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LOW NOISE AMPLIFIERS FOR CRYOGENIC APPLICATIONS

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6/9/2026

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Overview: LNAs for Cryogenic Applications

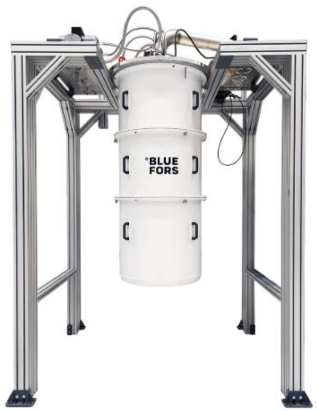
WHAT IS A CRYOGENIC ENVIRONMENT?

- Extremely cold ambient temperature:
  - 77 Kelvin (Liquid Nitrogen)
  - 4.2 Kelvin (Liquid Helium)
  - 10 to 50 millikelvin (Dilution Refrigerator)
- Vacuum pressurized chamber to prevent condensation and icing.
- Thermally insulated to minimize heat transfer from the outside.

WHAT IS A CRYOGENIC LNA?

- Low noise amplifiers designed to operate in a cryogenic environment:
  - Amplify signals while contributing the least added noise as possible.
  - Required for processing very low power signals typical in applications such as radio astronomy and quantum computing.
  - Designed to dissipate only a small amount of DC power to reduce the amount of heat added to the environment (usually between 0.2 and 10 mW)

XLDSI DILUTION REFRIGERATOR SYSTEM FROM BLUEFORS [1]



PROS & CONS OF OPERATING LNAS AT CRYOGENIC TEMPERATURES

Advantages:

- Achieve the best noise figure performance.
- Functional over very wide temperature range.
- Operate with low power consumption.

Disadvantages:

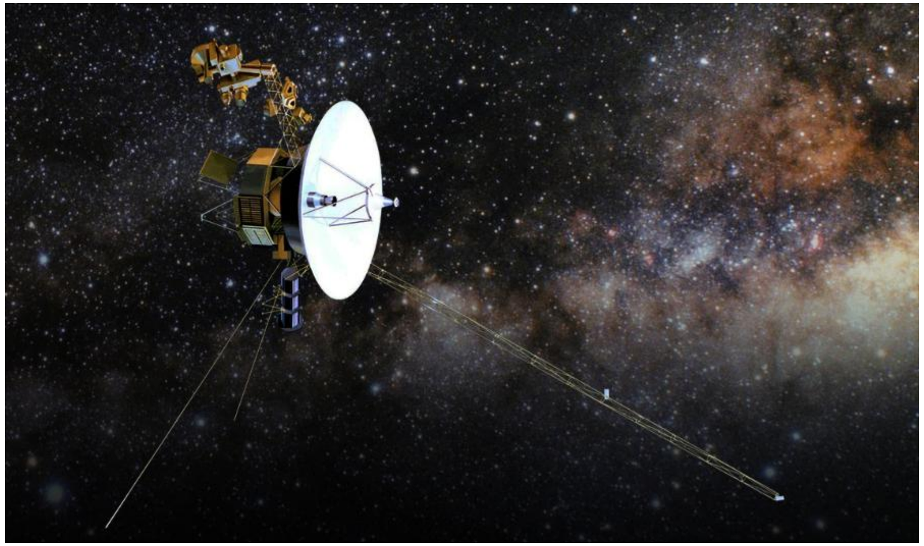
- Maintaining RF stability is more challenging.
- Need to withstand greater mechanical stresses (especially during cool down and warm up cycles).

Historical Applications: Established Uses of Cryogenic LNAs

Radio Astronomy:

- Uses EM radiation to study celestial objects in outer space.
- RF signals from space are received by a large antenna or antenna array.
- Requires highly sensitive receivers, which employ cryogenic LNAs.
- The signals are then processed and used to create images of the bodies that emitted them (for example, a heatmap showing object temperature). [2]

National Radio Astronomy Observatory: Atacama Antenna Array [3]



NASA’s Voyager 1 Spacecraft [4]

Deep-Space Communication / SATCOM:

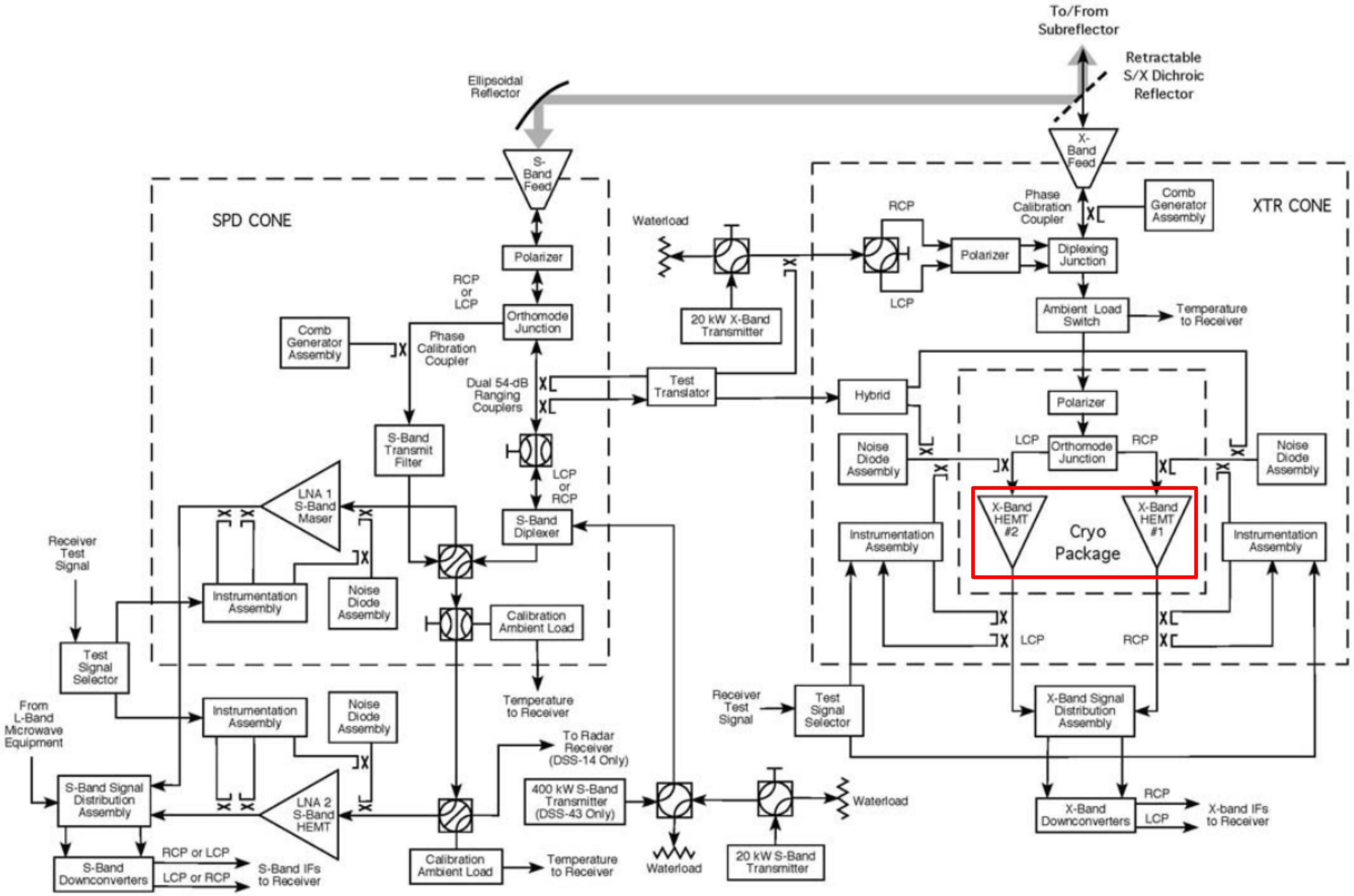
- Transmitting and receiving information between the Earth and distant spacecraft, for the command and control of such spacecraft and the receipt of telemetric and scientific data. [5]
- Cryogenic LNAs are used in ground stations to amplify the extremely weak signals sent to Earth by various satellites.

LNAs for Deep Space Communication: Enabling Celestial Exploration

NASA Deep Space Network (DSN) Station near Canberra, Australia [6]

Purpose of Cryogenic LNA:

- Amplify signals received from the tracked spacecraft / satellite.
- Located as close to the feed horn antenna as possible to minimize front-end losses.
- Typical System Performance [7]:
  - Noise Temperature ≈ 10 - 20 K (depending on frequency band & diplexing mode)
  - Receiver Gain > 60 dB

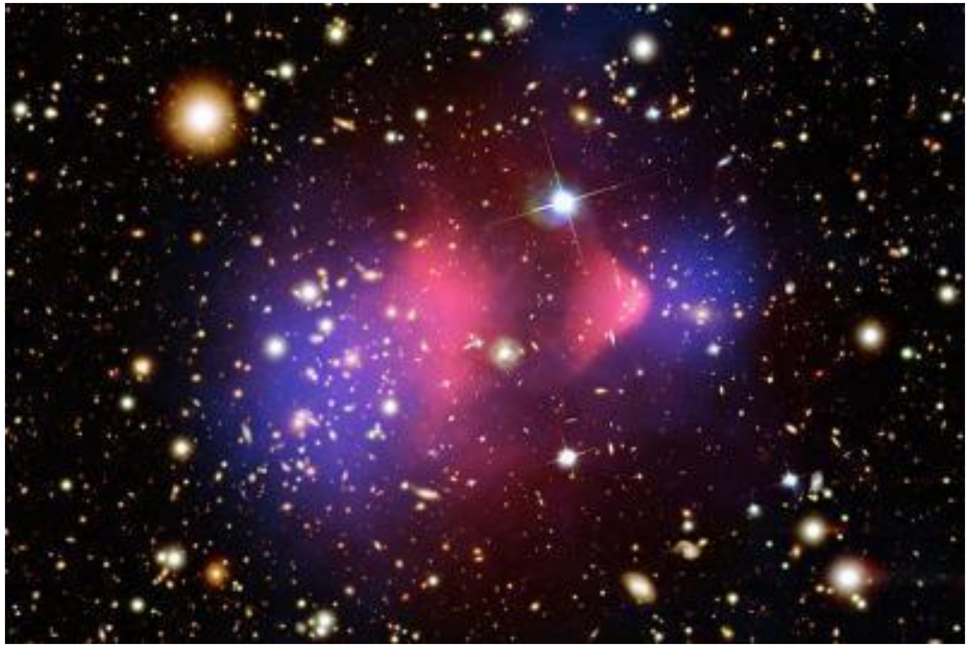


Functional Block Diagram of NASA DSN 70-m Microwave & Transmitter [8]

Emerging Applications: New Industries Employing Cryogenic LNAs

Low Temperature Physics Research:

- Involves the study of cosmological activity as well as the behavior of sub-atomic particles.
- One example is cryogenic LNAs are used to detect dark matter and other very low energy emitting phenomena. [9]



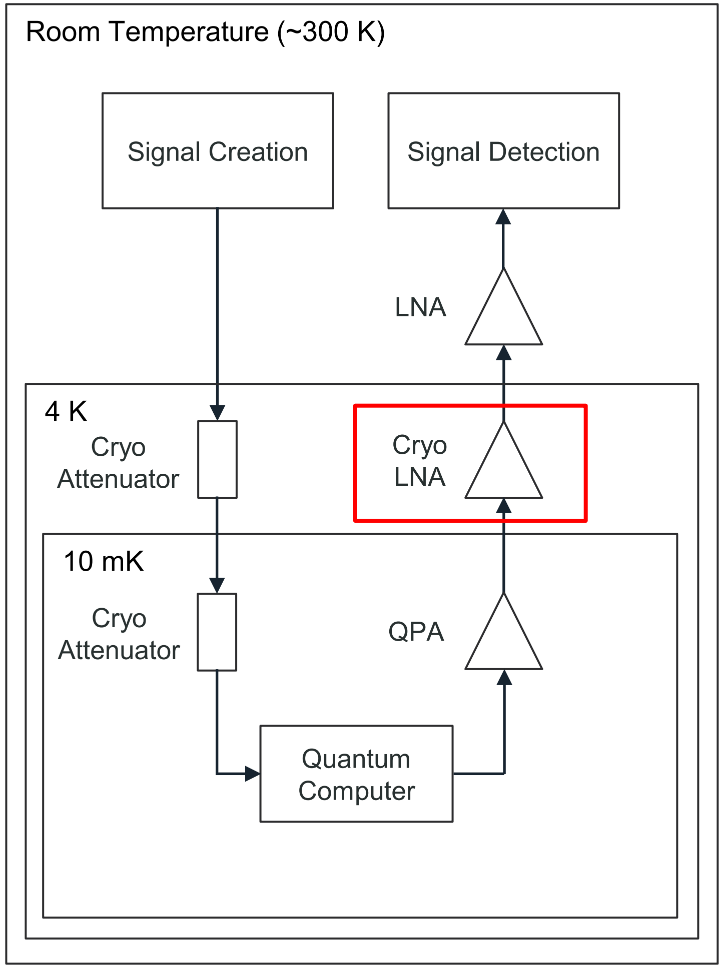
A collision of clusters of galaxies, showing separation of dark matter (shaded blue) from normal matter (shaded pink) [10]

IBM Quantum System Two [11]

Quantum Computing:

- Perform computations that require conventional computers to take an exponentially longer amount of time to complete.
- Highly anticipated developing technology with large investment backing.
- Uses cryogenic LNAs in the qubit readout chain to amplify the computed output.
- Lowest noise performance is necessary for minimizing readout error.

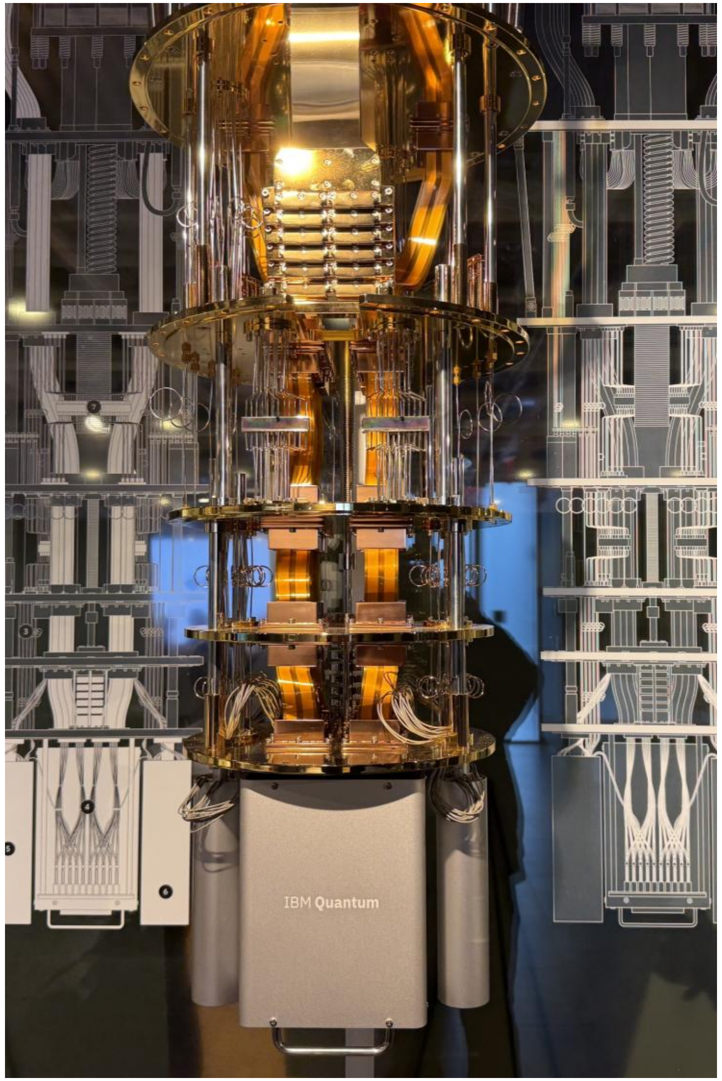
LNAs for Quantum Computing: Essential for Accurate Readout



Simplified Block Diagram of Quantum Computer

Function of the Cryogenic LNA:

- Provide qubit readout amplification while minimizing added noise.
- 2nd stage in the readout signal chain, preceded by a QPA (Quantum Parametric Amplifier).
- Usually accomplished using HEMT (High Electron Mobility Transistor) technology.
- Can also be implemented using Cryo-CMOS (Cryogenic Complimentary Metal Oxide Semiconductor) technology.
- Typical Characteristics & Performance Criteria:
  - Frequency Range, usually sub-bands inside 4 to 12 GHz
  - High Gain, > 30 dB
  - Low Noise Temperature, < 8 K
  - Minimal Power Consumption, < 5 mW
  - Small Physical Size



IBM Quantum Computer (Watson Research Center)

Device Technologies: Advantages and Disadvantages

Cryo-CMOS

Key Advantages:

- High Potential for Mass Production
- Lowest Fabrication Cost

Main Disadvantages:

- Highest Noise Figure
- Highest Power Consumption for Competitive Performance

SiGe HBT

Key Advantages:

- Can be Integrated with CMOS
- Lower Fabrication Cost than InP & GaAs

Main Disadvantages:

- Higher Noise Figure than InP
- Worse at Higher Frequencies than InP & GaAs

GaAs pHEMT

Key Advantages:

- Extensive Industry Heritage
- More Robust than InP

Main Disadvantages:

- Higher Cost than SiGe
- Diminished Electron Mobility Improvement as Temperature Decreases Compared to InP

InP HEMT

Key Advantages:

- Lowest Noise Figure
- Excellent Performance at Low DC Bias

Main Disadvantages:

- Highest Fabrication Cost
- Most Fragile Material

Discrete Technology

Advantages:

- Offers More Design Flexibility
- Precise Tunability Enables Best Achievable Performance

Disadvantages:

- High Manufacturing Complexity
- More Expensive to Mass Produce than MMIC based LNAs

MMIC Technology

Advantages:

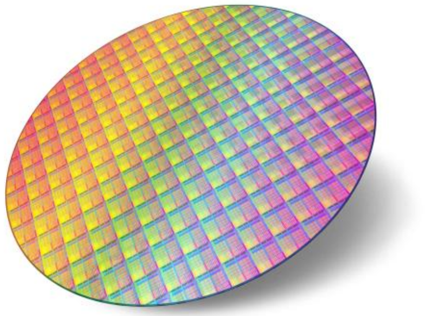
- Consistent Performance Yield
- Easier to Mass Produce

Disadvantages:

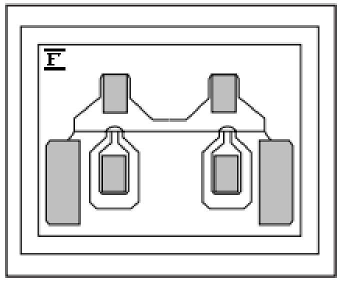
- Expensive to Fabricate Small Quantities
- Performance not quite on par with Hybrid Approach

Terminology:

InP → Indium Phosphide
GaAs → Gallium Arsenide
SiGe → Silicon Germanium
pHEMT → Pseudomorphic HEMT

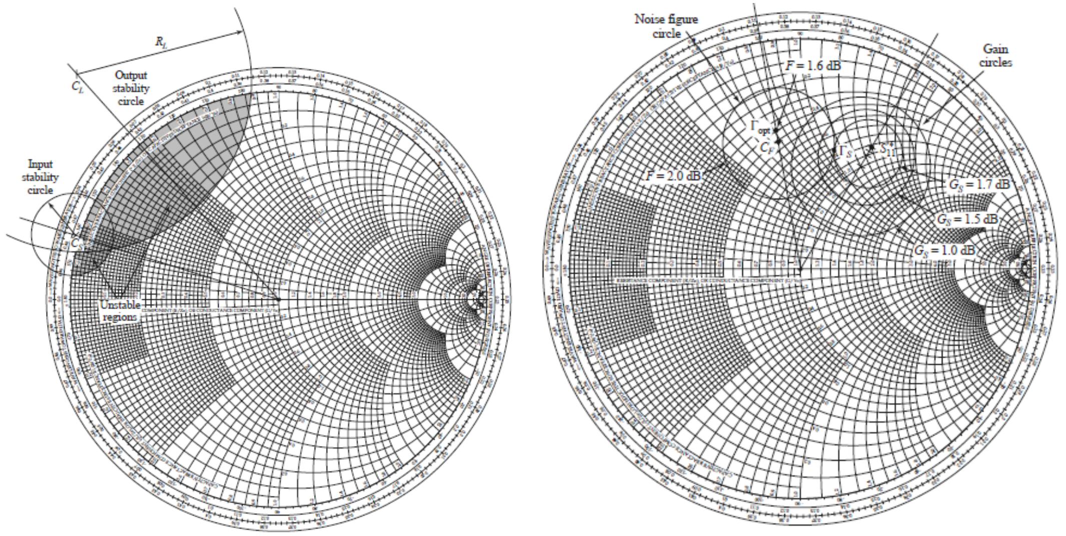


Silicon Wafer

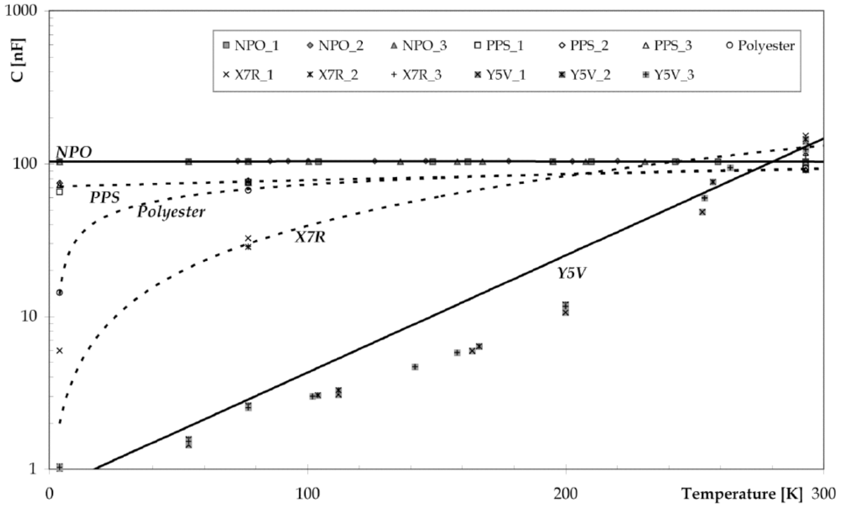


GaAs pHEMT FET [12]

LNA Design Considerations: Criteria for Operation at Cryogenic Temperatures



Example of stability circles (Left), Constant-gain & constant-noise figure circles (right) [13]



Different Types of 100 nF Capacitors, Capacitance vs Temperature [14]

Choosing Device Technology & Topology:

- Semiconductor material and transistor / MMIC type selected to meet the demands of the targeted application (scale, required performance, budget, etc.).

Selecting Components & Materials:

- Capacitors, resistors, etc. must maintain their characteristics at extremely cold temperatures.
- The designer should assess the component value degradation that can be tolerated.
- Metals and dielectric substrates need to have compatible temperature expansion properties.

Rigorous Circuit Design:

- The LNA must remain stable throughout the entire operating temperature range, without sacrificing in-band performance (S-parameters both in-band and out-of-band need to be considered).
- Minimizing front-end losses and proper impedance matching into the first stage active device are crucial.

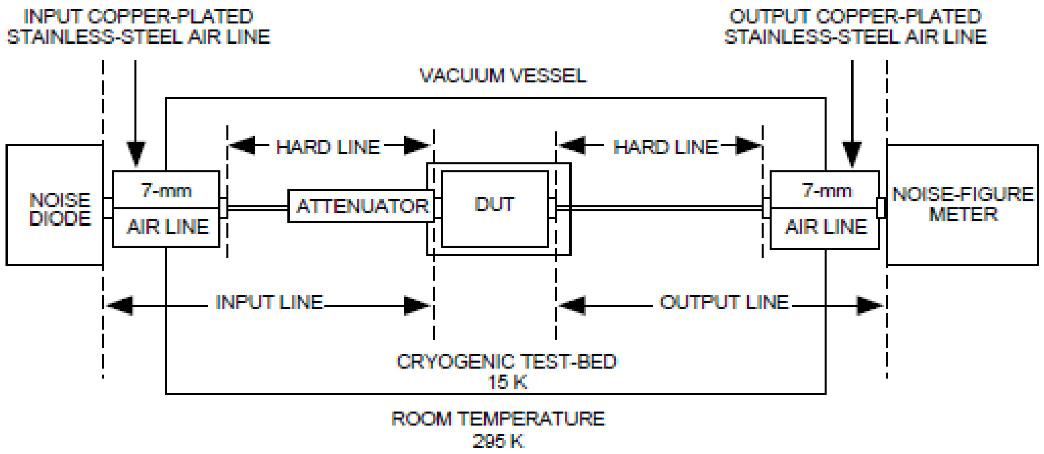
LNA Characterization: Making Measurements at Cryogenic Temperatures

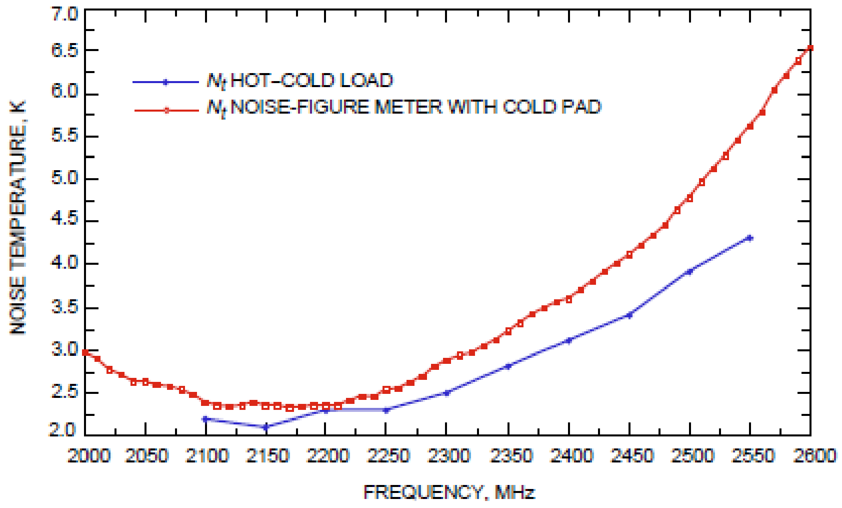
Testing S-Parameters:

- Full 2-Port Calibration:
  - Yields most accurate results
  - Necessary to measure Return Loss
  - Very time consuming & costly to perform
- Response Calibration (Thru-Cal):
  - Provides acceptable accuracy
  - Used only for Gain (S21) measurements
  - More practical & economical setup

Measuring Noise Temperature:

- Internal Hot-Cold Load Method:
  - Allows precise control of input noise to LNA
  - Slow measurement time is inconvenient
  - Care must be taken to prevent LNA heating
  - Sensitive to load impedance changes
  - Commercially available cryogenic H/C loads are scarce
- Cold Attenuator Method:
  - More accessible & still reasonably accurate
  - Input loss & noise source ENR accuracy are critical
  - Impedance changes have diminished effect on LNA
  - Faster test speed, easily obtain more data points





Block Diagram of Cold Attenuator Noise Measurement System (Top) [15]
Results Comparison Between Hot-Cold Load & Cold Attenuator Methods (Bottom)

Conclusion: LNAs for Cryogenic Applications

CRYOGENIC LOW NOISE AMPLIFIER, 6.0 - 9.0 GHz

CLNA-XX-0600-0900-5P-ND-DB

Revision 1.0

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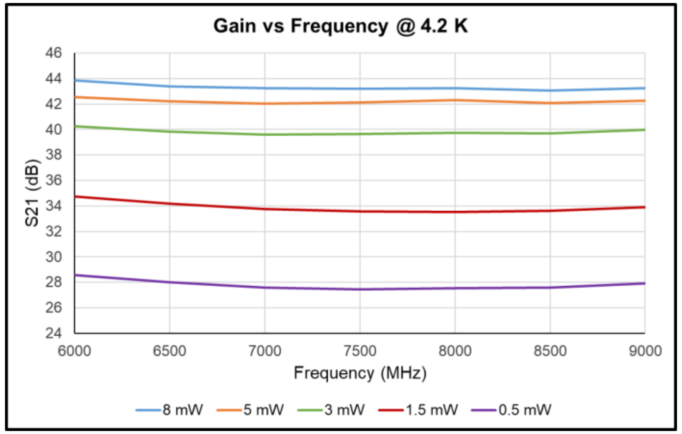
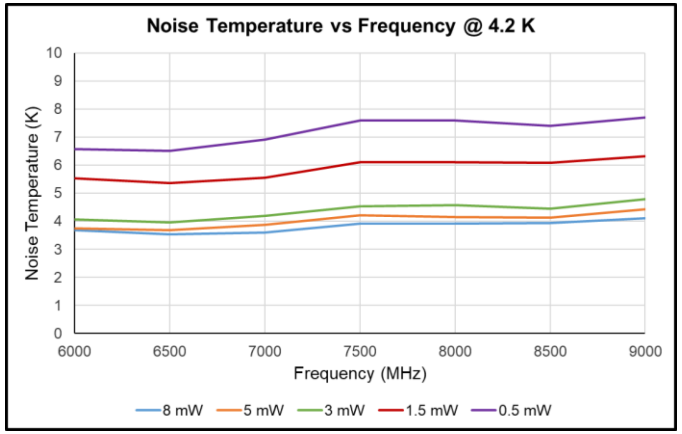
FEATURES

- Ultra Low Noise Performance
- Low DC Power Consumption
- Wide Operating Temperature Range: 4 K to +75 °C
- RoHS Compliant
- RF Ports Matched to 50 Ohms

TYPICAL APPLICATIONS

- Quantum Computing
- Radio Astronomy
- Deep Space Communication
- Satellite Communications
- SIGINT
- Low Temperature Physics





Narda-MITEQ’s CLNA Series:

- Typical Dual Bias Performance (Shown Left)
- Non-Magnetic Package Version (Shown Above)
- Typical Bias Settings:
  - 0.5 mW → V_D = 0.08 V, V_G = 0.104 V, I_D = 6.0 mA
  - 1.5 mW → V_D = 0.20 V, V_G = 0.094 V, I_D = 7.3 mA
  - 3.0 mW → V_D = 0.20 V, V_G = 0.115 V, I_D = 15.1 mA
  - 5.0 mW → V_D = 0.23 V, V_G = 0.126 V, I_D = 21.9 mA
  - 8.0 mW → V_D = 0.40 V, V_G = 0.104 V, I_D = 20.1 mA

Thank You, Questions?

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