# Submillimeter-wave Applications and Instrumentation


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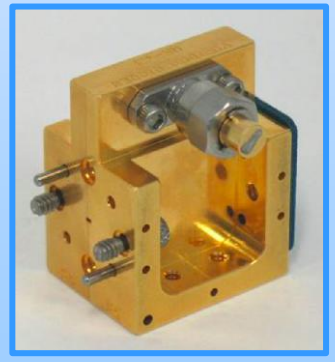

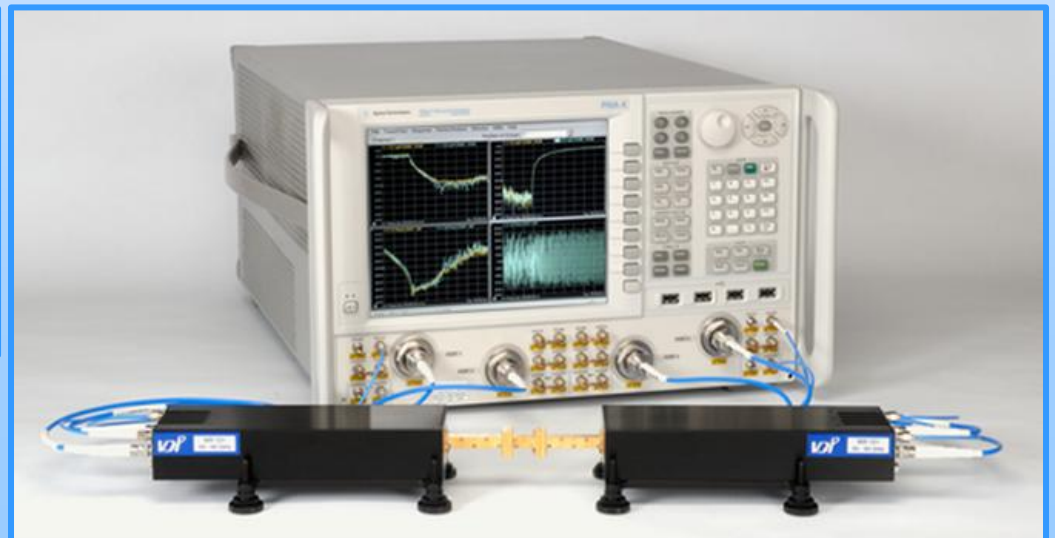

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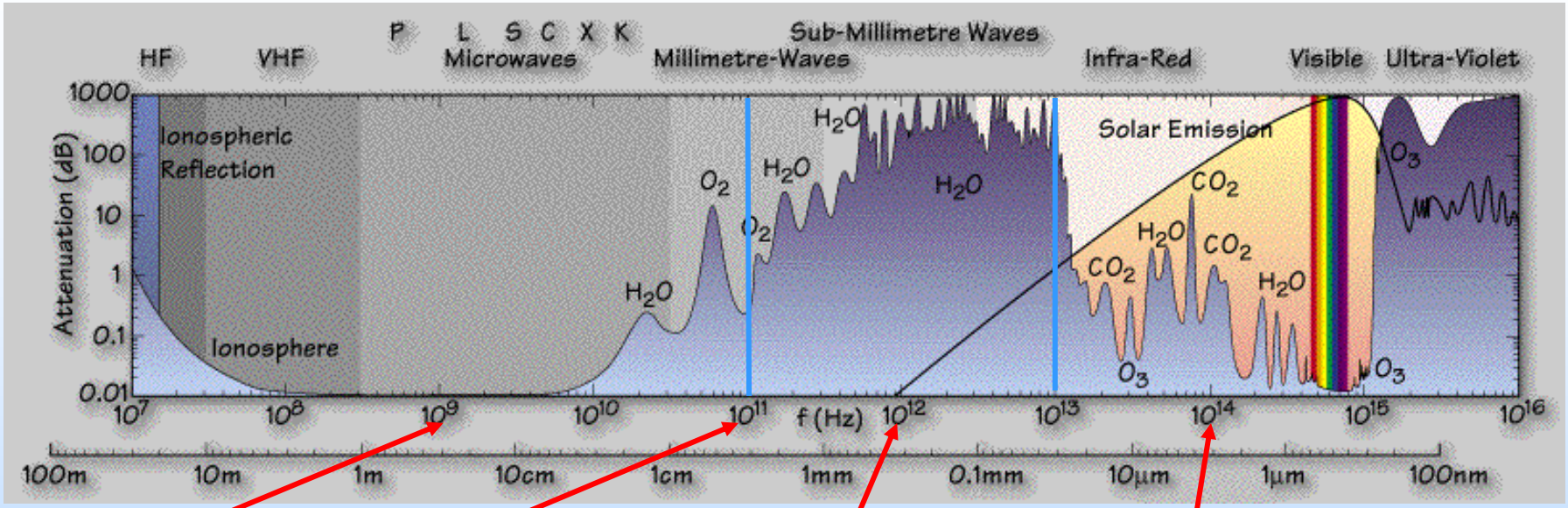
# Outline

- **Introduction**
- A variety of THz applications
- The base for THz instrumentation
  - Frequency multipliers
  - Mixers
  - waveguide
- THz instrumentation
  - Source Extenders
  - Spectrum Analyzer Extenders
  - Extenders for Vector Network Analyzers
- Conclusions

# Who is bsw?

- system integrator for RF, microwave and millimeterwave measurement solutions for characterization of on-wafer, coaxial and waveguide devices and systems for customers in semiconductor and telecommunication industry and public and academic research institutes.
- supplier of a variety of coaxial and waveguide components, typically used in the R&D lab.
- based in NL and DE, active in Benelux, German speaking countries and Scandinavia.

# What Makes THz Interesting??




1GHz=30cm, 100GHz=3mm, 1THz=300um, 100THz=3um
optical starts at ~0.7um

Change in 'intuition': electronics vs. optics and in-between

Not only electronic applications, also physics, materials, etc.

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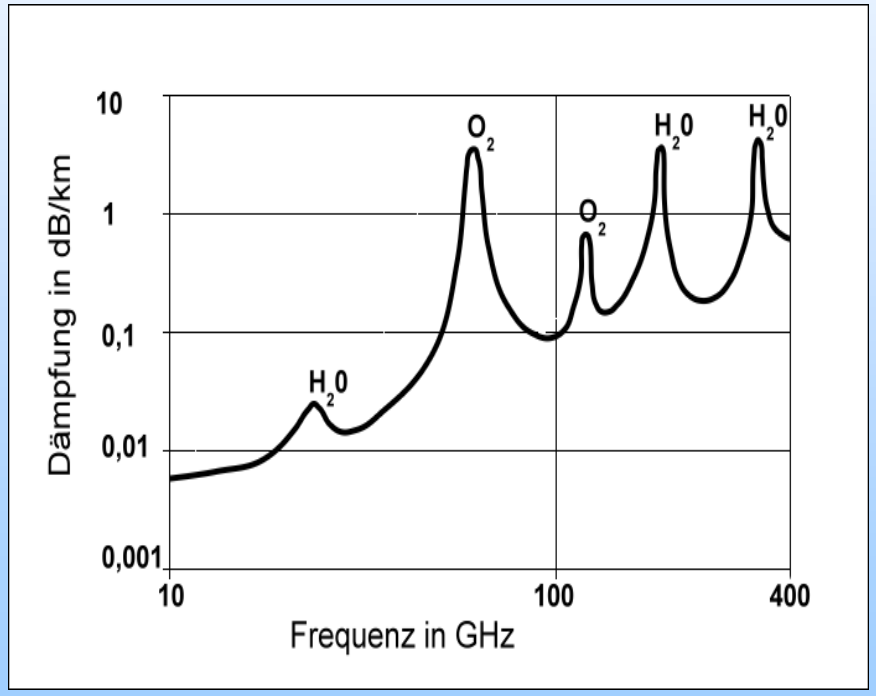
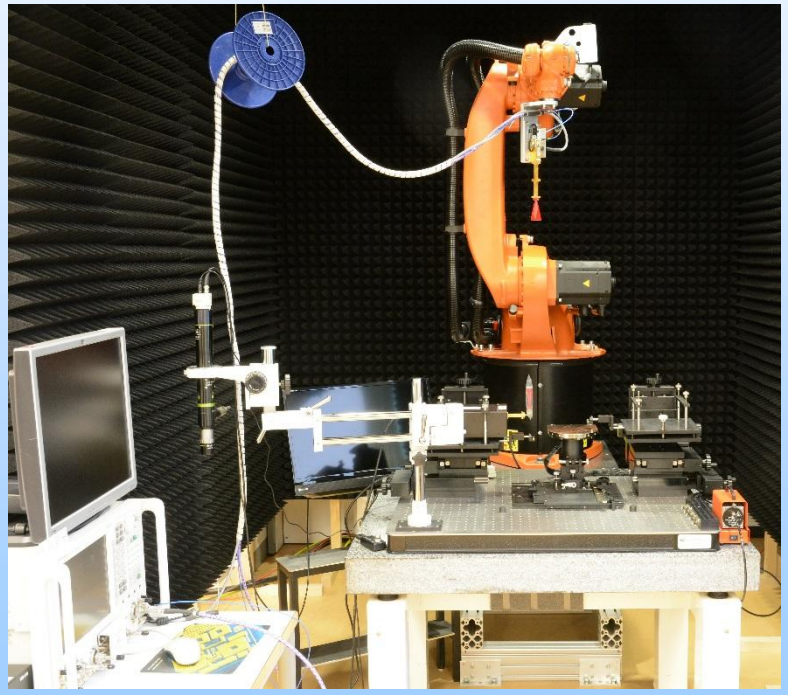
# Quest for more bandwidth

- Bandwidth as a percentage of the carrier freq
- (mis-)use atmospheric absorption spectrum



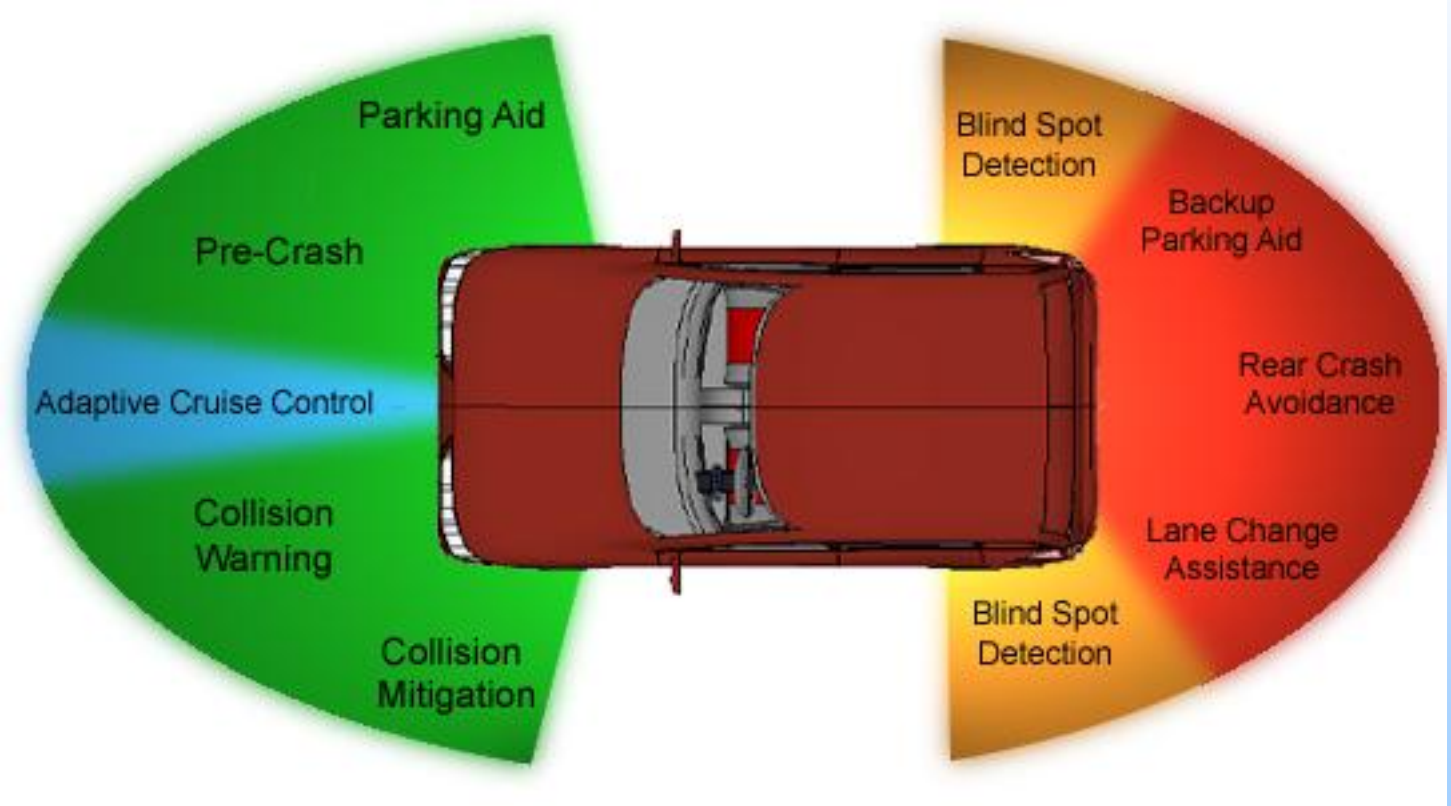

Source: wikipedia.



Source: university Ulm

# Radar

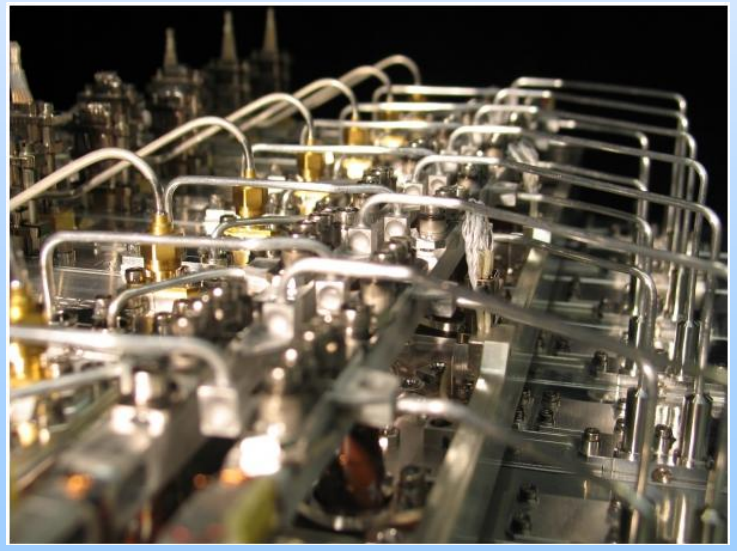
- Car radar



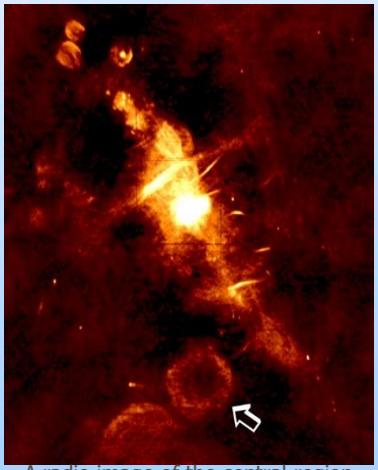

Source: wikipedia.

# Radio astronomy

- Use an array
- At RF, μw and mmWave

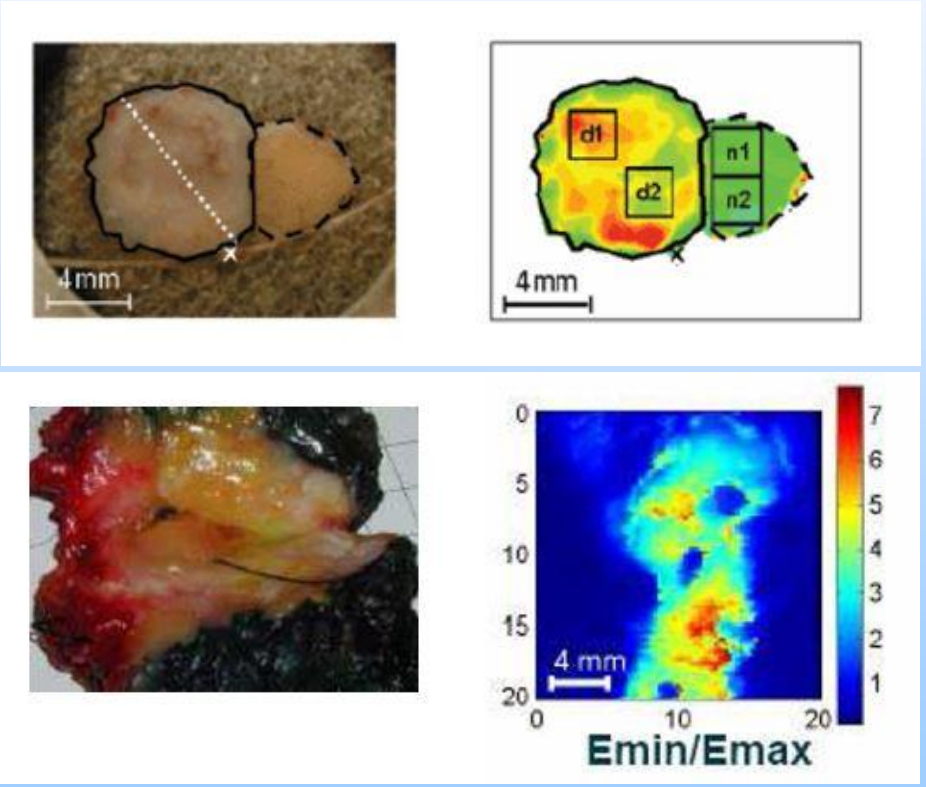
Source: SRON



A radio image of the central region of the Milky Way galaxy. The arrow indicates a supernova remnant which is the location of a newly discovered transient, bursting l ow-frequency radio.
Source: wikipedia

# Explore human tissue

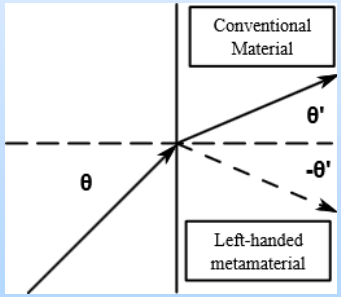
- Too low energy to 'hurt' human tissue
- Enough energy to penetrate for visualisation

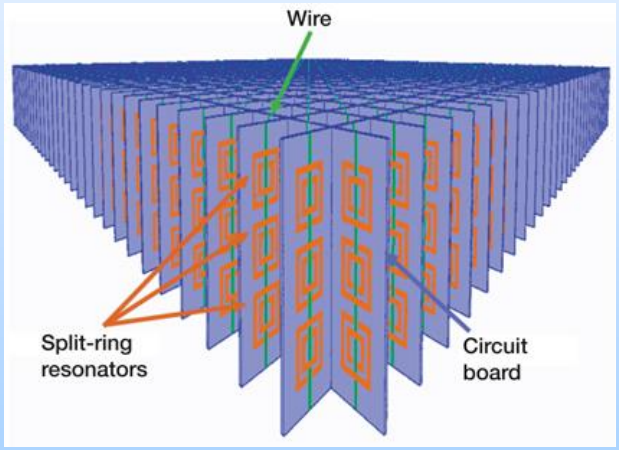


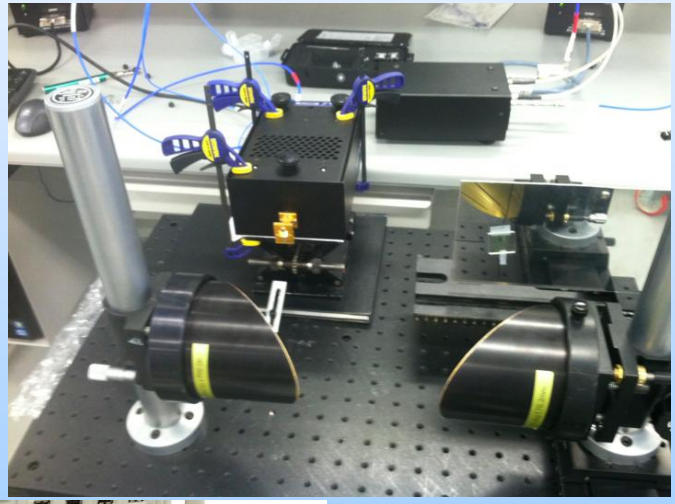

Source: Terasense, Inc.

# Design meta materials

- Measure material properties
- Create materials with 'unnatural' properties





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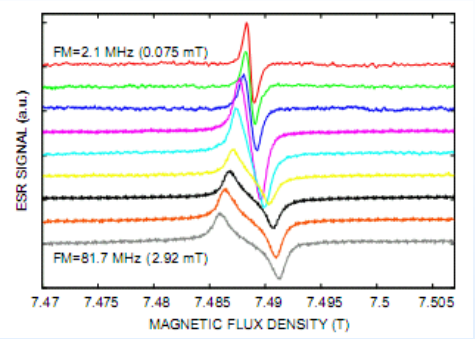
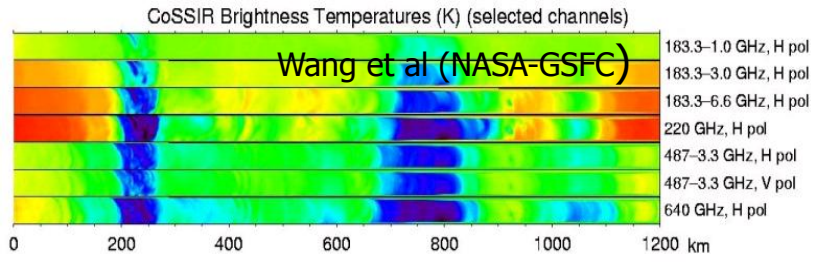
# And much, much more …

- ESR/EPR and NMR
- Molecular spectroscopy
- Plasma Diagnostics
- Weather Monitoring
- Security imaging and sensors
- Industrial process monitoring and control




Nafradi et al (EPFL)




Wang et al (NASA-GSFC)

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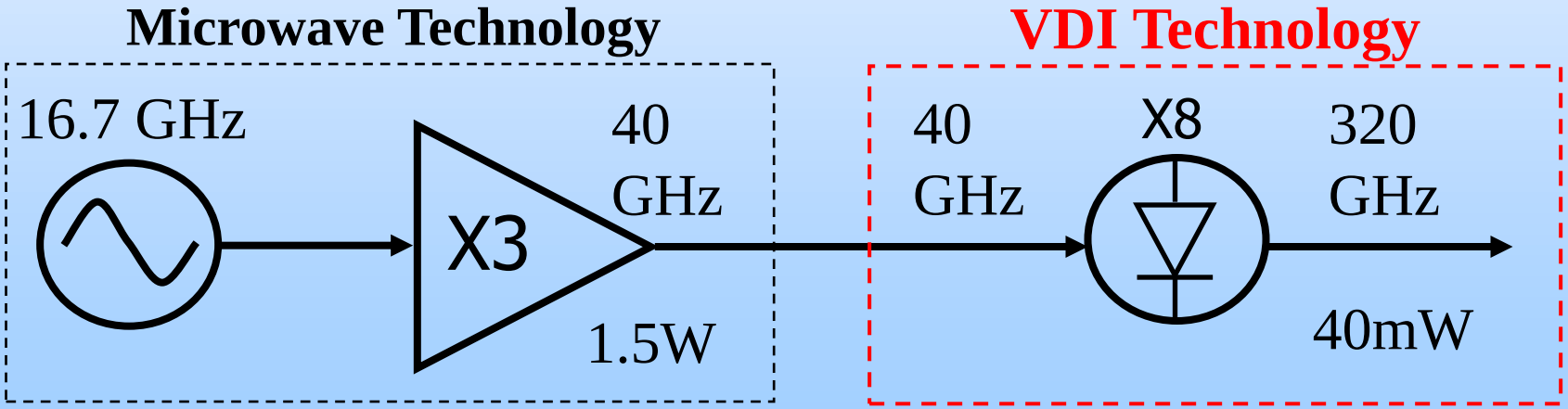
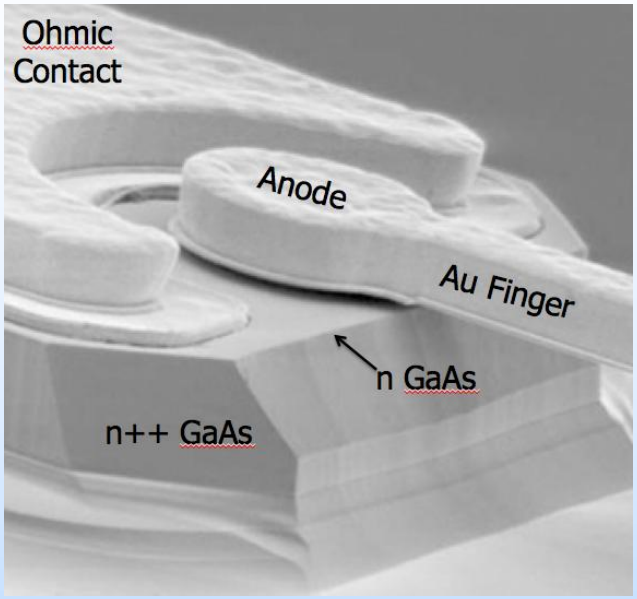
# mmWave signal generation

- Frequency multiplier:
  - Use nonlinear devices, create harmonics and filter $n^{th}$ component
- AMC: Amplifier Multiplier Chain



# Schottky Diode

- Metal-semiconductor junction
  - Majority carrier device
  - Cutoff frequencies well into the THz
  - Room temperature operation
  - Improves with cooling



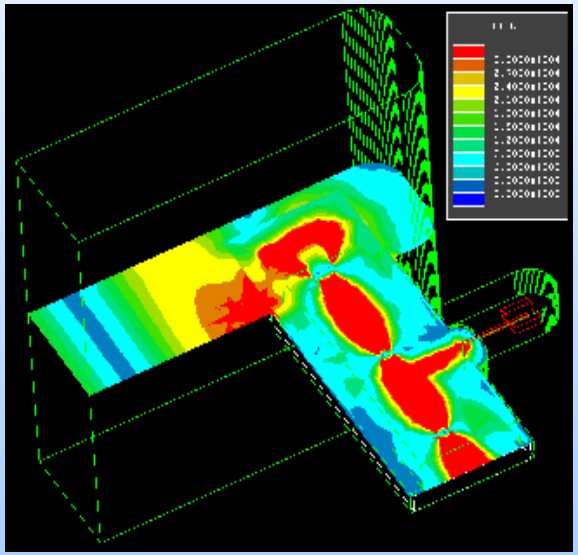

- Fairly simple model
  - quasi-static I-V and C-V equations

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

- Well-developed fabrication technology
  - Air-bridge used to reduce capacitance

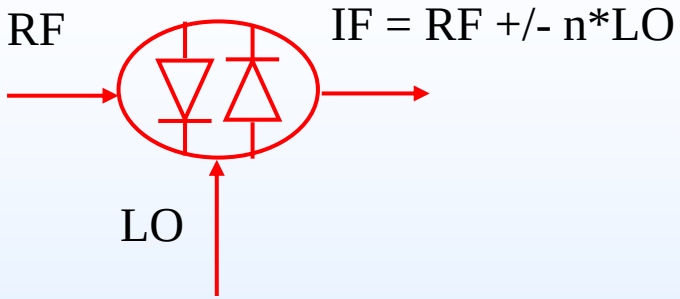
# Circuit/System considerations

- Low phase noise of driving generator
  - Increases with 20*LOG(N)
- Use commercially available and proven µW/RF microwave circuits!
- Optimized mmWave circuits
  - Broadband, Tunerless, High efficiency
- Balanced circuits
- Multiple diodes for increased power handling

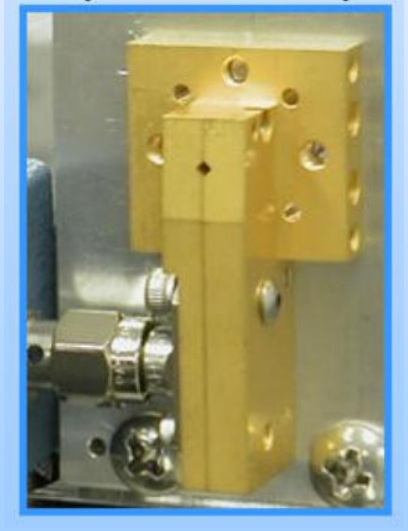


# Harmonic mixer

- (Sub-)harmonic Mixer
  - RF mixes with N*LO
- Tunerless broadband mixer design
- VDI has mixers from WR-15 up to WR-0.4 (2-2.8THz), typically full band




WR-0.65SHM
(1.1-1.7 THz)



WR-6.5SHM

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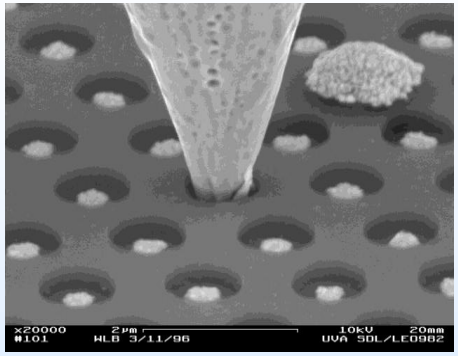
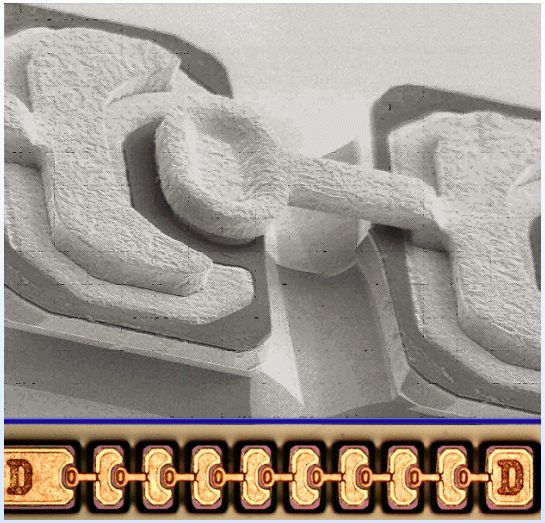
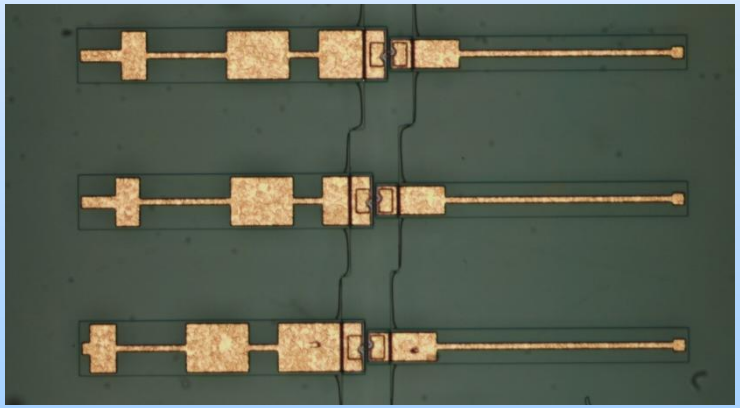
# More pictures



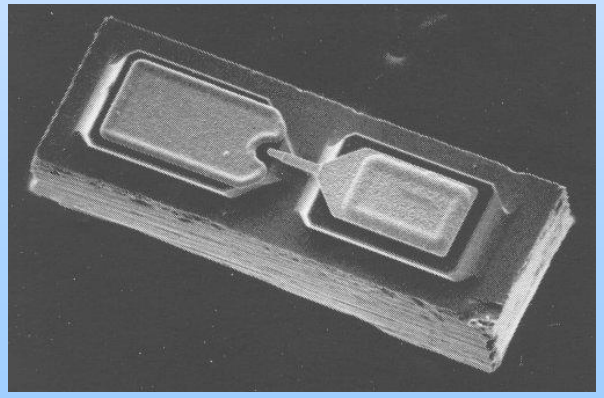

*A sub-quarter-micron whiskered diode for 2.5 THz*



*A planar varactor diode array for a 200 GHz doubler*



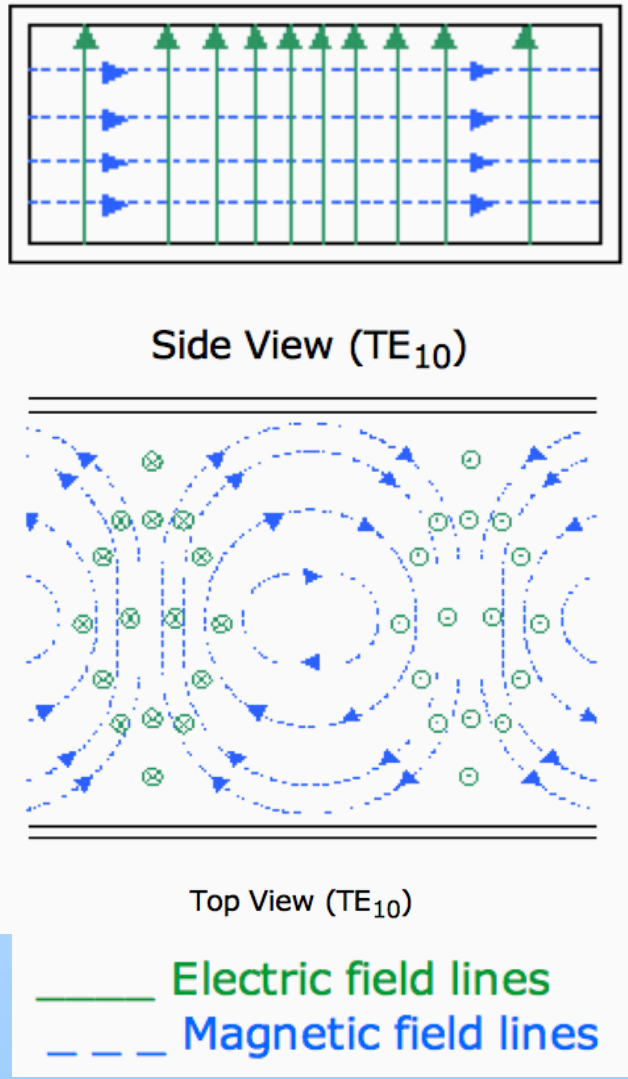
*An Integrated GaAs on quartz frequency mixer for 600 GHz with anti-parallel Schottky diodes*



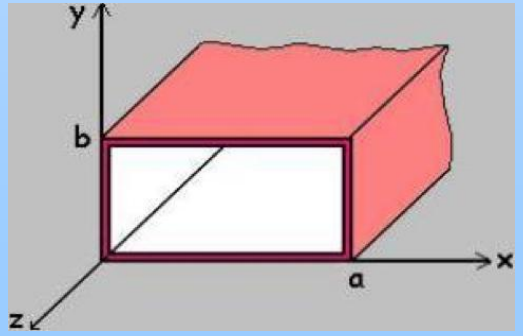
*Flip-chip planar diode*

# Rectangular Waveguide

- TE10 Mode preferred
- No propagation for $\lambda_c > 2a$
  - High pass filter
- >TE10 modes starts at $2*f_C$
- Best behaved between $1.25*f_C$ and $1.9*f_C$




Source: www.rfcafe.com

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# 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

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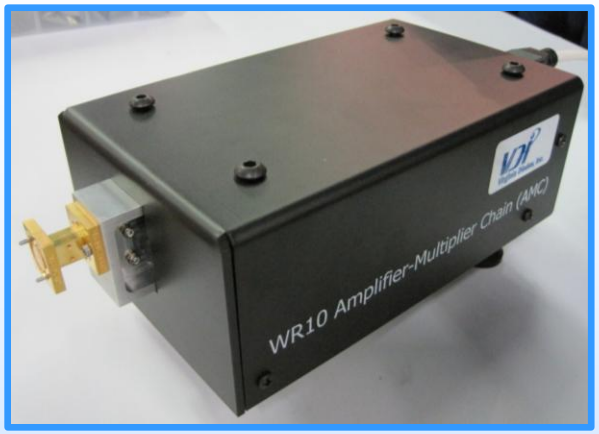
# Signal Generator Extenders, SGX

- Basically an AMC
- Low/high input frequency
- Full WG band operation
- High output power
- AM modulation and Power Control capability
  - Voltage controlled
  - May also be controlled by drive synthesizer

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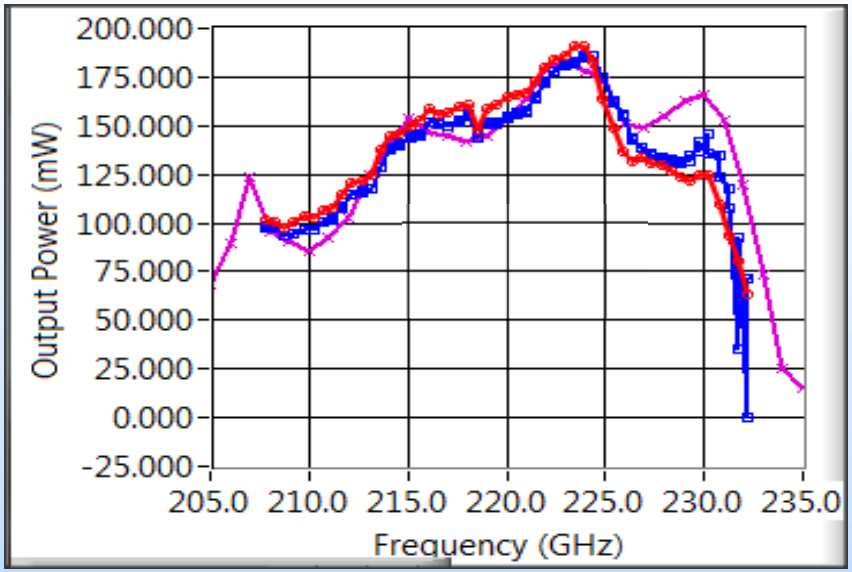
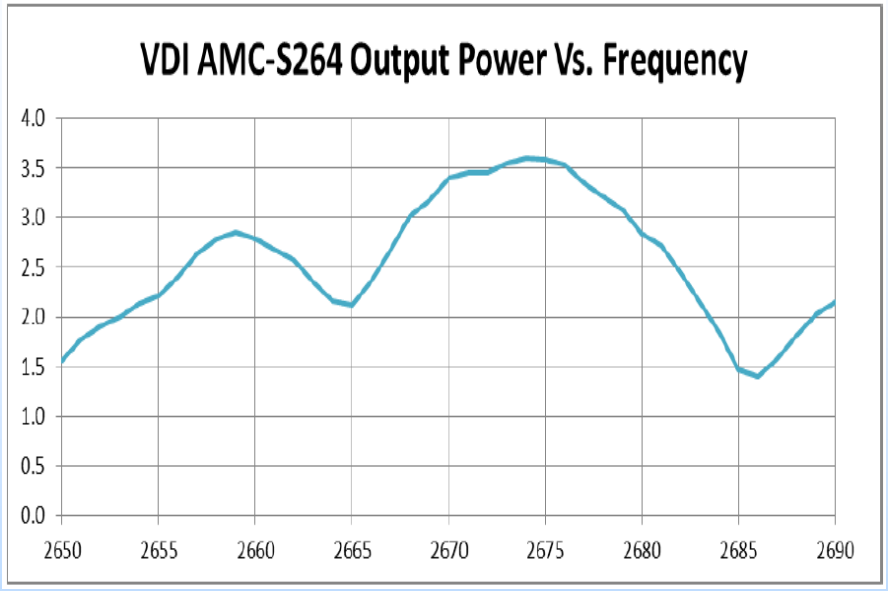
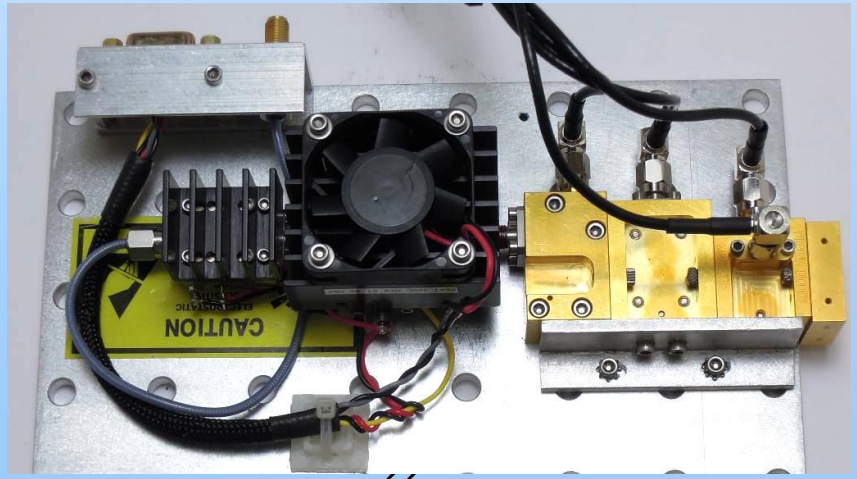
# Optimized Multipliers

180 mW @ 224 GHz




~3 uW @ 2.7 THz



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# WR9.0 THz Modular Kit: 170-1100 GHz


- Series of cascaded multipliers and detectors
  - Tunerless, instantaneous sweeping over > 40% bandwidth
  - Approx. 9-14GHz input
- Rapidly interchangeable components
  - Turn-key operation
- Built-in AM and Power Control capability

•WR-9: 82-125 GHz
  •Pout ~ 25 mW

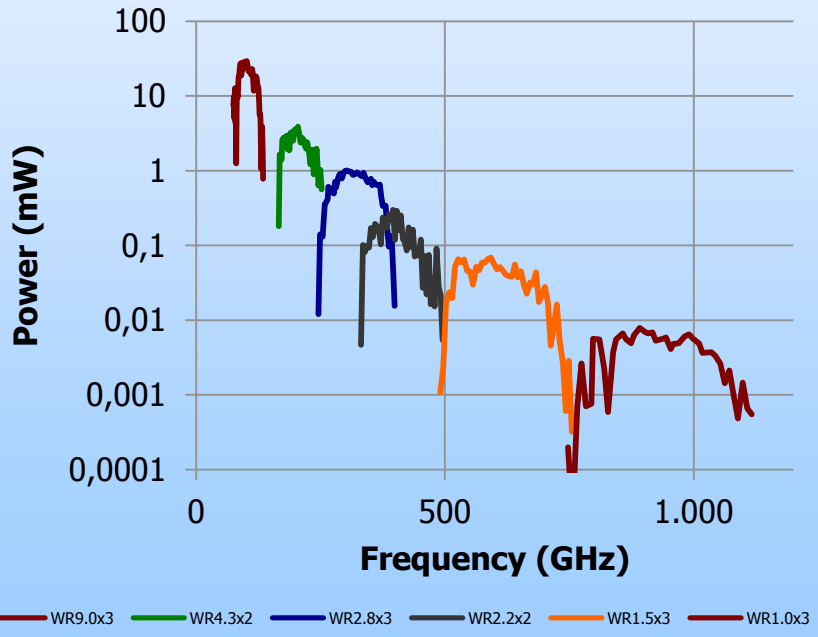
•WR-4.3: 170-250 GHz
  •Pout ~ 3 mW

•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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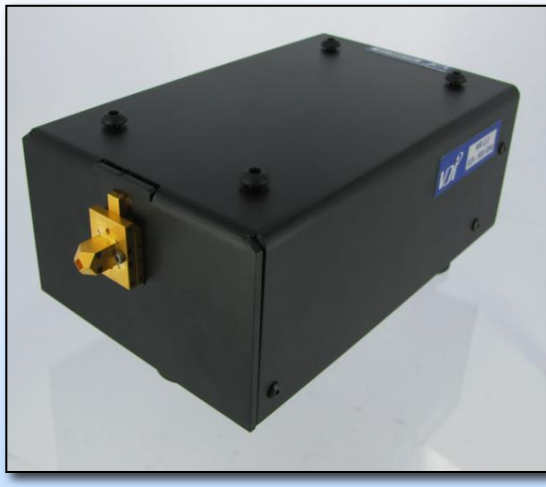
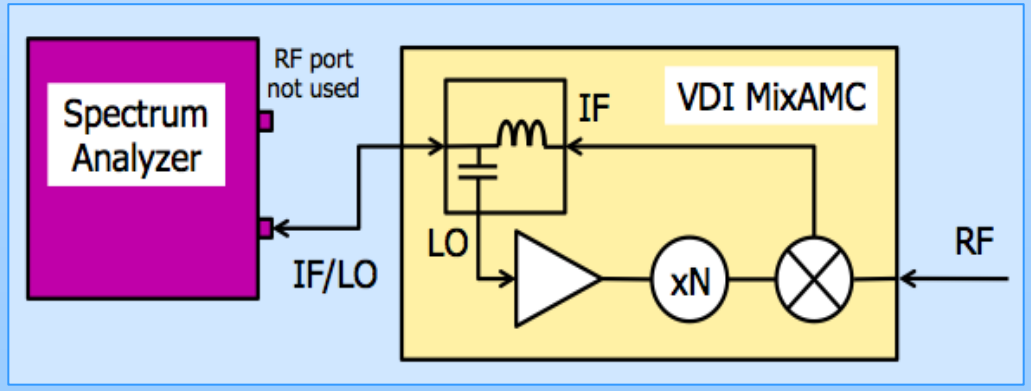
# Spectrum Analyzer Extenders, SAX

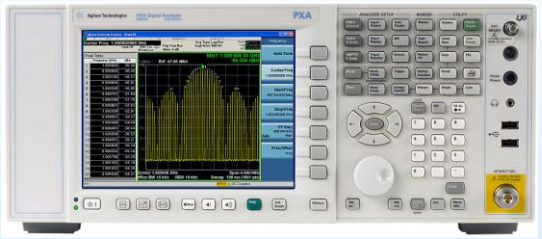
- Basically a Mixer+AMC (for the LO)
- Full WG band operation
- High sensitivity/low DANL
- IF bandwidth to 40GHz
- Swept or block down convertor



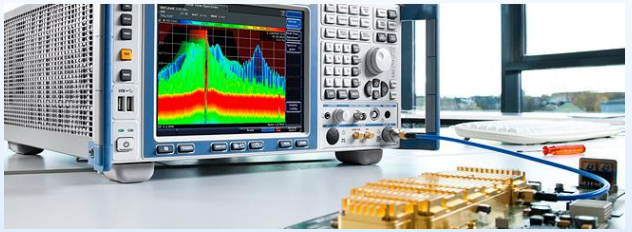


# Spectrum Analyzer Extenders, SAX

- Multiple vendors supported



Keysight PXA



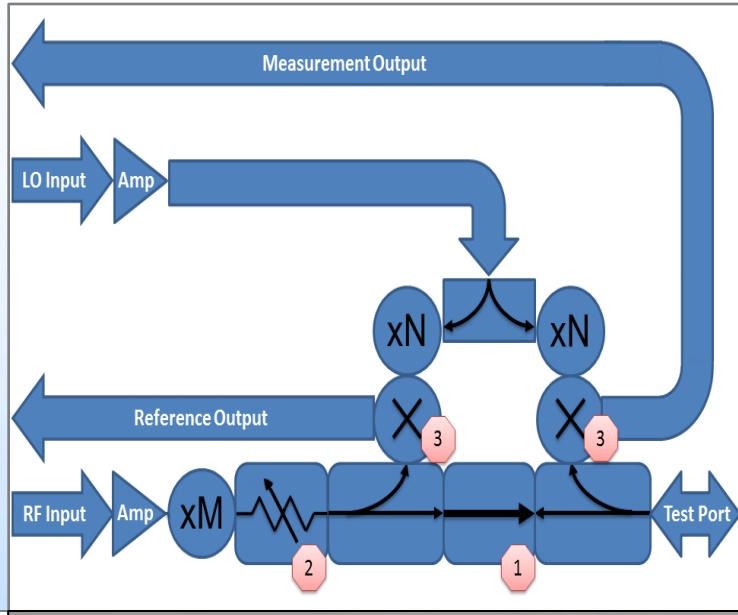
Rohde & Schwarz FSU

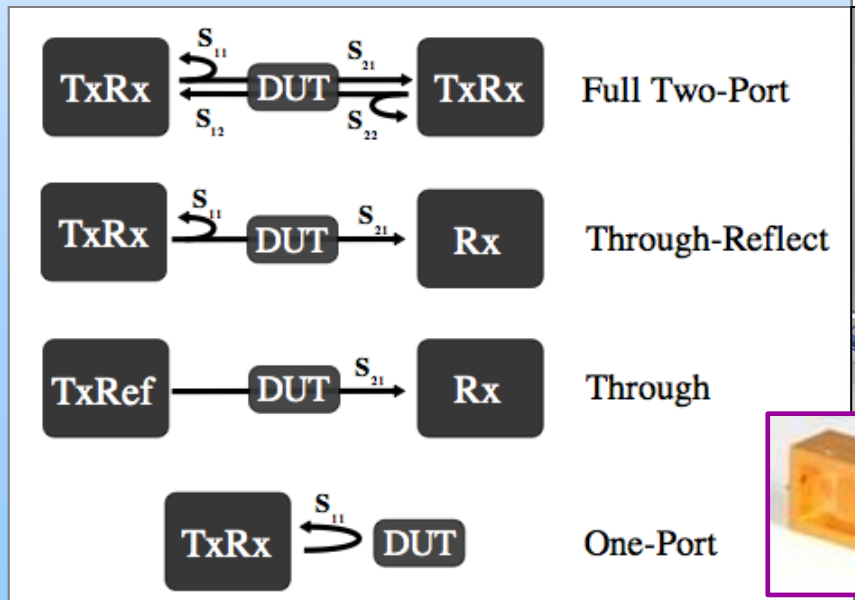
- Image removal option advisable
- DANL = A measure of the minimum detectable signal with 1 Hz bandwidth

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

# VNA Extenders, VNAX

- Basically adds to the VNA
  - External couplers,
  - Source extender (AMC),
  - Downconvertor (MixAMC).
- Different configurations

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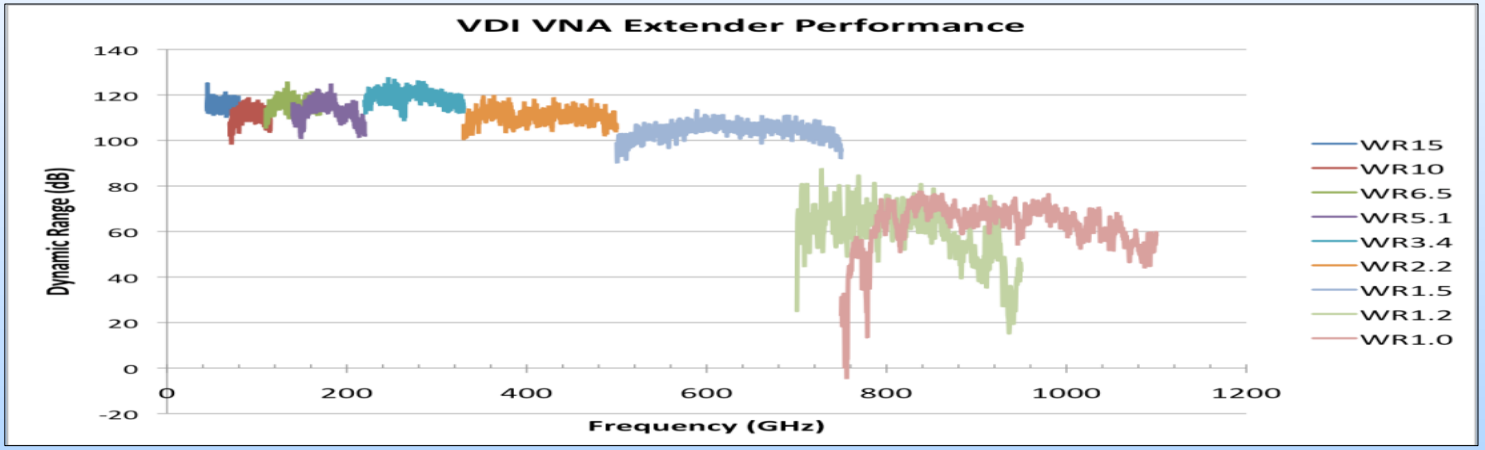
# VNA Extenders, VNAX

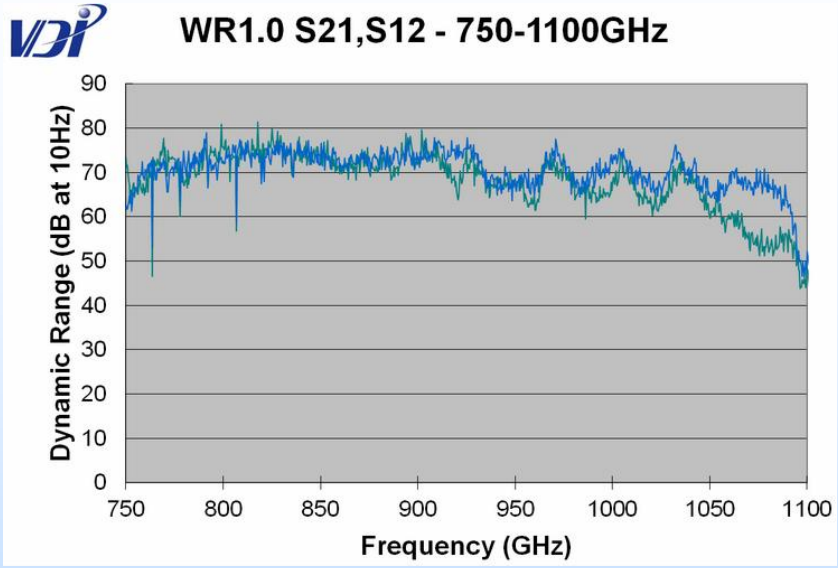
- VDI Extenders from WR-10 thru WM-250
  - State-of-the-art Dynamic range, due to high stimulus power and low noise MixAMC

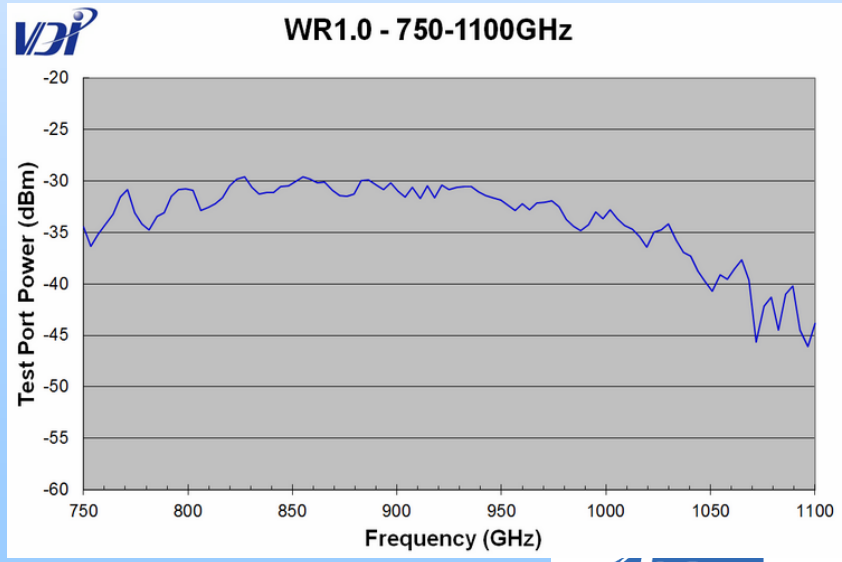



  - Excellent amplitude and phase stability
  - Fully calibrated measurements

# WM-250 (WR1.0) VNA Extender

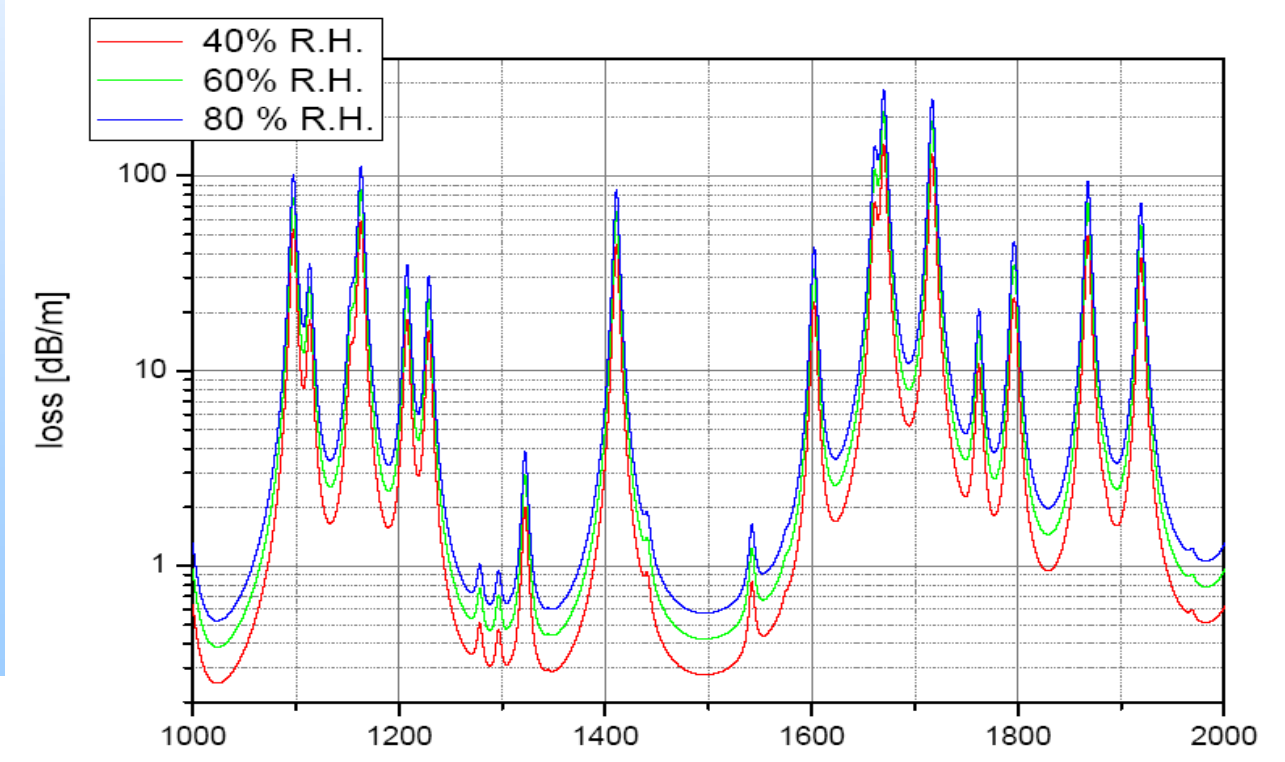
- Dynamic Range: 60 dB typical at 10Hz BW
- Dynamic Range: 40 dB minimum at 10Hz BW
- Magnitude Stability: ±1 dB
- Phase Stability: ±15°
- Test Port Power: -35 dBm
- Test Port Input Limit (dBm, saturation/damage): -20/13
- Directivity: 30 dB
- Typical Dimensions: 8 x 5 x 3 inches



# Atmospheric Losses Affect Measurements

- Due to air in system waveguide after couplers.
- General accuracy issue!



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# Outline

- Introduction
- A variety of THz applications
- The base for THz instrumentation
  - Frequency multipliers
  - Mixers
  - waveguide
- THz instrumentation
  - Source Extenders
  - Spectrum Analyzer Extenders
  - Extenders for Vector Network Analyzers
- **Conclusions**

# Conclusions

- Increasing interest in THz frequencies for various reasons
- This requires instrumentation to develop the THz application equipment

- Some fundamentals from THz instrumentation are presented:
  - Use of multipliers and (harmonic) mixers
  - Use of Schottky diode technology
- An overview of VDI full band instrumentation is given:
  - Source extenders, SGX
  - Spectrum Analyzer extenders, SAX
  - Vector Network Analyzer Extenders, VNAX
- Source power and frequency continues to increase.
- Higher levels of integration are allowing the development of more compact systems.