Cryogenic Amplifier Based Receivers for Submillimeter-Wave Sounders

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ESTO: ACT-10

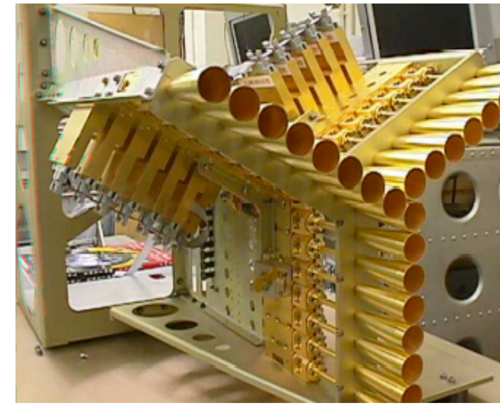
Objectives

- We developed a new ultra low noise dual-polarized and sideband separating radiometer front-end at submillimeter wavelengths using high electron mobility transistor (HEMT) amplifiers.
- The low-noise amplifier front-ends will be used in place of the SIS mixers currently proposed for the SMLS instrument on the GACM mission.
- The dual-channel SMLS will cover the 180-270 GHz and 620-660 GHz frequency bands. We'll design highly integrated amplifier based receivers with noise temperatures close to those of the existing SIS mixers, but at an operating temperature of 20 K rather than 4 K.
- This represents a major simplification in design; and mass, power, as well as risk reductions for SMLS.

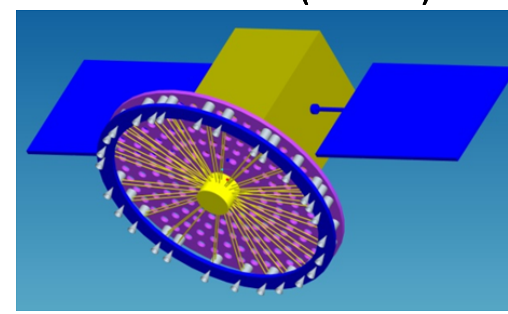
Applications: Earth Sciences

Terahertz Radiometers are used for Atmospheric Chemistry, Air Pollution, and Global Monitoring

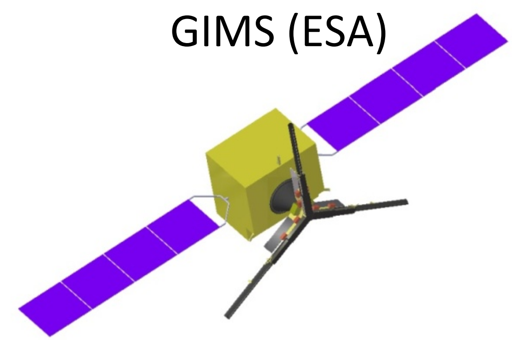
- Stratospheric and Tropospheric Chemistry
  - ozone layer modeling
  - economics vs. environment
  - water distribution/pollutants
- Clouds: Global Warming
  - ice crystal: size & distribution
- Aerosols, Volcanism, Dust

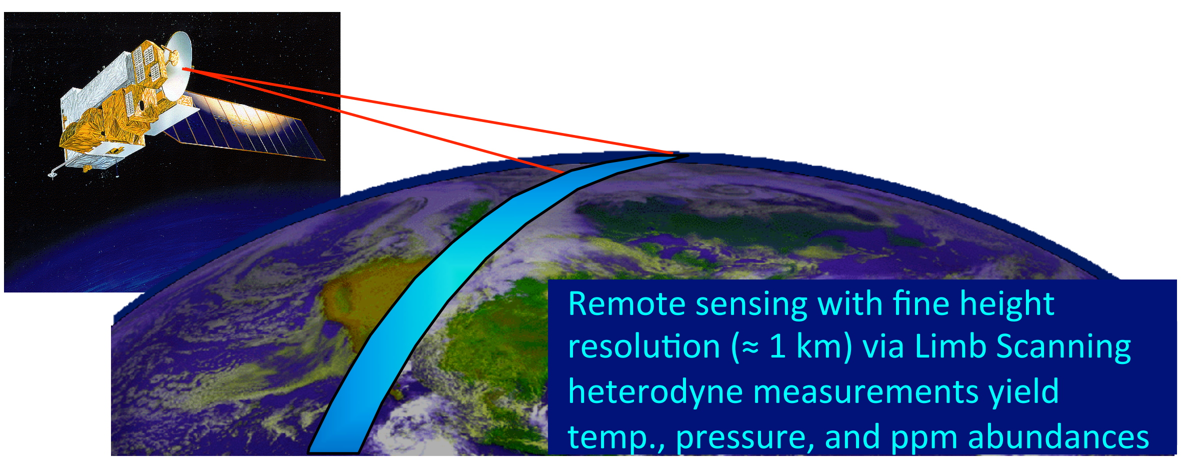


Geo-Star (NASA)



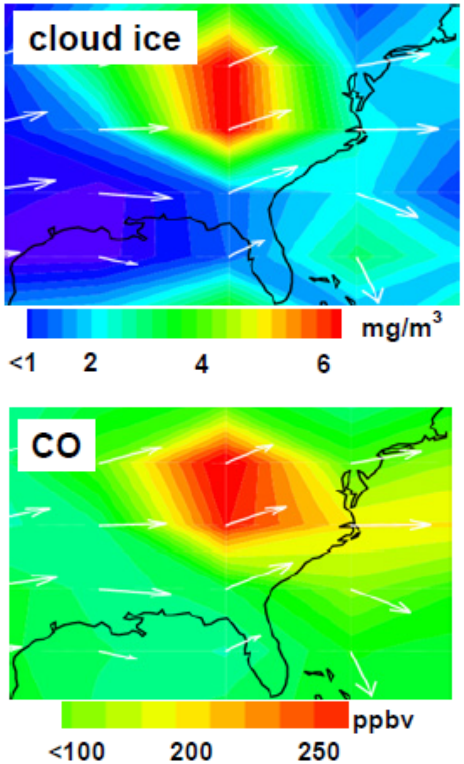
GIMS (ESA)





Applications: Earth Sciences

- Terahertz radiometer instruments provides the 3-D mapping and high temporal resolution capability.
- Broadband low noise receivers in space enables an unprecedented combination of sensitivity, resolution, and coverage to study Earth's atmosphere.
- What needed is a compact, low-mass, and low-power Earth observing instruments.
- They allow very short integration times for rapid detection of weak chemical species important to stratospheric composition studies.
- Broadband coverage enables simultaneous measurements of multiple chemicals in the troposphere and stratosphere.



Cloud ice and CO measurements at submillimeter wavelengths.

Applications: Astronomy

Astrophysics: High resolution heterodyne spectrometers

- **Star formation and key phases of galaxy evolution occur in regions enshrouded by dust that obscures them at infrared and optical wavelengths.**
- **The temperature range of the interstellar medium of ten to a few thousand Kelvin in these regions excites a wealth of submillimeter-wave spectral lines.**
- **With high-resolution spectroscopy, resolved line profiles reveal the dynamics of star formation, directly revealing details of turbulence, outflows, and core collapse.**

What astronomy at 400-700 GHz?

- $^3P_1$–$^3P_0$ fine-structure transition of neutral carbon, [CI], at **492 GHz** from a photon dominated region or a nearby galaxy.
- ^{12}CO *J=5-4*, **576 GHz** rotational transition line.
- ^{12}CO and ^{13}CO *J=6-5*, **691 GHz** line from nearby galaxy.

Why Amplifiers

Traditional submillimeter-wave heterodyne receivers for high resolution spectrometers use:

- Superconductor Insulator Superconductor (SIS) mixers
- Hot Electron Bolometer (HEB) mixers
- Schottky diode mixer

There were no amplifiers at the submillimeter-wave band

Amplifiers at submillimeter wavelengths:

- LNA with sufficient gain at the front-end, reduces noise contribution from mixers and IF amplifiers.
- Power amplifiers at these frequencies improves LO efficiency.
- High-level of integration of receiver front-ends – on a single chip or block.
- Leads to multi-pixel receiver designs.

Comparison of HEMT with SIS

RFE Technology	HEMT Amp		SIS Mixer	
Receiver Frequency	240 GHz	640 GHz	240 GHz	640 GHz
DSB Receiver Temperature	150 K (exp)	500 K (exp)	75 K	300 K
DSB System Temperature	280 K	650 K	205 K	450 K
Operating Temperature	20K		4K	
Cooler TRL	9		9	

Note: Although 4K cryo-cooler was flown by the Japanese team to the international space station, it failed after a couple of months of operation.

Cryogenic Amplifiers

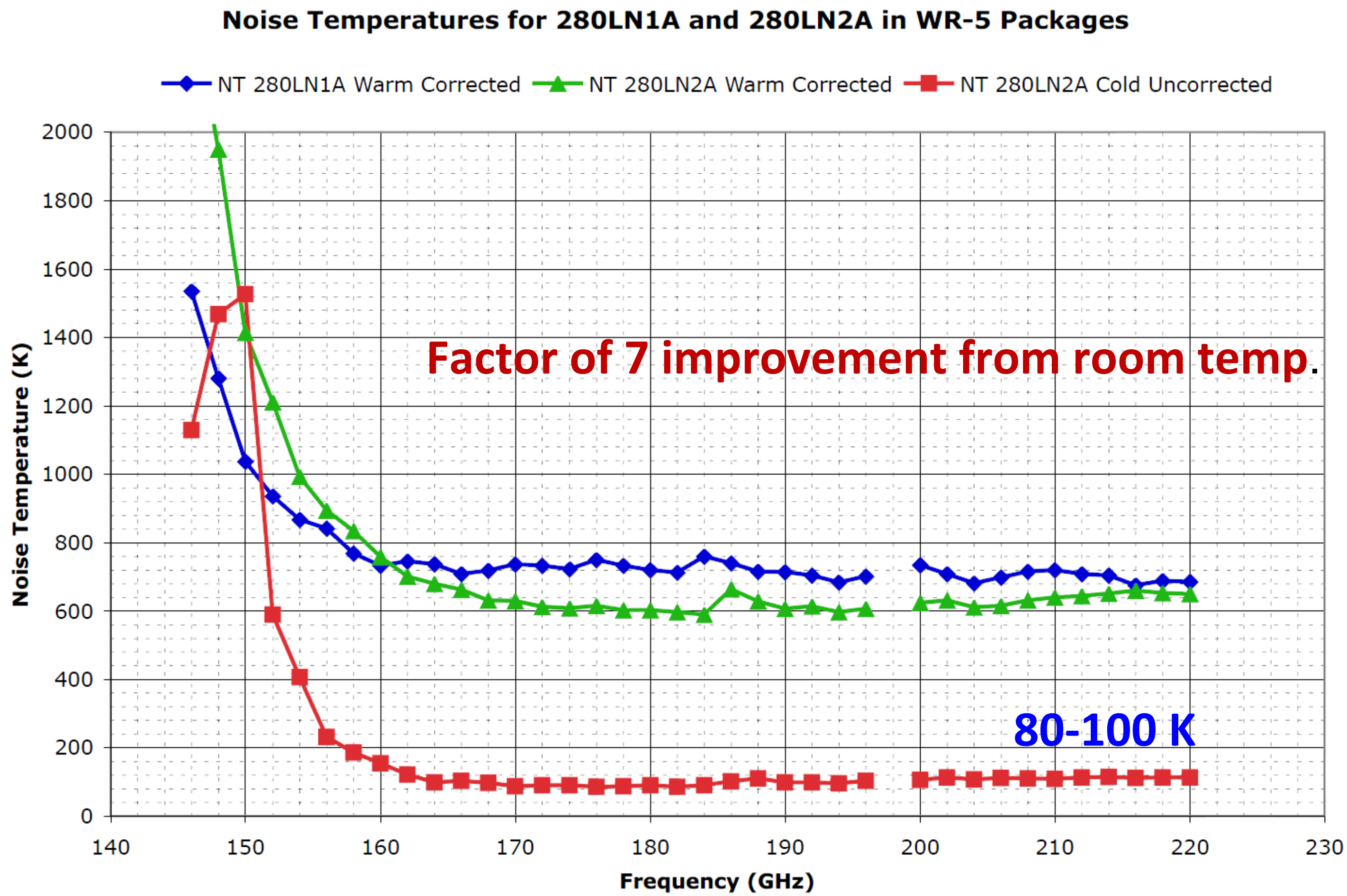
Amplifiers still cannot compete with SIS or HEB in noise performance!

Still, there are several advantages of using cooled amplifiers over SIS or HEB mixers:

- SIS and HEB mixers need 4K operations.
- Amplifiers perform well when cooled to **20K.**
- For space-based instruments, that is a big advantage – a significant reduction of risk and lower power requirement.
- If the temperature cannot reach 4K, SIS and HEB mixers will not work. Amplifiers will have graceful degradation of performance when temperature warms up.
- Multi-pixel operations with cryogenically cooled integrated amplifiers simplifies overall system design.

Cryogenic Amplifiers

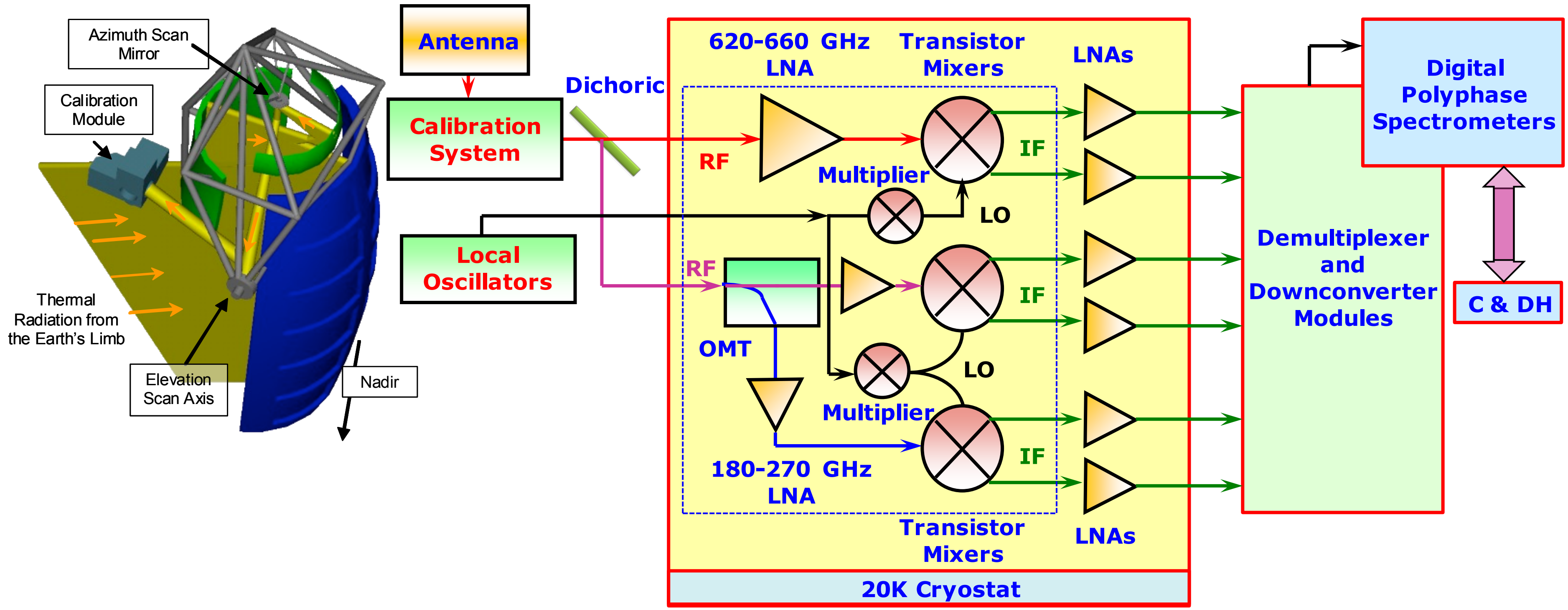
At lower frequencies, HEMT amplifiers cooled to 20K provide a significant improvement in noise over room temperature.



Data from R. Gawande et al., Caltech

Amplifier Based Earth Science Instrument

Schematic Block Diagram of Amplifier Based Receiver Front-End

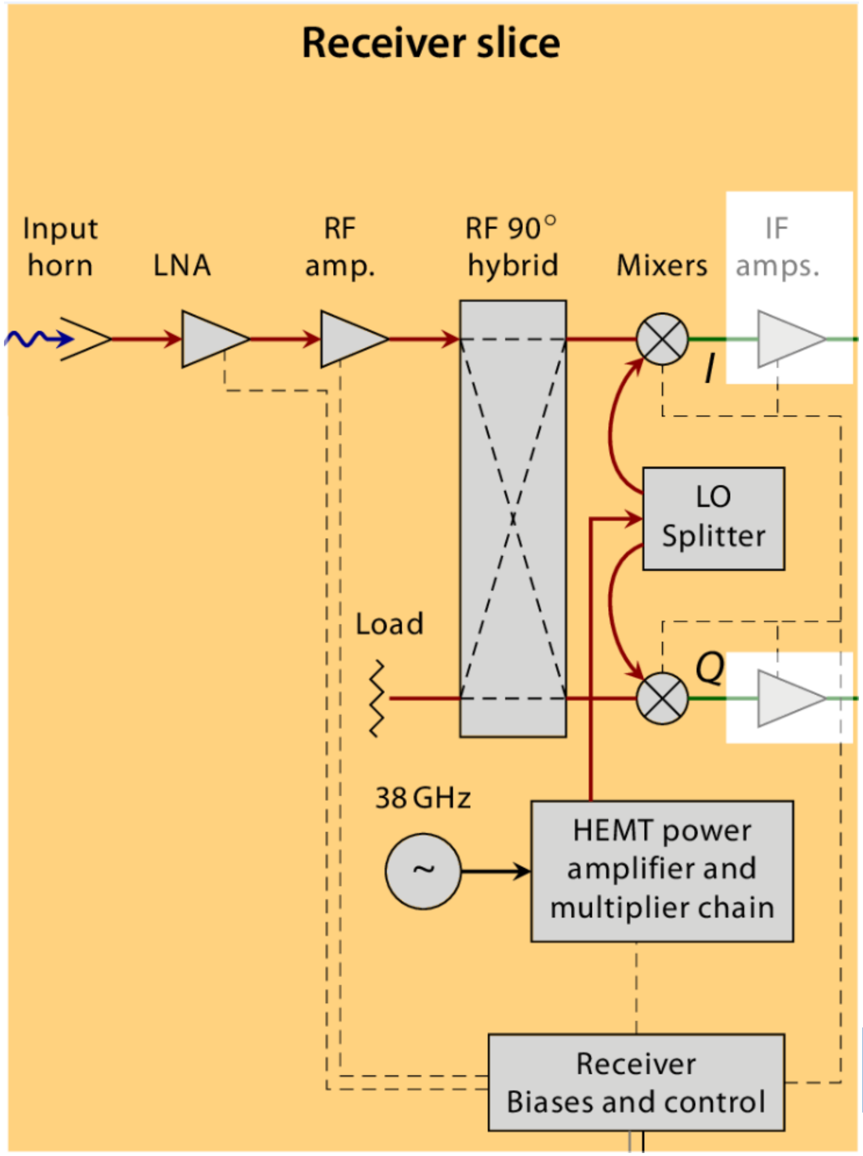


HEMT amplifier based receivers cooled to 20K down-convert the signals from the antenna for detection in the digital spectrometers.

ESTO: ACT-10 Program

Amplifier Based Earth Science Instrument

321-360 GHz
RF Input



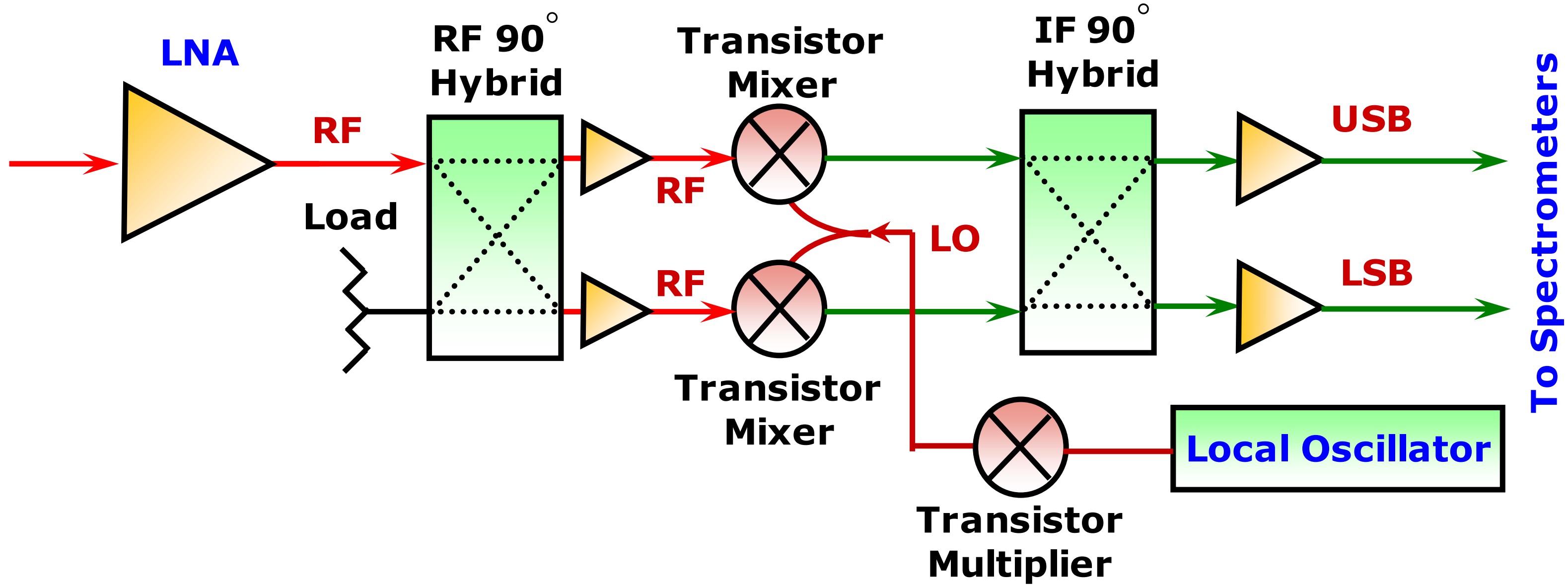
1-18 GHz
IF Output

1-18 GHz
IF Output

Broadband all HEMT amplifier based sideband separated receiver front-end.

ESTO: IIP-13 Program

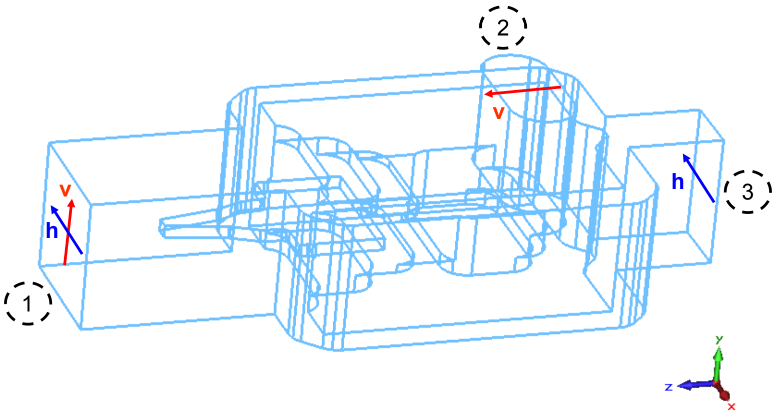
HEMT-Based Sideband Separating Receiver

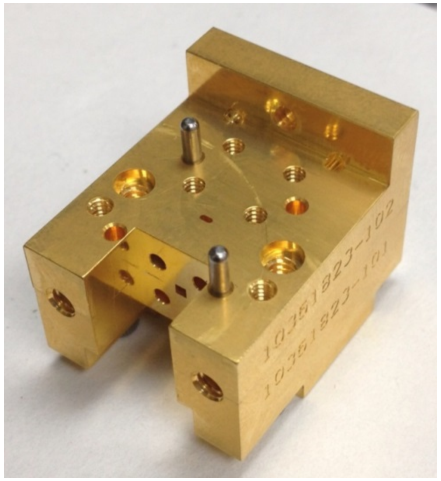


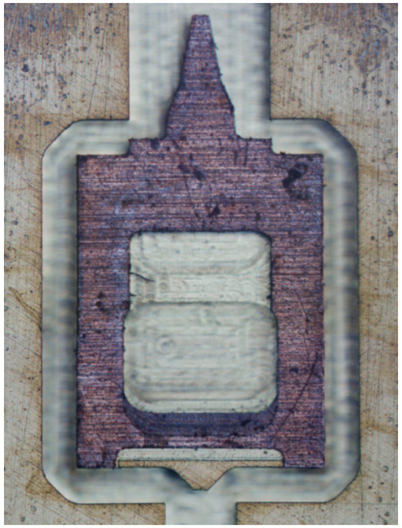
- The radio frequency (RF) signal is first amplified by a low-noise amplifier (can be cooled to 20K to improve signal to noise).
- RF hybrid circuit along with mixers separate the two sidebands.
- These are split in the back-end IF processing and spectrometer subsystems.

Dual Polarization and Ortho-Mode Transducer

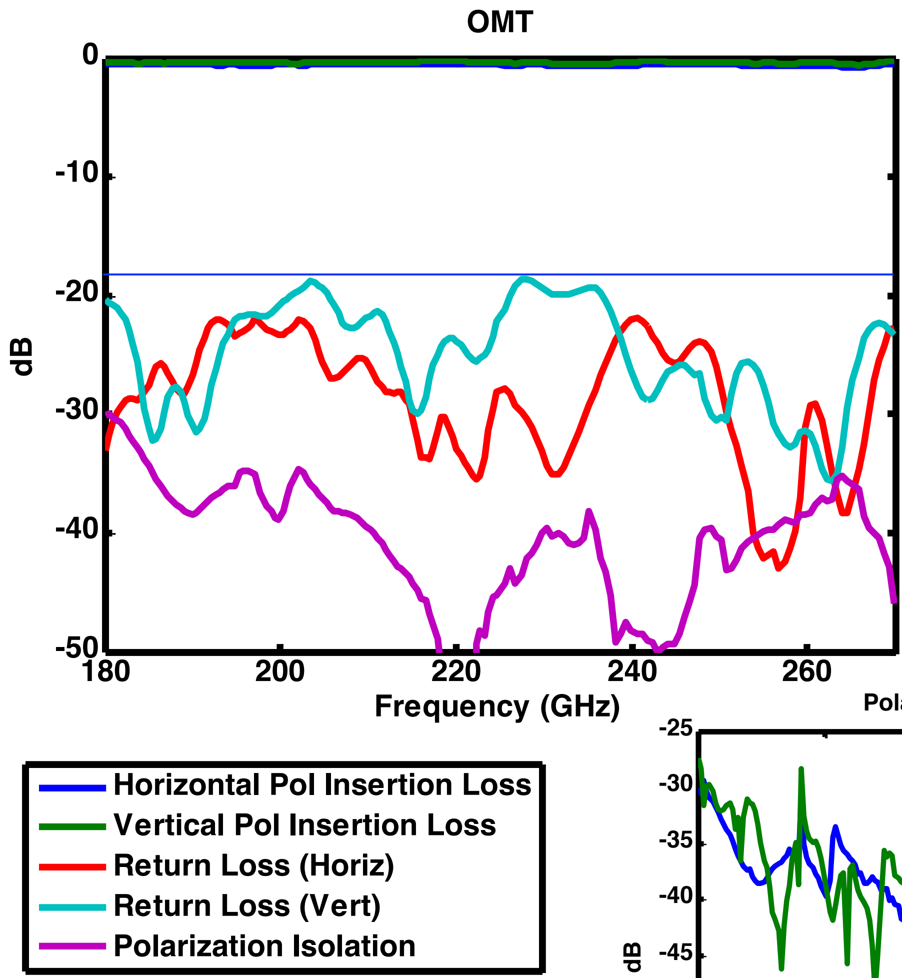
- **Ortho-mode transducers separate input signals to two linear polarizations.**
- **Biofot OMT for wideband performance.**

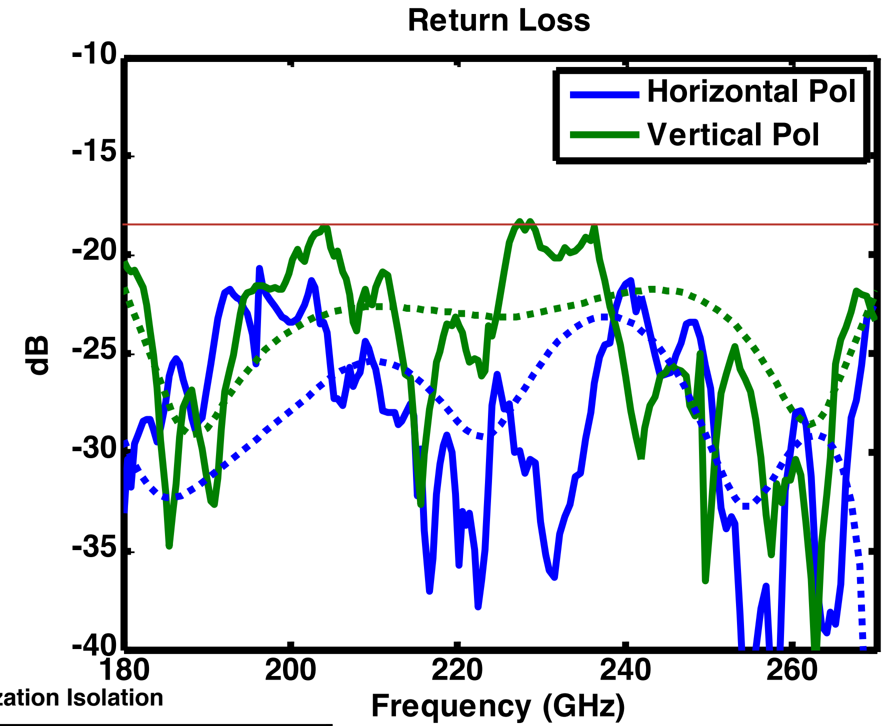


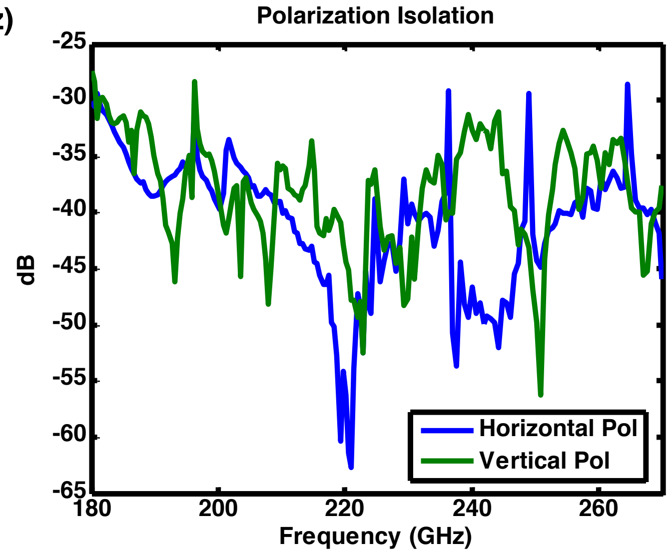




Dual Polarization and Ortho-Mode Transducer

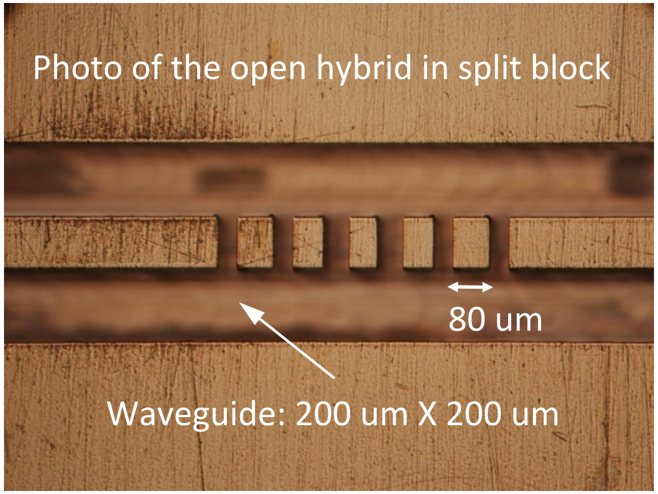


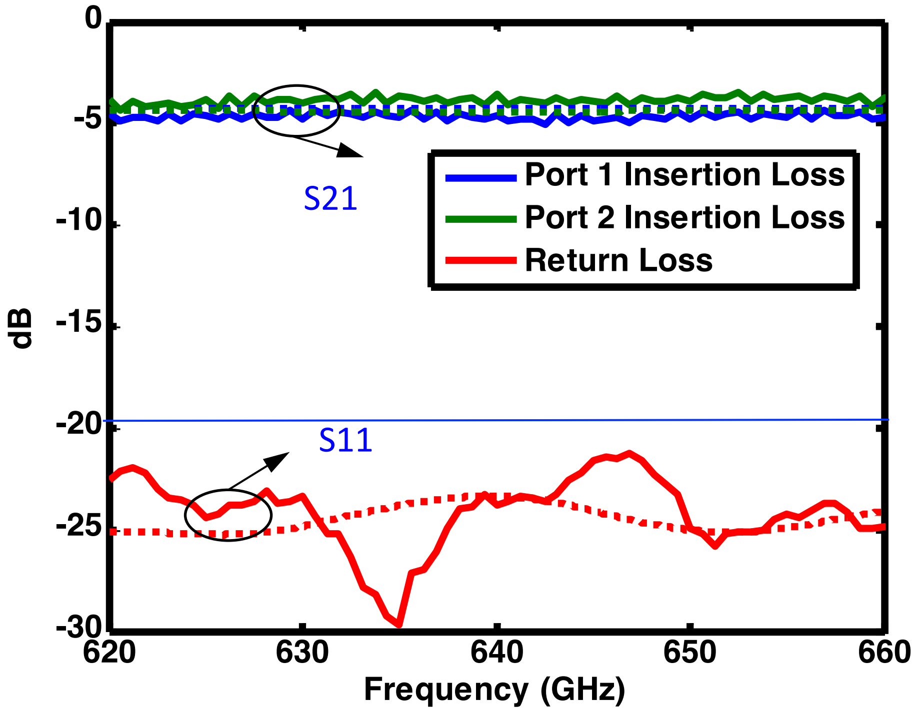


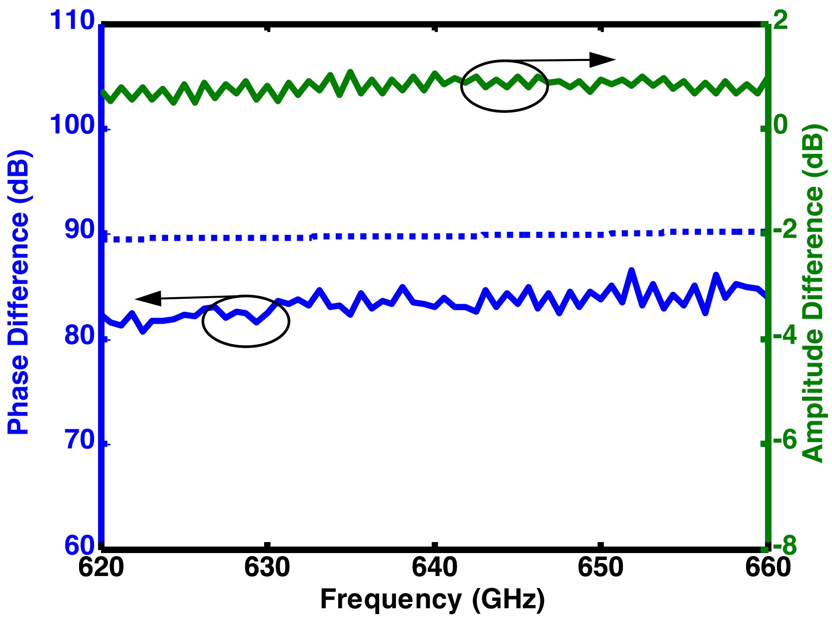


Waveguide Quadrature Hybrid

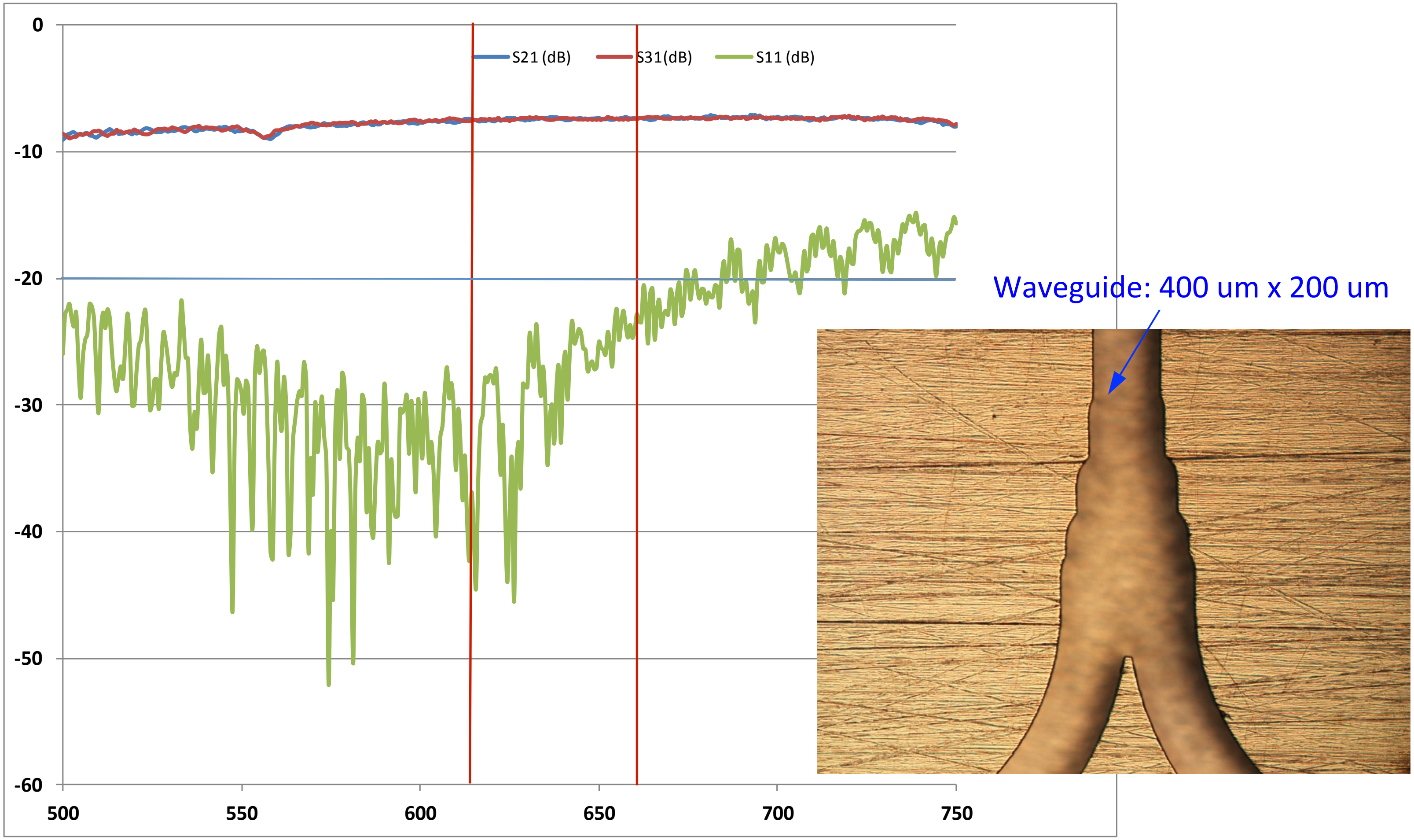
- 6-branch waveguide quadrature hybrid
- Performance from 620 – 660 GHz:
  - Measured balance ±1 dB
  - Measured phase 90±5°
  - Measured return loss < -25 dB
  - Measured isolation < -25 dB



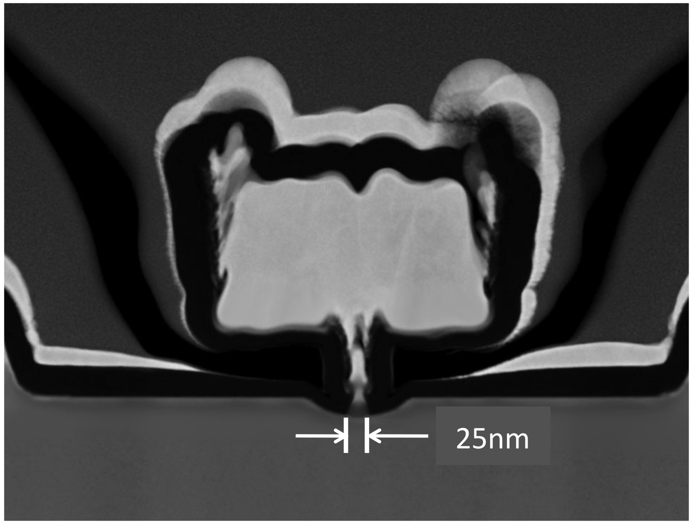




Waveguide 3-dB 620-660 GHz Power Divider



Terahertz InP HEMT



25 nm Gatelength

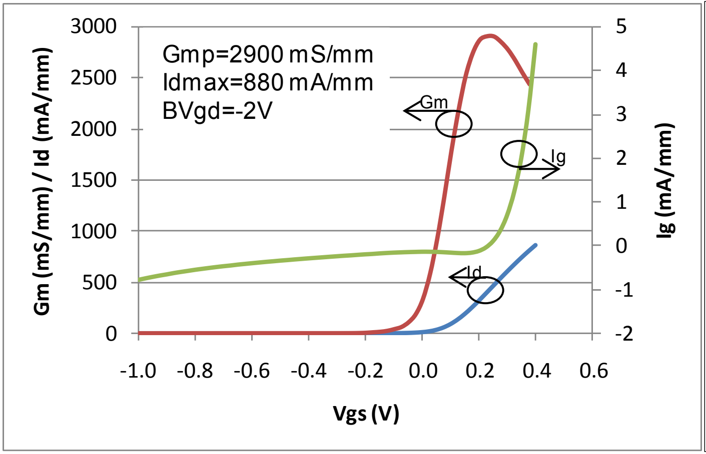
Gmp=3000 mS/mm

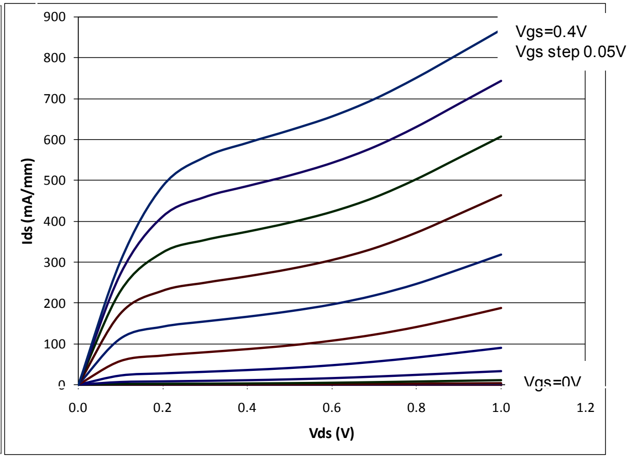
Idmax=880mA/mm

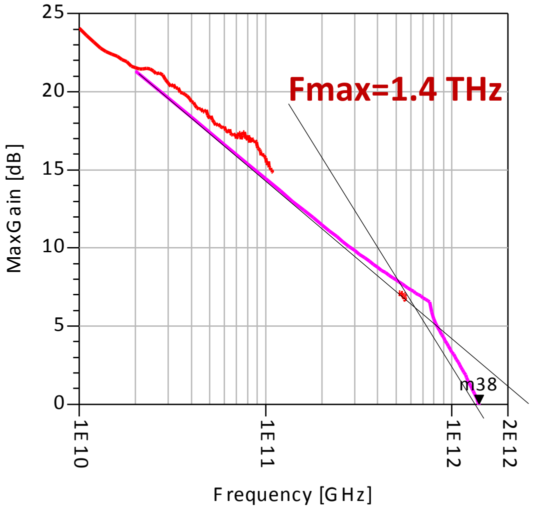
BVgd=-2V

f_T ~ 0.7 THz

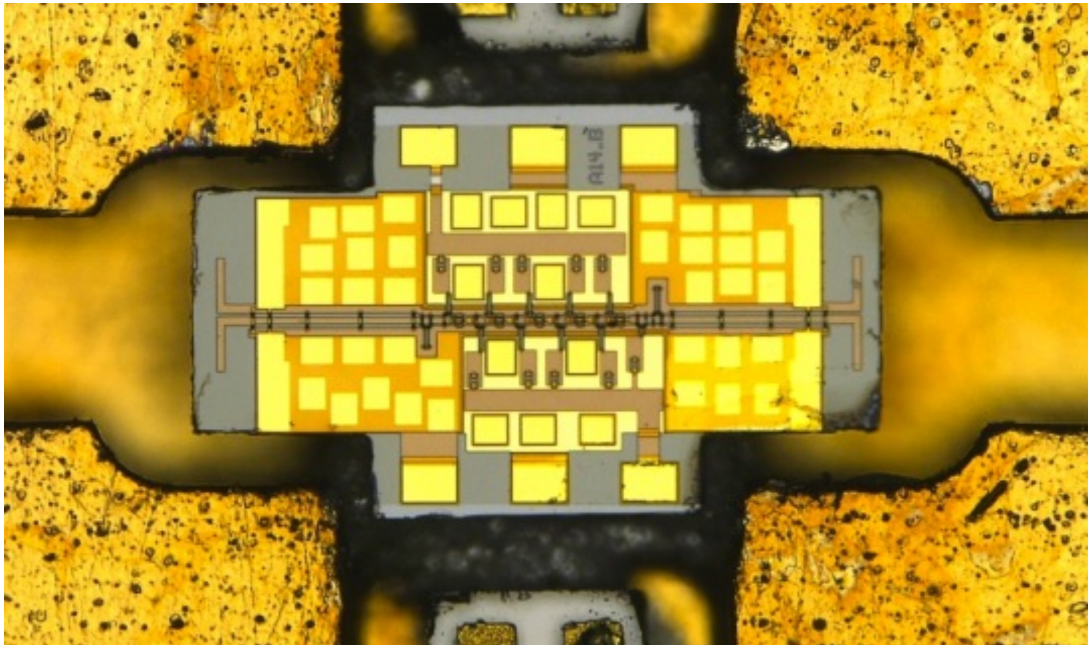
f_{max} ~ 1.4 THz

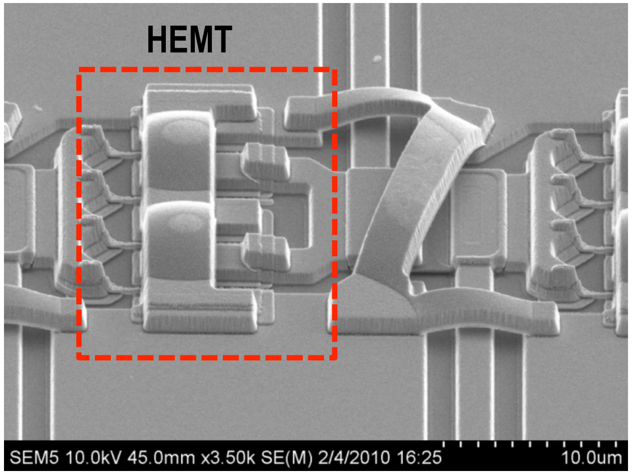




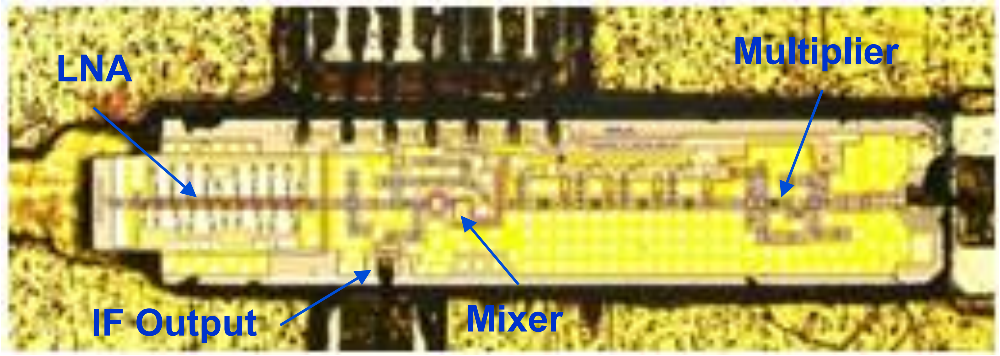


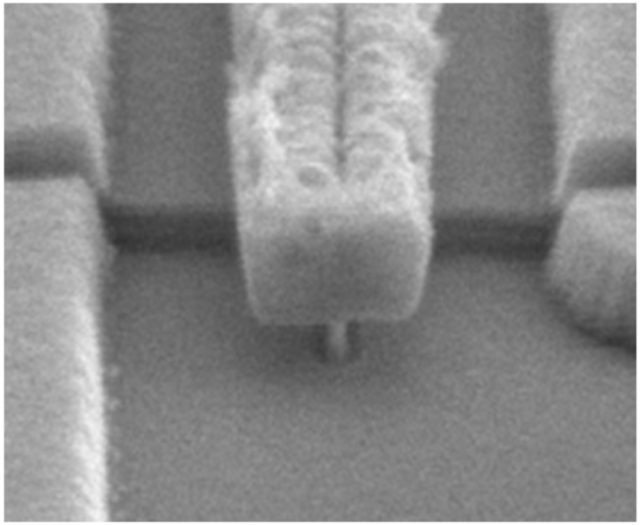
Terahertz InP HEMT Circuits





High Electron Mobility Transistor (HEMT) based Amplifier

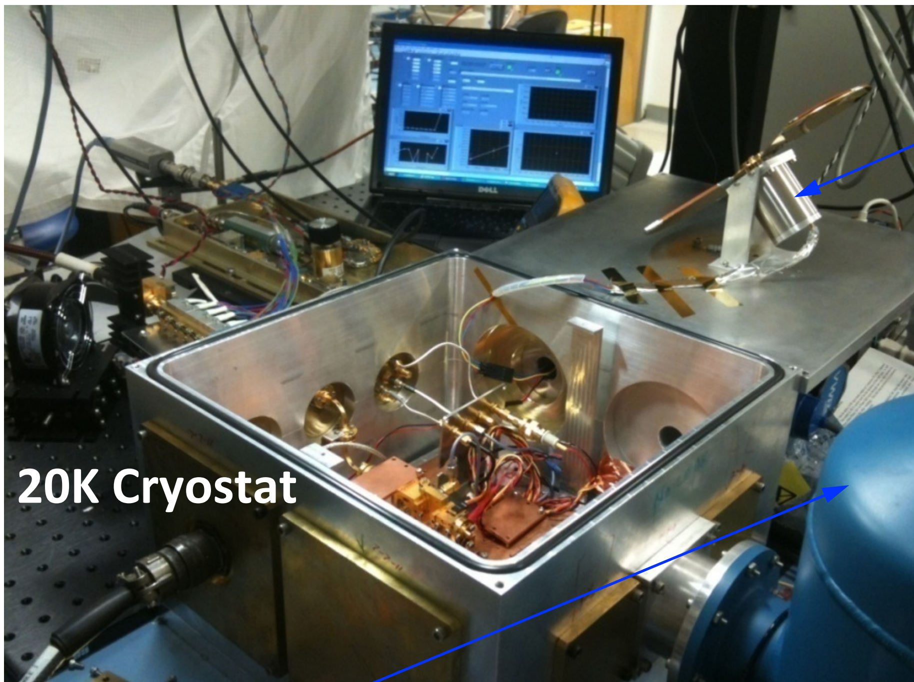


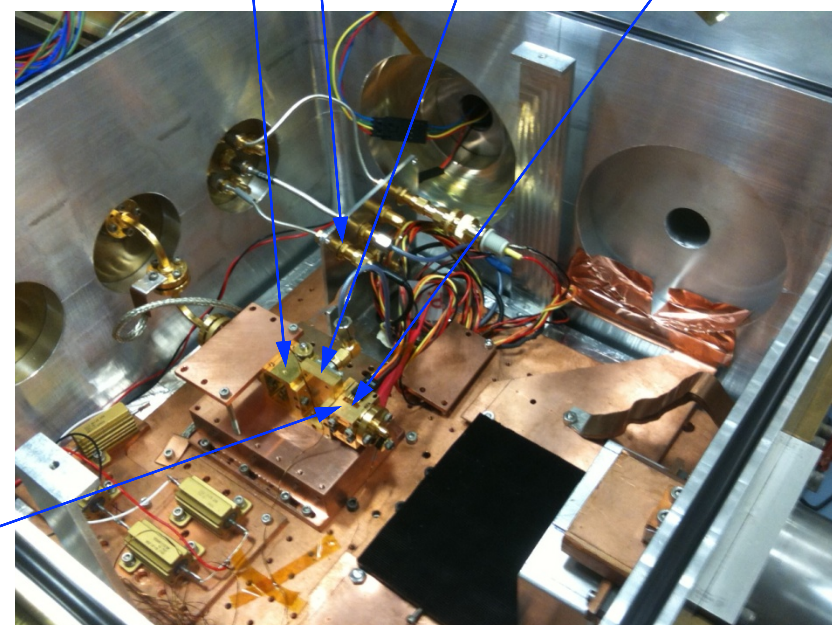


Ref: W. Deal, et al., IEEE Trans. THz Sc. Tech., vol. 1, no. 1, pp. 25-32, Sept. 2011

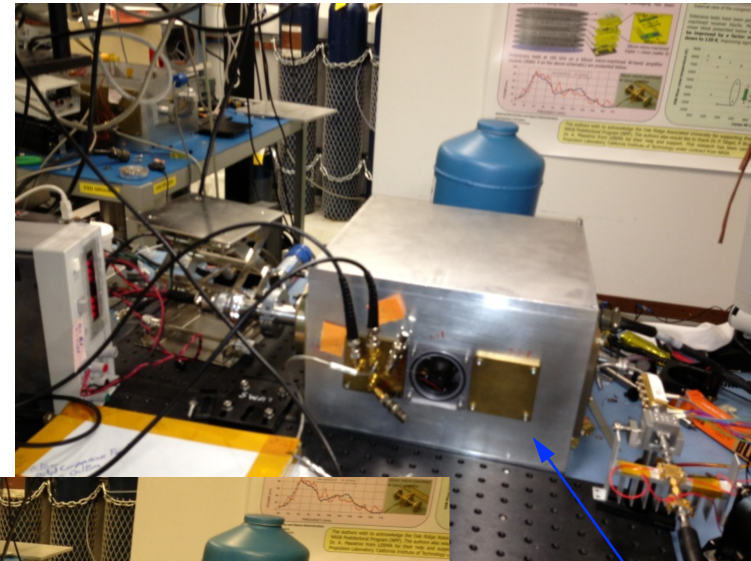
Cryogenic Measurement Set-Up

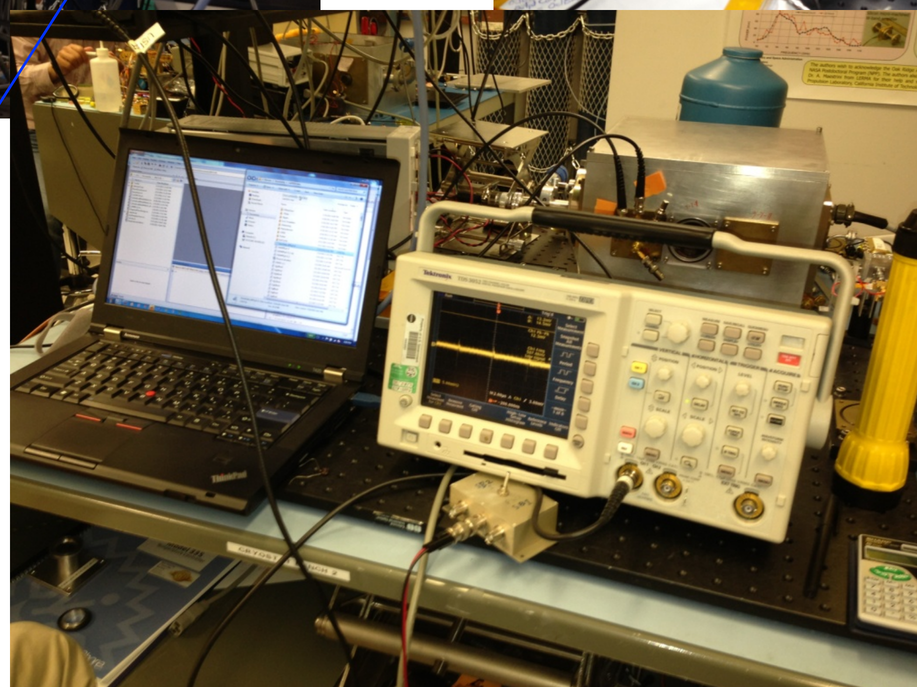
Cryogenic measurement set-up performs semi-automated measurements.





Cryogenic Measurement Set-Up





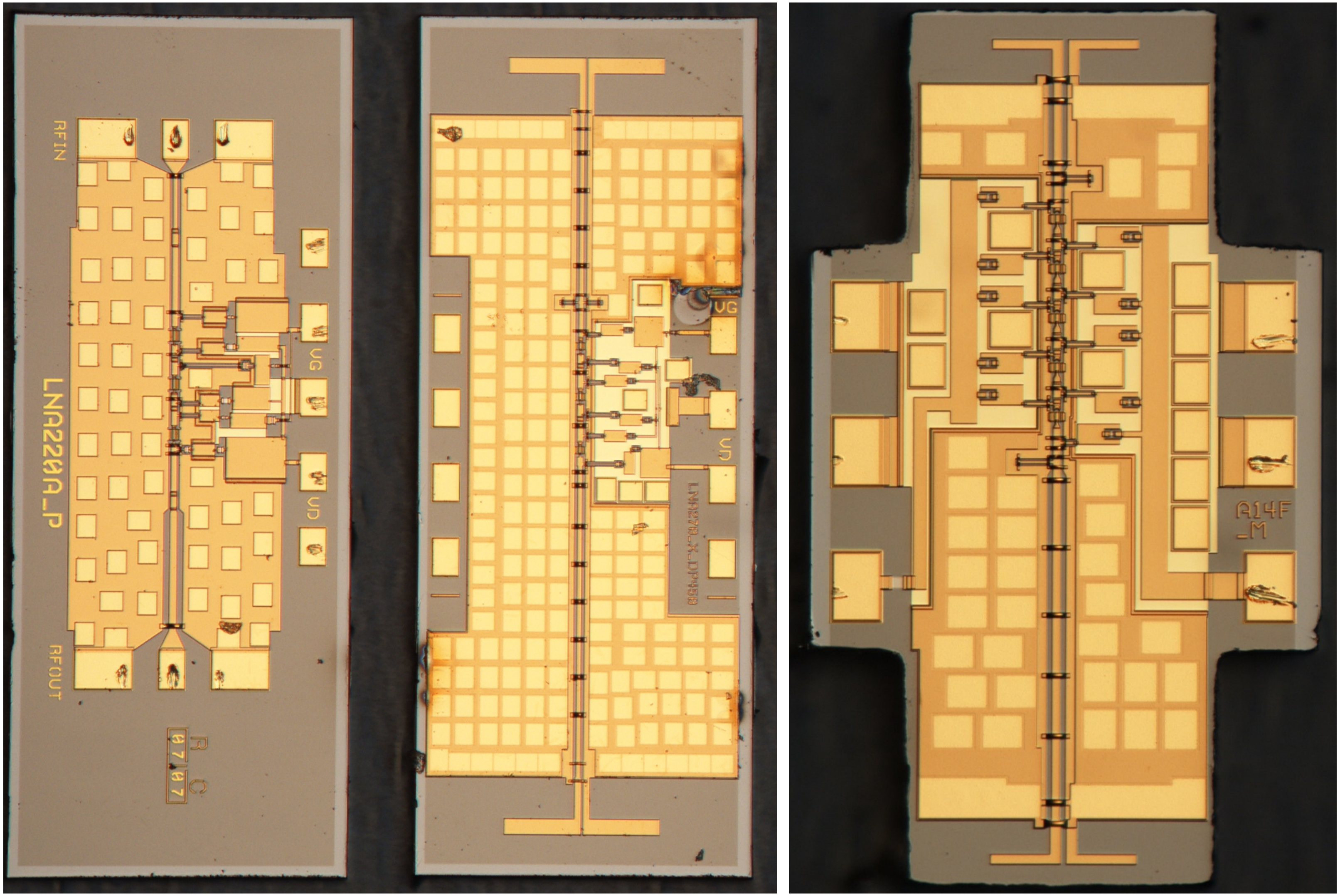
Bias Circuits

Power Meter

Cryostat

Transistor Based Amplifiers and Circuits

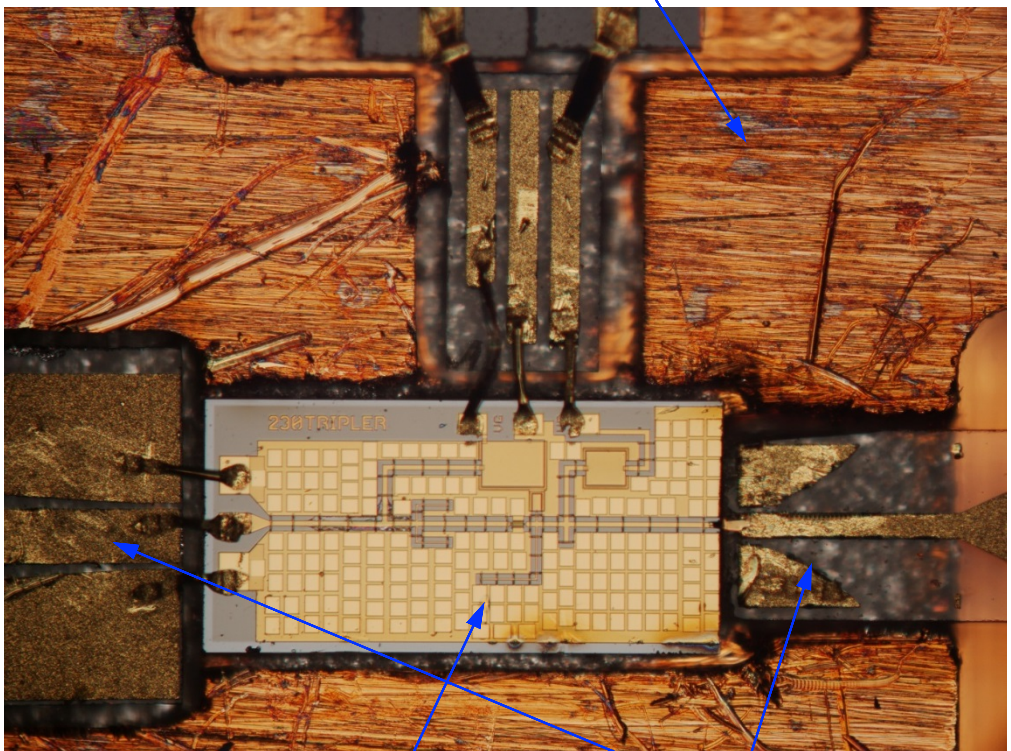
240 and 640 GHz Low Noise Amplifier Chips Diced

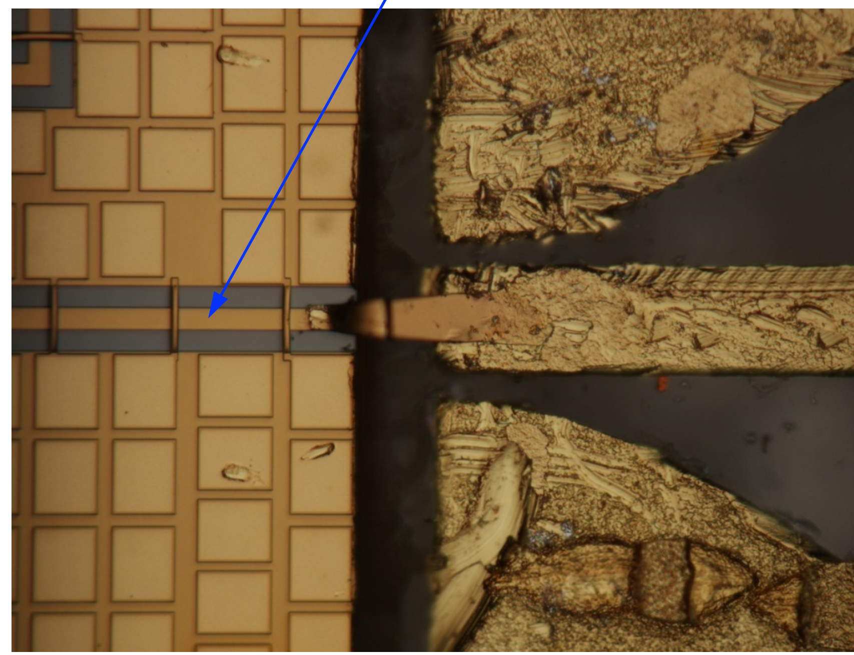


Transistor Based Frequency Multipliers

Waveguide housing

8um center conductor to which external probe is wire-bonded.



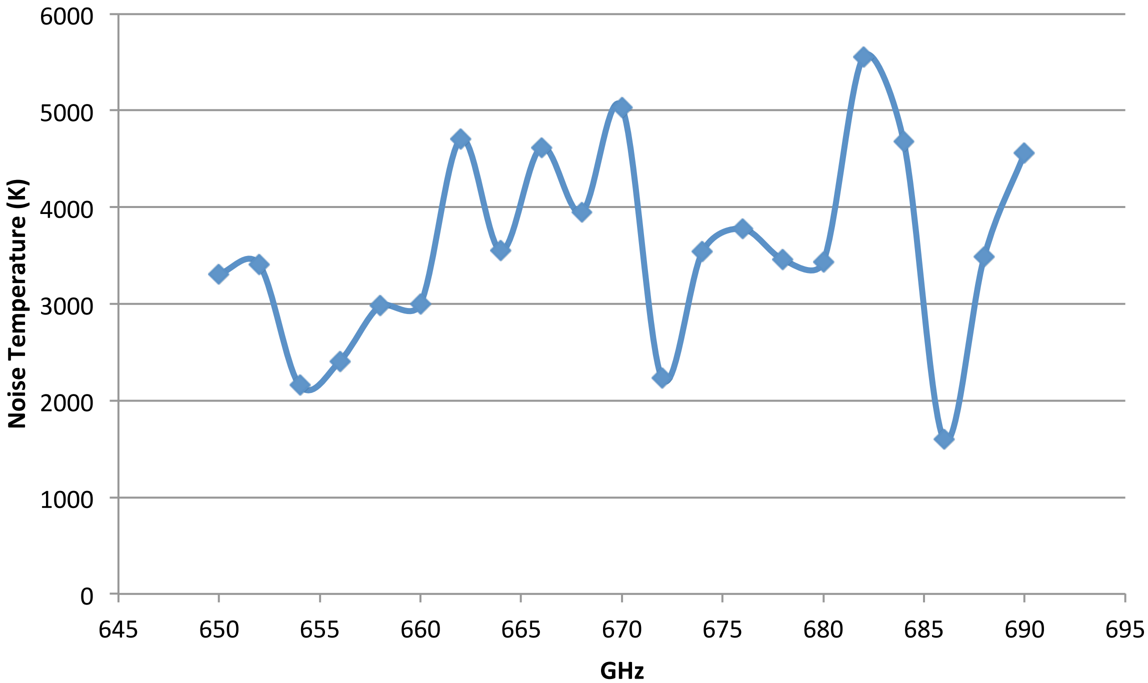


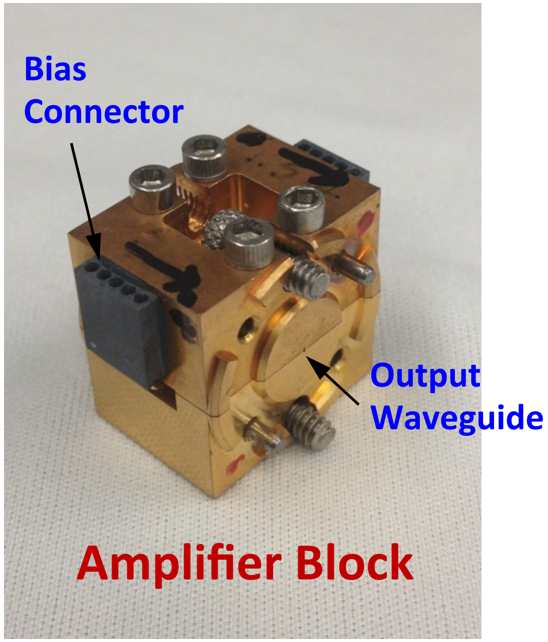
Diced chip

External probes

Amplifier Measurements

Amplifiers are measured individually at room and cryogenic temperatures.

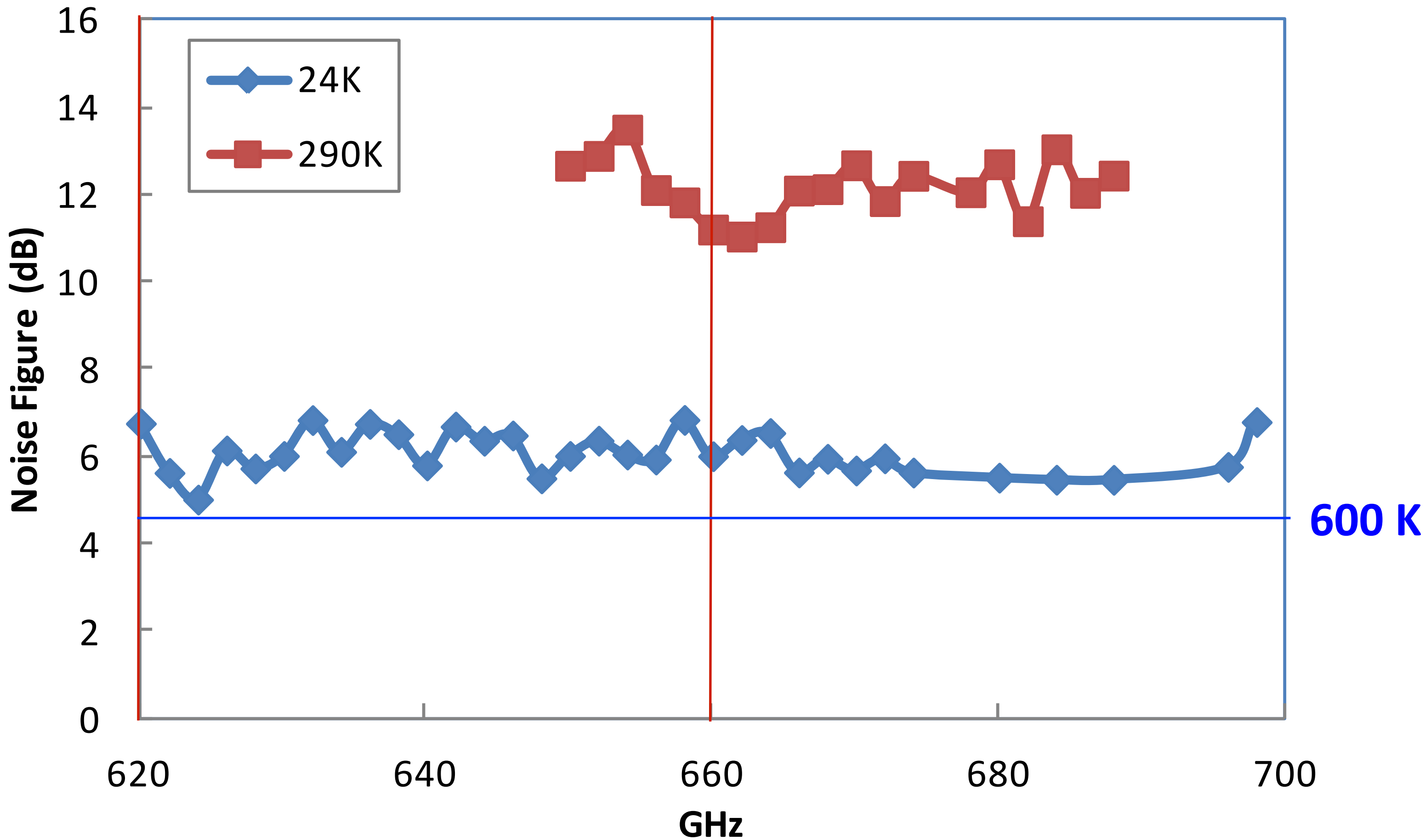




670 GHz LNA Performance at Room Temperature (4000-5000K)

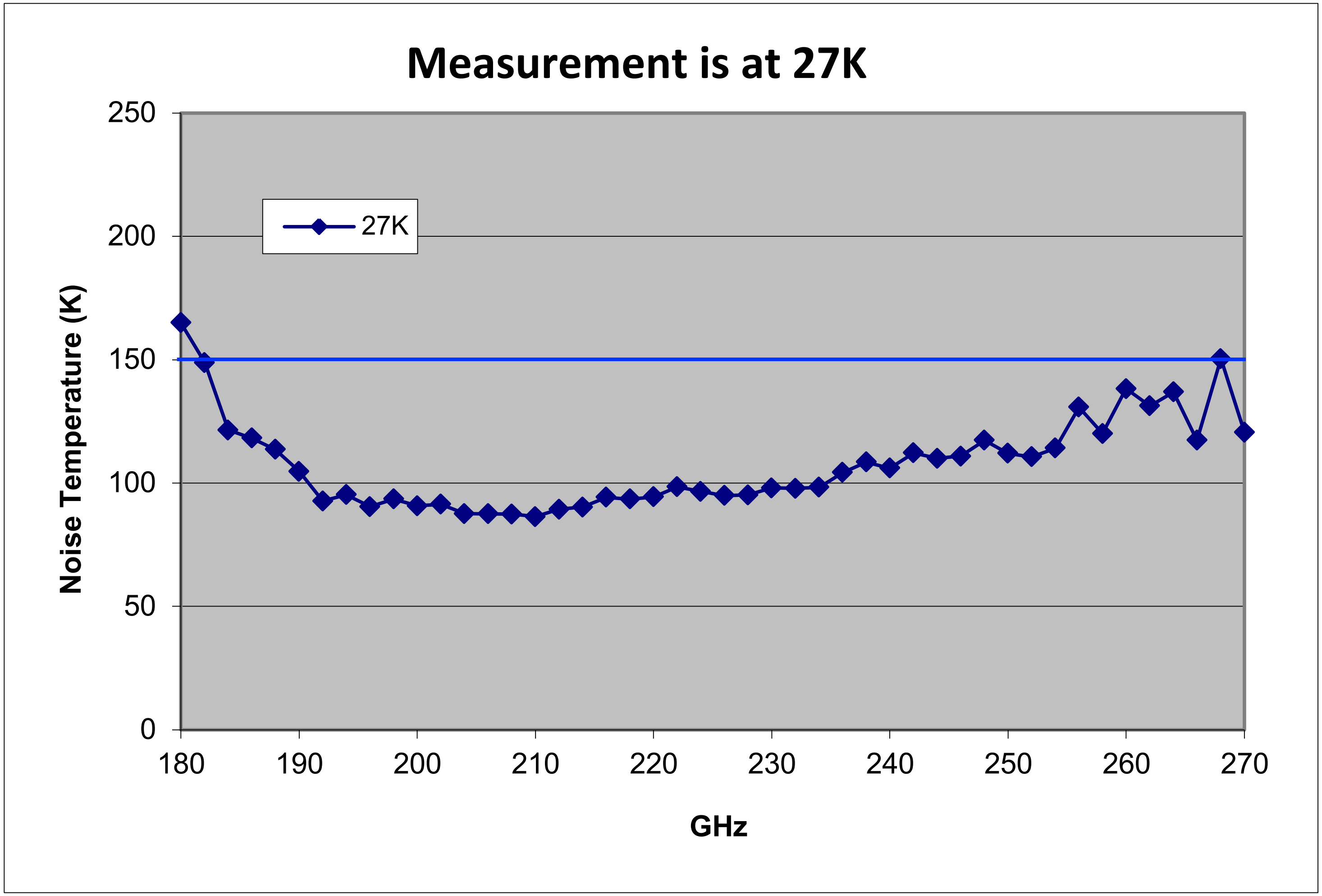
Amplifier Measurements

640 GHz Amplifiers: Cryogenic Noise Temperature Measurements

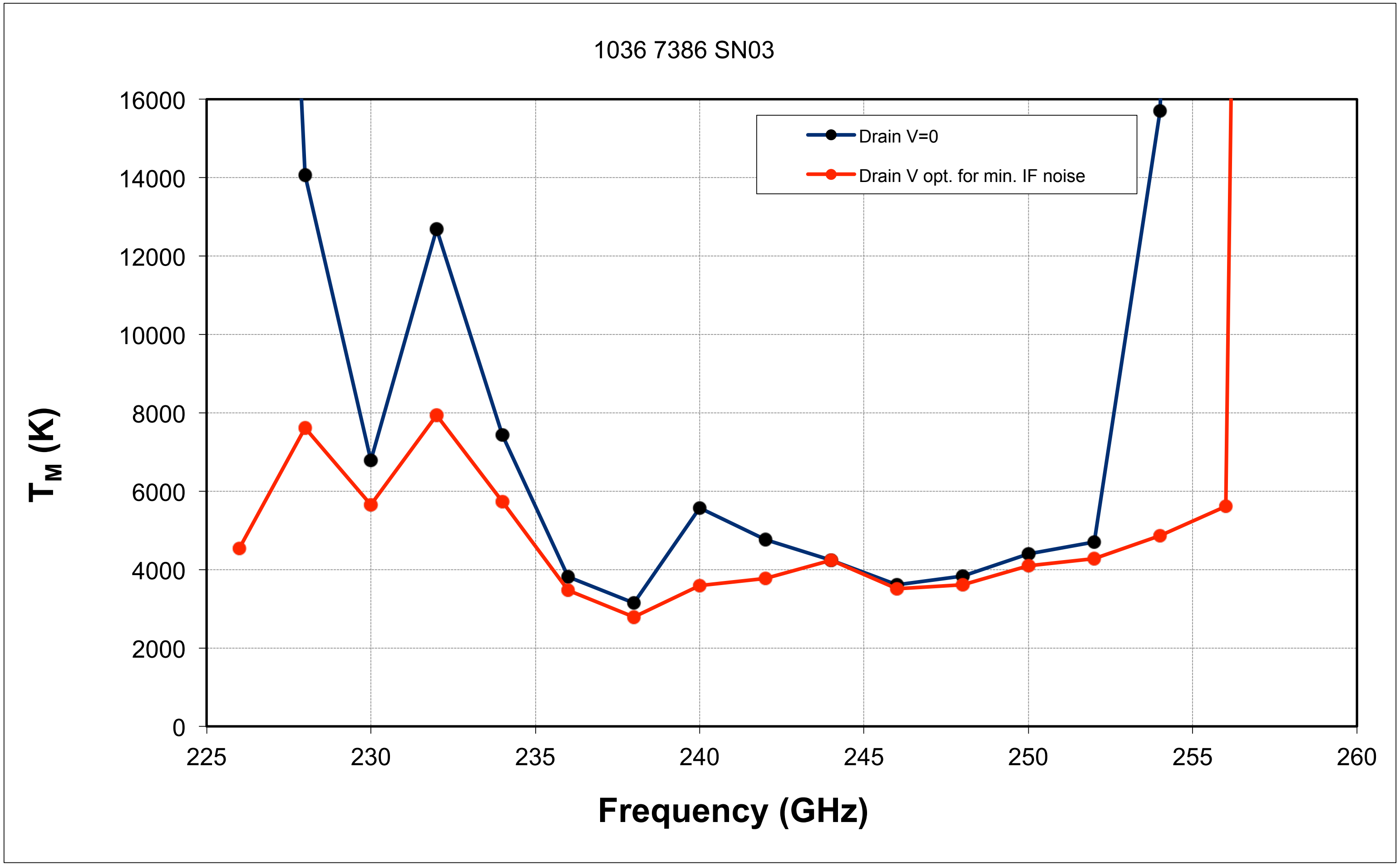


Amplifier Measurements

180-270 GHz Amplifiers: Cryogenic Noise Temperature Measurements

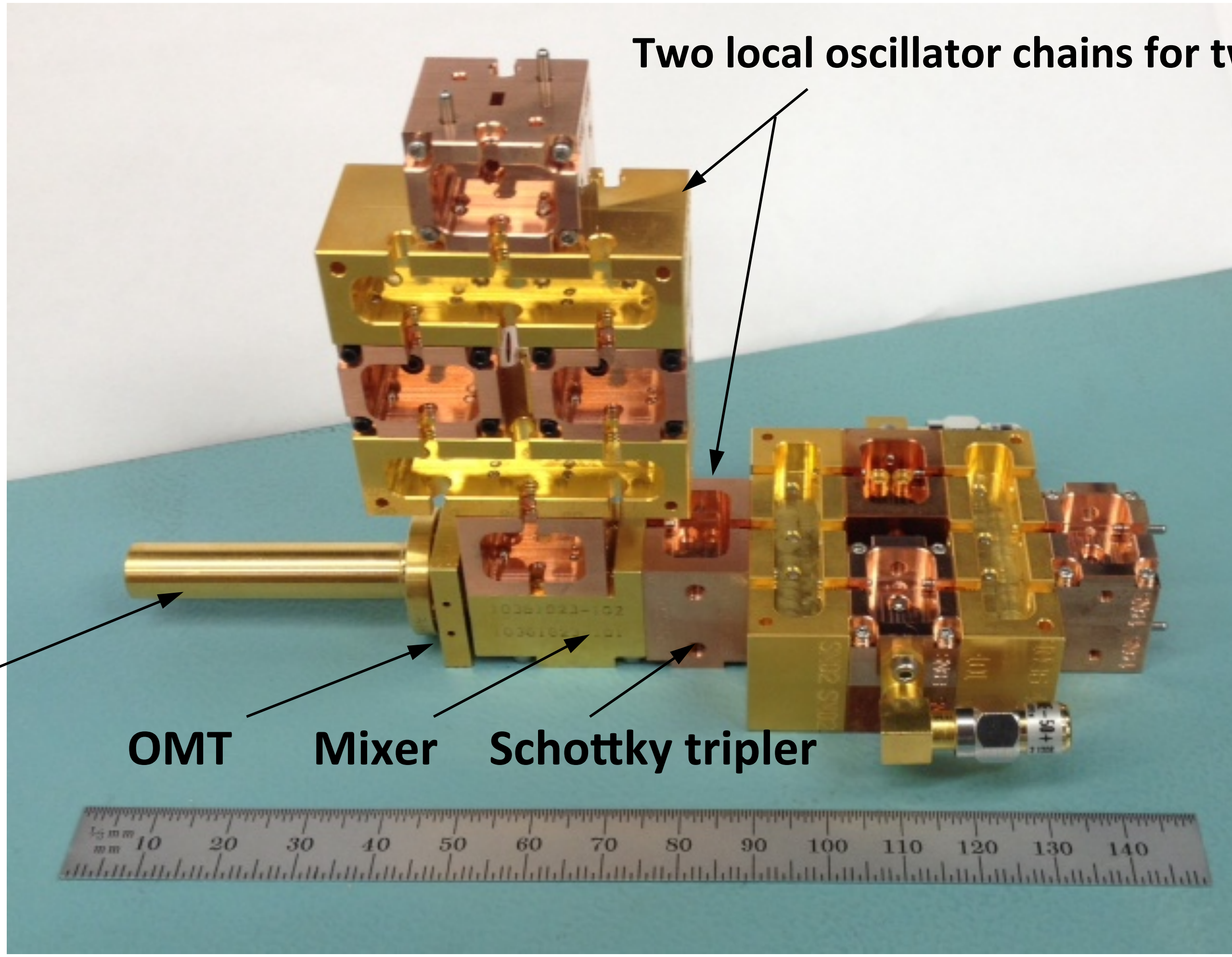


240 GHz HEMT Balanced Mixer



- We found a way to bias these devices in such a way so that the sensitivity improves.

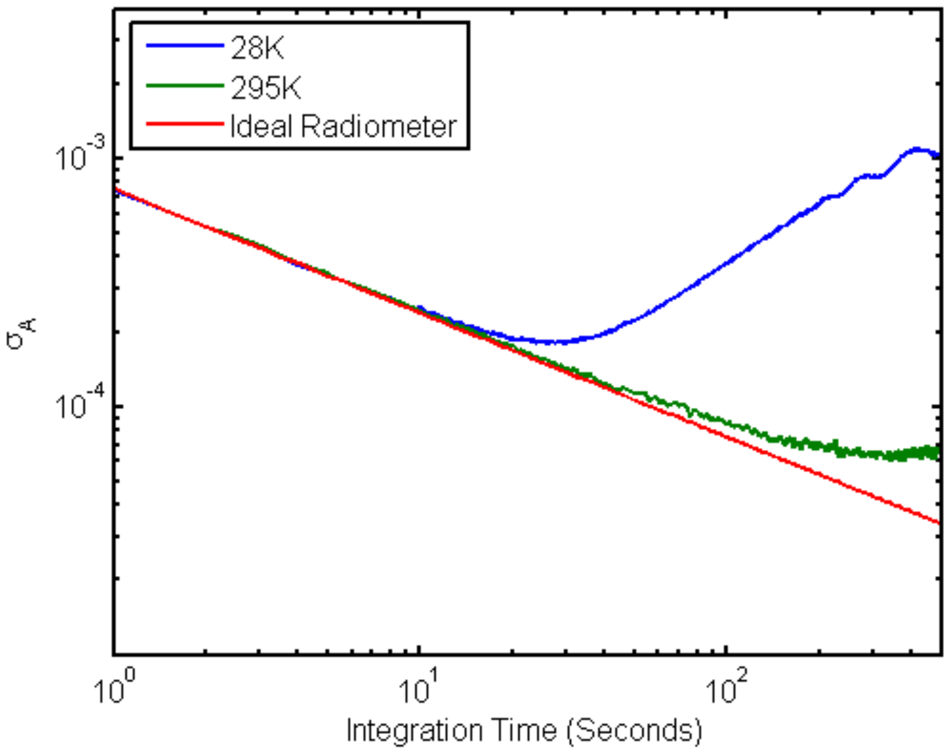
System Integration

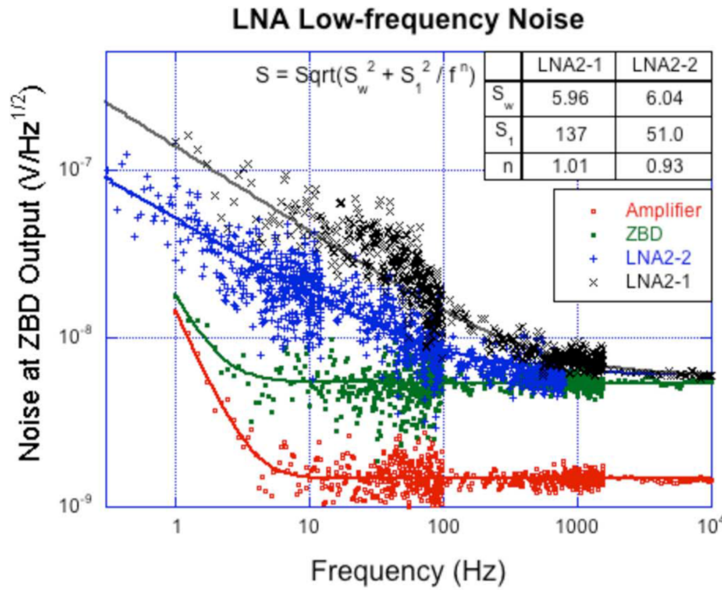


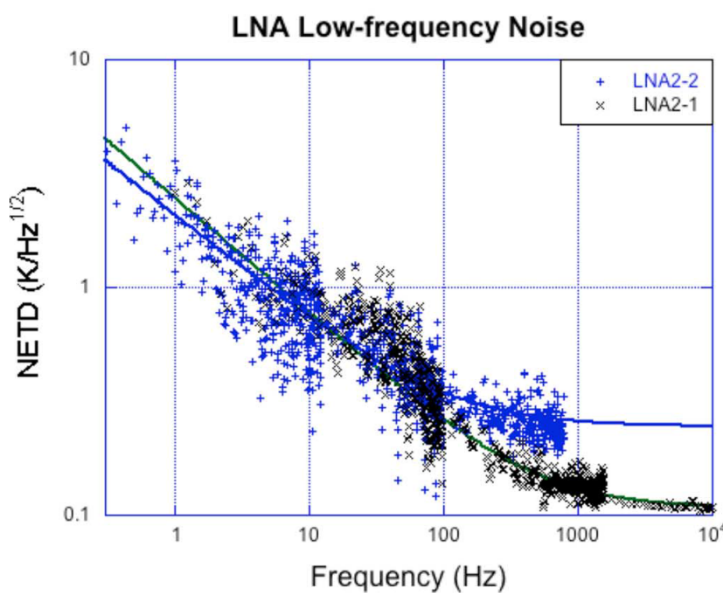
180-270 GHz HEMT-based dual-polarized sideband separating receiver

Amplifier Stability

Alan time







Noise spectra. The upper panel displays voltage noise referred to the ZBD output. The lower panel displays the same data for the LNAs, but referred to radiometric temperature at the horn input.

Ref: Erich N. Grossman, IEEE Trans. TST

Summary

- Cryogenic amplifiers at 240 and 640 GHz are showing almost a factor of eight improvements in noise temperature when cooled to 20K, similar to amplifiers at millimeter wavelengths.
- It is now feasible to design and develop HEMT based receivers which will offer performance close to SIS mixers, but at 20K.
- Integrated amplifier based sideband separating and balanced 240 GHz (integrated dual polarized) and 640 GHz receivers cooled to cryogenic temperatures will be available in January 2015.

Acknowledgement

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We want to thank Joseph Famiglietti and Eastwood Im for their support.