Submillimeter-Wave Sounders with Cryogenic Amplifier Based Receiver Front-End

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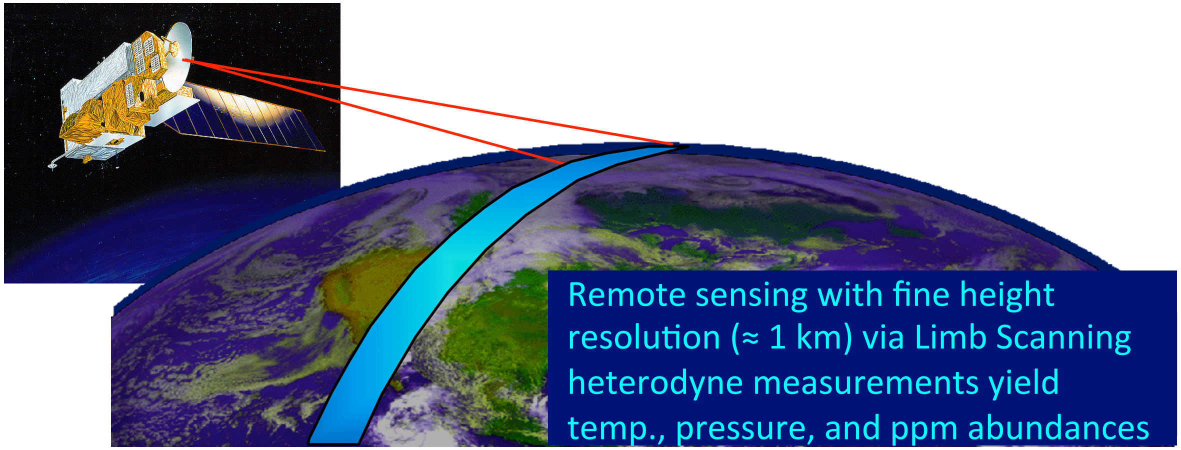
Objectives

- 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 cover the 180-270 GHz and 620-660 GHz frequency bands. We designed amplifier based receivers with noise temperatures close to those of the existing SIS mixers, but at an operating temperature of 20K rather than 4K.
- This represents a major simplification in design; and mass, power, as well as risk reductions for SMLS.

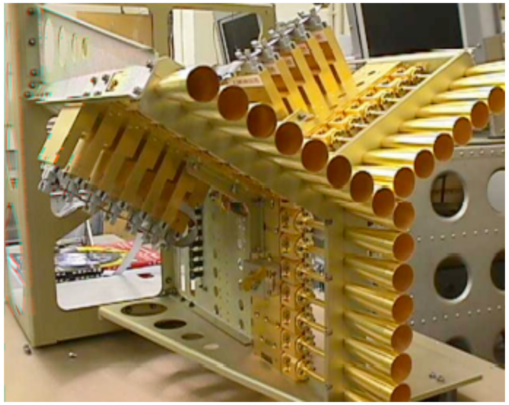
Science Drivers

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

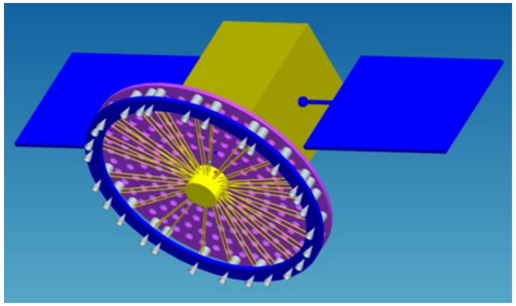
- Stratospheric and Tropospheric Chemistry
  - ozone layer modeling
  - economics vs. environment
  - water distribution/pollutants
- Clouds: Global Warming
  - ice crystal: size & distribution
- Aerosols, Volcanism, Dust



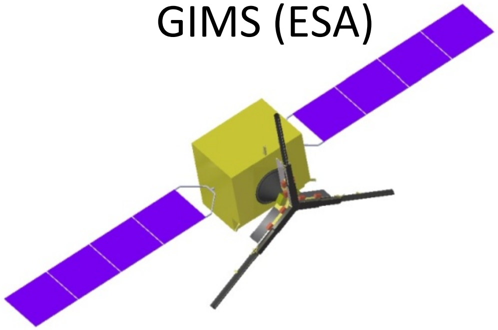
Remote sensing with fine height resolution (≈ 1 km) via Limb Scanning heterodyne measurements yield temp., pressure, and ppm abundances



Geo-Star (NASA)

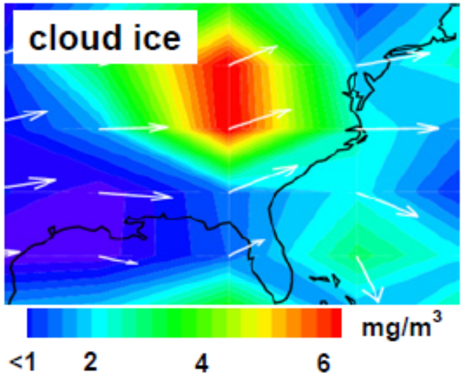


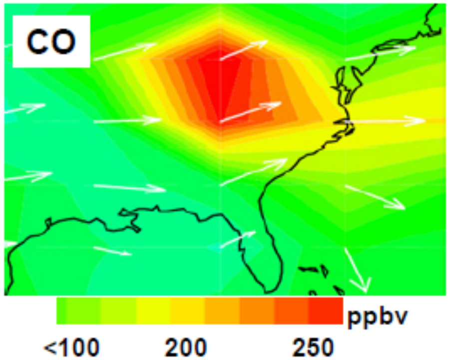
GIMS (ESA)



Science Drivers and SMLS Instrument

- The Scanning Microwave Limb Sounder (SMLS) on GACM will have the capability to map the composition of the upper troposphere and stratosphere with 50x50x1 km spatial sampling and six times daily mid-latitude repeat coverage.
- SMLS is a direct successor to the MLS instruments flown on NASA's UARS and Aura spacecraft launched in 1991 and 2004, respectively.
- Resolution of critical outstanding questions in climate stability, weather, and climate forecasting, and the long-range transport of air pollution, requires global measurements of upper tropospheric (8–16 km altitude) humidity, cloud ice, and composition with far better spatial and temporal resolution than currently available.
- The SMLS will provide these needed measurements, along with information required for understanding ozone layer stability.





Cloud ice and CO measurements at submillimeter wavelengths.

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**

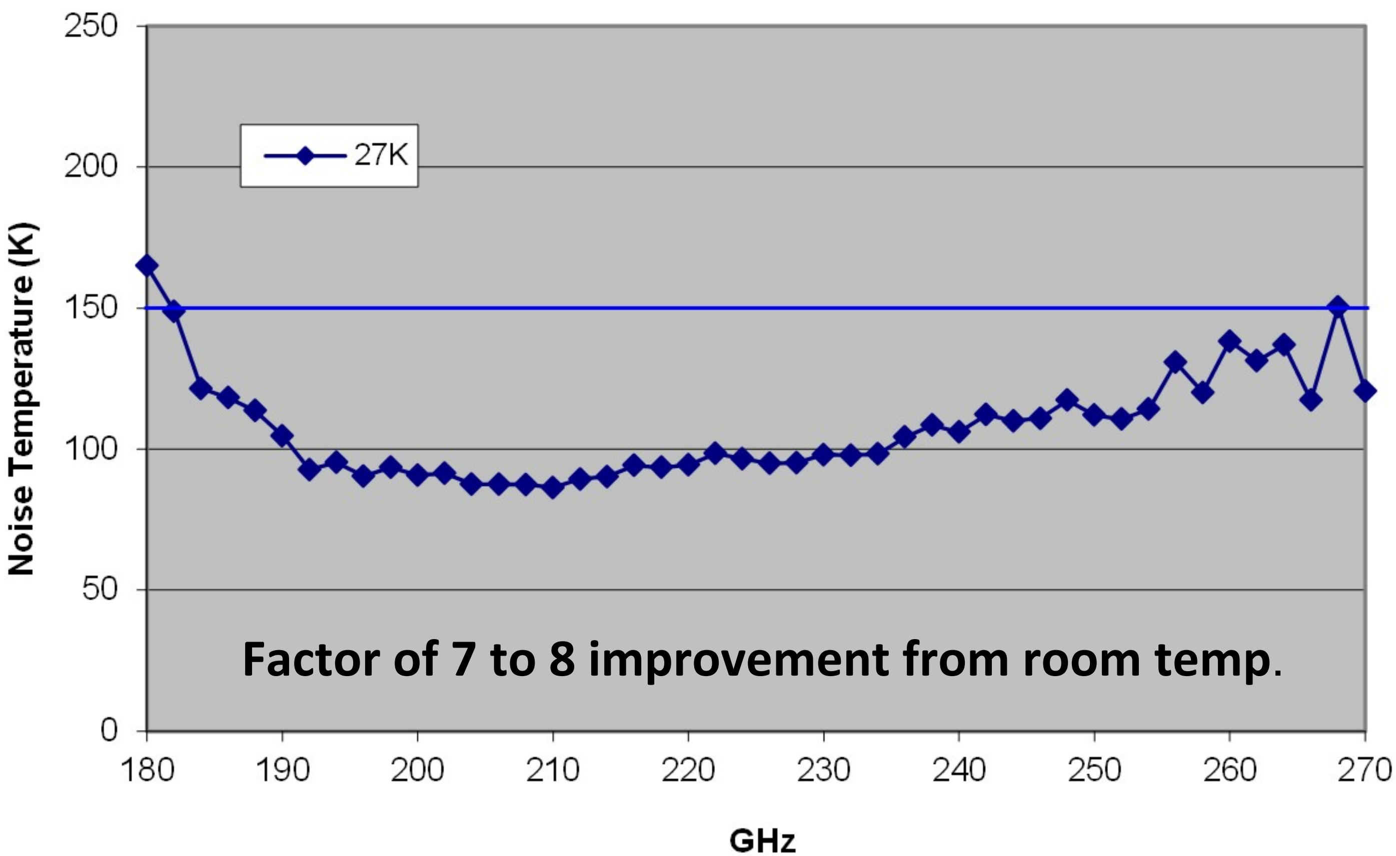
There were no amplifiers at the submillimeter-wave band

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.**

Cryogenic Amplifiers

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



Cryogenic Amplifiers

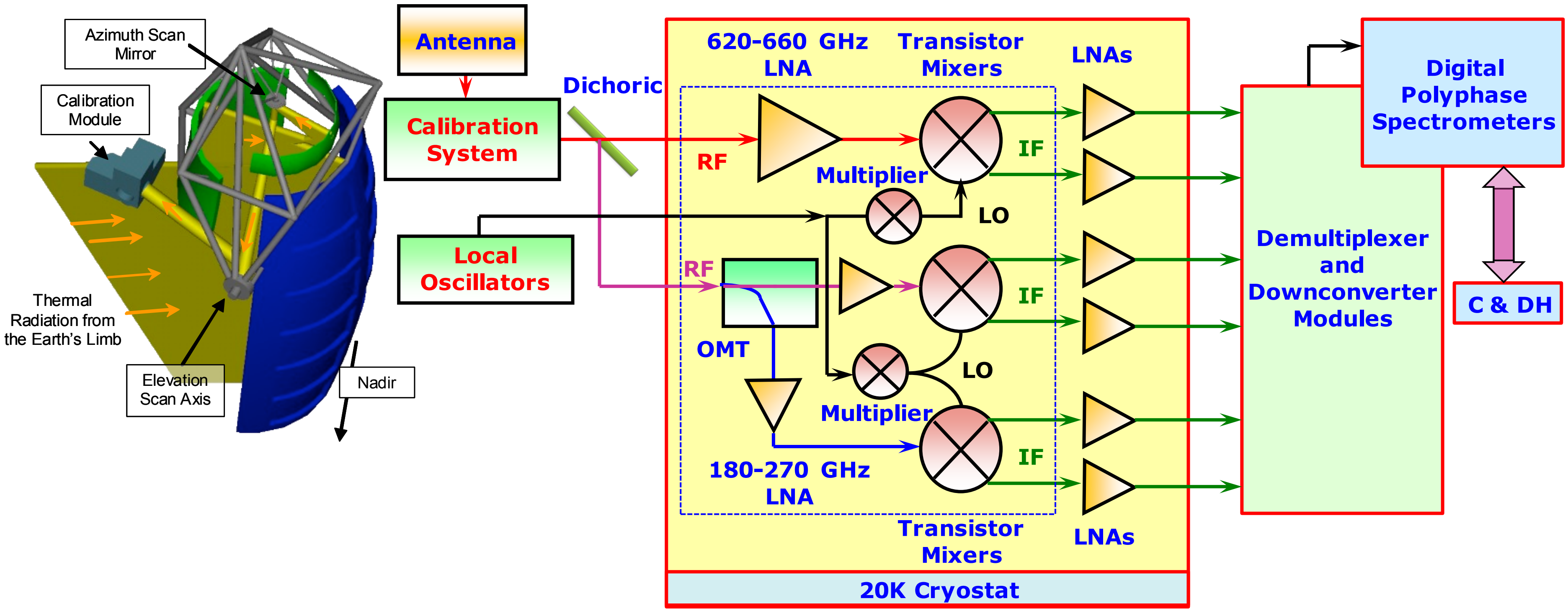
Amplifiers still cannot compete with SIS or HEB in noise performance!

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

- **It is much easier, and significantly lower in power, to cool to the higher temperature.**
- **The performance (sensitivity) of cooled MMIC and SIS systems is not that different, especially when you add the atmospheric brightness to the system temperature.**
- **The ability to run over a large range of temperatures is a big bonus, as a degraded cooling system results in degraded performance, not in a dead system (as would happen with an SIS front-end).**
- **MMIC systems are easier to work with from the 1st LO perspective, and that they are much more convenient when it comes to balanced amplifier configurations, correlation radiometers, and array systems.**

Amplifier Based Earth Science Instrument

Schematic Block Diagram of Amplifier Based Receiver Front-End

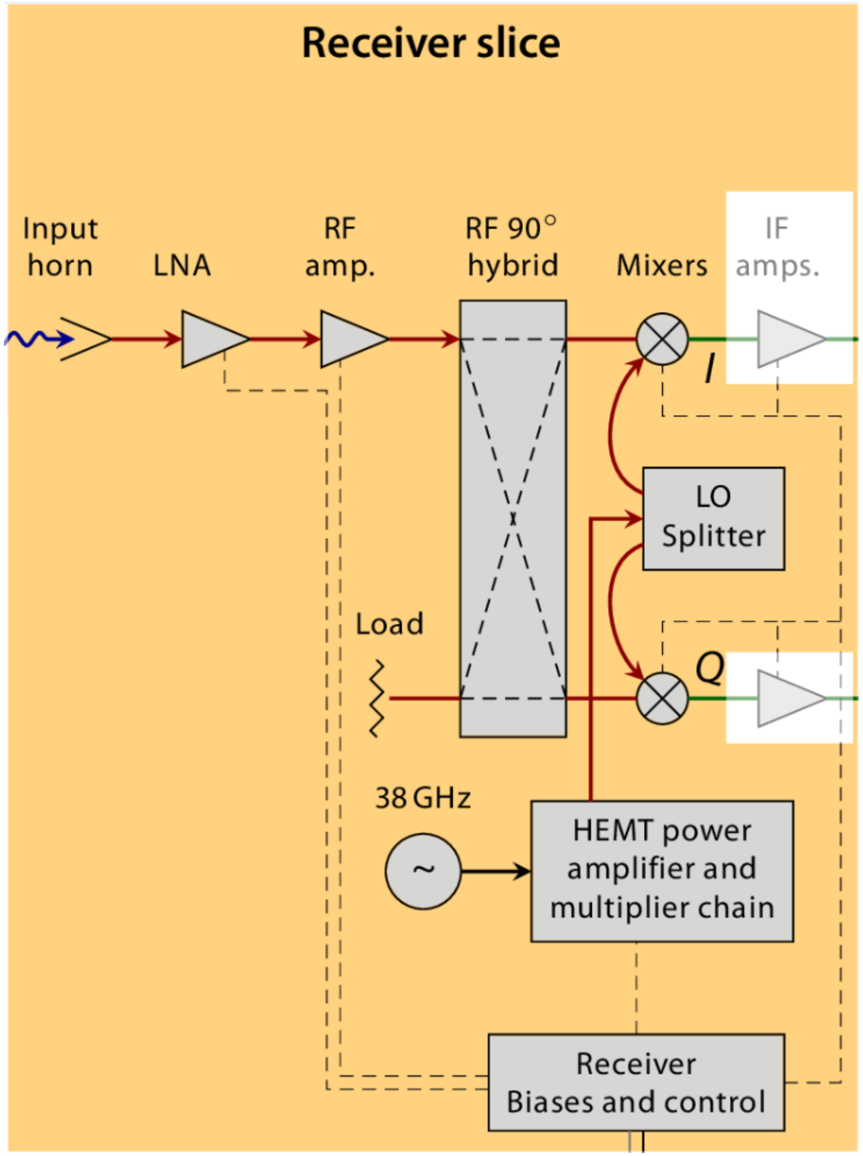


HEMT amplifier based receivers cooled to 20K down-convert the signals from the antenna for detection in the digital spectrometers.

ESTO: ACT Program

Amplifier Based Earth Science Instrument

321-360 GHz
RF Input



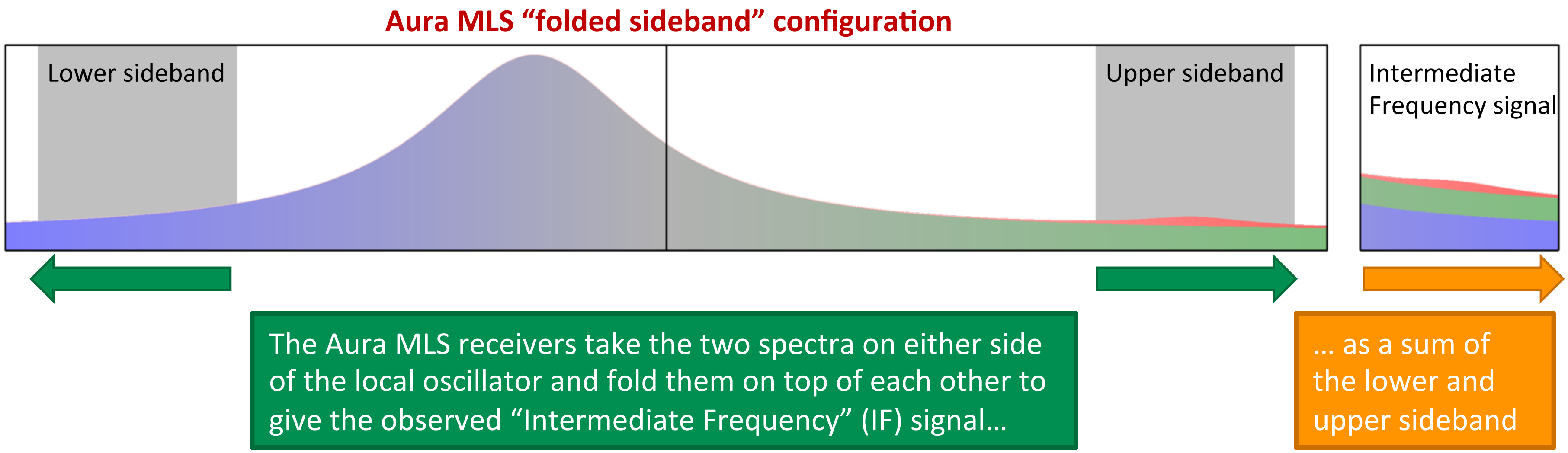
1-18 GHz
IF Output

1-18 GHz
IF Output

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

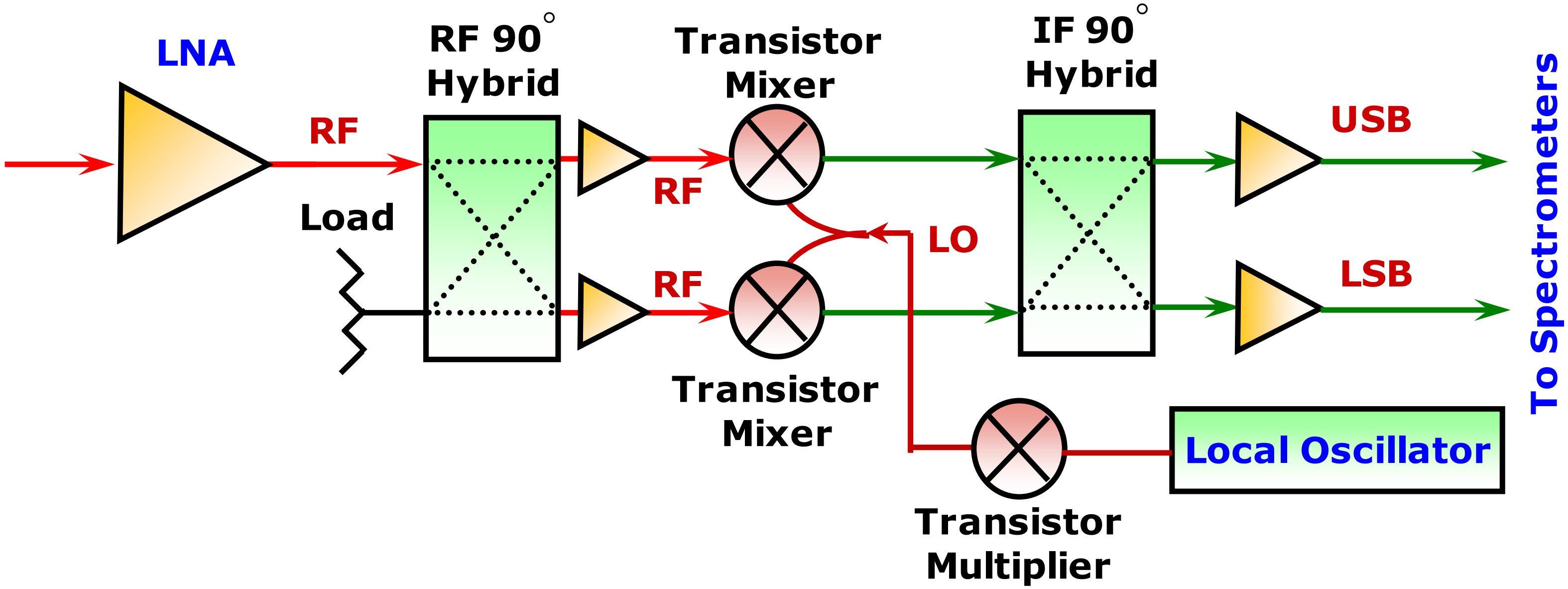
ESTO: IIP Program

Scientific Importance of Sideband Separation



- **The "folded sideband" nature of the Aura MLS signals presents a significant challenge to measurements in the UT/LS.**
- **The far-wing/continuum signal in the upper sideband (green) adds a "baseline" but also partially attenuate the weak spectral signal from the target molecule (red).**
- **The far-wing/continuum signal in the lower sideband (blue) simply adds more baseline.**
- **Deducing the abundance of the "red" molecule from the total signal, given the two differently behaving background signals, equates to pulling three unknowns ("red line" and two continua) from only two measurements ("line shape" and "background").**
- **We solve this by reporting upper and lower sideband separately.**

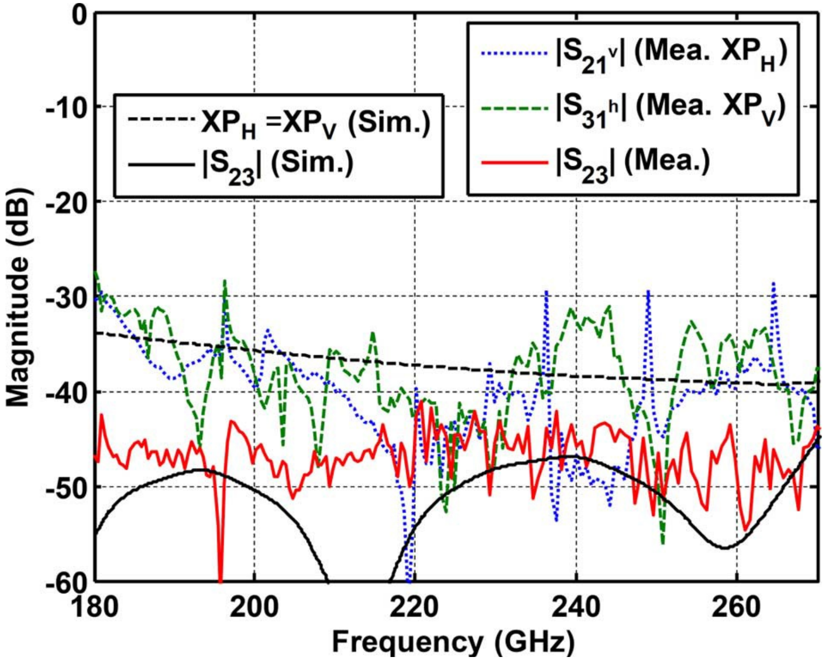
HEMT-Based Sideband Separating Receiver

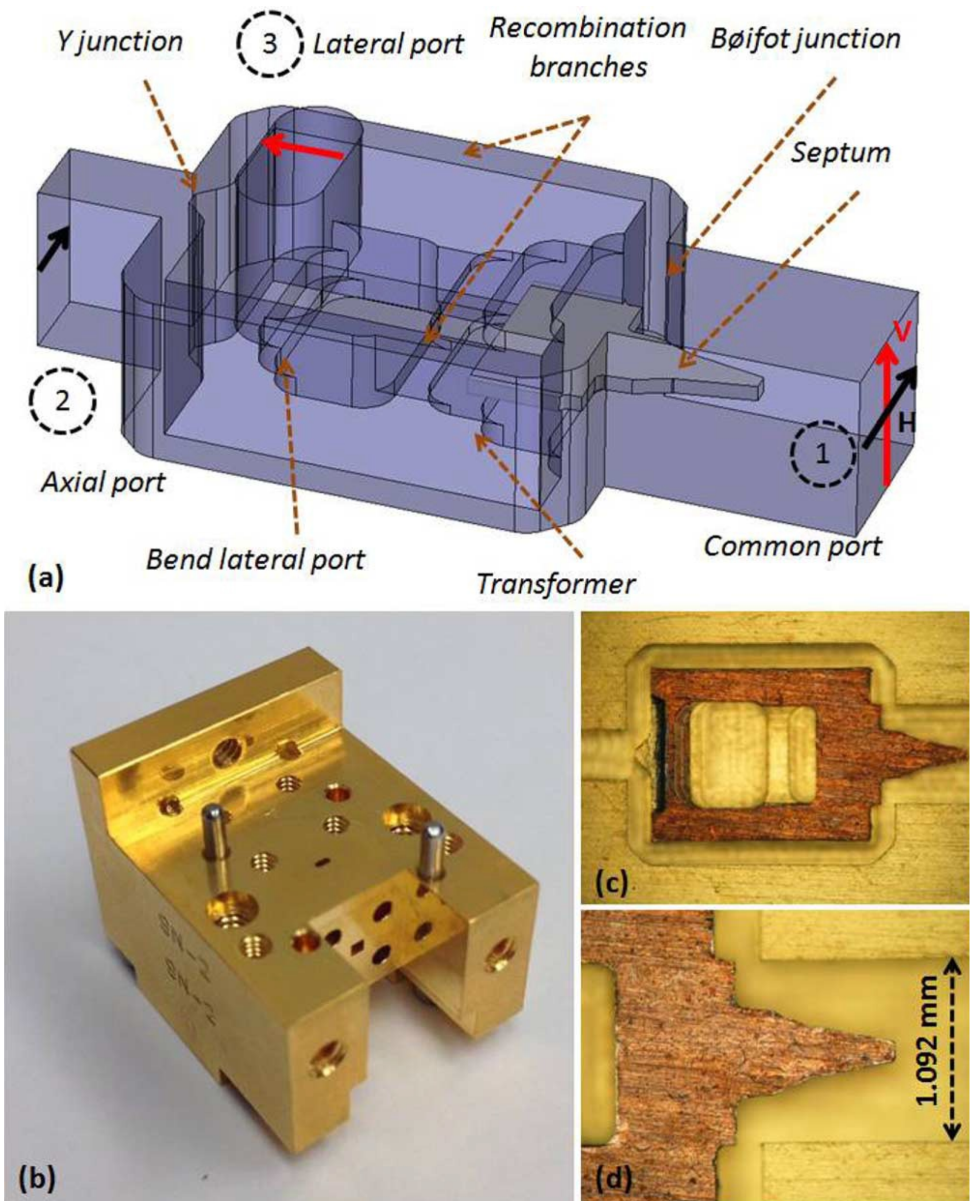


- The radio frequency (RF) signal is first amplified by a low-noise amplifier (can be cooled to 20K to improve signal to noise).
- RF hybrid circuit along with mixers separate the two sidebands.
- These are split in the back-end IF processing and spectrometer subsystems.

Dual Polarization and Ortho-Mode Transducer

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

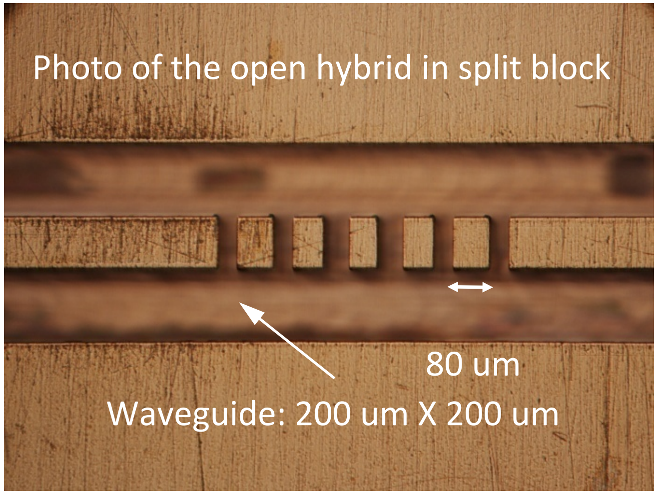


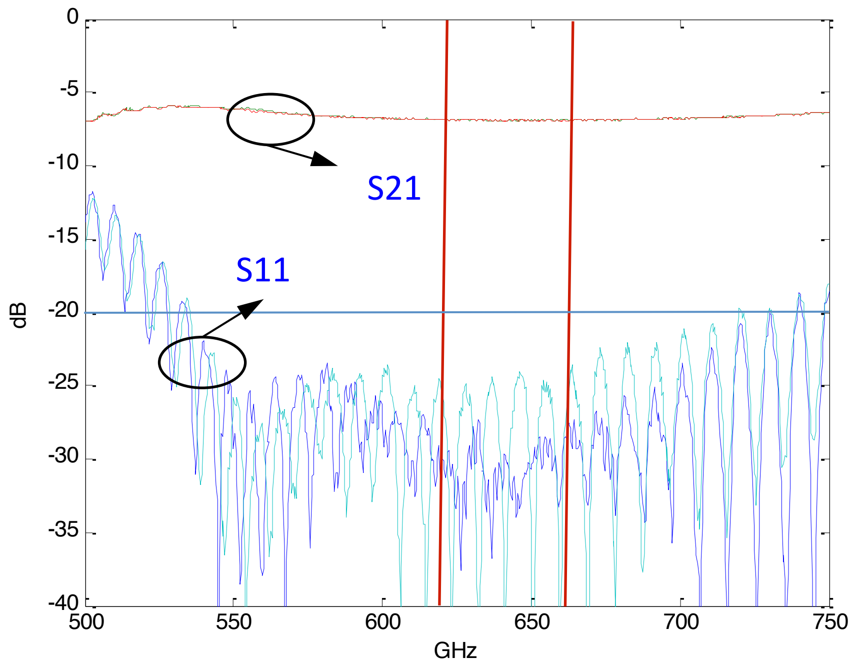


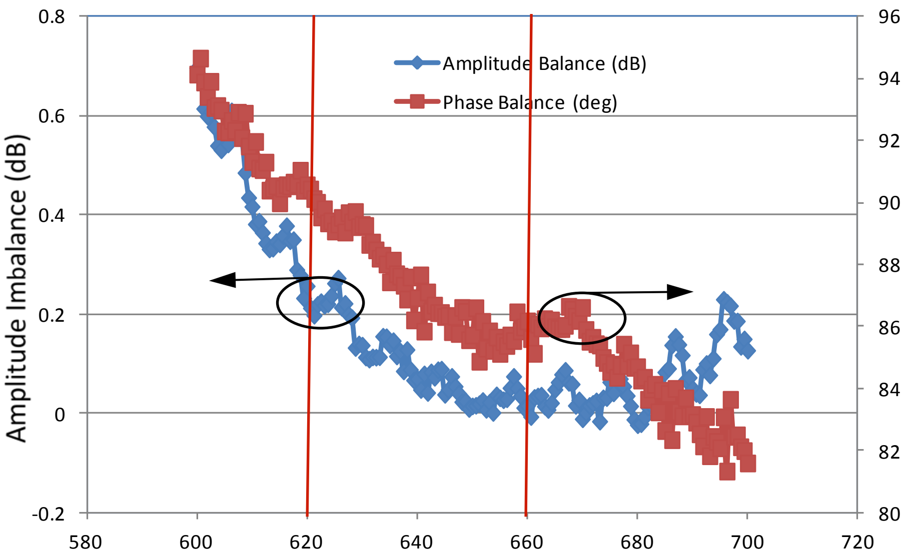
"Development of a Wideband Compact Orthomode Transducer for the 180-270 GHz Band," IEEE Trans. THz Sc. Tech., vol. 4, no. 5, pp. 634-636, September 2014.

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







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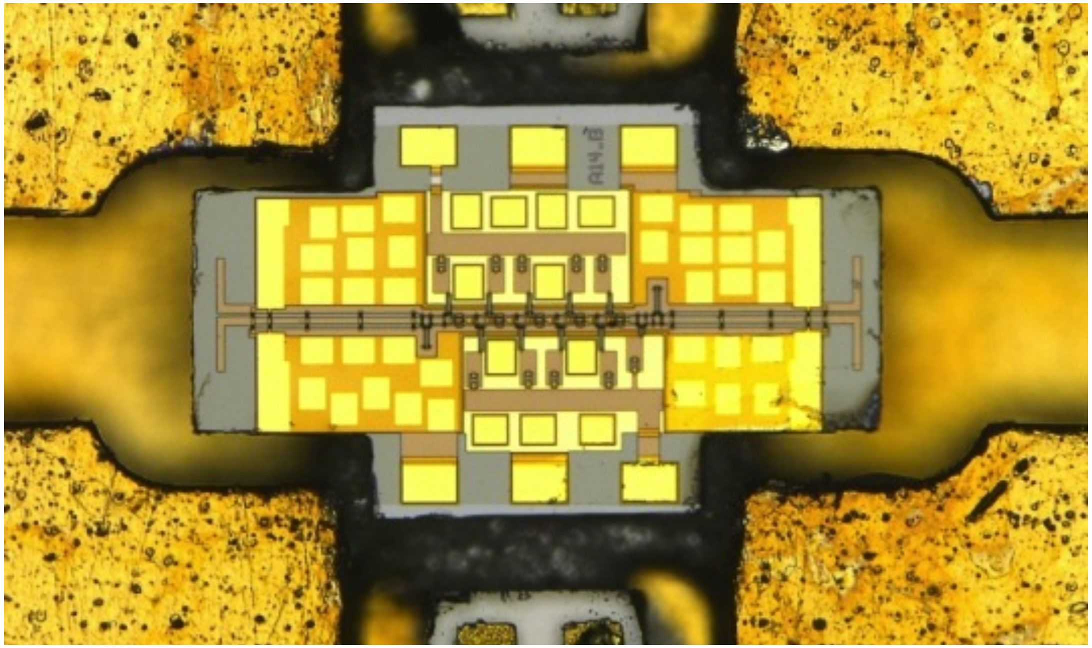
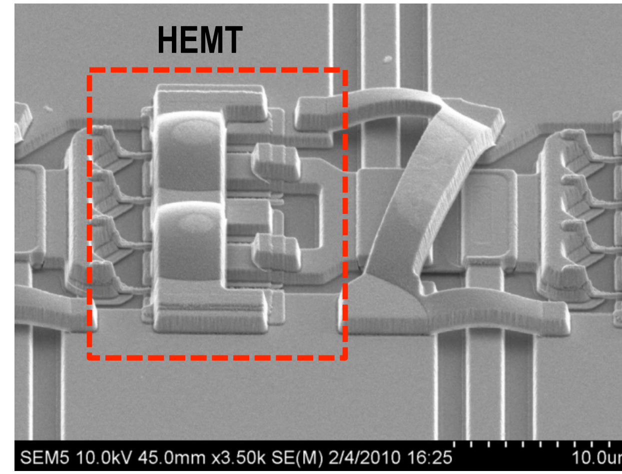
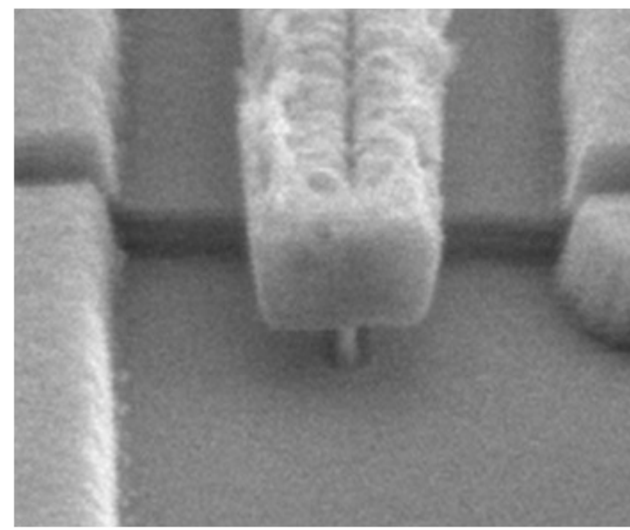
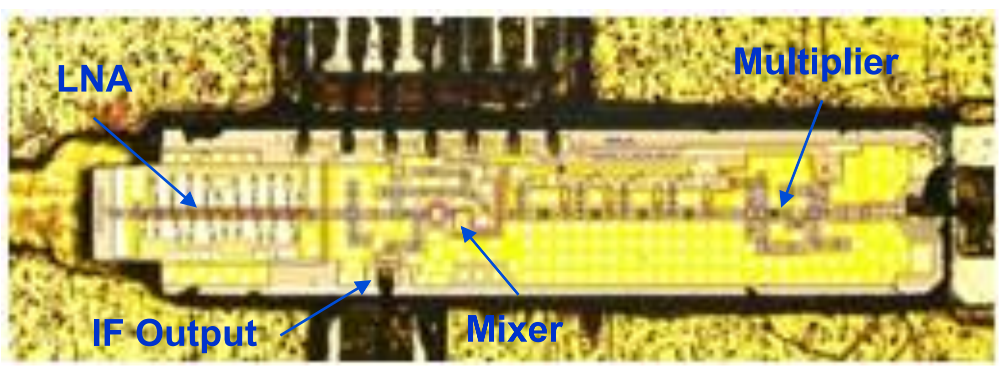
Terahertz InP HEMT Circuits





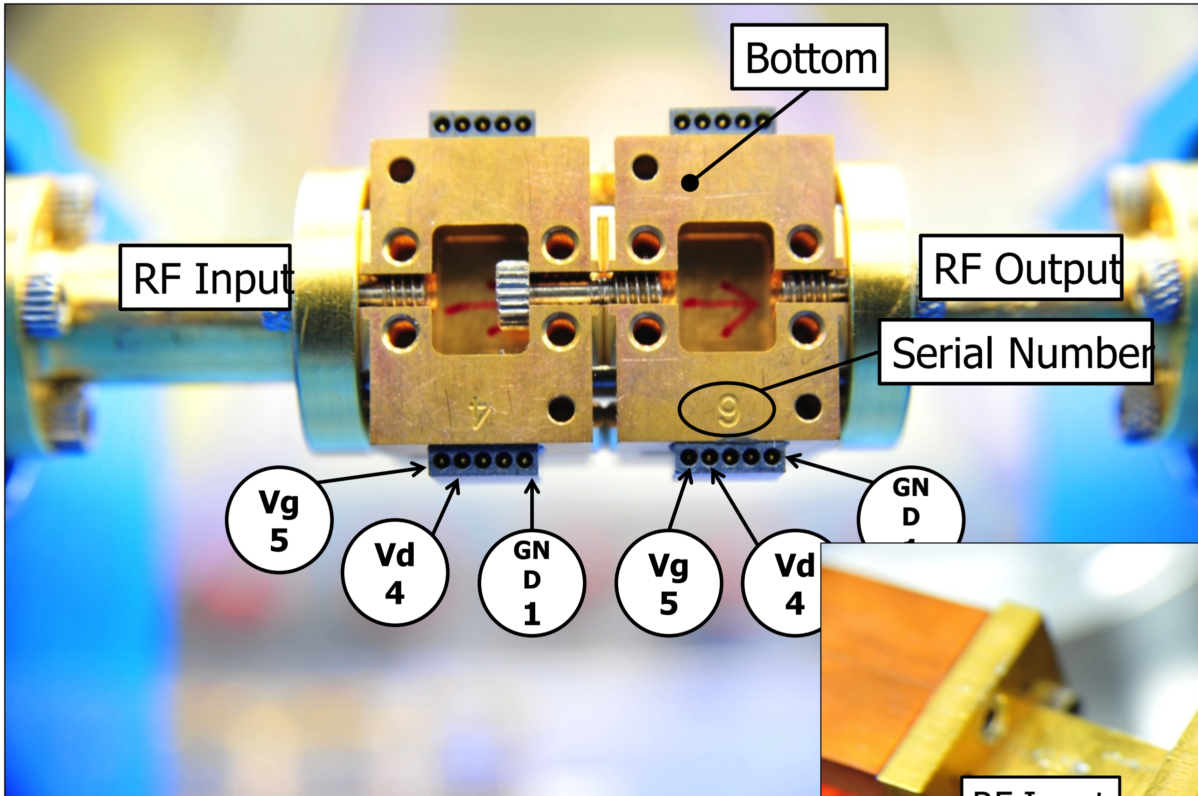


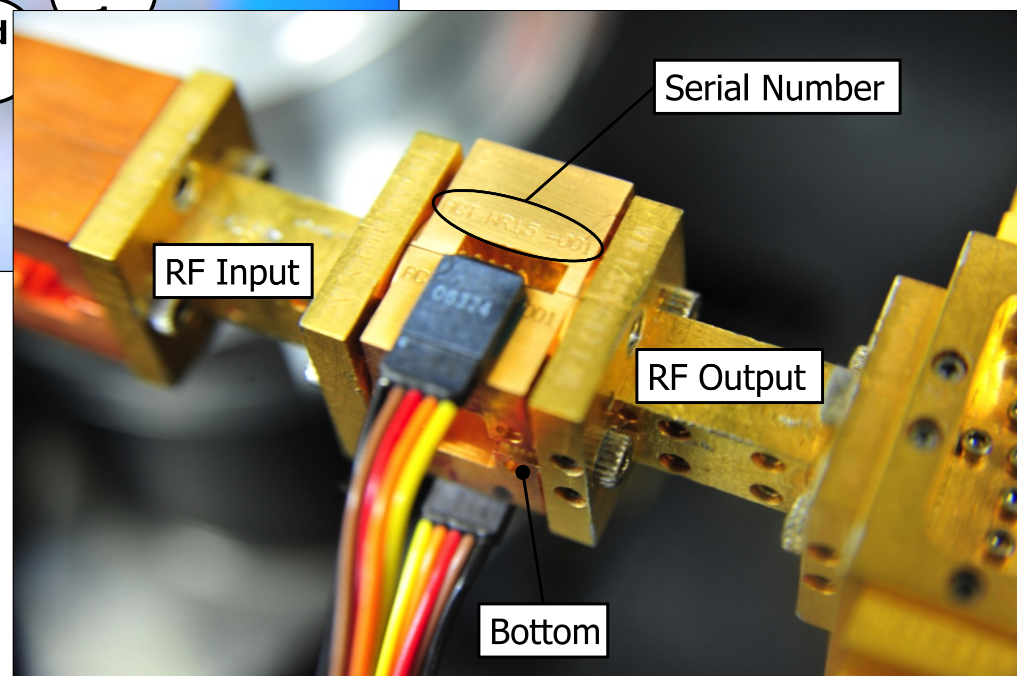
High Electron Mobility Transistor (HEMT) based Amplifier



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

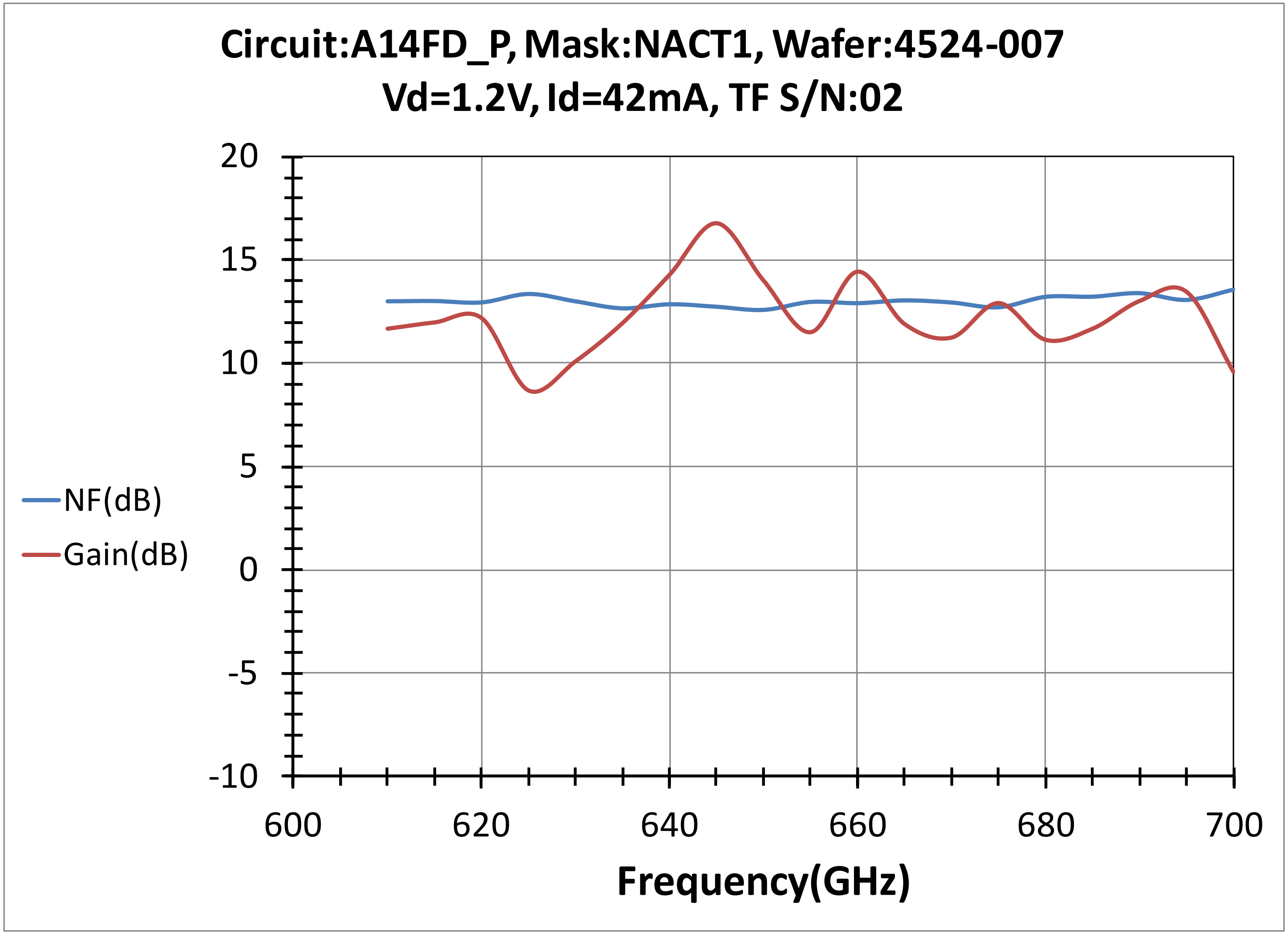
Terahertz InP HEMT Amplifiers





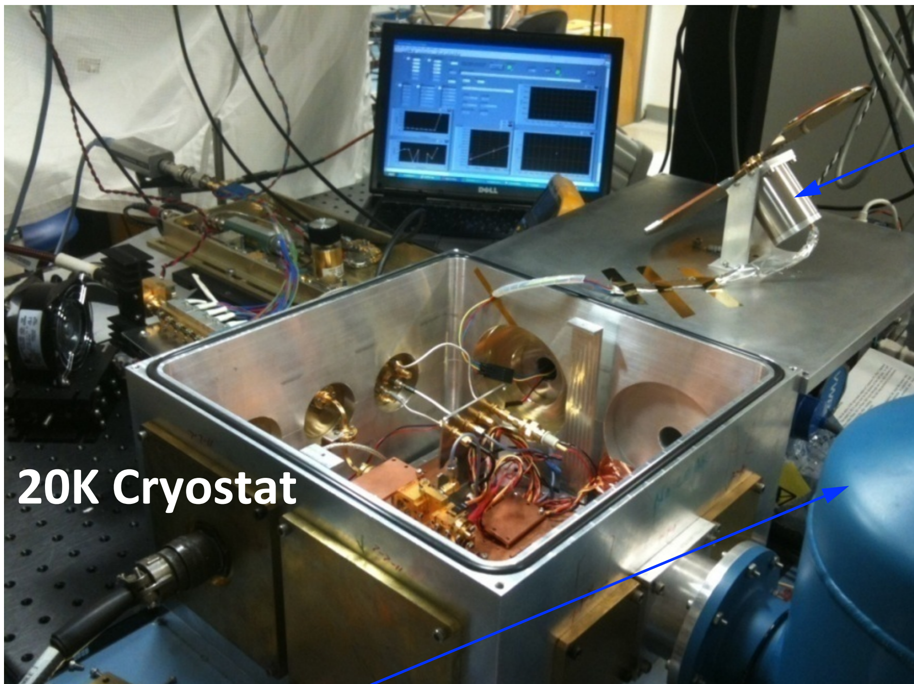
180-270 GHz and 620-660 GHz Amplifiers: S-parameters measured in waveguide packages.

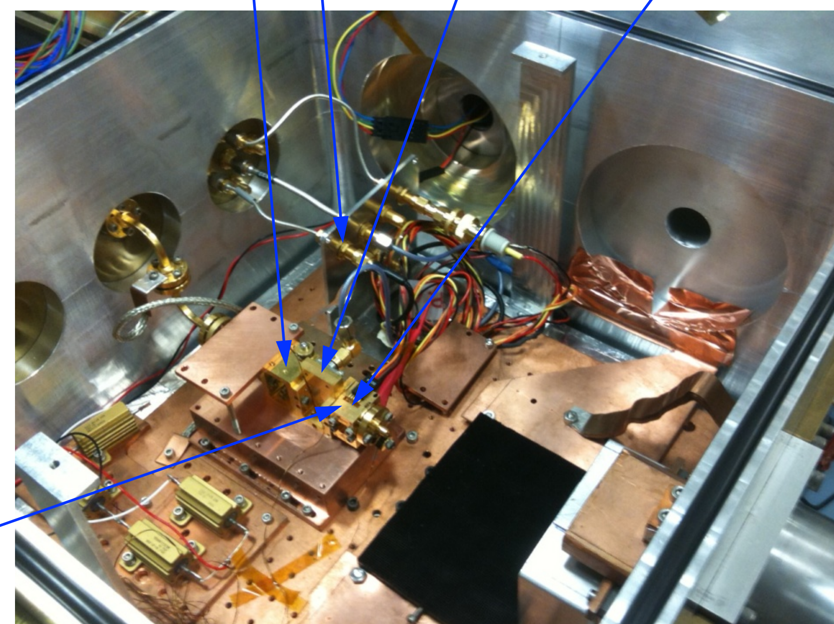
Terahertz InP HEMT Amplifiers



Cryogenic Measurement Set-Up

Cryogenic measurement set-up performs semi-automated measurements.





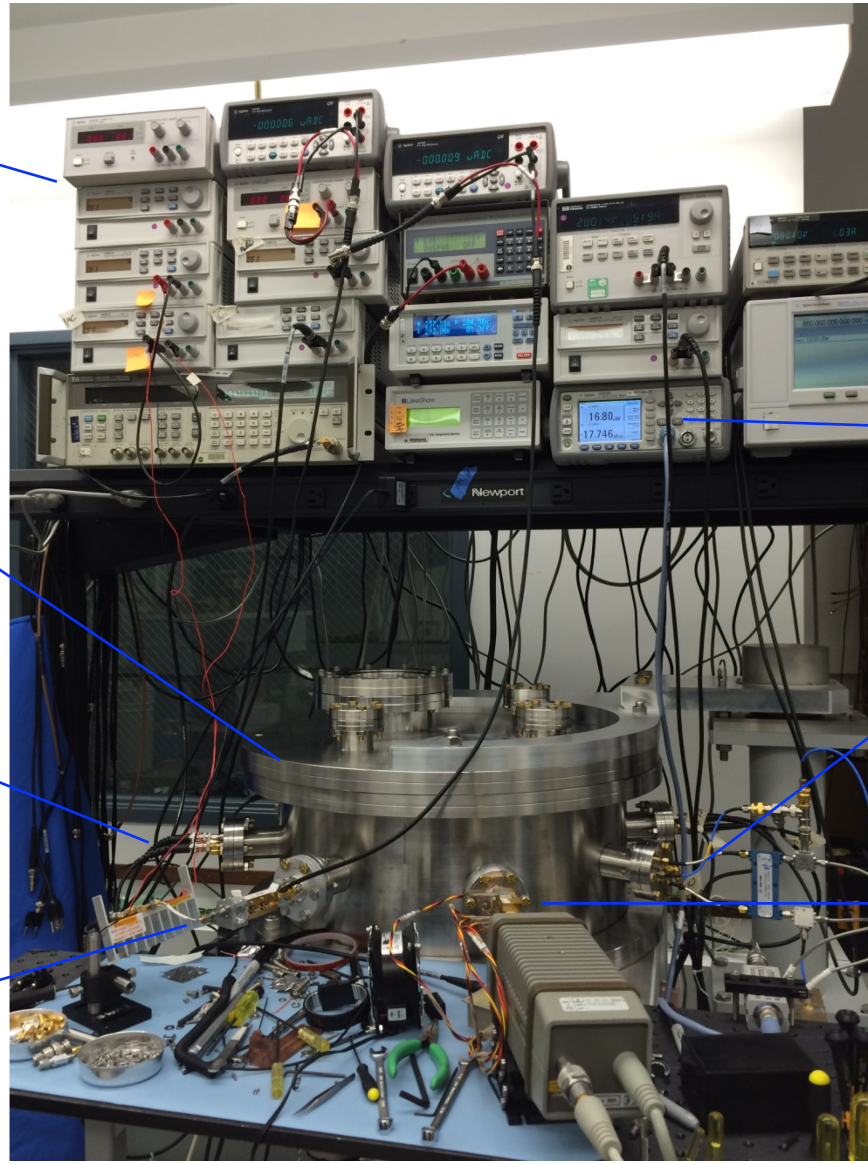
Cryogenic Measurement Set-Up

DC Bias

Cryostat

Bias Input

Signal Input for Sideband Measurement



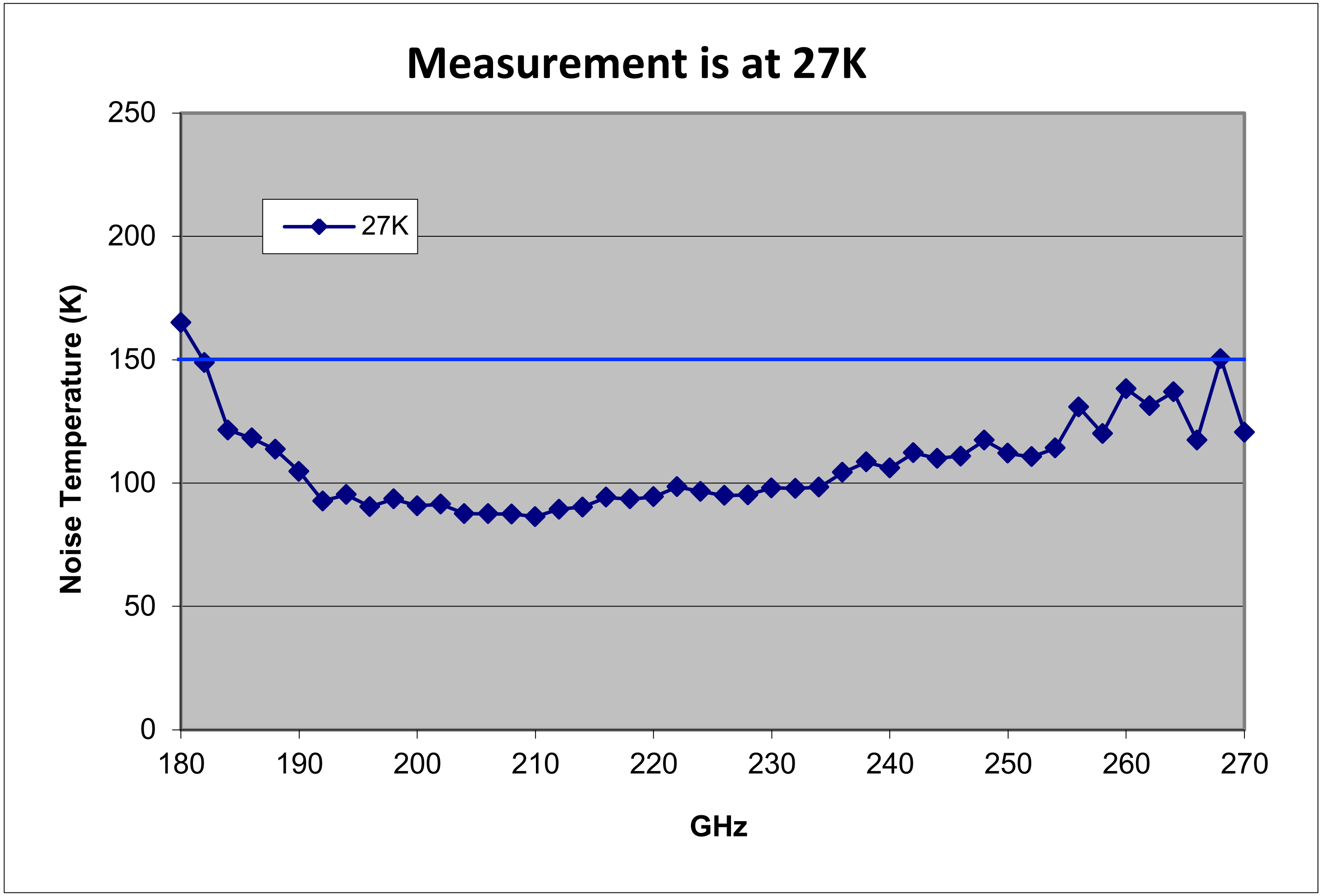
Power Meter

IF Output

Local Oscillator Input

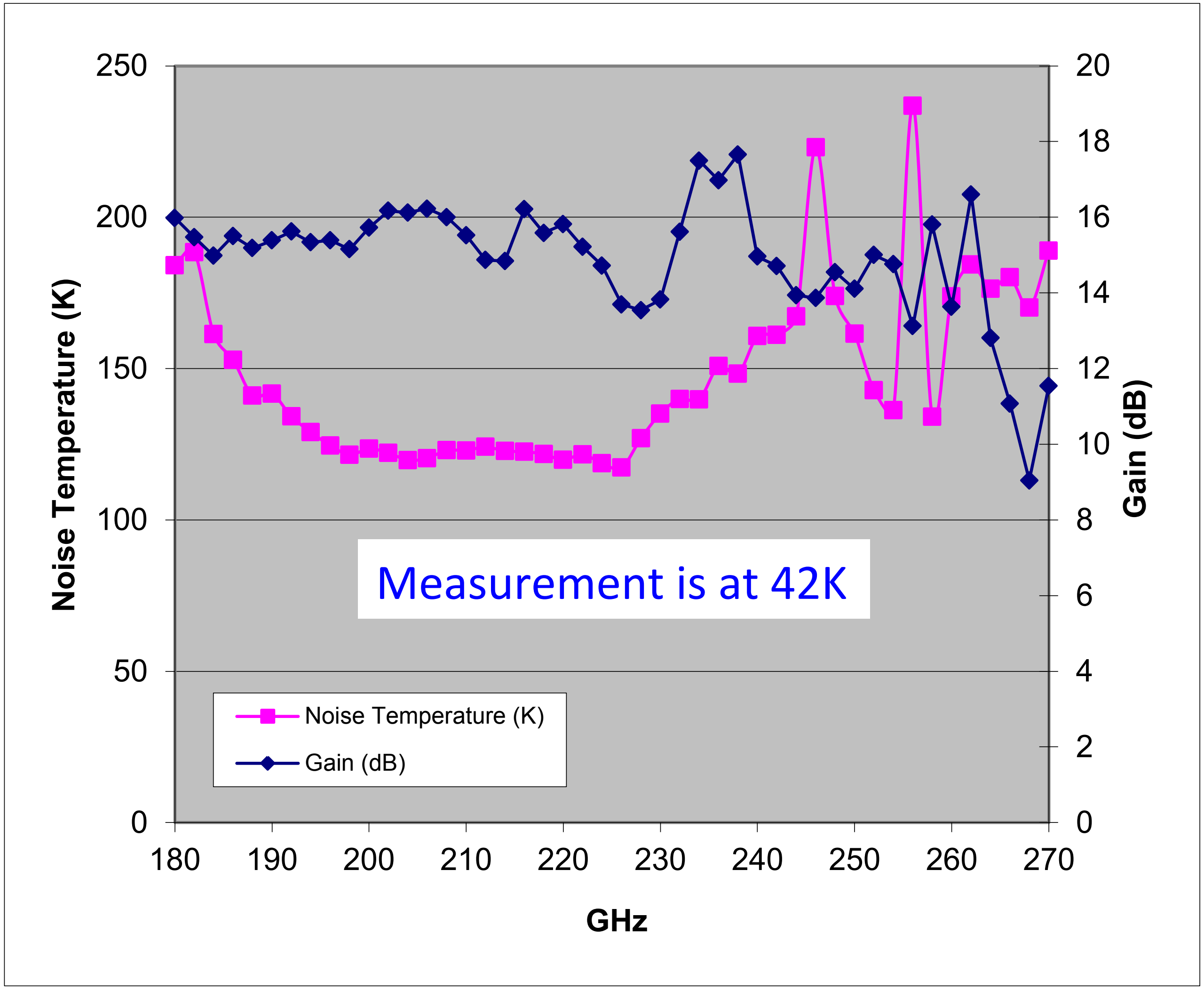
Amplifier Measurements

180-270 GHz Amplifiers: Cryogenic Noise Temperature Measurements



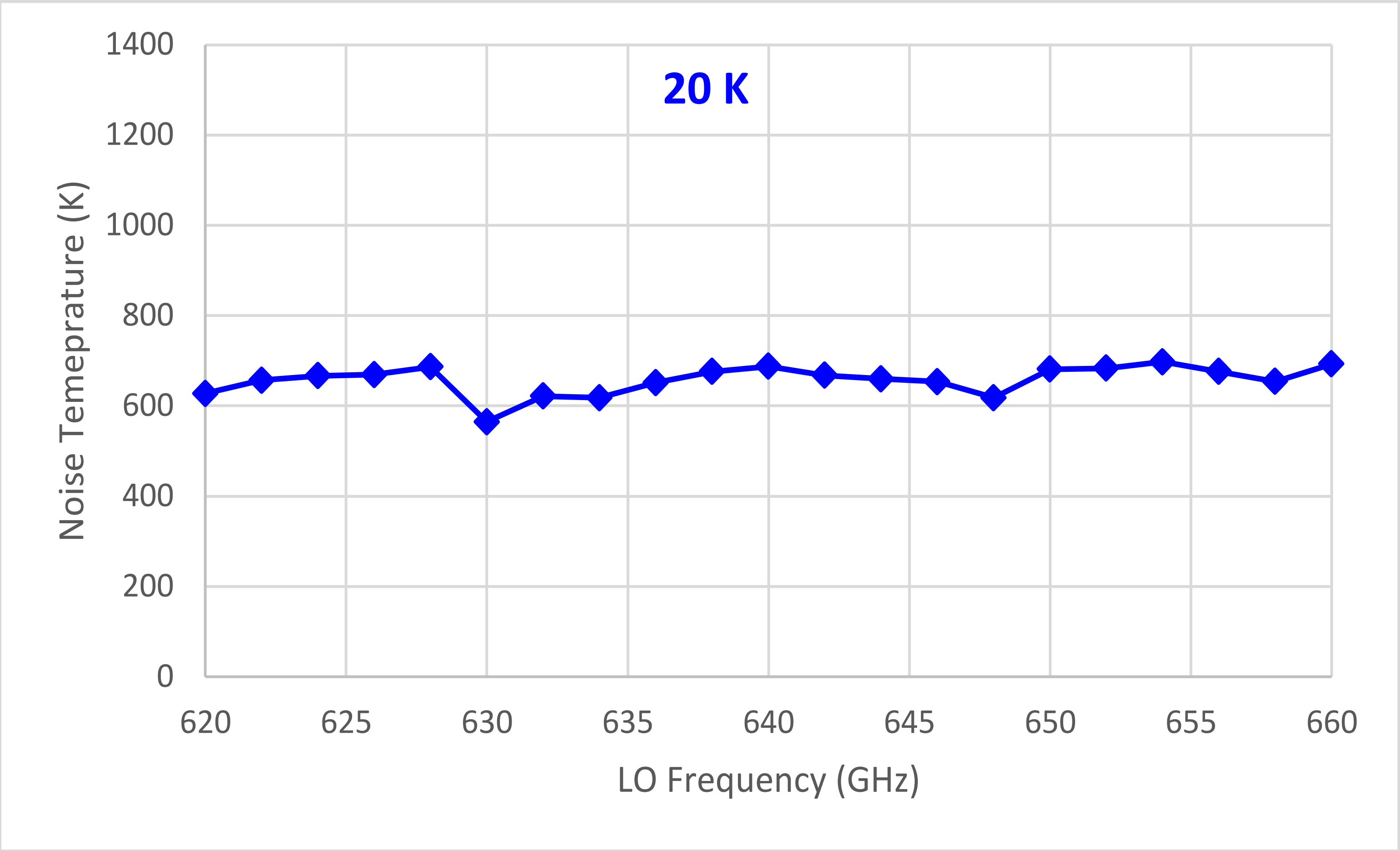
Amplifier Measurements

180-270 GHz Amplifiers: Cryogenic Noise Temperature Measurements



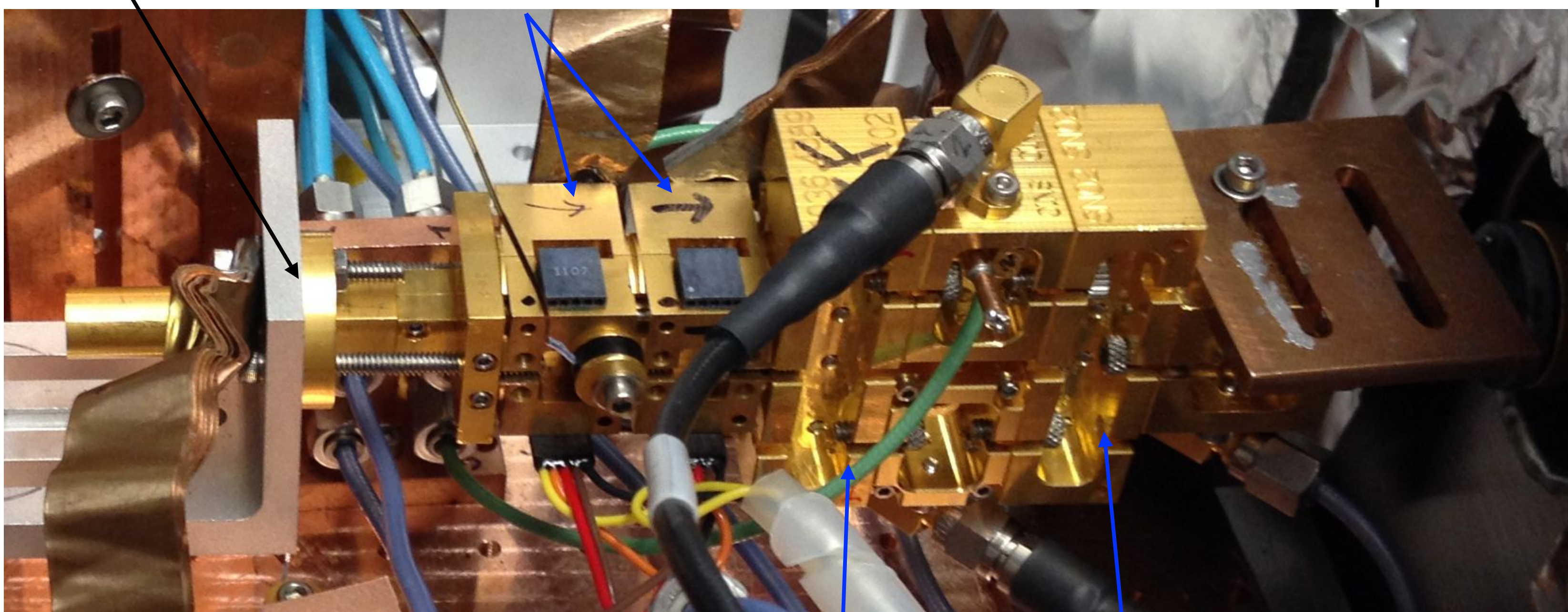
Amplifier Measurements

640 GHz Amplifiers: Cryogenic Noise Temperature Measurements

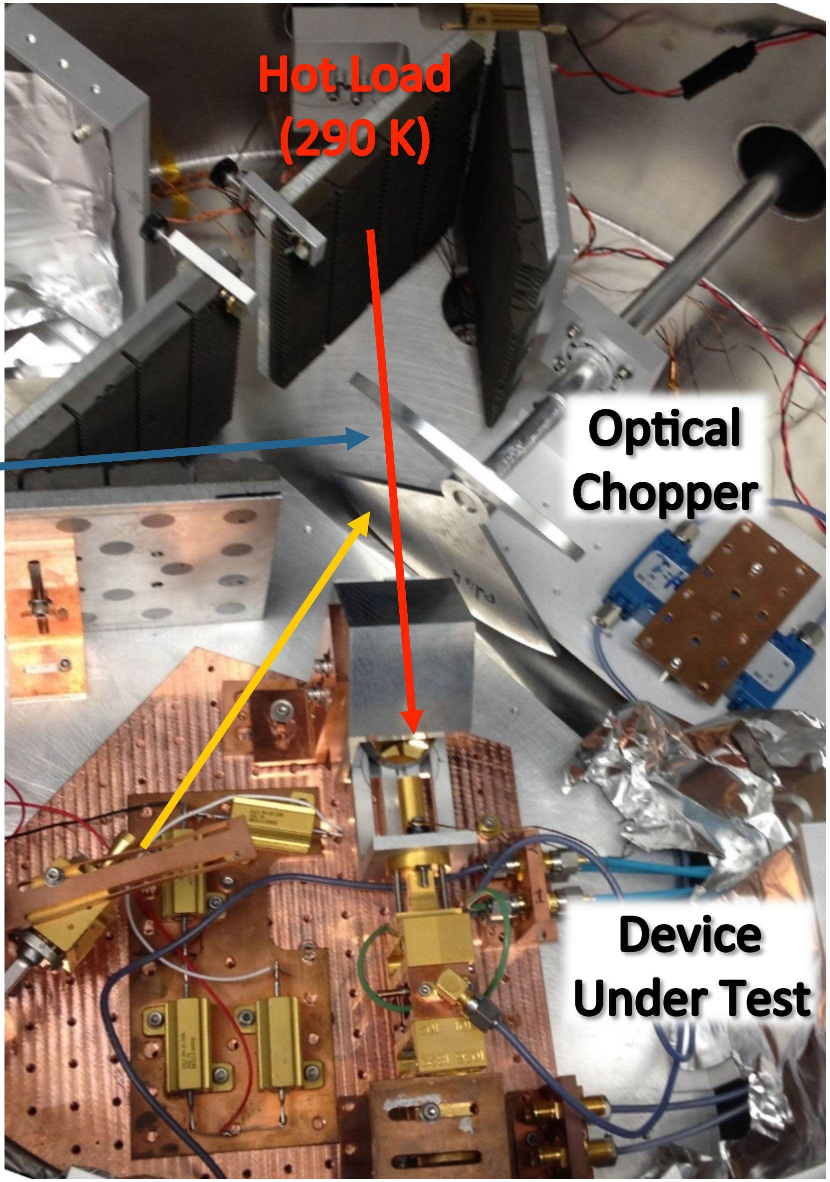


Best Measured Results (only two blocks had this results).

180-270 GHz Sideband Separated Receiver

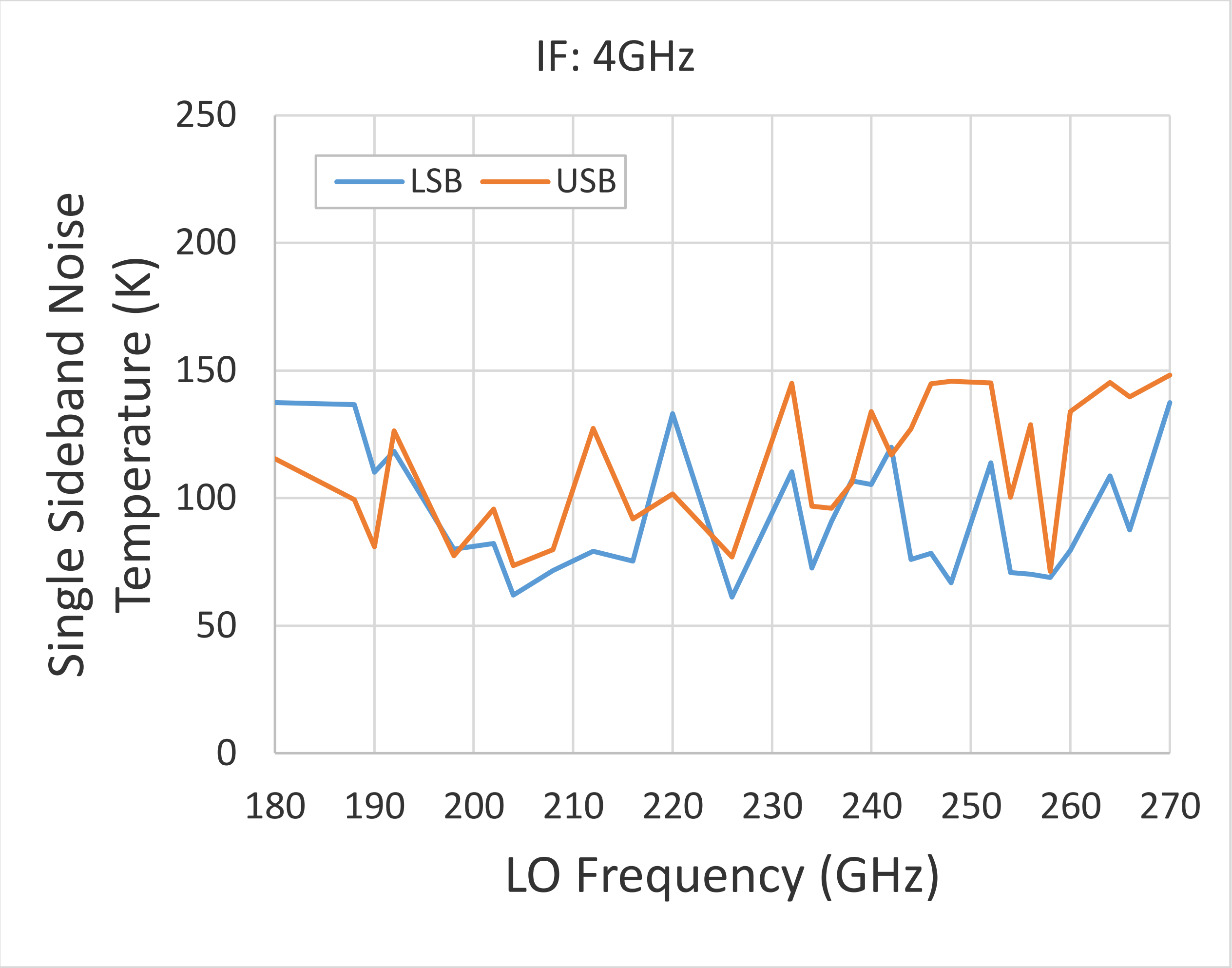


Cryogenic Sideband Separation Measurement



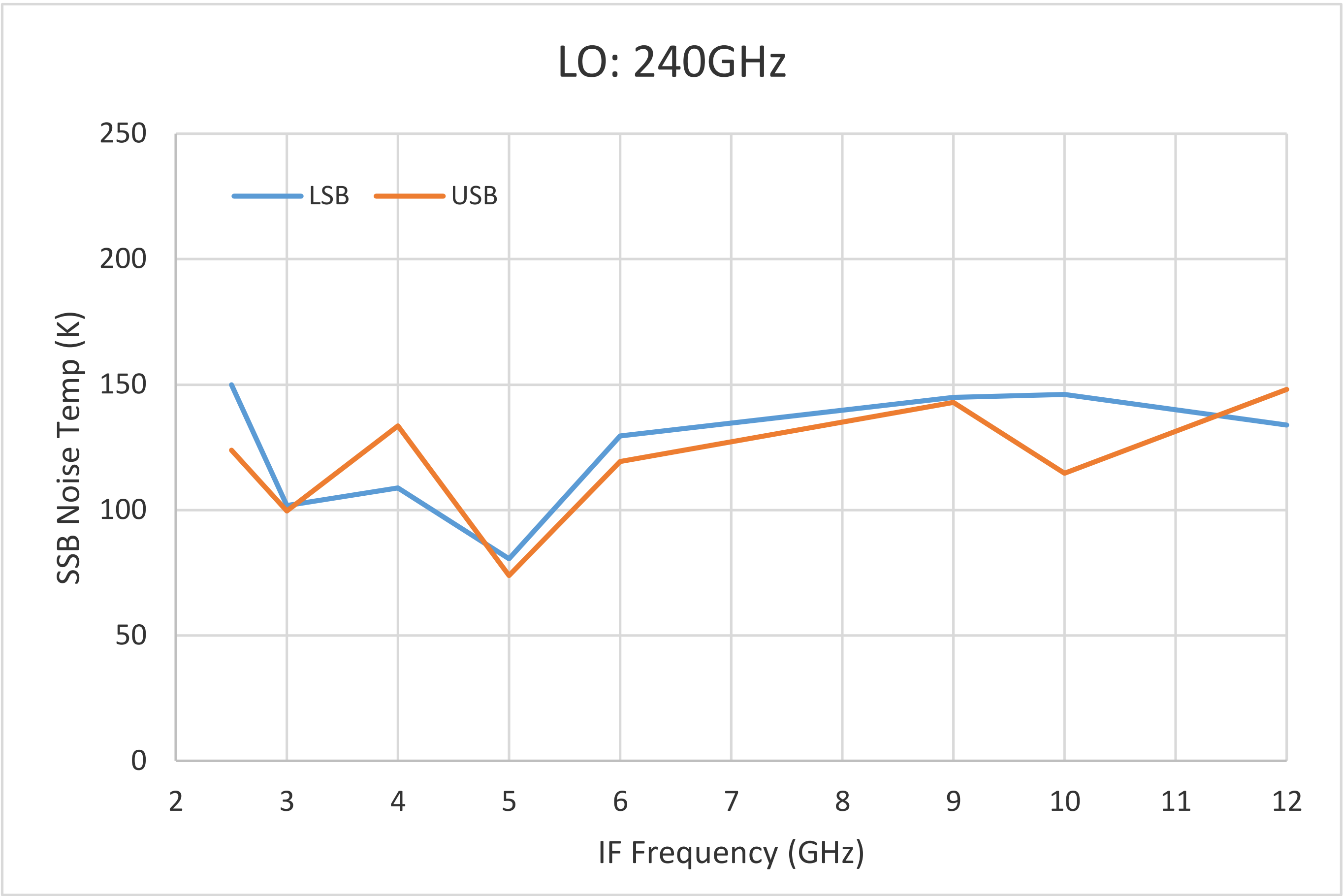
240 GHz Single Sideband Receiver Results

Noise Temperature at Both the Sidebands at 20K



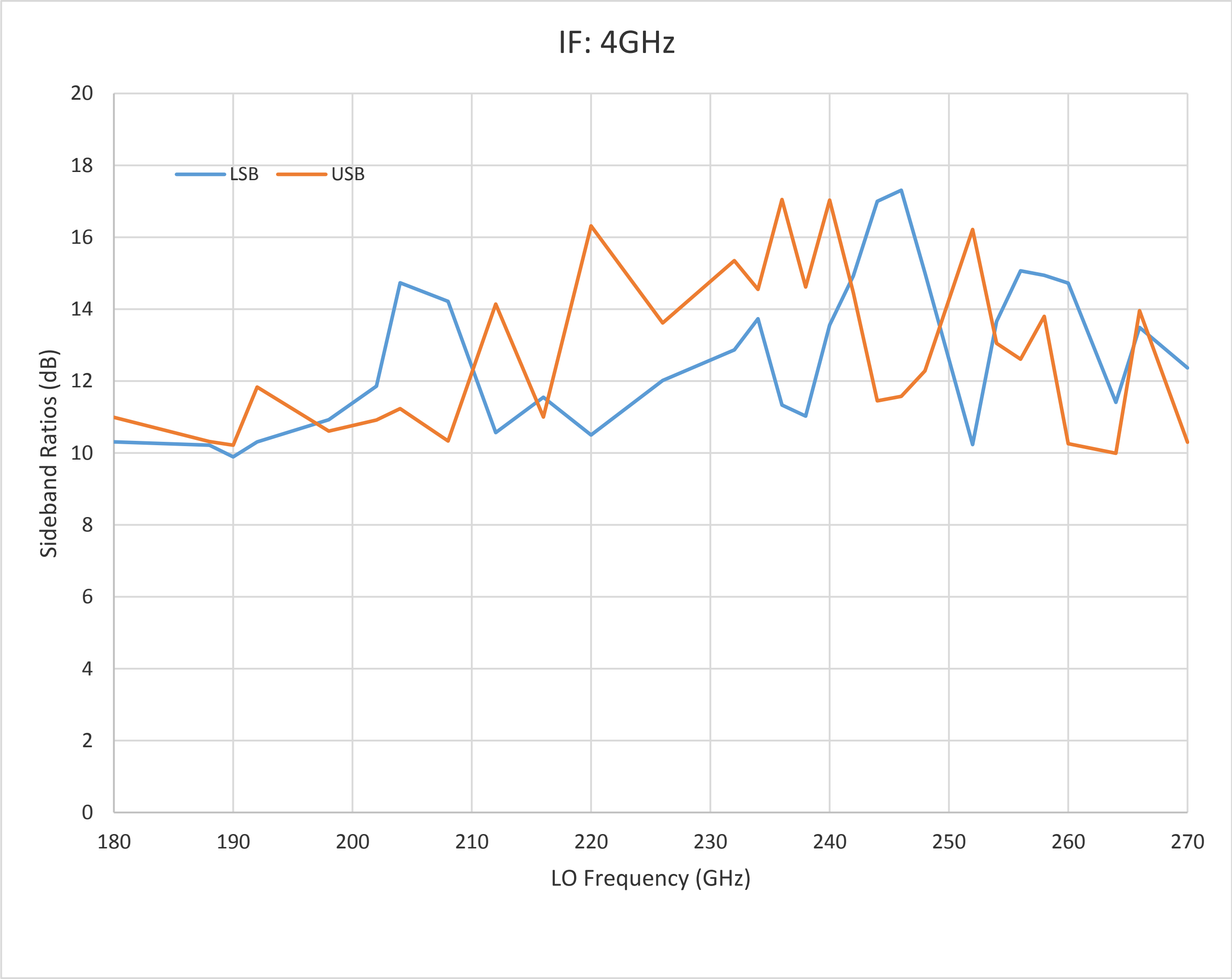
240 GHz Single Sideband Receiver Results

Noise Performance as a Function of IF Frequency at 20K



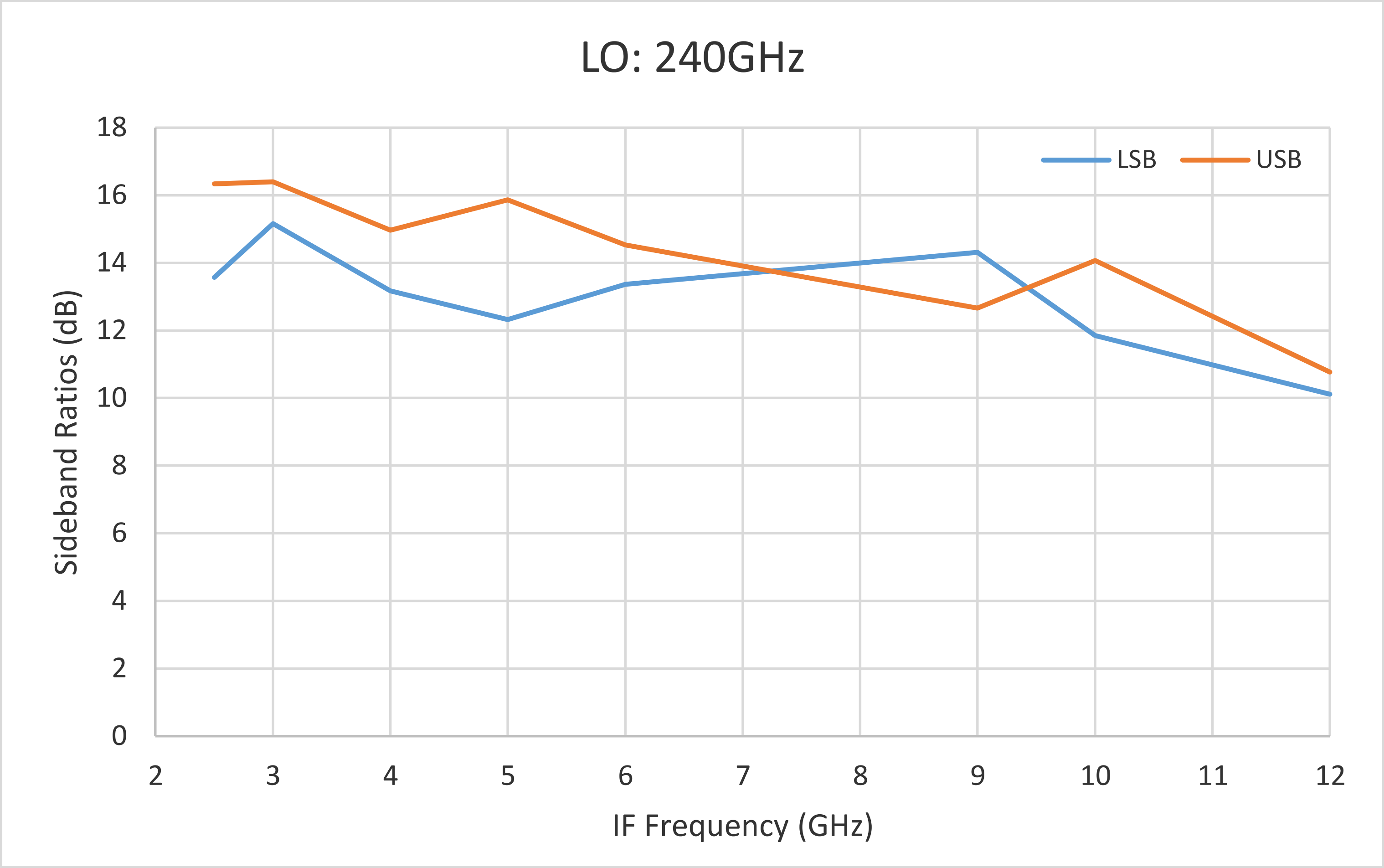
240 GHz Single Sideband Receiver Results

Sideband Ratios at 20K as a Function of RF Frequency



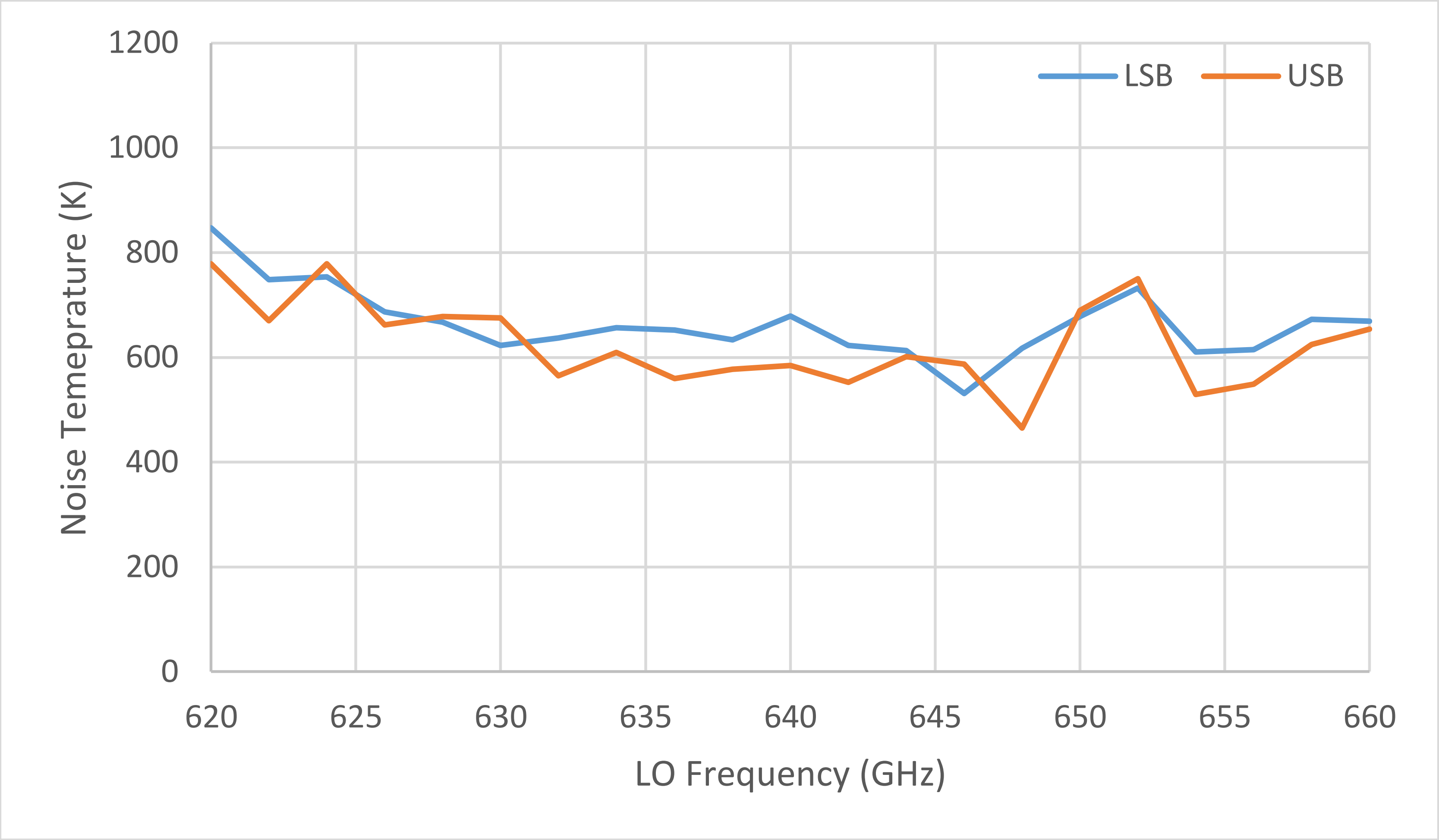
240 GHz Single Sideband Receiver Results

Sideband Ratios at 20K as a Function of IF Frequency



640 GHz Single Sideband Receiver Results

20K Results



Summary

- Cryogenic amplifiers at 640 GHz are showing a 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.
- Integrating mixers and frequency multipliers on the same chip leads to highly integrated receivers – opens the door for multi-pixel cooled terahertz receivers.

Acknowledgement

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