Challenges and Techniques in Measurements of Noise, Cryogenic Noise and Power in Millimeter-wave and Submillimeter-wave Amplifiers

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Purpose of this Presentation

- We will present the topic of noise measurements, including cryogenic noise measurements, of MMIC and S-MMIC amplifiers, both on-wafer, and interfaced to waveguide modules via coupling probes.

- We will also present an overview of the state-of-the-art in waveguide probe techniques for packaging amplifier chips, and discuss methods to obtain the lowest loss packaging techniques available to date.

- Linearity in noise measurements will be discussed, and experimental methods for room temperature and cryogenic noise measurements will be presented.

- We will also present a discussion of power amplifier measurements for millimeter-wave and submillimeter-wave amplifiers, and the tools and hardware needed for this characterization.

Outline

- Tools for On-Wafer Measurements
- State of the Art in Waveguide Packaging of MMICs and S-MMICs.
- Noise Measurements, On-wafer
- Noise Measurements, in Waveguide Housing
- Cryogenic Noise Measurements, Packaged
- Cryogenic Noise Measurements, On-wafer
- Power Amplifier Measurements for MMIC and S-MMICs, On-wafer and in Package

Tools for On-Wafer Measurements

- On wafer Tools for MM-wave and Submm-wave Measurements
- Vendors for Wafer Probes
- Hardware: S-Parameters: VDI heads, OML heads
- Power Meters (VDI (formerly Erickson Calorimeter))

On-Wafer Probes

On-Wafer Probes

Several vendors exist for On-Wafer Probes:

GGB Industries, Dominion, Cascade Microtech

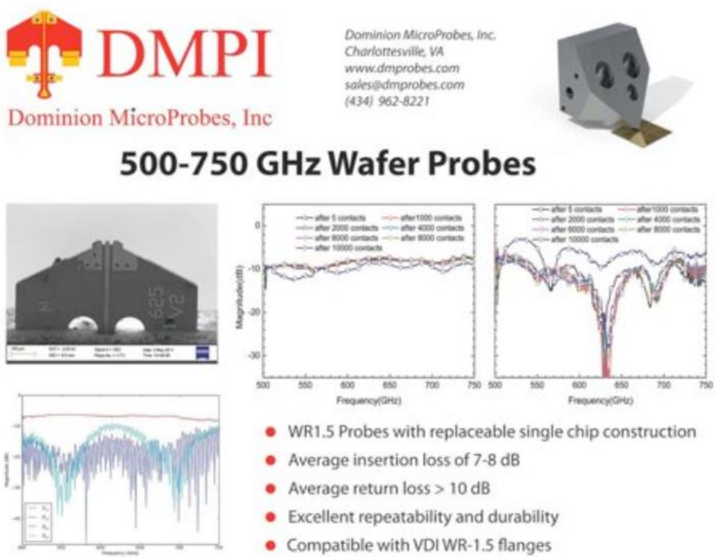
- Depending on Frequency, probes have real, substantial loss (3-6 dB per probe).
- For VNA measurements, this loss is calibrated out.
- For on-wafer noise and power measurements, one must remove the probe loss from the measurement to obtain the DUT parameters.

On-Wafer Probes

Dominion MicroProbes has a selection of waveguide band wafer probes up to 1100 GHz http://dmprobes.com/index.html

Dominion MicroProbes, Inc.

Our colleagues from the University of Virginia recently founded DMPI with the mission of supplying novel high-frequency wafer probes to the THz community. They have developed durable, single-chip, replaceable wafer probes for the WR1.5 (500-750GHz) waveguide band. DMPI's probes are compatible VDI components and are essential for facilitating THz on-wafer test and measurement. Please take a look at their information below and visit their website, http://dmprobes.com

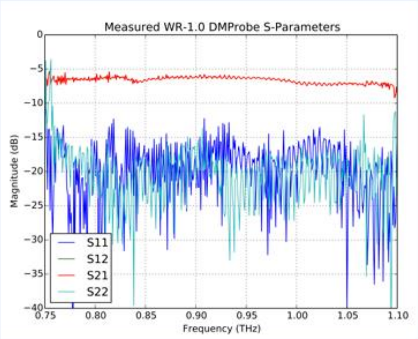


MP-1100 (750-1100GHz) WR1.0 Probe

Direct Connection Method

- **Only existing wafer probe at WR1.0**
- **Low insertion loss**
- **Probe *pitch* of 25 microns**
- **Integrated DC bias-T with low-profile GPPO connector**
- **Low *repair cost* and short repair time**
- **Unlike our competitors (unless the robust metal block itself has been damaged - an unusual event), the probe can be repaired repeatedly for years, with typical performance "as new"**
- **Unlike our competitors, no limit to the number of probe repairs, per month, per customer**
- **DMPI offers additional machined waveguide components to attach your DMPI probe to existing probe stations. TRL calibration substrate is include with each probe at no additional cost.**

Download MP-1100 Information Sheet



On-Wafer Probes

GGB Industries has a selection of On-wafer full waveguide band probes: ggb.com

Picoprobe®
BY GGB INDUSTRIES INC.

Model 500B High Performance Microwave Probes

Features

- Durable
- 325 GHz to 500 GHz
- Insertion loss 4 db typ.
- Return loss 15 db typ.
- Individually spring loaded contacts
- Bias T option available
- Coaxial design

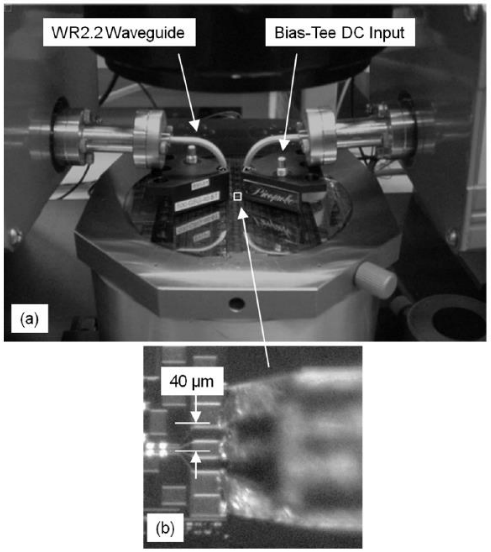


Fig. 1. (a) Photo of GGB Industries Inc. WR2.2 probes connected to OML Inc. WR2.2 frequency extenders. (b) Photograph of the Port 2 CPW probe tip focused at the plane of contact with a TMIC.

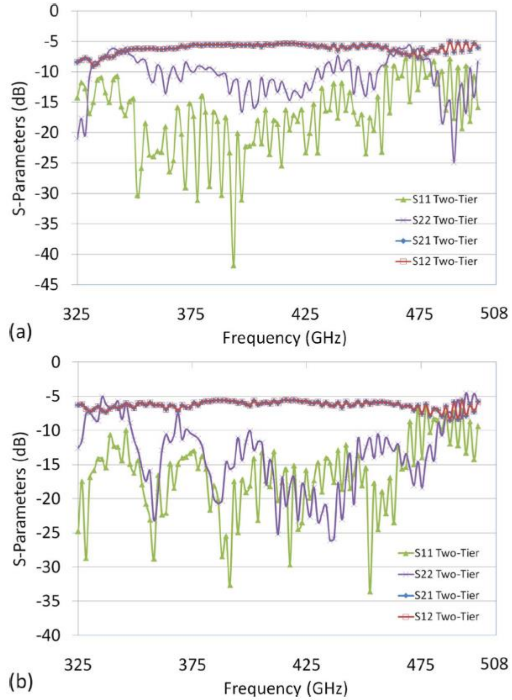


Fig. 2. Insertion and return loss data of two GGB WR2.2 probes deduced from a two-tier calibration and measurement. Port 1 is the waveguide flange. Port 2 is the CPW probe tip. (a) Probe 1 data. (b) Probe 2 data.

Reference: Fung et al, *IEEE TRANSACTIONS ON TERAHERTZ SCIENCE AND TECHNOLOGY*, VOL. 2, NO. 2, MARCH 2012

On-Wafer Probes

Cascade Microtech: Waveguide probes for up to 500 GHz

http://cascademicrotech.com/products/probes/rf-microwave/infinity-probe/waveguide-infinity-probe/waveguide-infinity-probe

Waveguide Infinity Probe

With the advent of Silicon CMOS and SiGe technologies, devices are getting smaller and faster. Test engineers need to validate the performance of their devices up to 500 GHz and beyond in some cases. This component/on-wafer probing solution is designed to meet the challenges of high-frequency probing for advanced on-wafer modeling and characterization while providing low, stable contact resistance on 50 micron pads. At 500 GHz the toughest problem is electrical fields around the probe. The Waveguide Infinity Probe's new membrane GSG contact tip design reduces stray EM fields near probe tip. Control of EM fields near the tip allows repeatable measurements up to 500 GHz and improved crosstalk performance between the tips.Benefits include:

- Probe loss is 3 dB typical between 140 and 200 GHz, S11/S22 15 dB typical
- Reduced unwanted couplings and transmission modes
- Able to shrink pad geometries to 25 x 35 µm (best case)
- Typical contact resistance < 0.05 Ω on Al, < 0.02 Ω on Au
- A solution that expands to 500 GHz and beyond

Ref. R. Campbell, Membrane Tip Probes for On-Wafer Measurements in the 220 to 325 GHz Band, *Int. Symp. Space THz Tech*, 2008.

VNAs for Submillimeter-THz

Vector Network Analyzers

Virginia Diodes

http://vadiodes.com/index.php/products/vector-network-analyzer

These work with Conventional VNAs (Agilent, Rohde & Schwarz, e.g.) to extend the frequency beyond 50 GHz up to 1.1 THz

VDI Vector Network Analyzer (VNA) Extenders - Summary of Specifications

Waveguide Band (GHz)	WR15 50-75	WR12 60-90	WR10 75-110	WR8.0 90-140	WR6.5 110-170	WR5.1 140-220	WR4.3 170-260	WR3.4 220-330	WR2.8 260-400	WR2.2 325-500	WR1.5 500-750	WR1.0 750-1100
Dynamic Range (BW=10Hz,dB,typ)	120	120	120	120	120	120	115	115	100	100	100	60
Dynamic Range (BW=10Hz,dB,min)	100	100	100	100	100	100	100	100	80	80	80	40
Magnitude Stability (±dB)	0.15	0.15	0.15	0.15	0.25	0.25	0.3	0.3	0.5	0.5	0.8	1
Phase Stability (±deg)	2	2	2	2	4	4	6	6	8	8	10	15
Test Port Power (dBm, standard/high power)	6/13	6/10	6/10	0	0	-6	-6	-9	-16	-17	-25	-35
Test Port Input Limit (dBm, saturation/damage)	16/20	16/20	16/20	16/20	9/20	9/20	-3/13	-4/13	-10/13	-10/13	-19/13	-20/13
Directivity (dB)	30	30	30	30	30	30	30	30	30	30	30	30
Typ. Dimensions (LxWxH, in.)	11x5x3	11x5x3	11x5x3	11x5x3	11x5x3	11x5x3	11x5x3	11x5x3	11x5x3	11x5x3	11x5x3	8x5x3
External Drawings	VNAX Rx VNAX TxRx VNAX TxRx Internal Attenuator											

Vector Network Analyzers

OML Inc. (Formerly Oleson Microwave Labs)

http://omlinc.com/

These work with Conventional VNAs to extend the frequency beyond 50 GHz up to 500 GHz. Calibration kits available.

Available Products By Waveguide Band (GHz)	VNA Extension Module	VNA Calibration Kit	Signal Generator Extension Module	Spectrum Analyzer Extension Module	Specialty Products	
					Scalar Network Analyzer	Converter
Download Brochure	VxxVNA2	VxxCAL	SxxMS	MxxHWD	RxxRFT	CxxLNC
WR-15 (50-75)	V15VNA2	V15CAL	S15MS	M15HWD	R15RFT	Contact Factory
WR-12 (60-90)	V12VNA2	V12CAL	S12MS	M12HWD	R12RFT	
WR-10 (75-110)	V10VNA2	V10CAL	S10MS	M10HWD	R10RFT	
WR-08 (90-140)	V08VNA2	V08CAL	S08MS	M08HWD	Contact Factory	
WR-06 (110-170)	V06VNA2	V06CAL	S06MS	M06HWD		
WR-05 (140-220)	V05VNA2	V05CAL	S05MS	M05HWD		
WR-03 (220-325)	V03VNA2	V03CAL	S03MS	M03HWD		
WR-02.2 (325-500)	V02.2VNA2	V02.2CAL	S02.2MS	Contact Factory		
> 500	Contact Factory With Your Custom Needs					

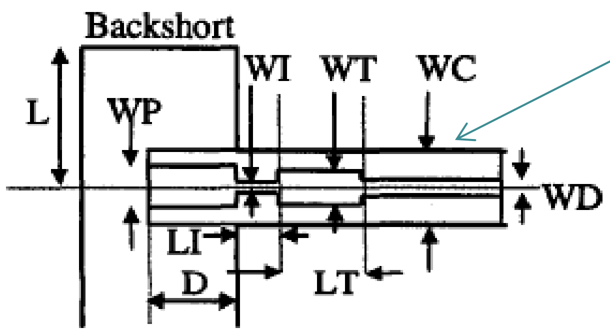
V02.2VNA2 Series
WR02.2 Frequency Extension Modules
325 to 500 GHz

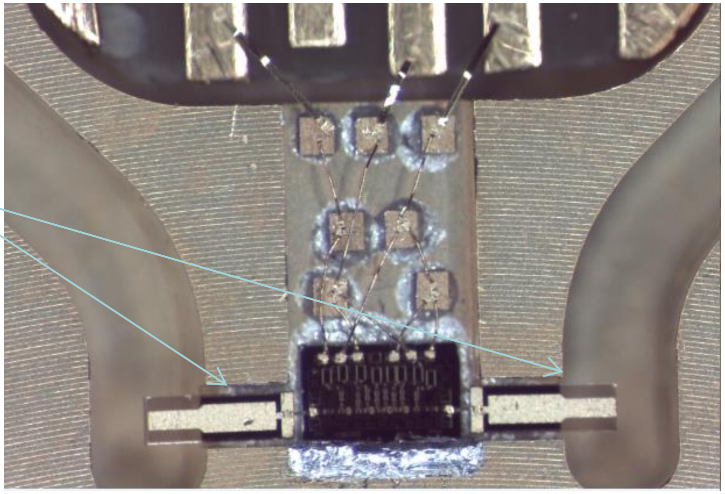
Waveguide Packaging Techniques

Waveguide Packaging

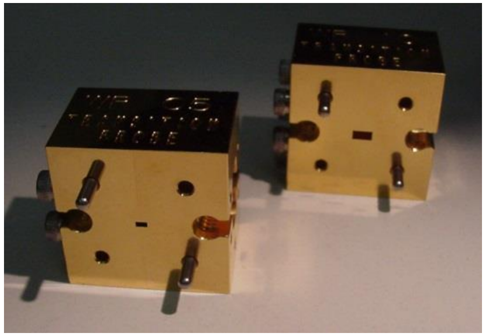
Why? To couple radiation from a waveguide into a MMIC Chip

Common Configuration: E-plane Probe





Y. C. Leong and S. Weinreb, "Full Band Waveguide-to-Microstrip Probe Transitions," *IEEE MTT-S Int. Microwave Symp. Dig.*, pp. 1435-1438, June, 1999.



Waveguide Packaging

Performance

- For WR10, loss of one probe is < 1 dB
- Full band matching is achievable.
- Thickness of probe is critical to obtaining wideband, high frequency waveguide-to-amp coupling

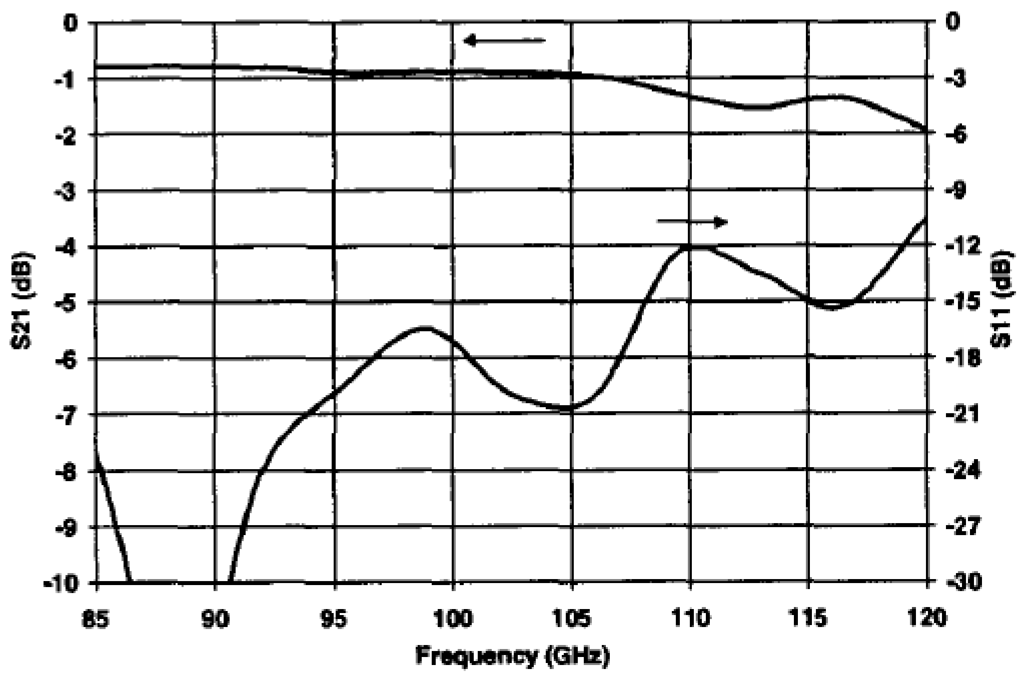


Fig. 4. Measured insertion and return loss for 2 Longitudinal alumina probes(back to back)

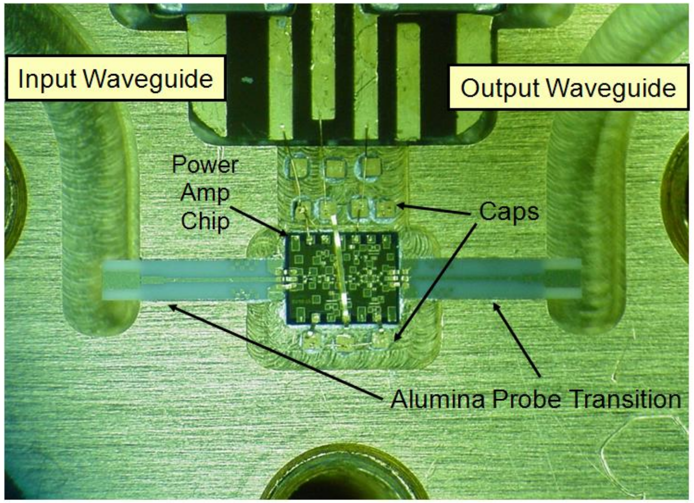
Waveguide Packaging

MMIC coupled to Waveguide probe with Wire Bonds

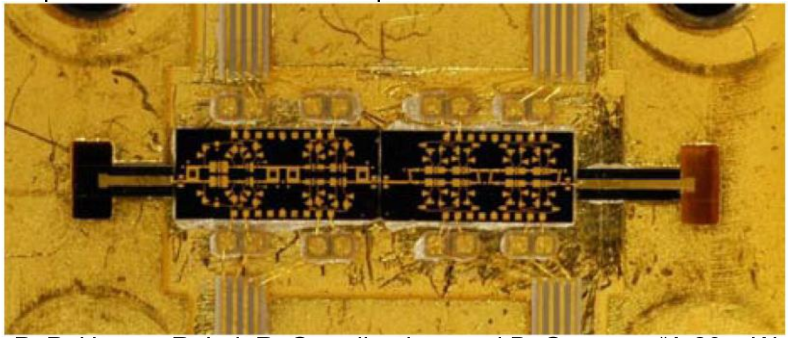
Wirebonds must be short at high frequencies or wirebond loss will dominate.
Ribbon bonds are useful, and wire or ribbon has been used successfully up to ~300 GHz.

Advantages: Inexpensive process (rectangular MMIC chip), probe can be made of other material with lower loss, probe can be smaller width to reduce higher order modes from propagating.

Disadvantages: Wire bond loss and associated inductance will start to break down the performance above 300 GHz.



L. Samoska, S. Weinreb, A. Peralta, "A Waveguide Power Amplifier Module for 80-150 GHz," NASA Tech Briefs, May 2006. http://www.techbriefs.com/component/content/article/1536

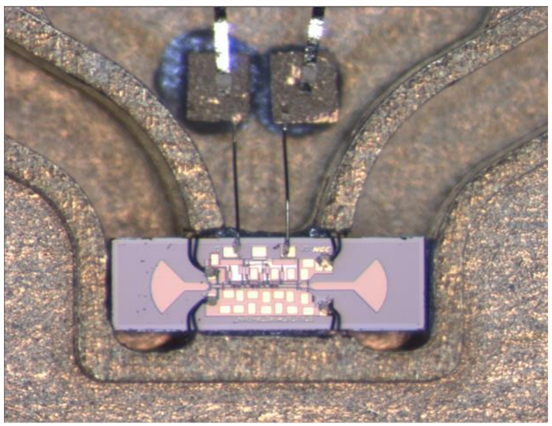


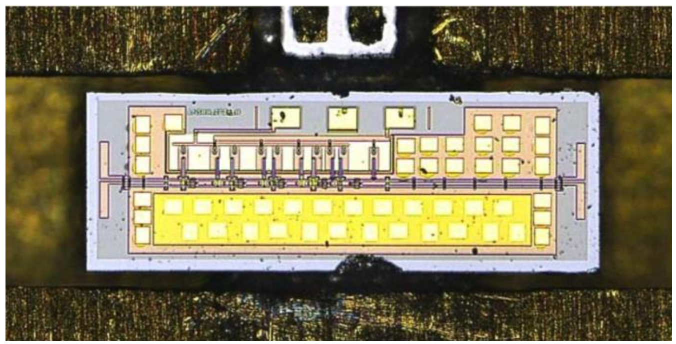
P. P. Huang, R. Lai, R. Grundbacher, and B. Gorospe, "A 20 mW G-Band Monolithic Driver Amplifier using 0.07mm InP HEMT," *IEEE MTT-S Int. Microwave Symp. Dig.,* June, 2006, pp. 806–809.

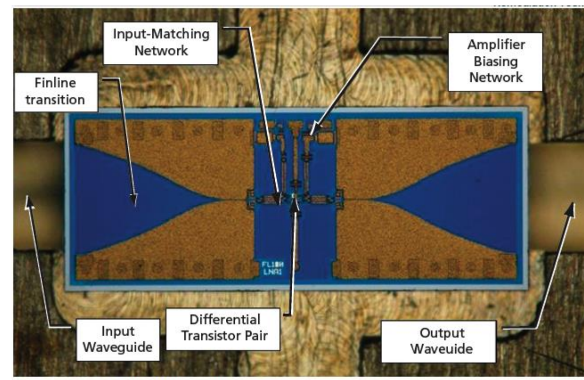
Waveguide Packaging

DUT coupled to Waveguide probe with Integrated Probe transition

a. Rectangular Chip







A Differential Amplifier MMIC is embedded in a waveguide package.

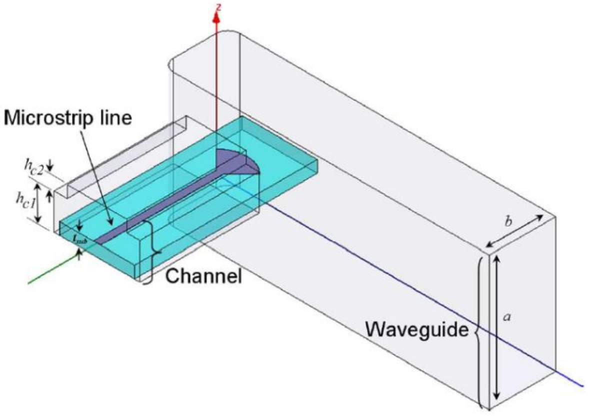
Refs:

- L. Samoska, W. R. Deal, G. Chattopadhyay, D. Pukala, A. Fung, T. Gaier, M. Soria, V. Radisic, X. Mei, and R. Lai, “A Submillimeter-Wave HEMT Amplifier Module with Integrated Waveguide Transitions Operating Above 300 GHz,” *IEEE Trans. Microw. Theory Tech.*, Vol.56, Issue 6, June 2008, pp. 1380-1388.
- K. Leong, W. R. Deal, V. Radisic, X. B. Mei, J. Uyeda, L. Samoska, A. Fung, T. Gaier, R. Lai, "A 340 GHz integrated CBCPW- to-waveguide transition for sub millimeter-wave MMIC packaging," *IEEE Microwave and Wireless Compo Lett.*, vol. 19, no. 6, June 2009, pp. 413-415.
- W.R. Deal, X.B. Mei, V. Radisic, K. Leong, S. Sarkozy, B. Gorospe, J. Lee, P.H. Liu, W. Yoshida, J. Zhou, M. Lange, J. Uyeda, R. Lai , “Demonstration of a 0.48 THz Amplifier Module Using InP HEMT Transistors,” *IEEE Microw. Wireless Compon. Lett.,* Vol. 20, no. 5, May, 2010, pp. 289-291.
- P. Kangaslahti, E. Schlecht, and. L. Samoska, “Differential InP HEMT MMIC Amplifiers Embedded in Waveguides,” *NASA Tech Briefs*, Aug. 2009.

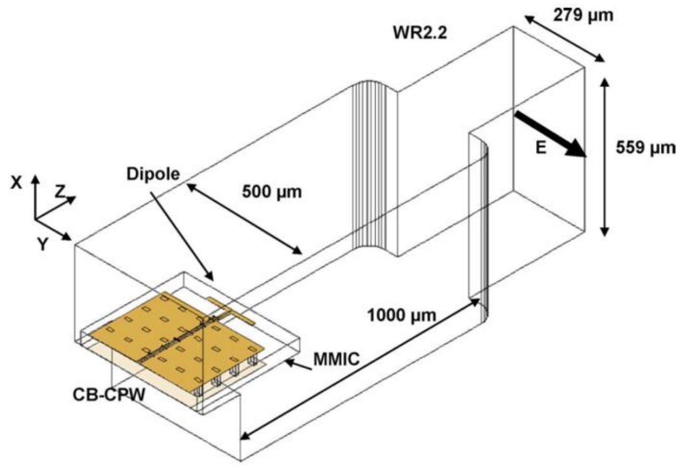
Waveguide Packaging

DUT coupled to Waveguide probe with Integrated Probe transition:

a. Rectangular Chip



E-Plane Transition

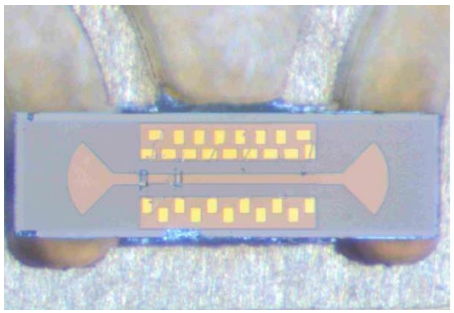


Dipole Transition

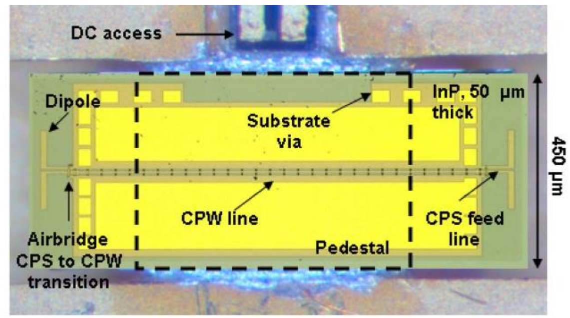
Waveguide Packaging

Performance of Integrated Probes

Back-to-Back Probes



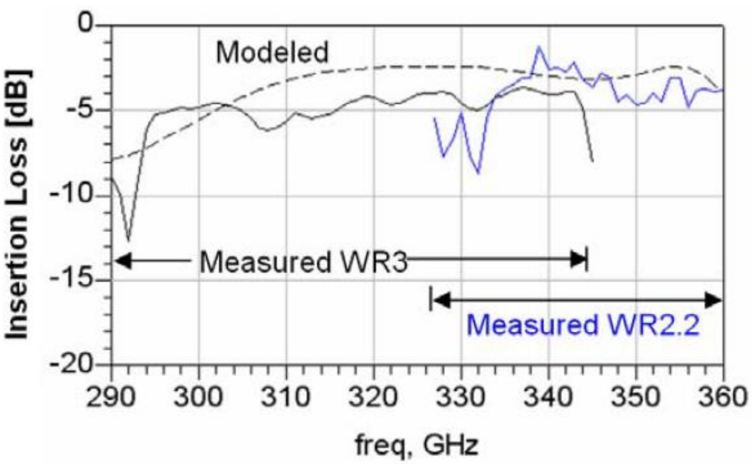
Back-to-Back Probes

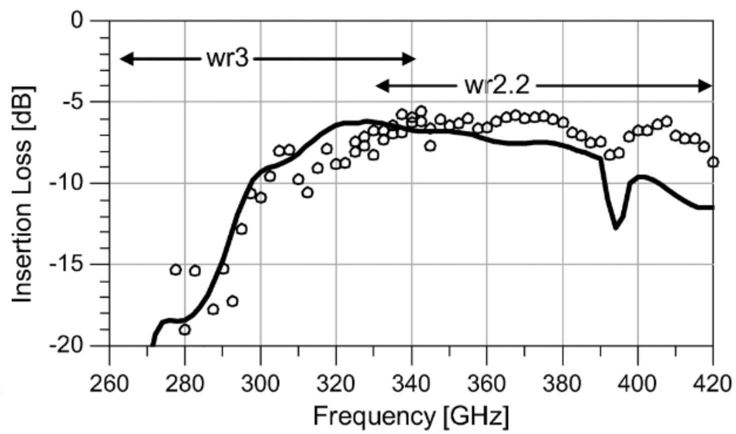


Insertion loss of 1-2 dB per probe is typical for ~300-700 GHz

*There is also wg loss which is separate from the probe loss.

Tunable depending on thickness





Waveguide Packaging

a. Integrated Probe, Rectangular Chip

Advantages:

- Chip and Probe can be integrated on single MMIC/S-MMIC.
- One unit, no assembly required.

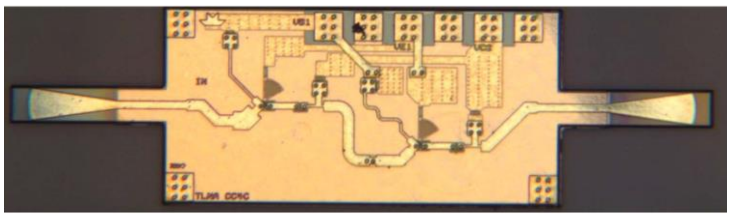
Disadvantages:

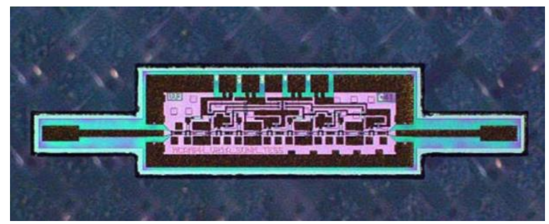
- Higher loss dielectric substrate must be used for the probe transition
- Chip width is restricted to width of the probe (which may limit bandwidth and complexity on-chip)

Waveguide Packaging

DUT coupled to Waveguide probe with Integrated Probe transition

b. Non-rectangular chip

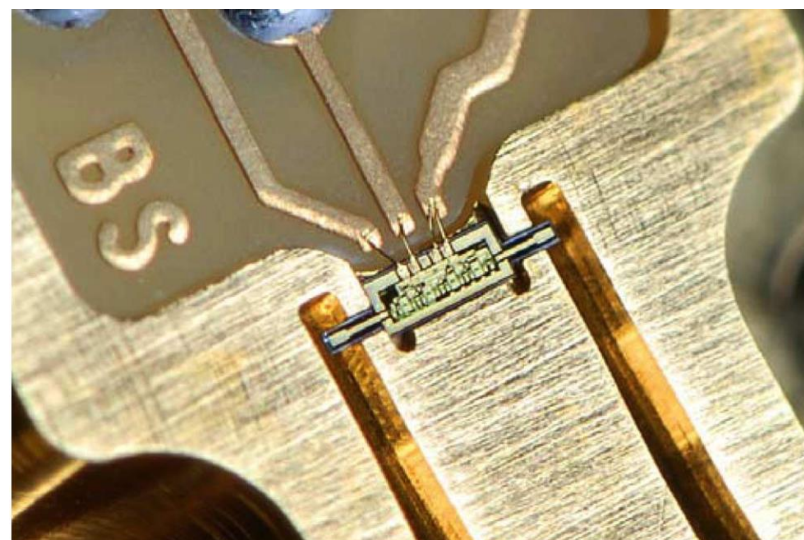




Refs:

- M. Urteaga, M. Seo, J. Hacker, Z. Griffith, A. Young, R. Pierson, P. Rowell, A. Skalare, M. J. W. Rodwell, "InP HBT Integrated Circuit Technology for Terahertz Frequencies," *IEEE CSICS,* Oct., 2010, pp. 1-4.

- Axel Tessmann, Arnulf Leuther, Volker Hurm, Ingmar Kallfass, Hermann Massler, Michael Kuri, Markus Riessle, Martin Zink, Rainer Loesch, Matthias Seelmann-Eggebert, Michael Schlechtweg, and Oliver Ambacher, "Metamorphic HEMT MMICs and Modules Operating Between 300 and 500 GHz," IEEE JOURNAL OF SOLID-STATE CIRCUITS, VOL. 46, NO. 10, OCTOBER 2011, pp. 2193-2202.



Waveguide Packaging

b. Integrated probe, Non rectangular chip

Advantages:

- **Probe width may be much smaller than MMIC/S-MMIC chip width, so bandwidth will not be limited.**
- **One chip (though delicate) with no assembly required.**

Disadvantages:

- **Probe material may still be the high dielectric lossy semiconductor substrate, so probe loss may still be high.**
- **May be expensive processing involved (Laser dicing, precise etching.)**

Noise Measurements

Noise Measurements

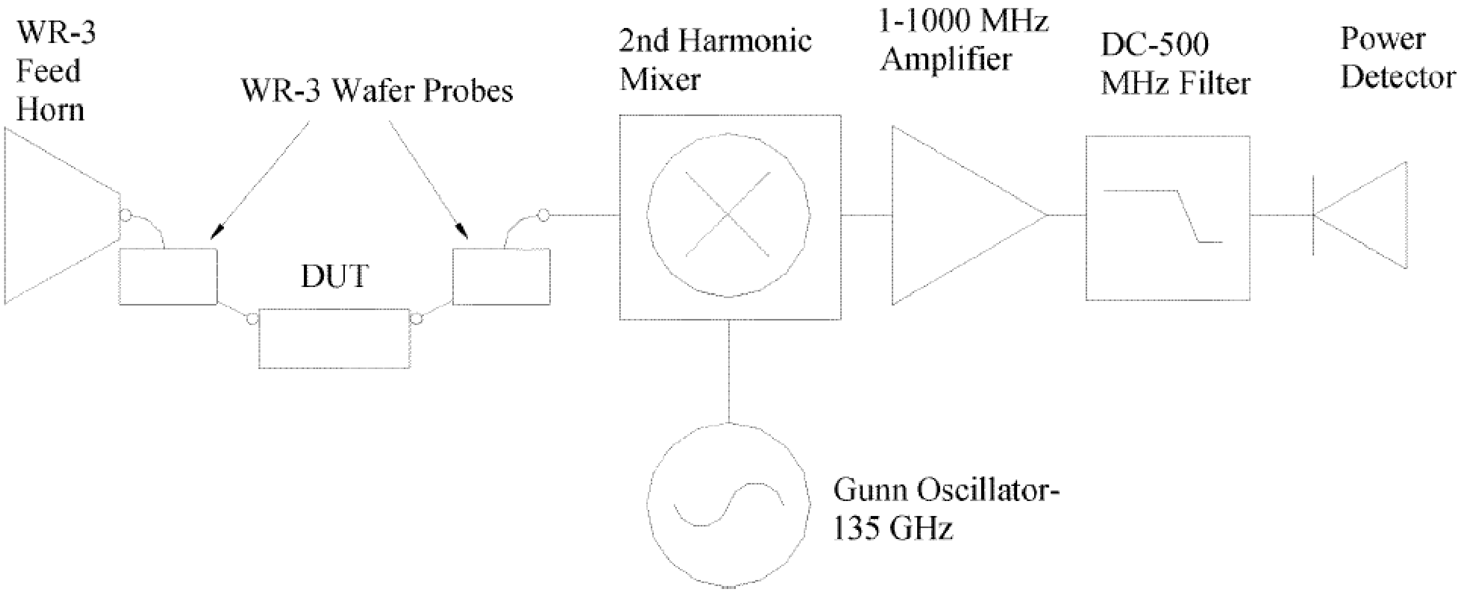
Principals: "Y Factor Method"

- Power available from a black body: $P=k_B T \Delta f$ *(One measures noise power)*
- The Y-factor is defined as

$$Y = \frac{P_H}{P_C} = \left(\frac{T_{\text{noise}} + T_H}{T_{\text{noise}} + T_c} \right)$$

- *Present DUT with known T_{hot} and T_{cold} thermal loads, measure noise power of DUT*
- *Solve for T_{noise} given known T_{hot} and T_{cold} thermal loads*
- *Frequently, T_{hot}= room temperature, T_{cold} = LN2 or 77K*
- *Other T_{load} temperatures are possible – in the lab on the bench, liquid nitrogen is a convenient "cold load."*

Noise Measurements, On-Wafer

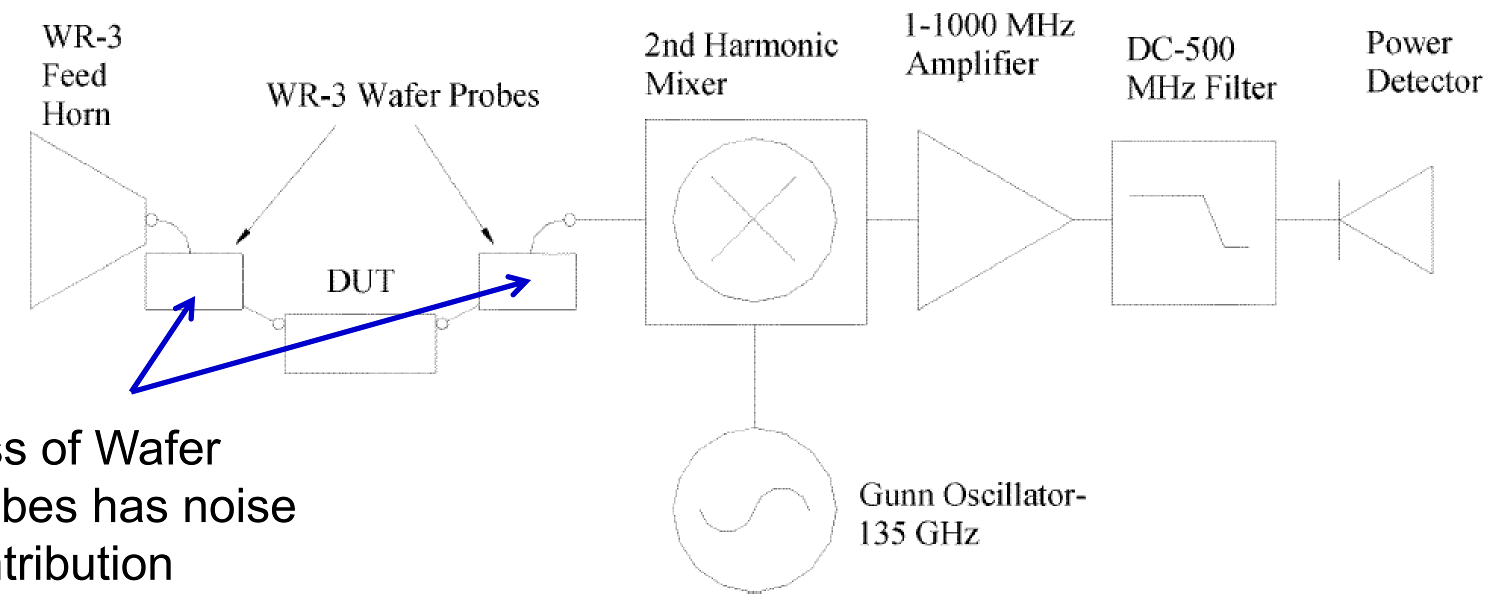


1. Build a Receiver.
2. Present different temperature loads to the receiver at the antenna.
3. Measure power under the different loads.
4. Calculate the Noise from the Y-factor.

Ref.: "Measurement of a 270 GHz Low Noise Amplifier with 7.5 dB Noise Figure," T. Gaier, L. Samoska, A. Fung, W.R. Deal, V. Radisic, X.B. Mei, W. Yoshida, P.H. Liu, J. Uyeda, M. Barsky, R. Lai, *in IEEE Microwave and Wireless Components Letters, Vol. 17, No. 7, July 2007, pp. 546-548.*

Noise Measurements, On-Wafer

Typical On-Wafer Noise Test Set for Submillimeter-wave



Loss of Wafer Probes has noise contribution

When measuring on-wafer noise of a DUT, noise contribution of the lossy wafer probes must be accounted for accurately. Most importantly, the input probe loss must be measured or inferred.

Noise Measurements, On-Wafer

How it looks on a probe station:

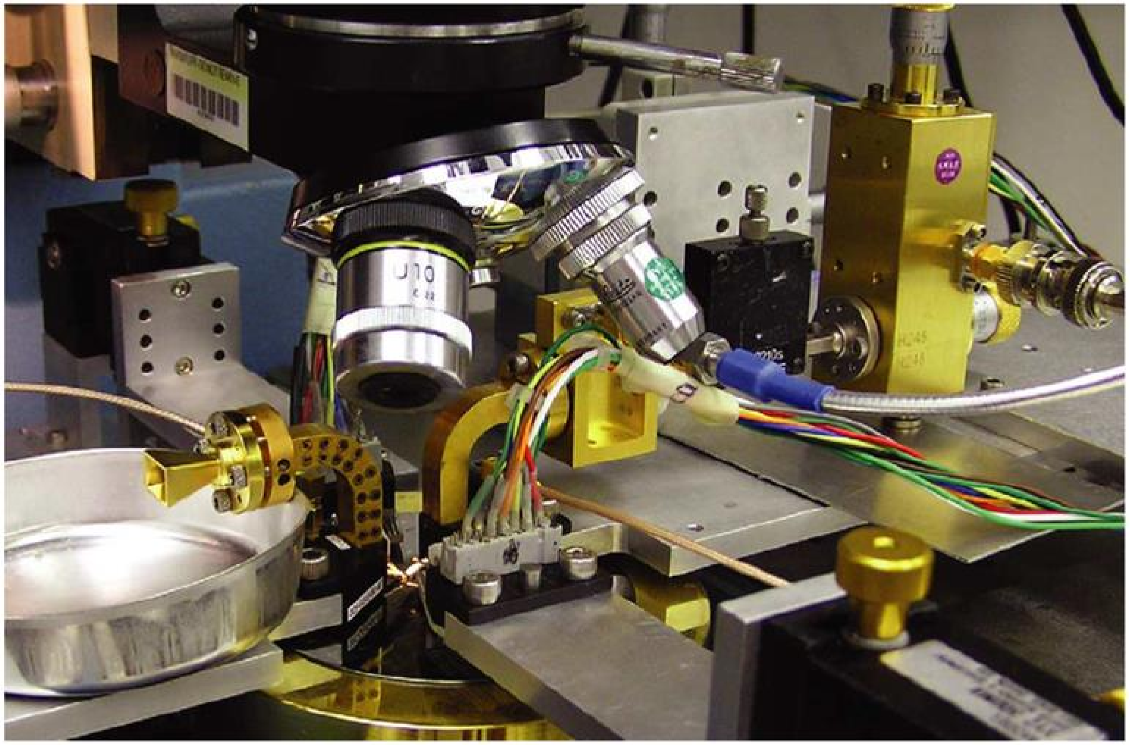


Fig. 2. Photograph of test set on probe station. At the left is the feed horn attached to the input probe contacting a wafer containing the DUT. The output probe visible left of center is connected to a mixer driven by the Gunn oscillator at right, through a variable attenuator.

Noise Measurements, On-Wafer

Another Noise Method: Chopped Amplifier as Noise Source

- Idea: An Amplifier when biased “ON” with no RF input signal generates noise.
- When Biased “OFF” it generates a different noise equivalent to the black body power of a room temperature load.
- If one can calibrate the noise temperature of the amplifier in the “ON” state, one can use the amplifier as a noise source to produce T_{hot} *and* T_{cold}.

Reference: T. Gaier, L. Samoska, C. Oleson, and G. Boll, “On-wafer testing of circuits through 220 GHz,” in *Proc. Ultrafast Opt. Electron. Conf.*, Snowmass, CO, Apr. 1999, vol. 28, pp. 20–26.

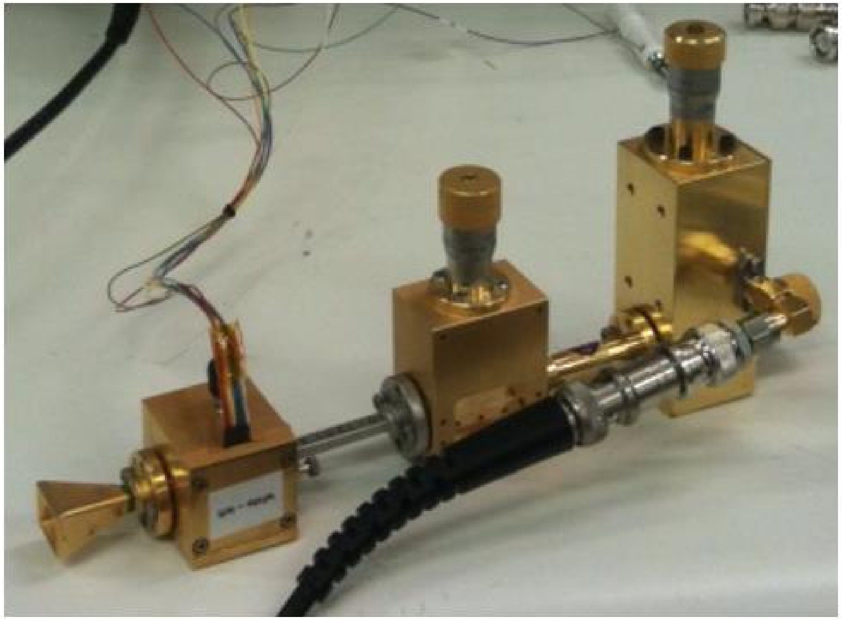
Noise Measurements of Packaged MMICs/S-MMICs

Noise Measurements - Packaged

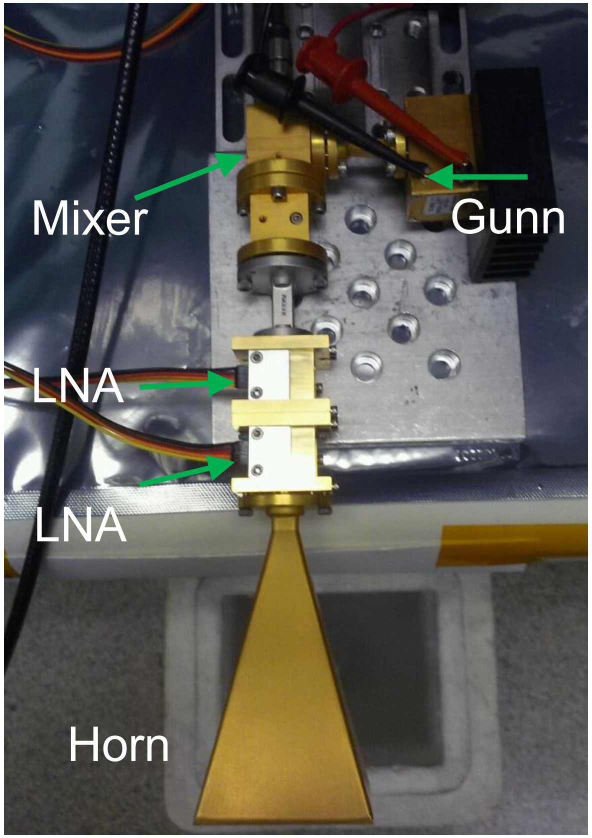
- Packaged LNA blocks (Waveguide) are convenient for noise measurements on the bench.
- Blocks can easily be cascaded to add gain and minimize backend noise contributions.
- Room temperature and LN2 (77K) loads are very convenient.
- Pitfalls: Cascading amplifiers with a lot of gain can amplify room temperature black-body noise power and cause compression in later amplifier stages.
- Compression (nonlinear response) can distort noise measurements.

Noise Measurements - Packaged

Example of Noise Measurements of LNA in a Waveguide



150 GHz MMIC receiver module, with local oscillator applied.



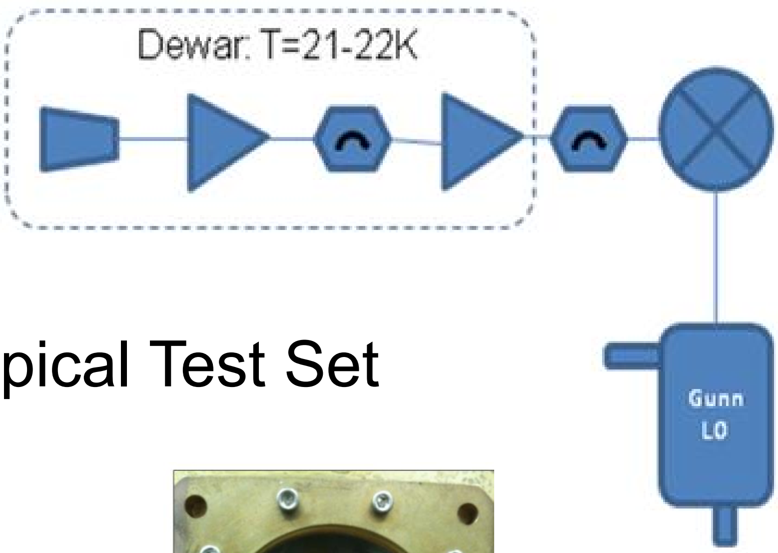
Cryogenic Noise Measurements

Why Cryogenically Cool LNAs?

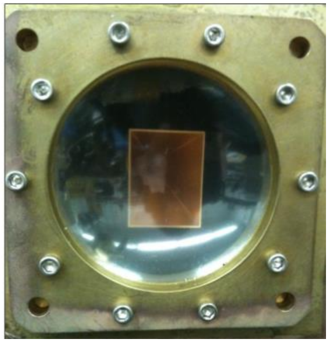
- HEMT-based amplifiers offer a distinct advantage in noise and gain properties when cooled (more so than HBT devices).
- Noise may decrease to one tenth of the room temperature noise when cooling a HEMT LNA from ~300K to 20-30K.
- Noise contribution of Waveguide Housing is also reduced when temperature is reduced.

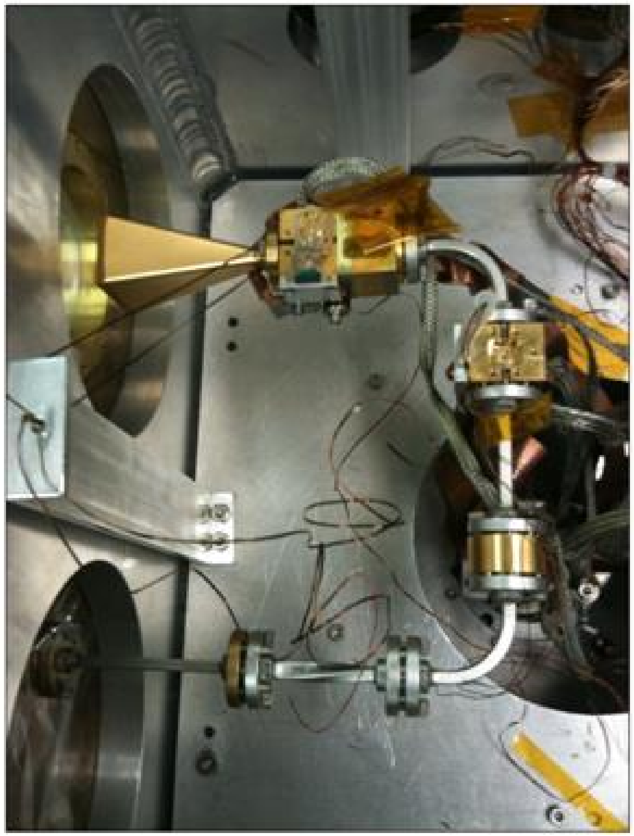
Cryogenic Noise Measurements

Cryogenic Noise of LNA Waveguide Modules



Typical Test Set

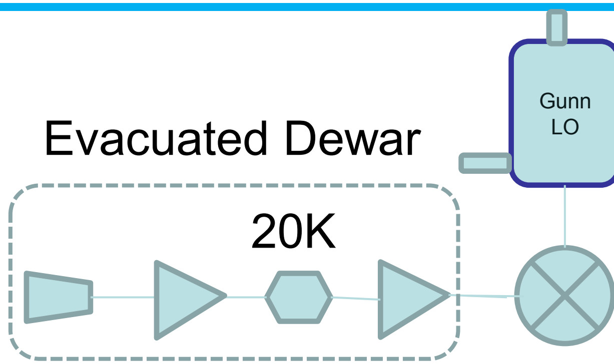


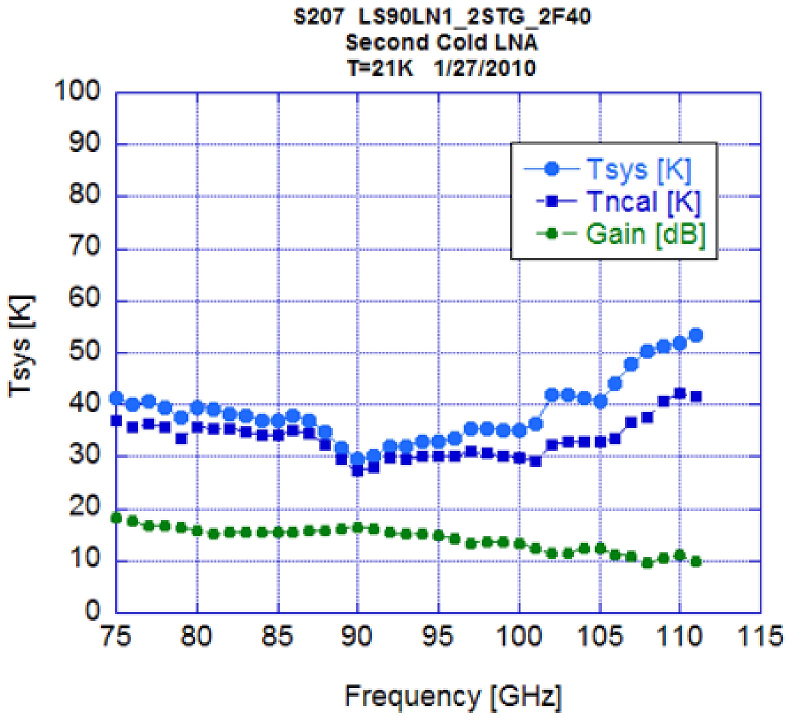


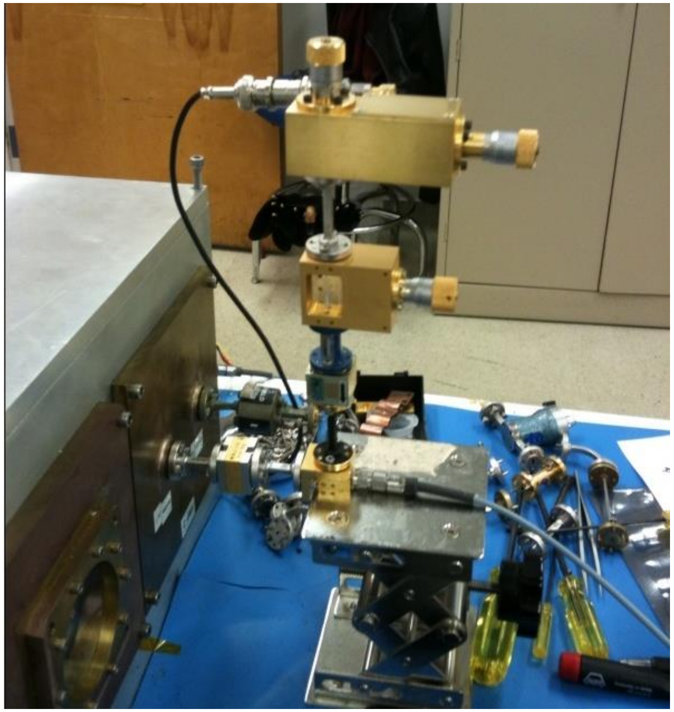
Cryogenic Noise Measurements

Details of Test Set

- Two Cold LNAs were inserted in the dewar with an isolator between them.
- WR10 horn and 1 mil mylar window used.
- Tamb=21.6K

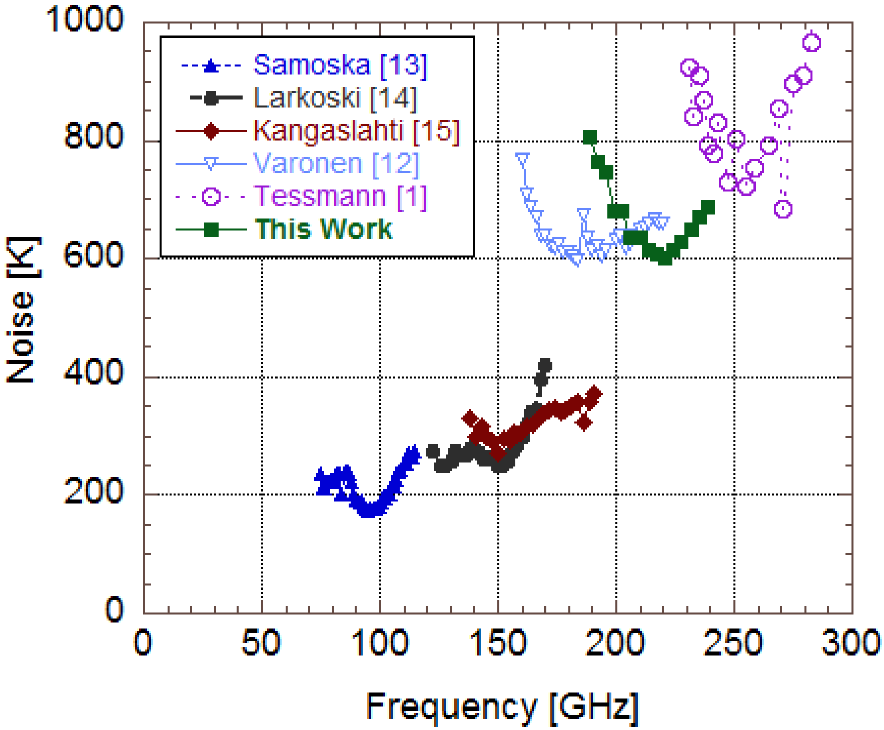




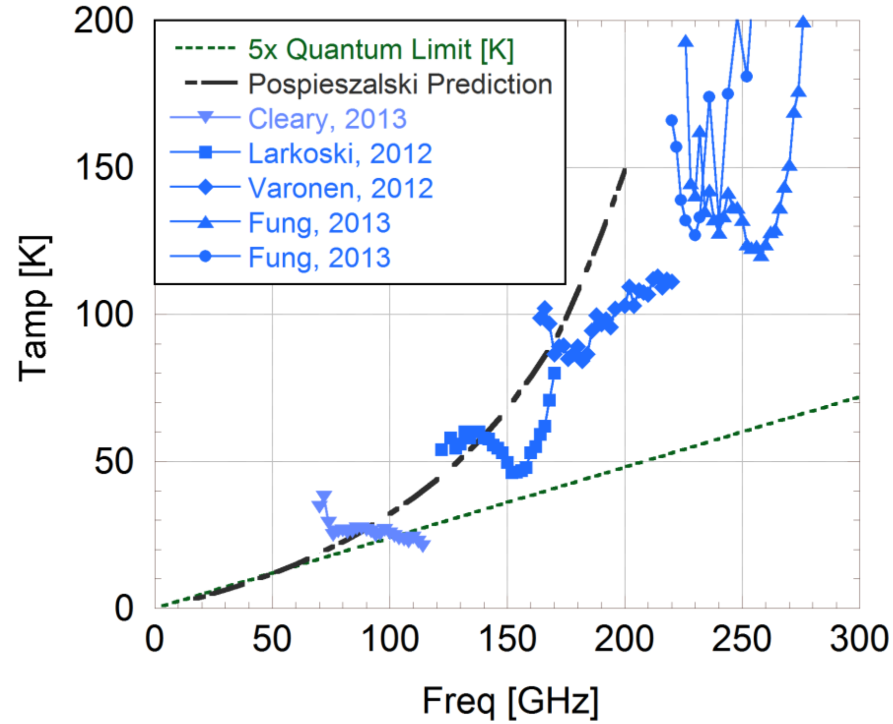


Cryogenic Noise Measurements

Cryogenic Noise of Packaged DUTs: Typical LNA noise is reduced up to a factor of 6-10 between room temperature and 20K.



Room Temperature (300K)



Cryogenic Temperature (20K)

Cryogenic Noise: On-Wafer

On-Wafer Cryogenic Noise

- **Very useful technique for screening LNAs.**
- **Particularly important in astrophysics, earth science where cryogens are easily obtained for ground-based instrumentation.**
- **Probe station designed with a cryogenic vacuum dewar and baffle to allow probe manipulation.**
- **Vacuum window for observing chip placement.**
- **Cryogenic load implemented by changing the temperature of a variable temperature load inside the dewar.**

Cryogenic Noise: On-Wafer

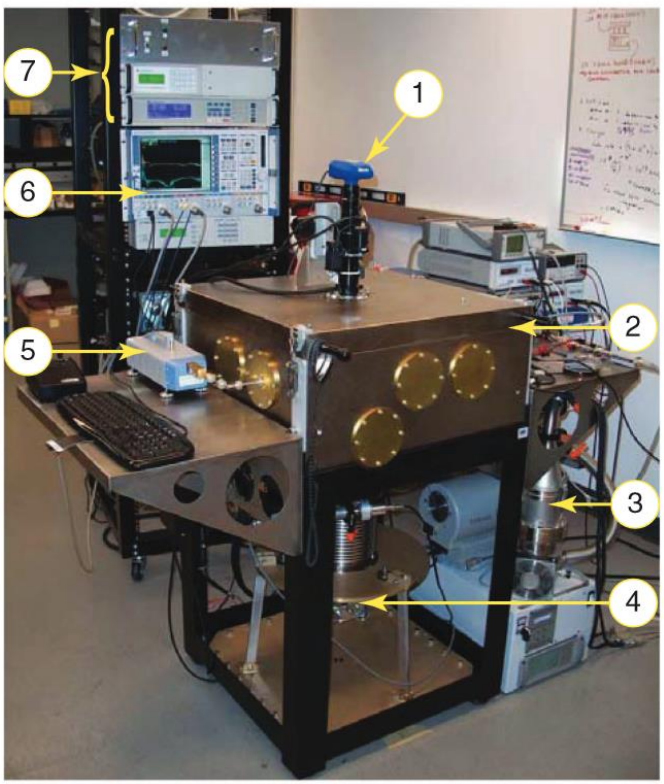
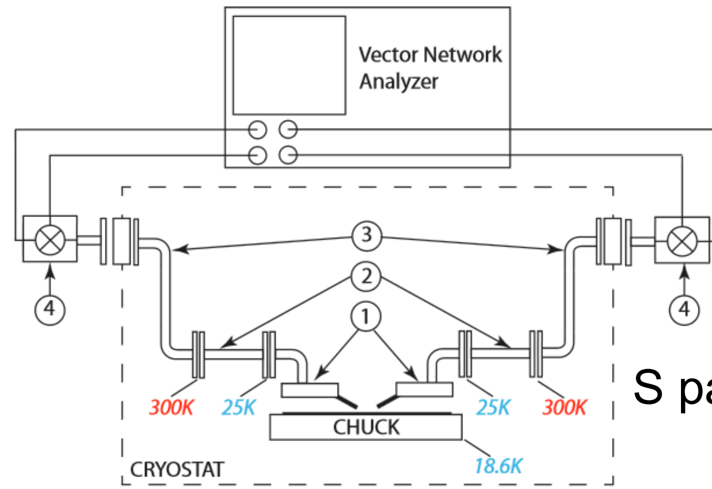
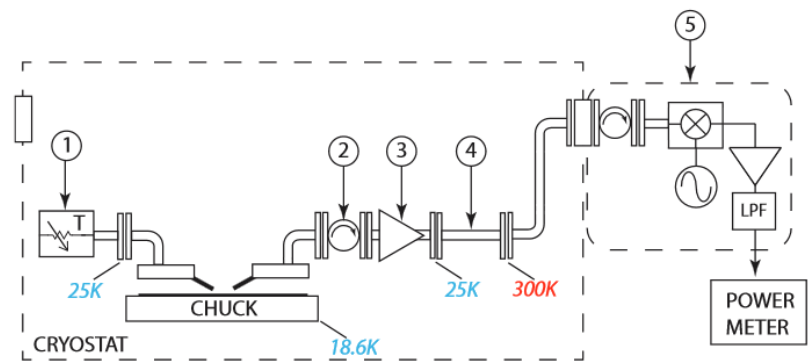


FIG. 1. Completed cryogenic probe station, located in the Cahill Center for Astronomy and Astrophysics at The California Institute of Technology. (1) Microscope and camera, (2) Cryostat, (3) Vacuum pump, (4) Cryocooler, (5) Millimeter wave head, (6) Vector network analyzer (VNA), and (7) Stepper motor, heater, and temperature sensor electronics.

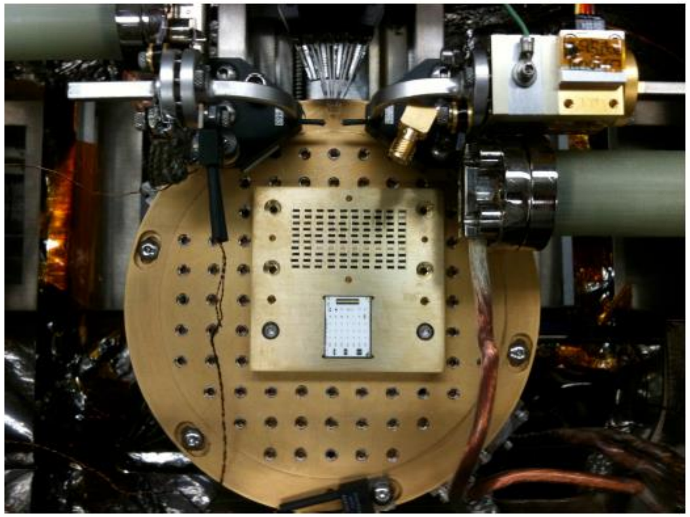


S parameters



Noise

From: Rev. Sci. Instruments 83, D. Russell, 2012



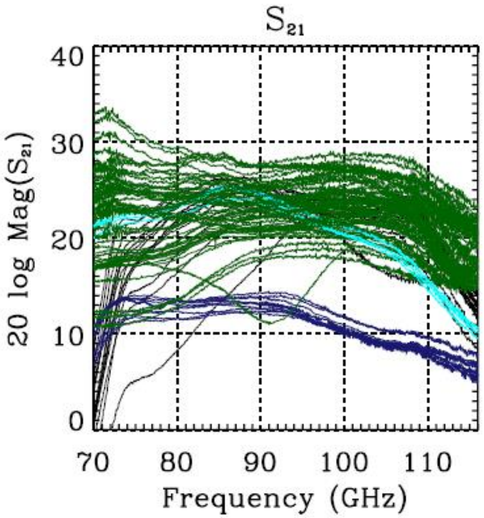


Fig 2. (left) Caltech cryogenic probe station interior, showing the RF and DC probes and the chip carrier with inset calibration substrate. (right) Cryogenic gain of 76 W-band amplifiers measured in 8 hours using the cryogenic probe station.

- How do you hold chips down in vacuum?
- How do you calibrate for noise measurements (drift, etc.)?
- Hundreds of chips can be probed relatively quickly for screening.

K. Cleary, American Astronomical Society Meeting, Jan., 2013.

Cryogenic Noise Measurements

Challenges:

- DUTs will change electronically when cooled.
- LNAs which are stable at room temperature can become unstable at 20K ambient.
- HEMT transistor parameters (Cgs, gm, etc.) change with cooling.
- This is an advantage in reducing noise, but there is always a balance with LNA stability.
- Characterization and modelling (at cryogenic temps) of the transistors used in the design is critical.
- Choice of load temperature is critical for maintaining linearity. With a 300K room temp load, a cooled LNA can become compressed.

Power Measurements

Power Meters for Submm: Tools

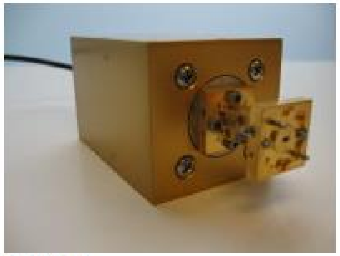
Erickson Calorimeter 75 GHz to > 2 THz

http://vadiodes.com/index.php/products/power-meters-erickson

Submillimeter Power Meter
Model PM4

- Extremely wide bandwidth
- Excellent input match
- High sensitivity
- RS232 interface

Readout



Sensor

The PM4 is a waveguide dry calorimeter designed to be a primary standard for power measurements throughout the mm-submillimeter range. It is constructed with a waveguide load having a 6 second thermal time constant, and an excellent RF match. A thermal feedback circuit makes the sensor much faster (~0.1 sec TC) for most measurements. A calibration heater resistor is mounted on the load at nearly the same location that most of the input power should be dissipated. Very efficient coupling to the load may be made using standard linear tapers to any smaller waveguide band, and the response is fairly insensitive to the mode content. Input loss is minimized through the use of a very short waveguide. The PM4 is similar to its predecessor the PM3, except that all signal processing is digital, and it includes a digital interface. It is much faster in response, and more accurate than earlier models, the PM1 and PM2.

Power Meters for Submm

Erickson Calorimeter

Settling time is important for power measurements. The lower the power, the longer time it takes to register the correct reading. Some typical settling times are noted below:

Typical performance

Scale (FS)	time for 90% response*	RMS noise
200 mW	0.1 s	~3 μW
20 mW	0.15 s	~0.3 μW
2 mW	1.3 s	0.1 μW
200 μW	15 s	0.01 μW

Power Meters for Submm

Non-Waveguide absolute power meters, e.g., Alphanov

http://www.alphanov.com/10-terahertz-imaging-terahertz-power-meter.html

TERAPOWER: ABSOLUTE POWER-METER FOR BROADBAND TERAHERTZ METROLOGY

Description | Technical Specifications | Mechanical drawings

The **TERAPower** is a broadband new auto-calibrated power-meter for the TeraHertz (THz) range. It offers a low-cost, versatile and easy-to-use device for TeraHertz metrology.

The **TERAPower** is implemented as an absolute THz flux-meter for a wide range of CW and pulsed commercial THz sources, offering high sensitivity, making use of the large detector area. It is perfectly suited for characterizing THz and sub-THz sources such as electronic diodes (Gunn, IMPATT, TUNNETT), backward-wave oscillator, quantum cascade lasers, molecular lasers and free electron laser.

Key Features:

- Absolute auto-calibrated power-meter
- Large detector area
- Broadband THz beam metrology
- Cost-efficient and easy-to-use

Key Applications:

- THz scientific metrology
- THz active imaging and tomography
- Non-destructive testing
- Volume inspection of opaque materials

TERAPower:

Absolute power-meter for broadband TeraHertz metrology

The *TERAPower* is a broadband new auto-calibrated power-meter for the TeraHertz (THz) range. It offers a low-cost, versatile and easy-to-use device for TeraHertz metrology.

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TeraPower detector head

Key Features:

- Absolute auto-calibrated power-meter
- Large detector area
- Broadband THz beam metrology
- Cost-efficient and easy-to-use

Key Applications:

- THz scientific metrology
- THz active imaging and tomography
- Non-destructive testing
- Volume inspection of opaque materials

Power Measurements, On-Wafer

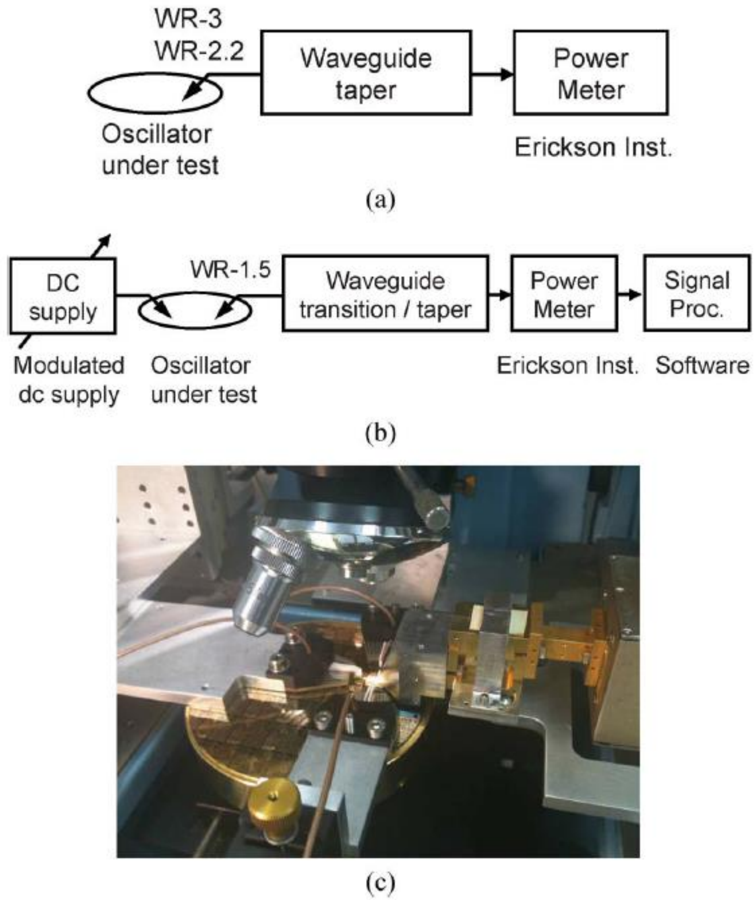

Fig. 15. Setup for oscillator power measurement. (a) WR-3 (220-325 GHz)/ WR-2.2 (325–500 GHz) band designs. (b) WR-1.5 band (500–750 GHz) oscillator. (c) Photograph of the WR-1.5 band (500–750 GHz) setup.

For low power measurements (~10 μW) settling time of power meters can be quite long (~ 10 sec). Power meter drift due to thermal conditions, etc., can make measurement inaccurate since the drift can be as large as the true input power.

One group (Seo, Skalare, Teledyne/JPL 2011) has devised a modulated test set.

DUTs are switched on/off, while power meter readout is averaged.
Averaging of ~100 cycles was found to give reasonable accuracy.

From: "InP HBT IC Technology for Terahertz Frequencies: Fundamental Oscillators Up to 0.57 THz." M. Seo, M. Urteaga, J. Hacker, A. Young, Z. Griffith, V. Jain, R. Pierson, P. Rowell, A. Skalare, A. Peralta, R. Lin, D. Pukala, and M. Rodwell, *IEEE J. Solid-State Circuits*, Vol. 46, Oct., 2011, 2203.

Packaged Power Measurements

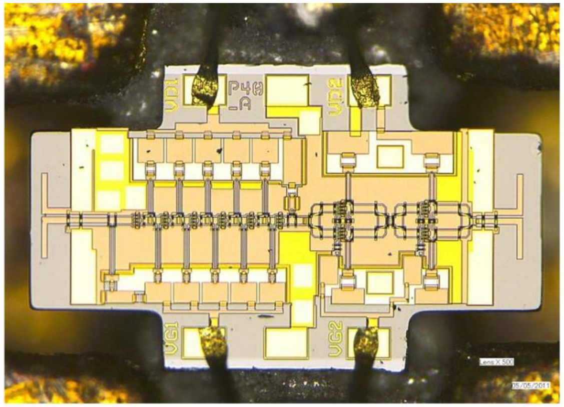

Fig. 3. Microphotograph of 643-GHz TMIC amplifier mounted in the module. Die size is 655 μm × 375 μm.

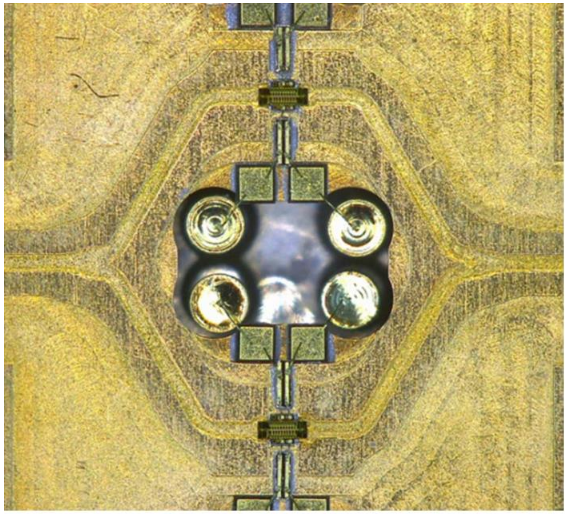

Fig. 6. Microphotograph of the dual TMIC module.

Using integrated waveguide probes described earlier, waveguide power-combining can produce unprecedented output power at near THz frequencies.

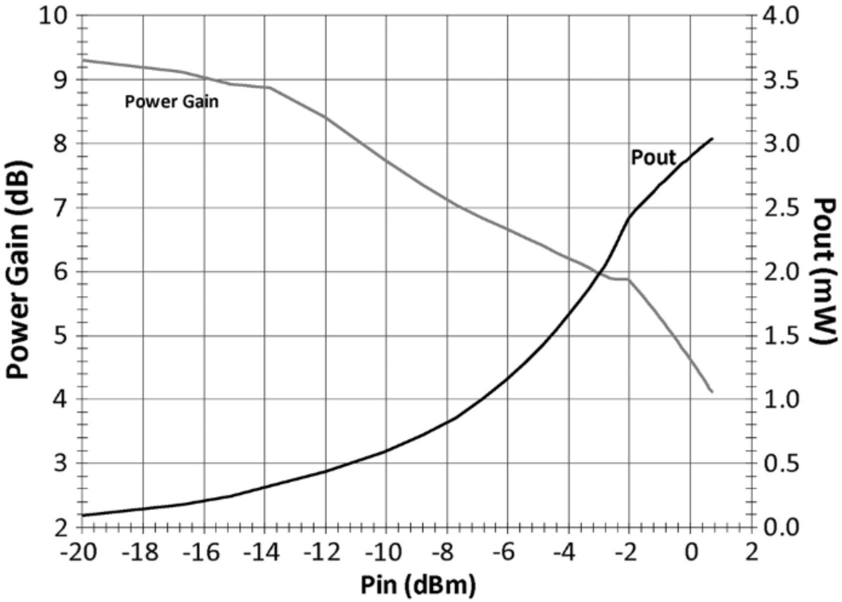

Fig. 13. Measured output power and power gain at 653.5 GHz of the dual module.

3 mW @ 653 GHz

From: "Power Amplification at 0.65THz Using InP HEMTs." V. Radisic, K. M. K. H. Leong, X. Mei, S. Sarkozy, W. Yoshida, W. R. Deal, *IEEE Trans*. MTT, Vol. 60, Mar., 2012, 724.

Summary

- We presented hardware, tools, and test sets for on-wafer and packaged MMIC/S-MMIC noise and power characterization
- Waveguide packaging/coupling to Amplifier Chips
- Noise measurements (room temp vs. cryogenic), on-wafer and in package.
- Power measurements (on-wafer and in package)

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- This work was performed in part at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.