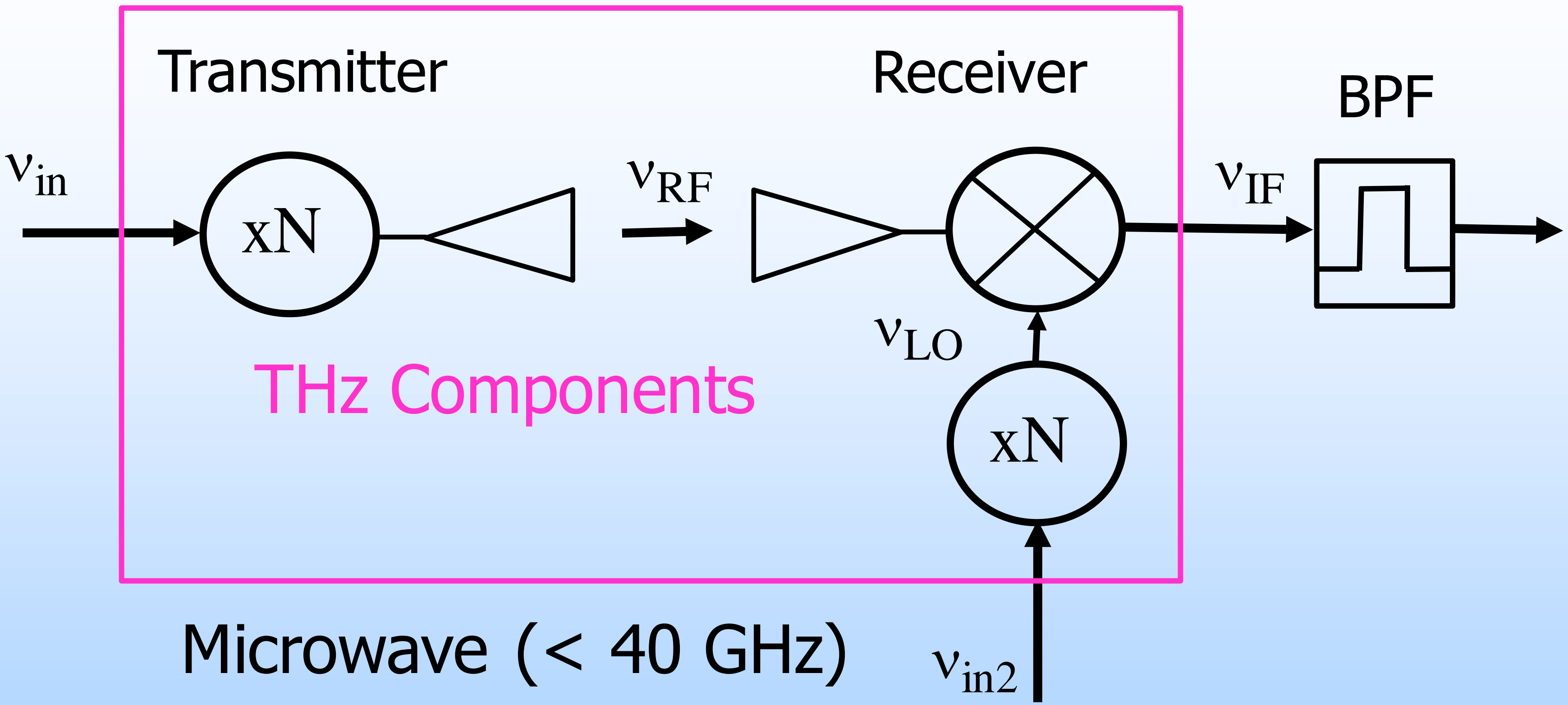
Spindler - JMR 2017

Virginia Diodes, Inc.

This Presentation

- Introduction
  - THz Applications
  - Schottky Diode Technology
- Schottky-Based THz Heterodyne Transceiver Components
  - THz Signal Generation
  - Waveguide Interfaces
  - THz Signal Detection
    - Generation of Wideband Modulated Signals at THz
- **THz Transceivers**
  - Chirped Transform Spectroscopy
- Solid-State Sources & DNP
- Conclusions

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

Virginia Diodes, Inc.

www.vadiodes.com

ESR System Examples – St. Andrews

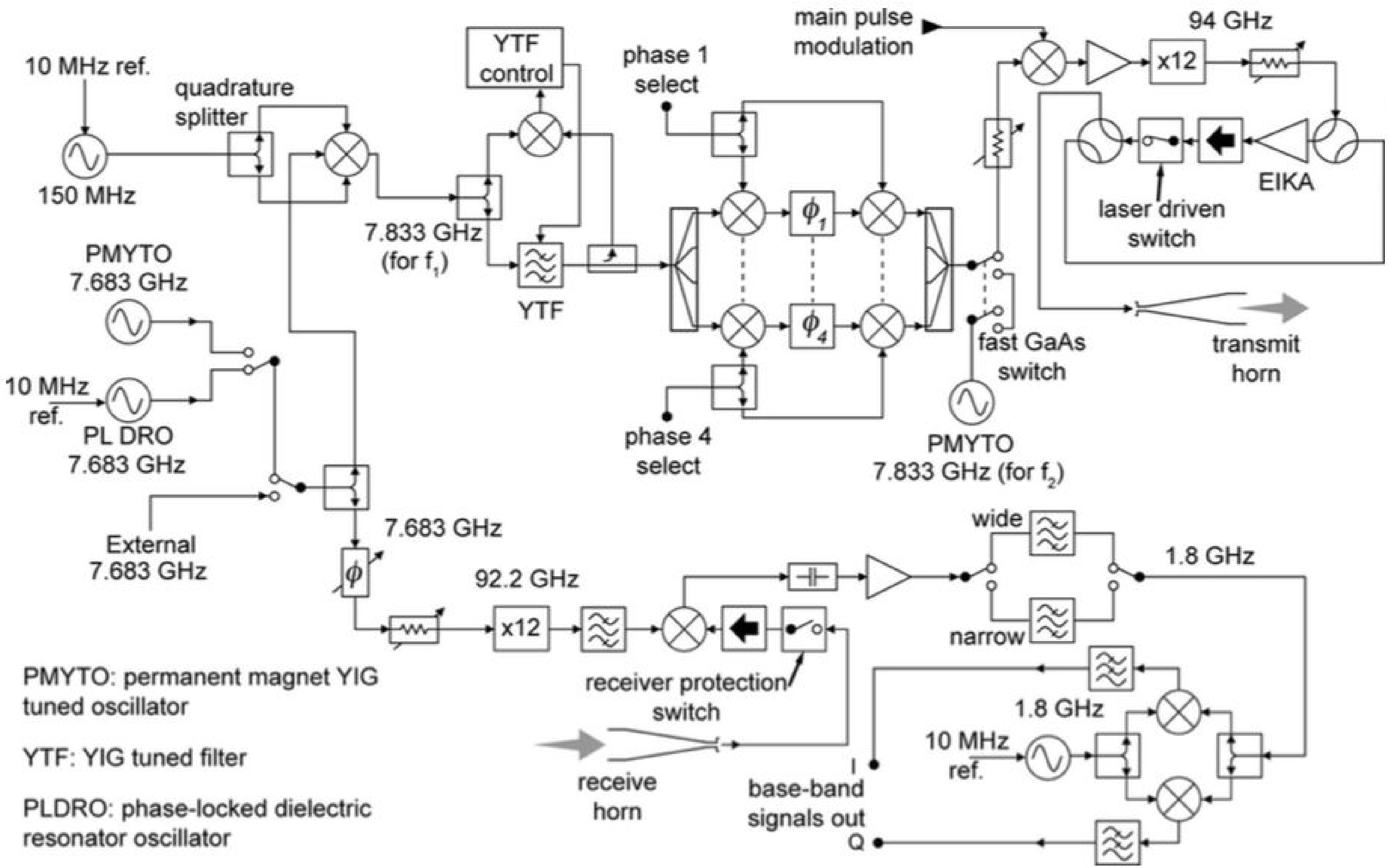


FIG. 2. Basic system diagram showing the transmit and receive electronics of the high-power EPR spectrometer. The upper part shows the transmit section and the lower part shows the receive section. The two parts are coupled through a high-performance quasioptical system.

ESR System Examples – St. Andrews

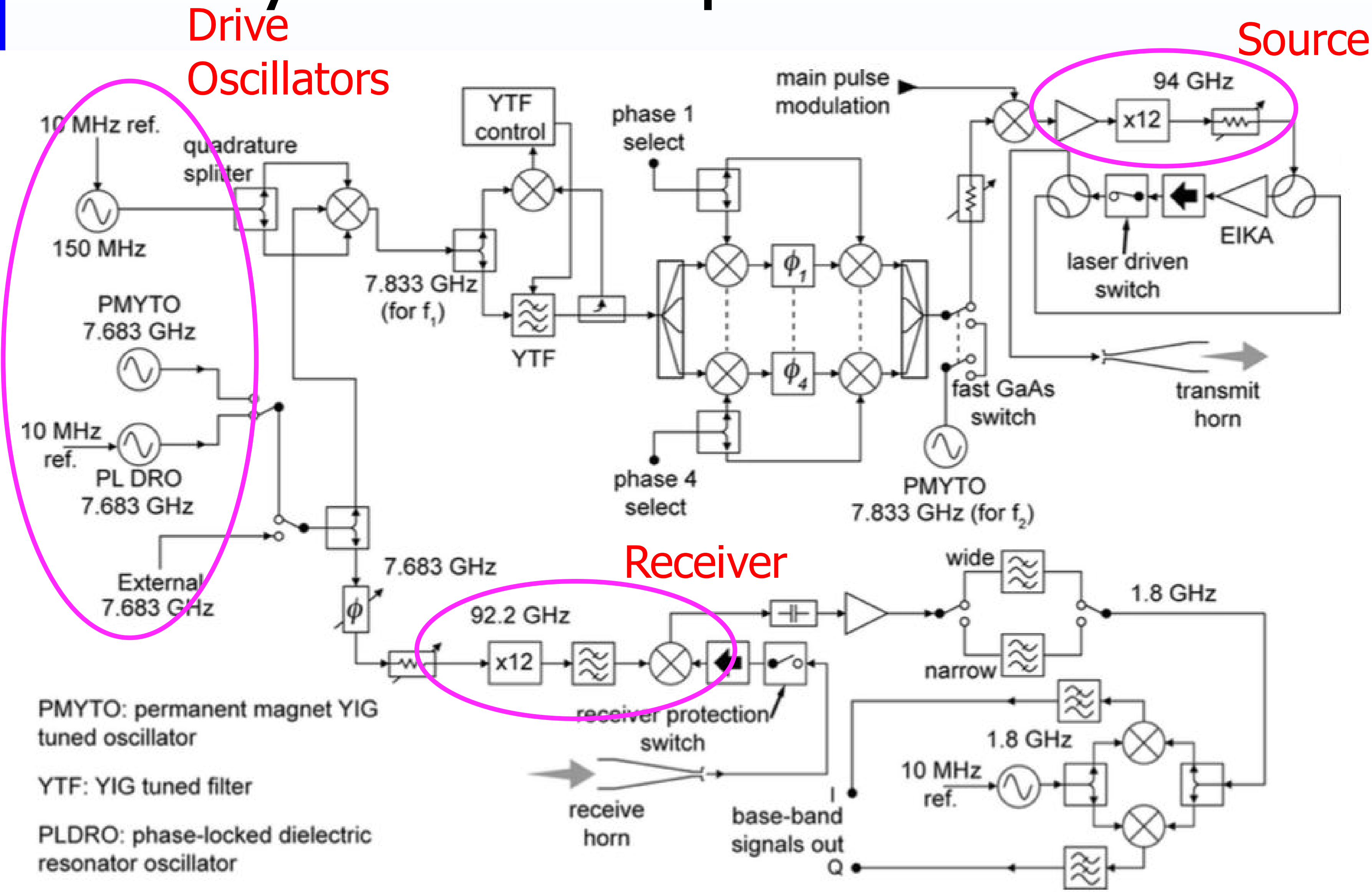


FIG. 2. Basic system diagram showing the transmit and receive electronics of the high-power EPR spectrometer. The upper part shows the transmit section and the lower part shows the receive section. The two parts are coupled through a high-performance quasioptical system.

This Presentation

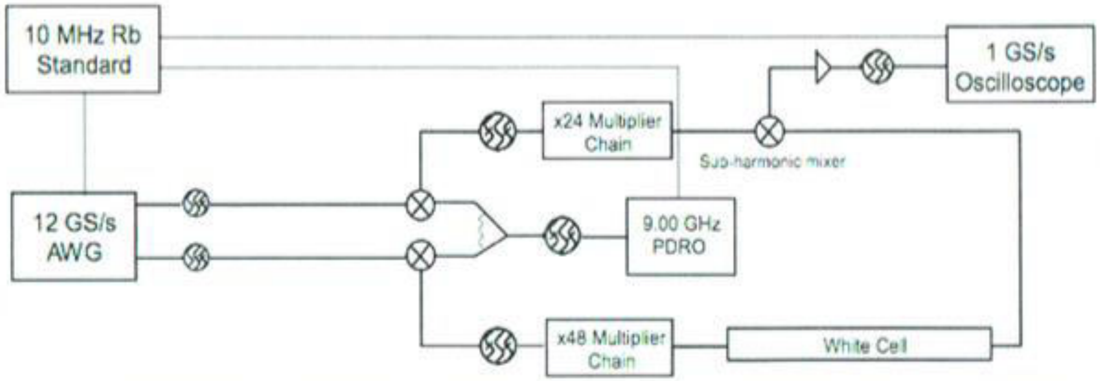
- Introduction
  - THz Applications
  - Schottky Diode Technology
- Schottky-Based THz Heterodyne Transceiver Components
  - THz Signal Generation
  - Waveguide Interfaces
  - THz Signal Detection
    - Generation of Wideband Modulated Signals at THz
- THz Transceivers
  - **Chirped Transform Spectroscopy**
- Solid-State Sources & DNP
- Conclusions

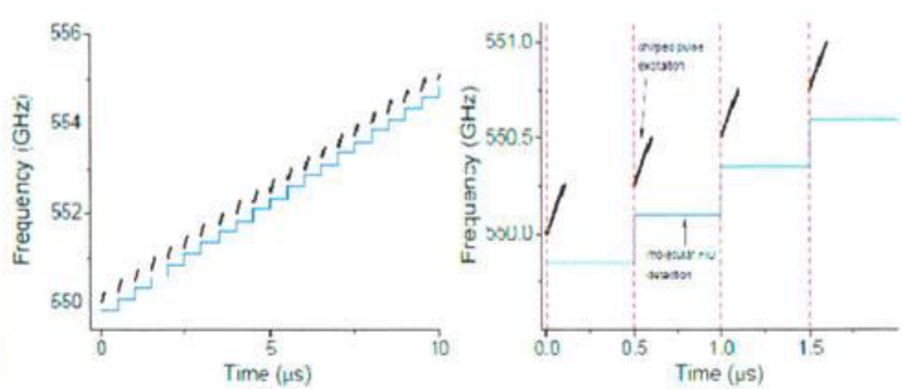
Segmented Chirped-Pulse Fourier Transform Spectroscopy: Unprecedented Speed and Sensitivity

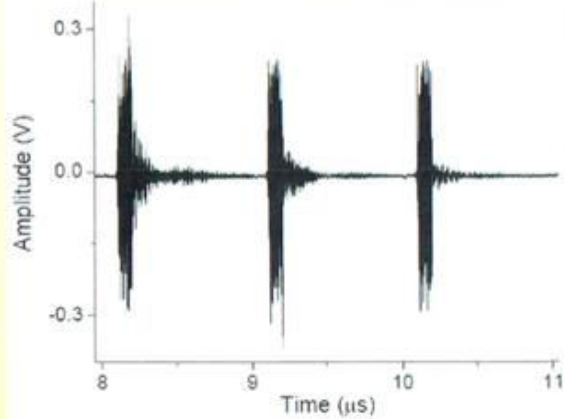
Center for Chemistry of the Universe

CCU Collaboration: Tektronix, Virginia Diodes, UVa, NIST

Segmented CP-FT Measurement Concept

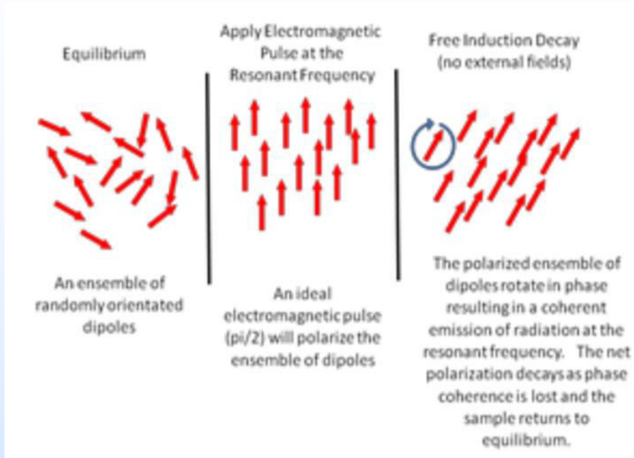


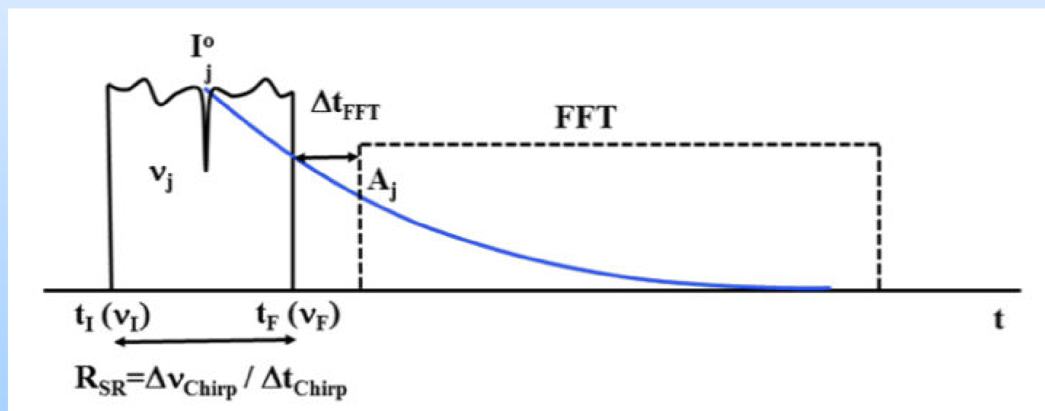




Acquire both the excitation pulse and the molecular FID

Chirped-Pulse Fourier Transform Spectroscopy

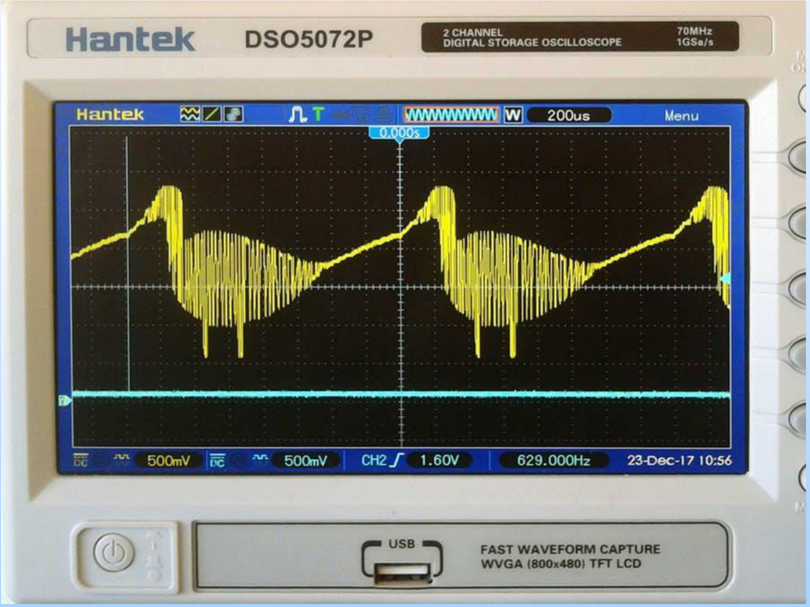




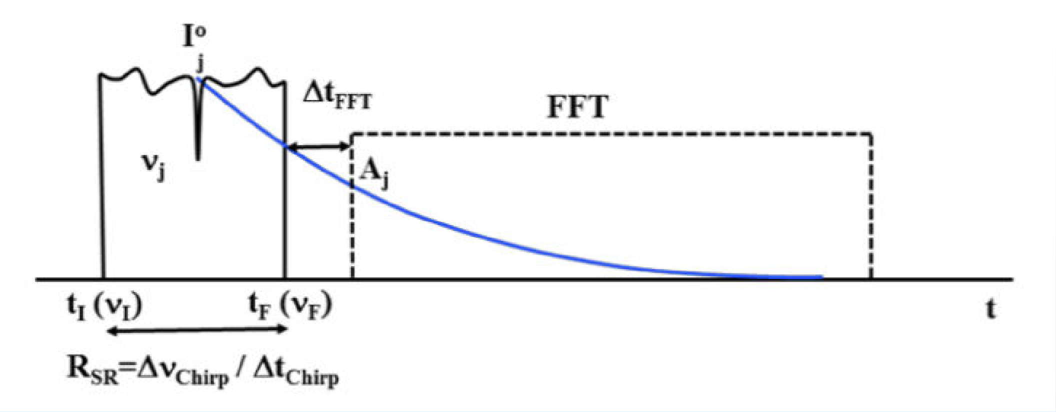
Gerecht – Optics Express 2011

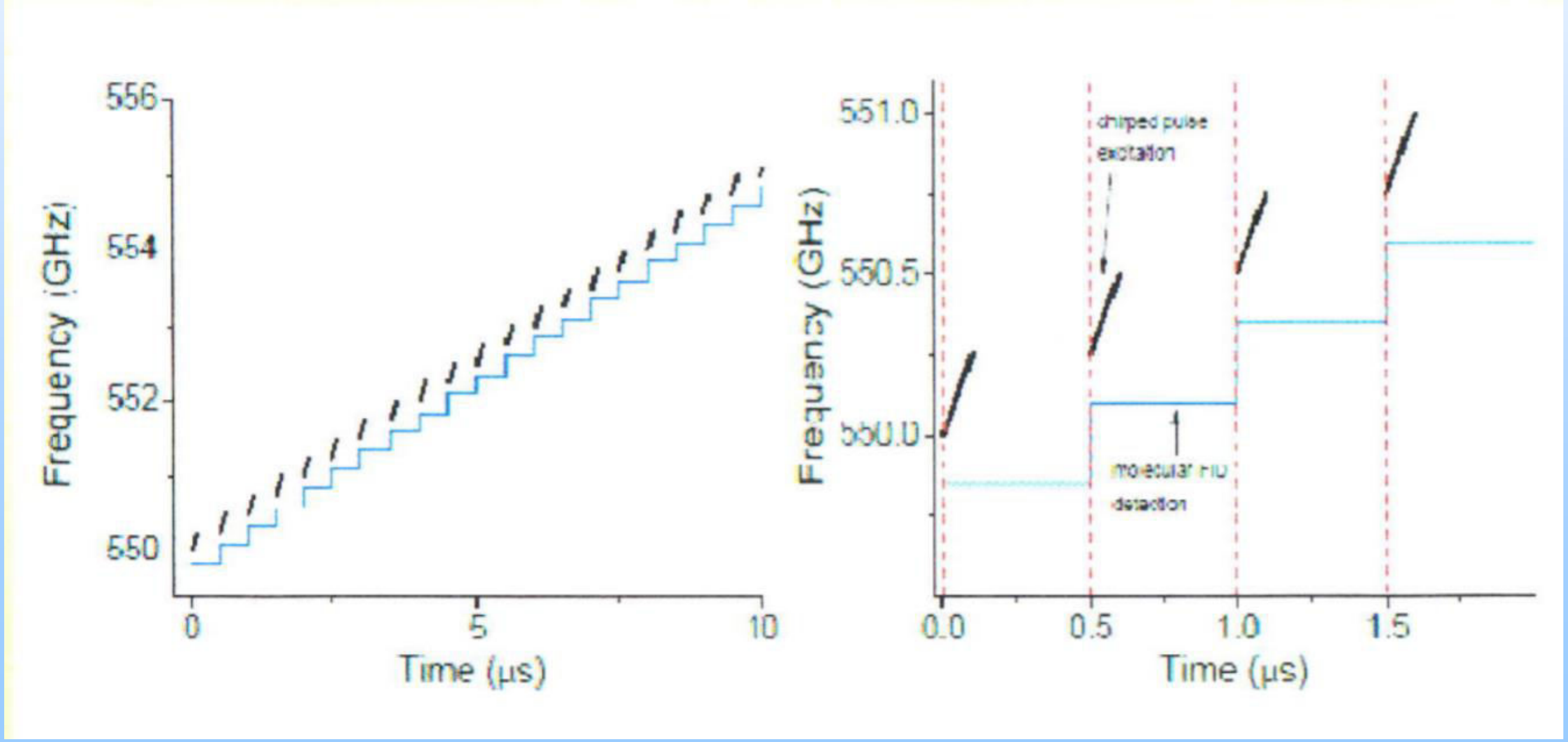
Arbitrary Waveform Generator

- Allows the generation of any signal shape at output
  - A fast Digital to Analog converter
  - Sample rates to 120 GSa/s

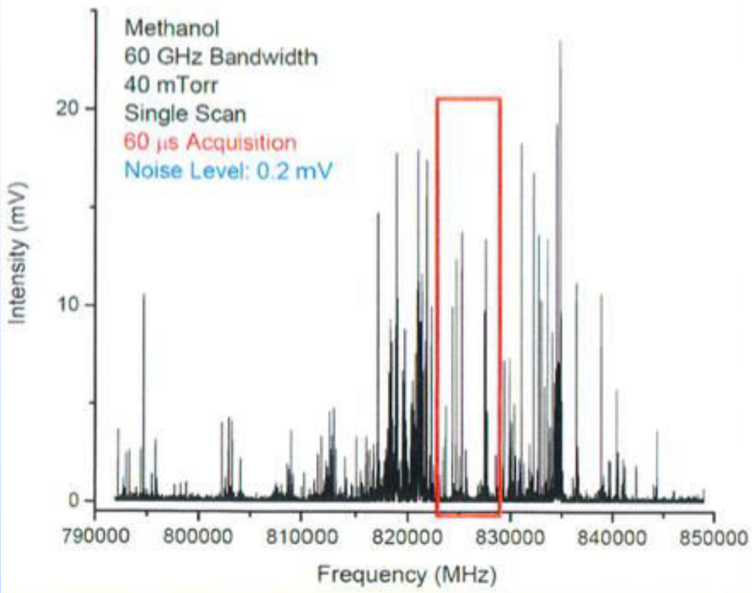


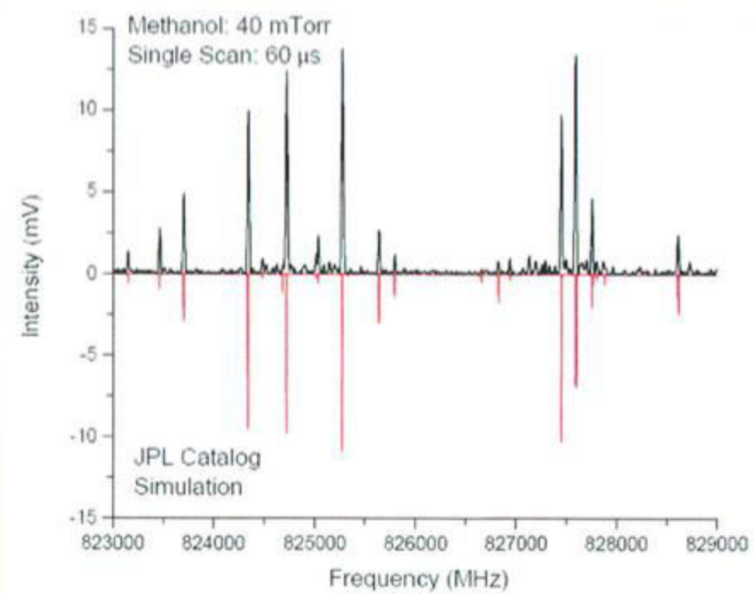
Chirped-Pulse Fourier Transform Spectroscopy





Chirped-Pulse Fourier Transform Spectroscopy





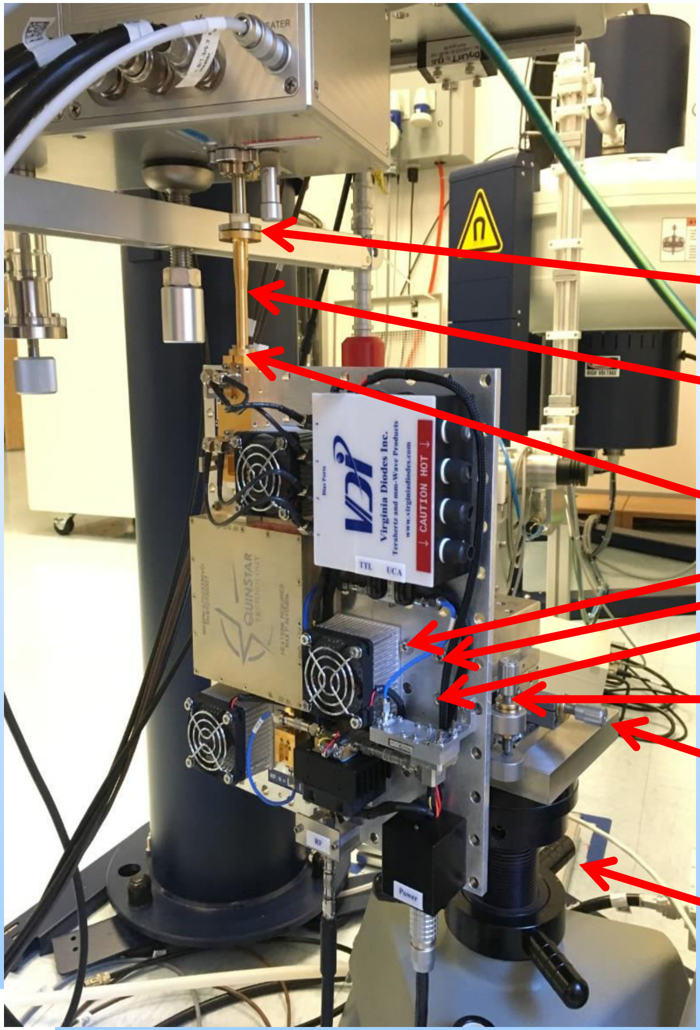
Neill 2013 Optics Express

- 67 GHz bandwidth spectrum of methanol (spanning from 792 to 859 GHz) acquired in 58 µs
- Speed advantage of many orders of magnitude over that of traditional spectroscopy methods

This Presentation

- Introduction
  - THz Applications
  - Schottky Diode Technology
- Schottky-Based THz Heterodyne Transceiver Components
  - THz Signal Generation
  - Waveguide Interfaces
  - THz Signal Detection
    - Generation of Wideband Modulated Signals at THz
- THz Transceivers
  - Chirped Transform Spectroscopy
- **Solid-State Sources & DNP**
- Conclusions

262 GHz Source Tested at Bruker



Waveguide connection (z-gap)

Taper WR4.3-7.6 mm ID

VDI AMC output

Mounting screws

Fine adjust (z)

Fine adjust (x/y)

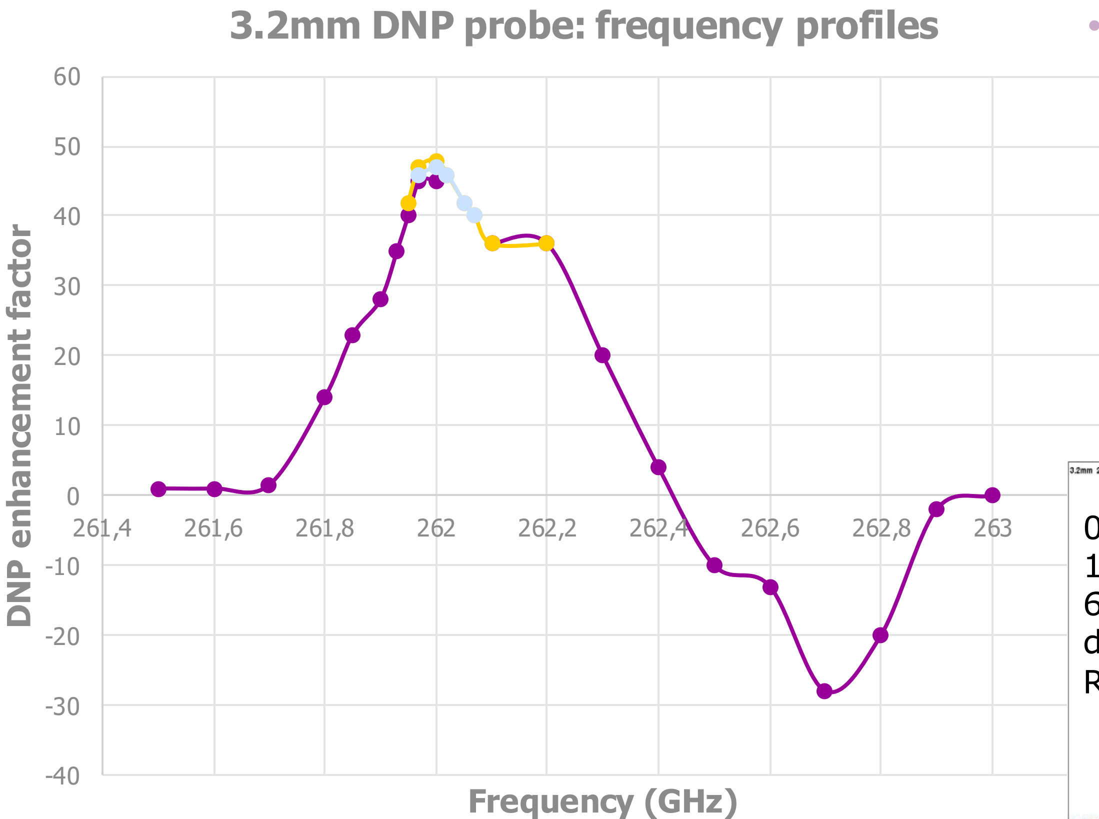
Coarse Z adjustment

Virginia Diodes, Inc.

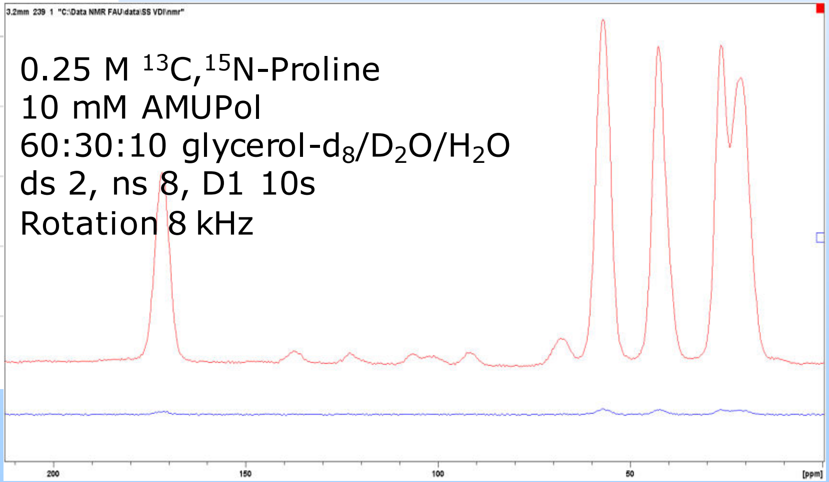
www.vadiodes.com

BRUKER

3.2mm DNP probe with 200+ mW VDI source
Frequency profiles



- Maximum DNP gain at 262.0 GHz: **45-48** (gyrotron: 240)
  Ratio gyrotron/SS: 5.3
- Reproducibility tests: Different insert/eject at different days
- CP stability test (1h30)



^1H-^{13}C CP-MAS spectra **with** and **without** DNP

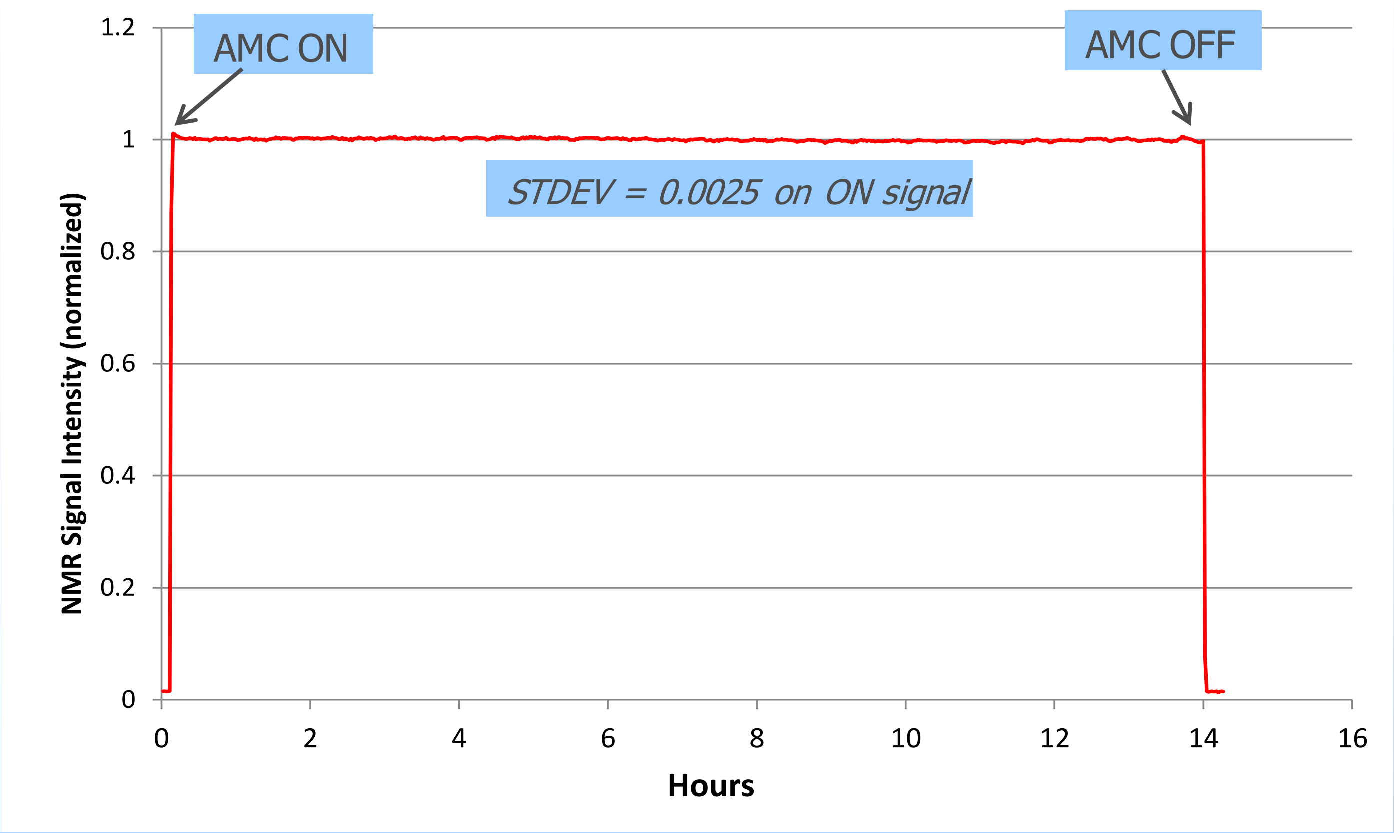
Spinning frequency: 8 kHz
SFO1 ^1H: 397.8727097 MHz

Virginia Diodes, Inc.

www.vadiodes.com

BRUKER

262 GHz DNP with VDI Source Overnight Stability Measurement



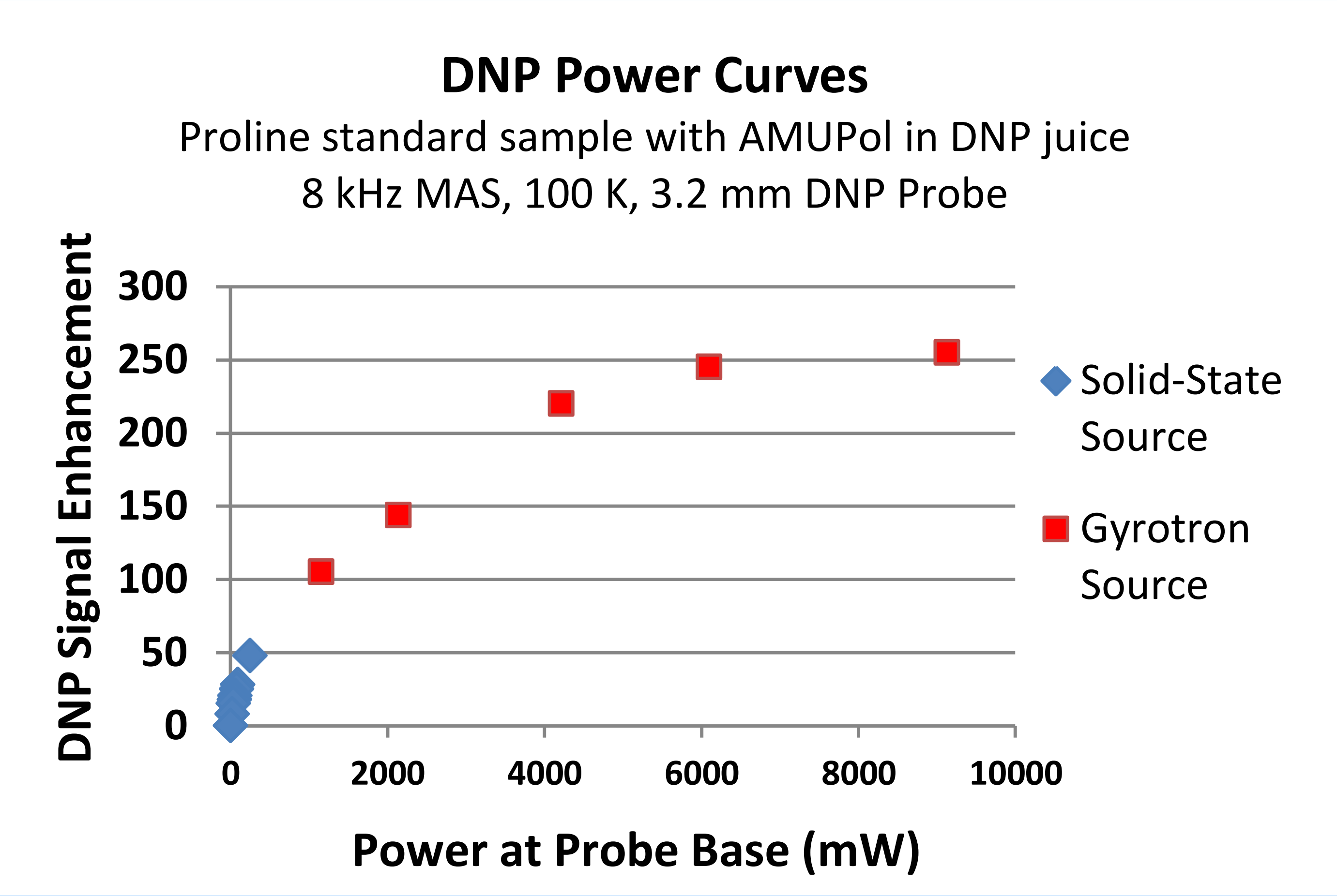
- Stability measurement on proline sample (in optimized rotor/optimized probe) with AMUPol in DNP juice, 8 kHz MAS, 100 K sample temperature. Measurement repeated every 80 seconds. Numerous stability measurements all indicate excellent stability.

Virginia Diodes, Inc.

www.vadiodes.com

BRUKER

DNP Enhancement vs MM-wave Power



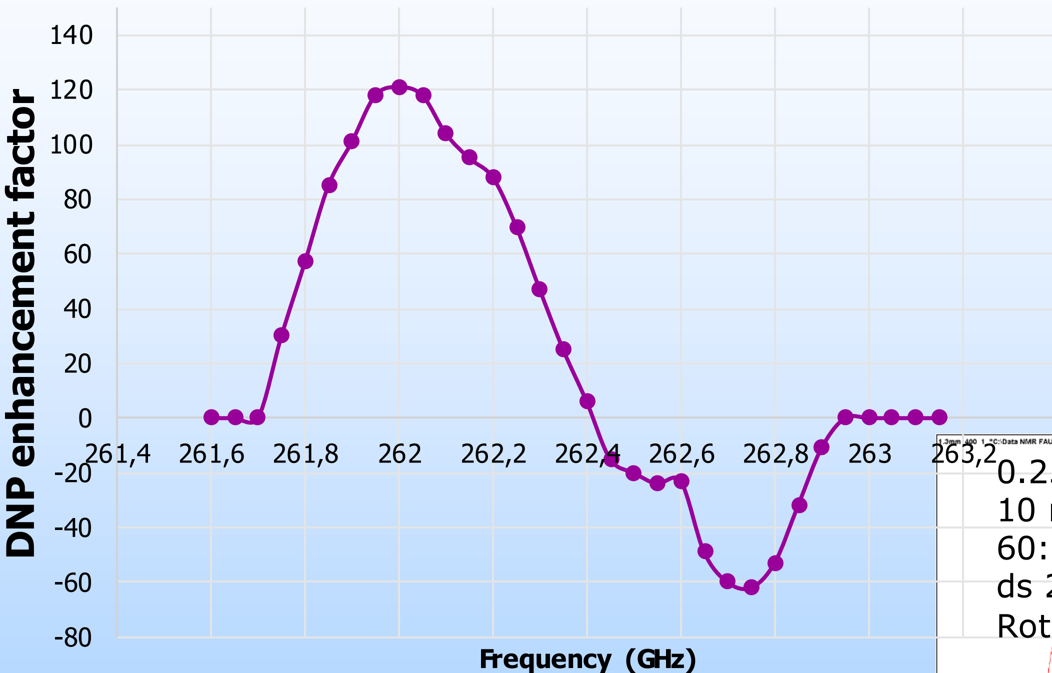
Virginia Diodes, Inc.

www.vadiodes.com

BRUKER

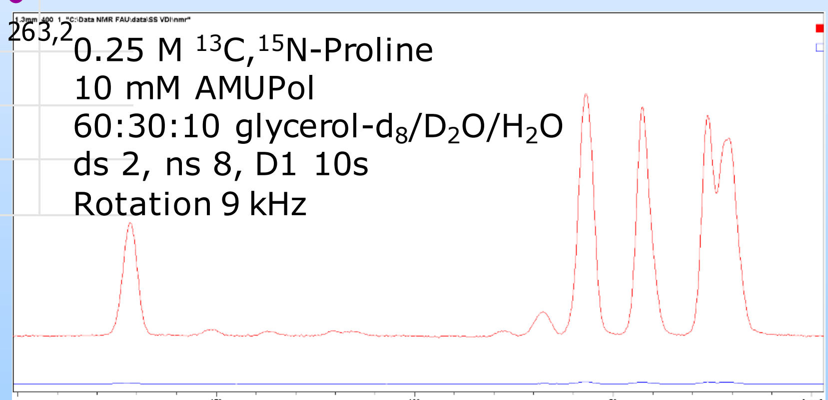
1.3mm DNP probe, VDI source
Frequency profiles

1.3mm DNP probe: frequency profile



- Maximum DNP gain at 262.0 GHz: **115-120** (gyrotron: 350) Ratio gyrotron/SS: 2.9

- Reproducibility tests: Different insert/eject at different days



^1H-^{13}C CP-MAS spectra **with** and **without** DNP

Spinning frequency: 9 kHz
SFO1 ^1H: 397.8727097 MHz

Virginia Diodes, Inc.

www.vadiodes.com

BRUKER

DNP Measurements, VDI Source, 8 kHz MAS, 100 K
All at maximum frequency match position

Probe	Regular Rotor 100 mW	Regular Rotor ~ 225 mW[A]	Optimized Rotor ~ 225 mW[A]
3.2 mm standard	28	50	42[B]
3.2 mm optimized		48	58-65[C]
1.3 mm optimized	90[B]	115-120	

[A] Source operates at maximum power only, ~ 225 mW assuming 2.5 dB insertion loss in directional coupler used as attenuator. Erickson power meter off scale at full power.

[B] Single measurement. All other numbers from multiple measurements.

[C] Variation between different insert/eject/sample freezing cycles on same packed rotor. Reproducibility on DNP-enhanced signal is excellent (±1%) for multiple experiments on same sample maintained at 100 K.

Virginia Diodes, Inc.

www.vadiodes.com

BRUKER

Future Work

- Ruggedization and Lifetime Testing for 263 GHz Sources
- More power at 263 GHz (0.5-1.0W)
  - Using power amplifier at 130 GHz
  - 4-way combining of frequency doublers
  - Cryogenic cooling of final doublers and amplifier?
- 395 and 527 GHz sources (100mW and 50mW respectively)
- Pulsed operation (arbitrary amplitude and phase)
  - Using IQ mixer at 130 GHz before final amplifier

500mW source at 240 GHz

Virginia Diodes, Inc.

www.vadiodes.com

Summary

- Terahertz technology is an emerging field with many established applications in basic science, as well as a host of commercial applications that are now under development.
- A primary need is fast, convenient and accurate Test & Measurement tools.
  - "If you can measure it, you can improve it"
- Full waveguide band frequency extenders are now available for signal generators and signal analyzers up to 1.1 THz
- Scientific Applications are driving development to 3 THz and beyond!