Connecting Minds. Exchanging Ideas.

WSF-10

Scaling Measurement Methodologies Using Cryogenic TaaS Framework for Higher Quality cryo-LNAs and Reliable Qubit Readout Chains

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Outline

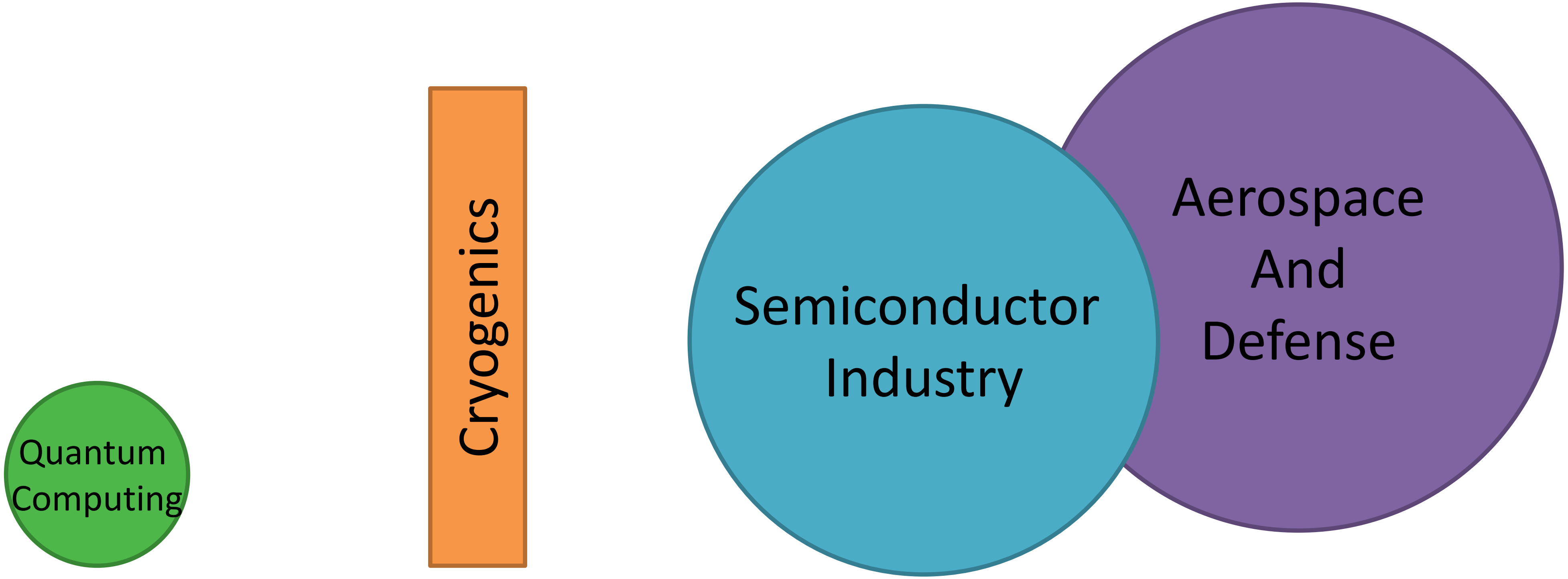
- Quantum Market and Supply Chain
- TaaS Framework
- Measurement Setup
- Methodology
- Results
- Next Steps

Quantum Market Overview

- The quantum computing market is rapidly scaling
- Approaching 1000+ qubit processors by the end of the year
- Each qubit requires ultra low noise environments

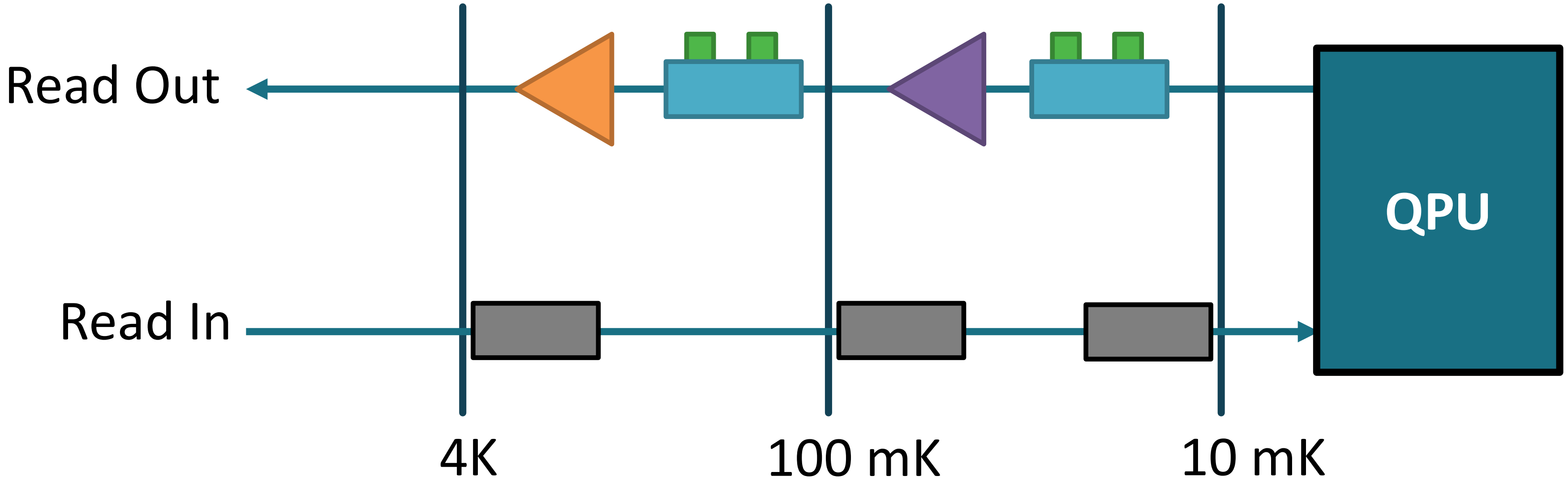
Supply Chain Challenges

- New products require multiple design-fab-test cycles
- Cryogenic Systems are a major capital investment
- RF and Cryogenic engineering are highly specialized fields



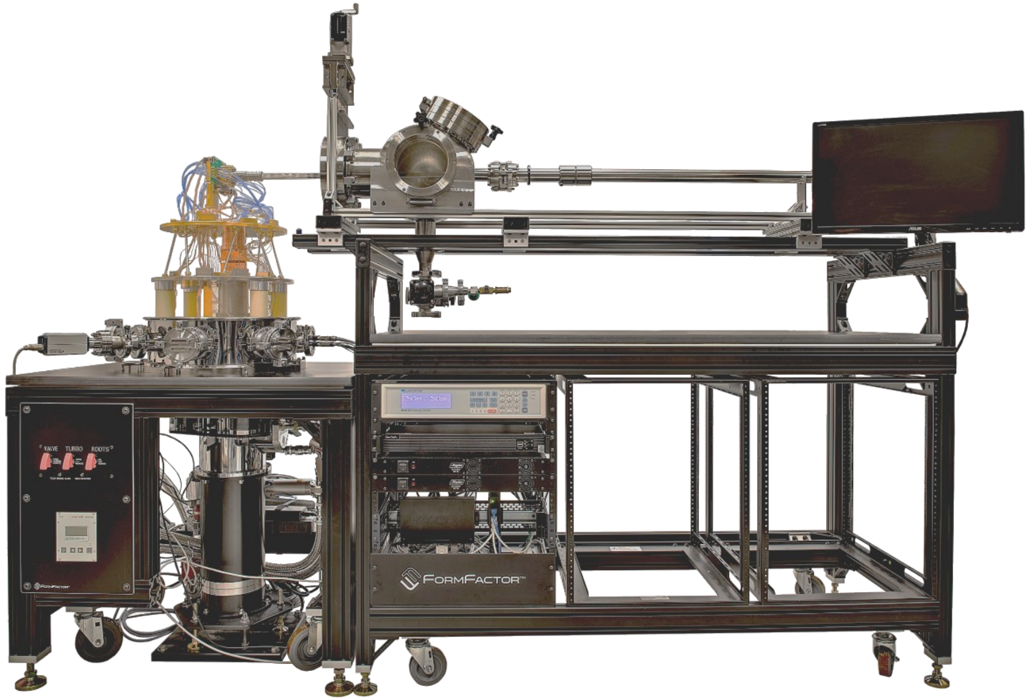
A Need to Scale

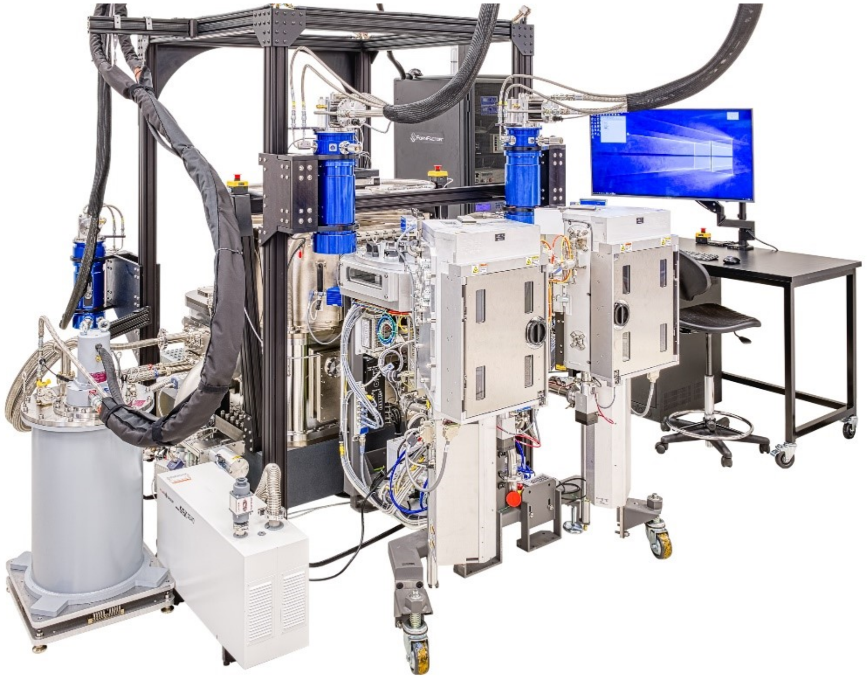
- Typical readout chain has two levels of amplification
- Each read out line supports around 5 qubits
- About 200 chains to support 1000+ qubits in 2023
- About 20,000 to support 100,000+ qubits by 2026+



Developments in Cryogenics

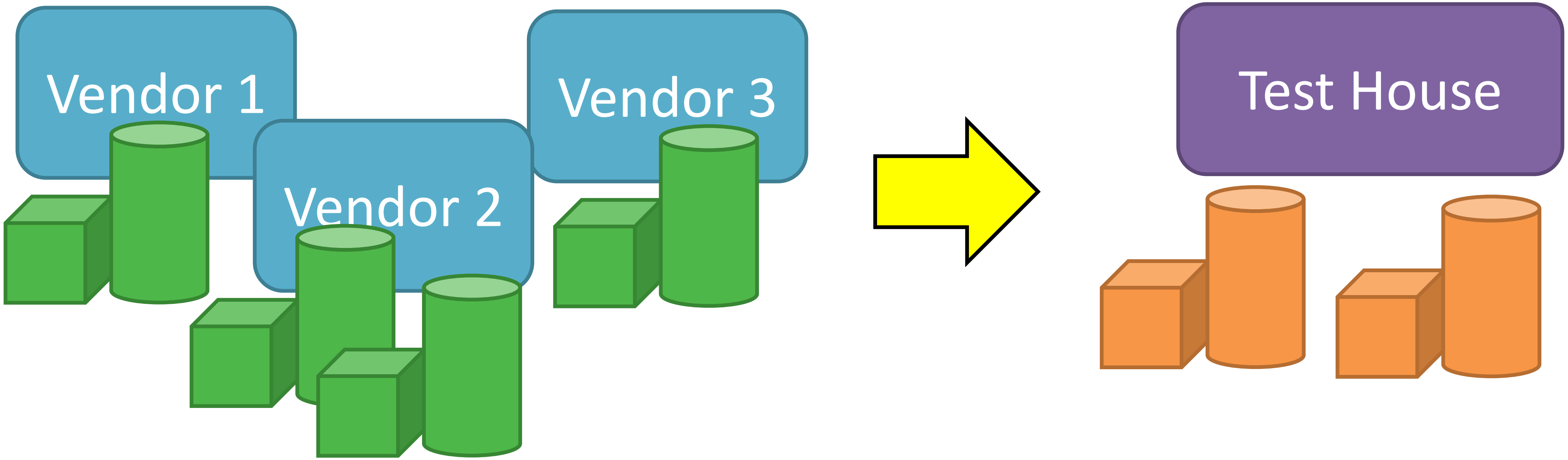
- Closed loop or “Dry” fridges eliminate the use of LHe
- Standardized products rather than custom one-off builds
- Load-locks to rapidly cycle samples rather than the system



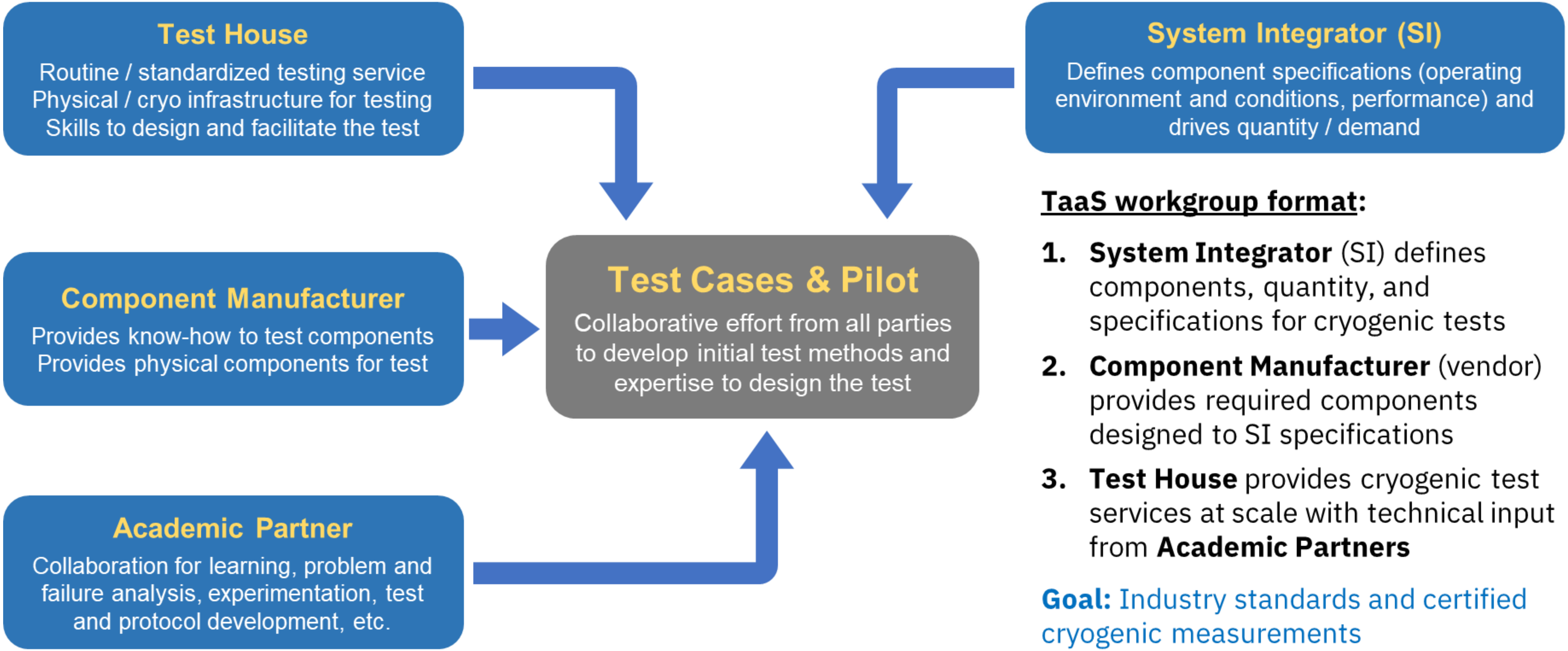


Why TaaS?

- Large costs make investment too risky for a young market
- Centralized location would be more accessible
- Total cost to industry would be reduced



TaaS Development Framework



TaaS workgroup format:

1. **System Integrator** (SI) defines components, quantity, and specifications for cryogenic tests
2. **Component Manufacturer** (vendor) provides required components designed to SI specifications
3. **Test House** provides cryogenic test services at scale with technical input from **Academic Partners**

Goal: Industry standards and certified cryogenic measurements

Roles and Motivation

System Integrator

- Sets the spec for the end user
- Drives demand in the market
- Leads workgroups to develop capabilities
- Reliable and fully characterized components

Component Manufacturer

- Supply the market
- Drives innovation to support the spec
- Provides samples to the workgroup
- Easier access to enter the market and expanded production capacity

Test House

- Performs the measurements
- Drives scalability in the measurement
- Provides the infrastructure to the workgroup
- Revenue and applications to sell its products

Academic Partner

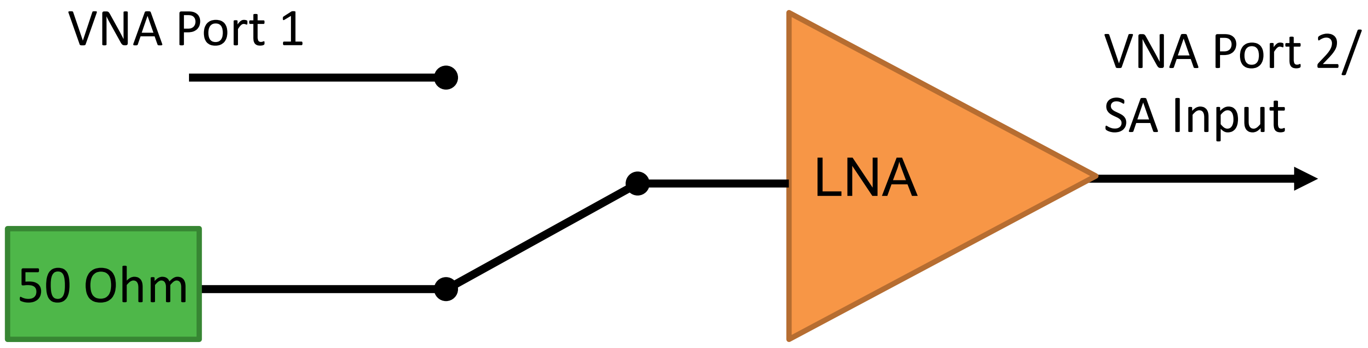
- Performs in-depth analysis and certifies test methodologies
- Drives research in the industry
- Provides knowledge to the workgroup
- An avenue to commercialization for research

Pilot Test Case

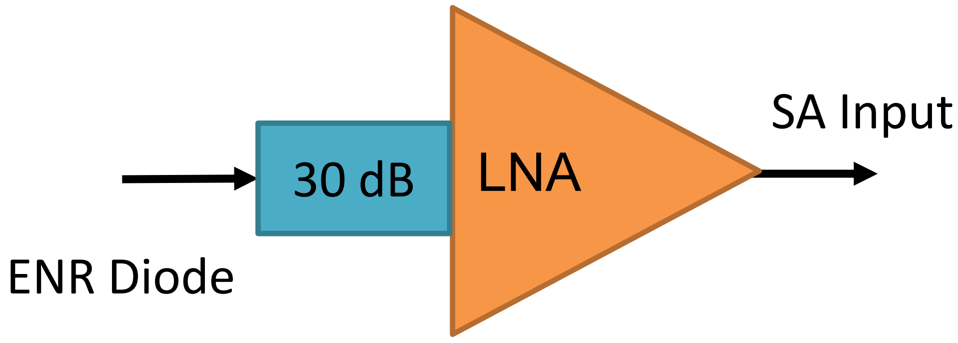
- LNAs are a critical component in the Quantum readout chain
- Extensive research has already been done
- It is a difficult measurement requiring cryogenics and RF
- Methods are relevant to other critical components

Common Methods

- Scalar vs. Vector measurement
  - Scalar is simpler, but only 50 Ohm impedance
- Cold Load vs. Cold Attenuator
  - Cold Load requires two measurements and another switch



Cold Load



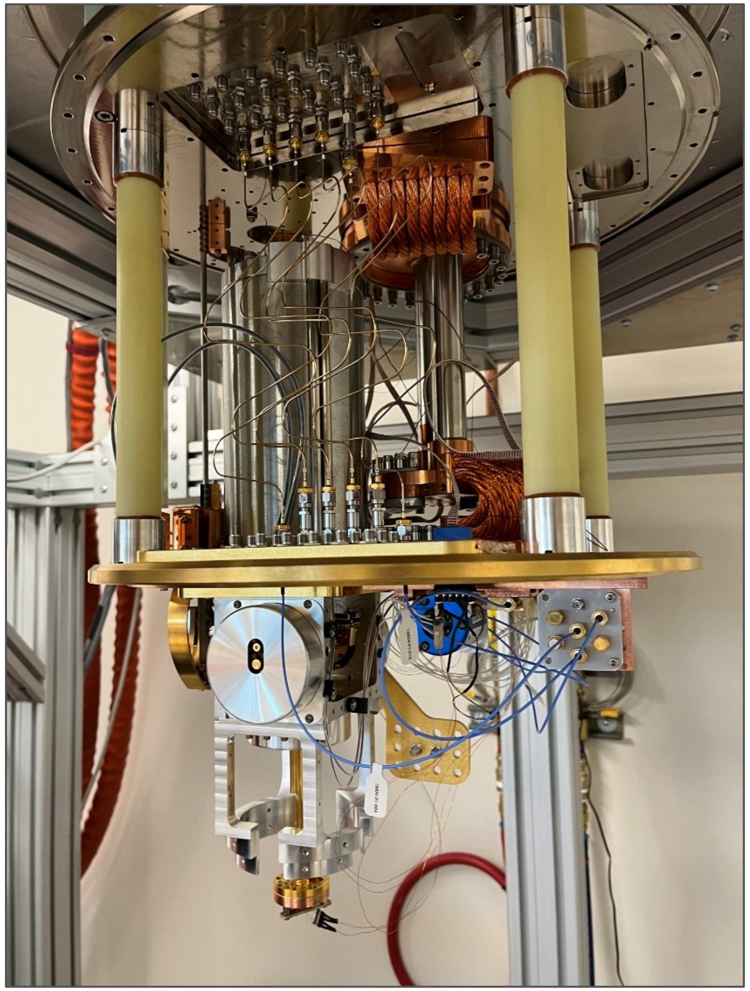
Cold Attenuator

Cold Attenuator

- Most similar to standard room temperature method
- No cryogenic impedance tuner required
- Easiest to automate
- Most common method used by component manufacturers

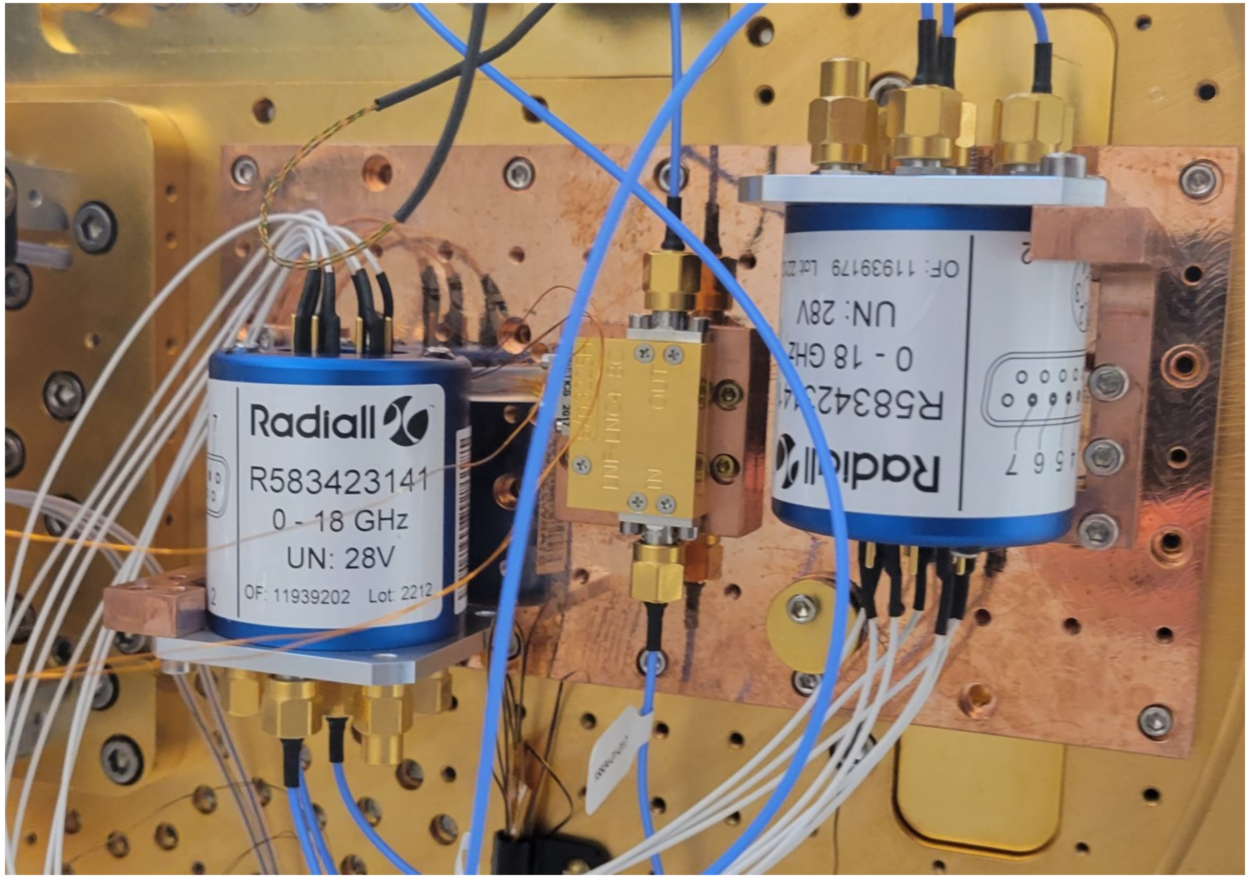
HPD Model 106 ADR Cryostat

- Pros:
  - Large 4K space for test fixture
  - 2.7K second stage base temperature
  - Shielded and well controlled environment
  - Designed for 30mK on second ADR stage
- Cons:
  - Long test cables with high loss
  - More mass results in slower cooldowns

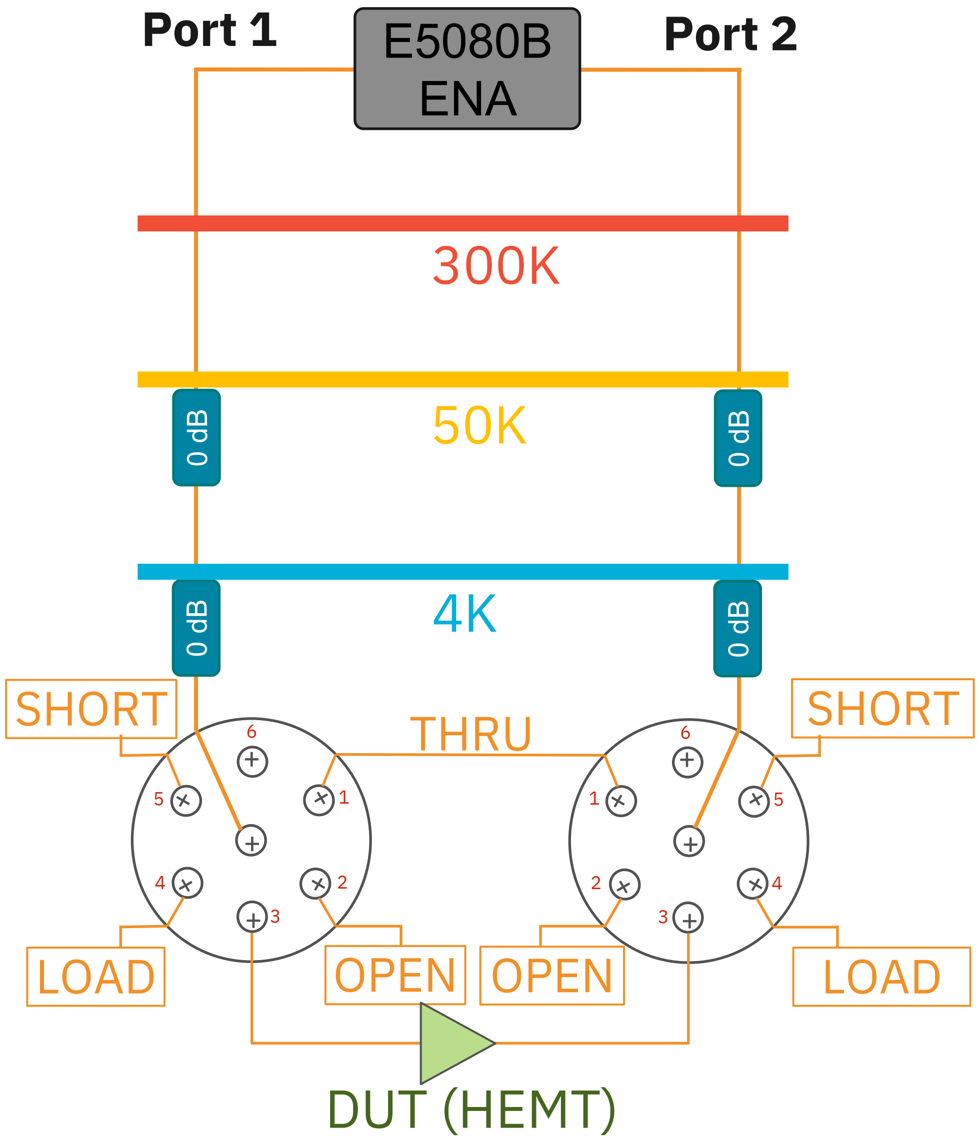


Test Fixture

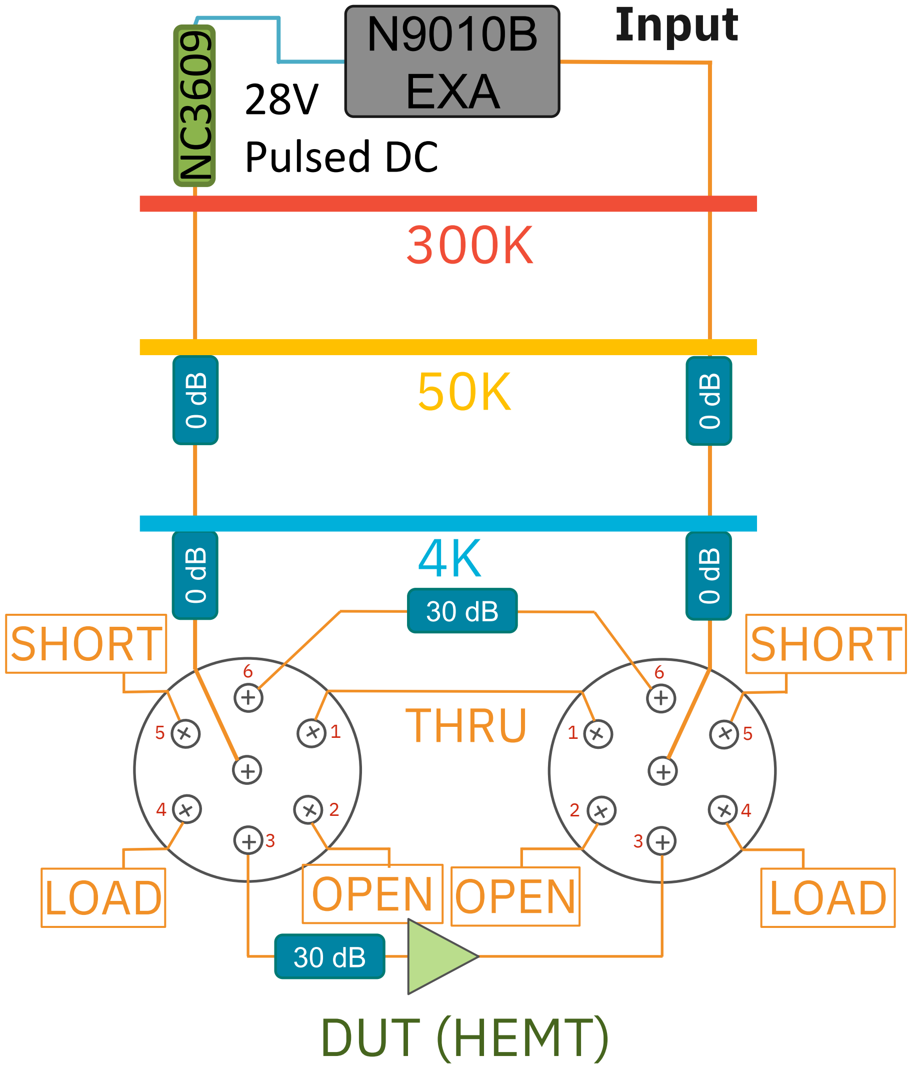
- Two cryogenic SP6T switches for two port calibration
- LNA mounted in the middle
- Calibrated Cernox for accurate temperatures
- Cryogenic standards to set measurement plane



S-Parameter Setup

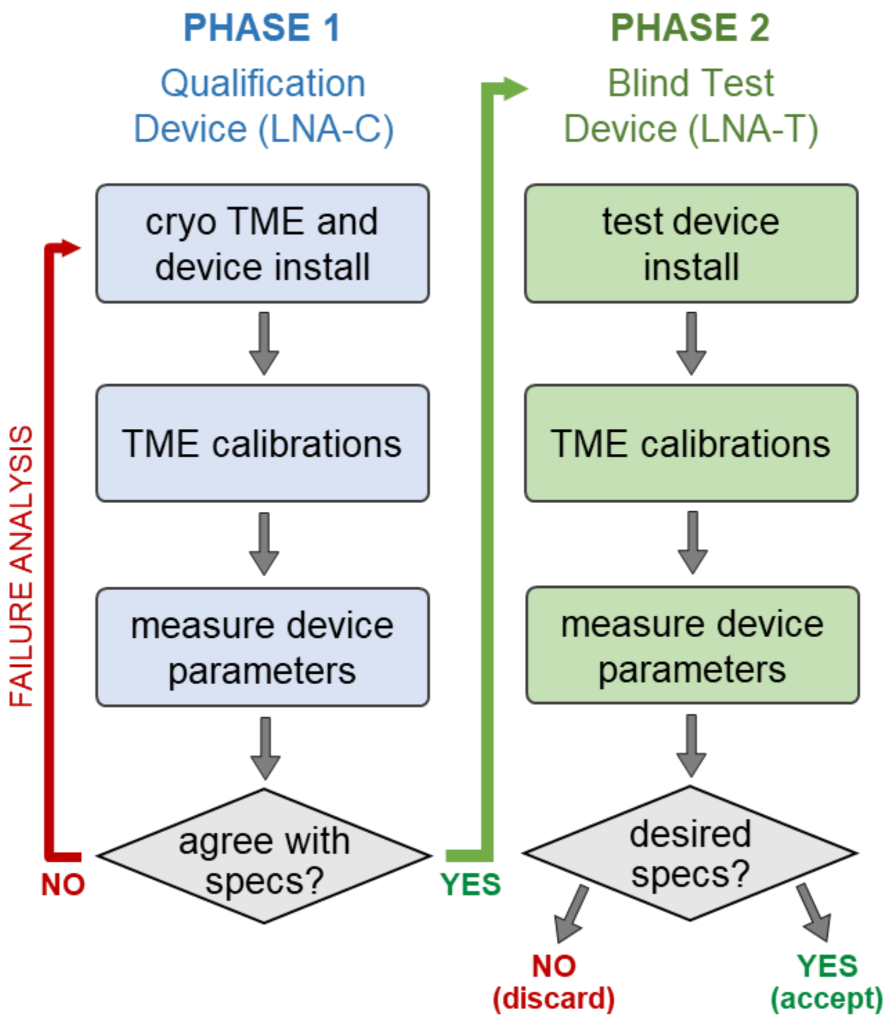


Noise Temperature Setup



LNA Test Protocol

- LNA-C is a control component with data at cryo
- LNA-T is a proof-of-concept prototype with no cryo data
- Test setup is validated using LNA-C
- LNA-T is used to demonstrate the TaaS model

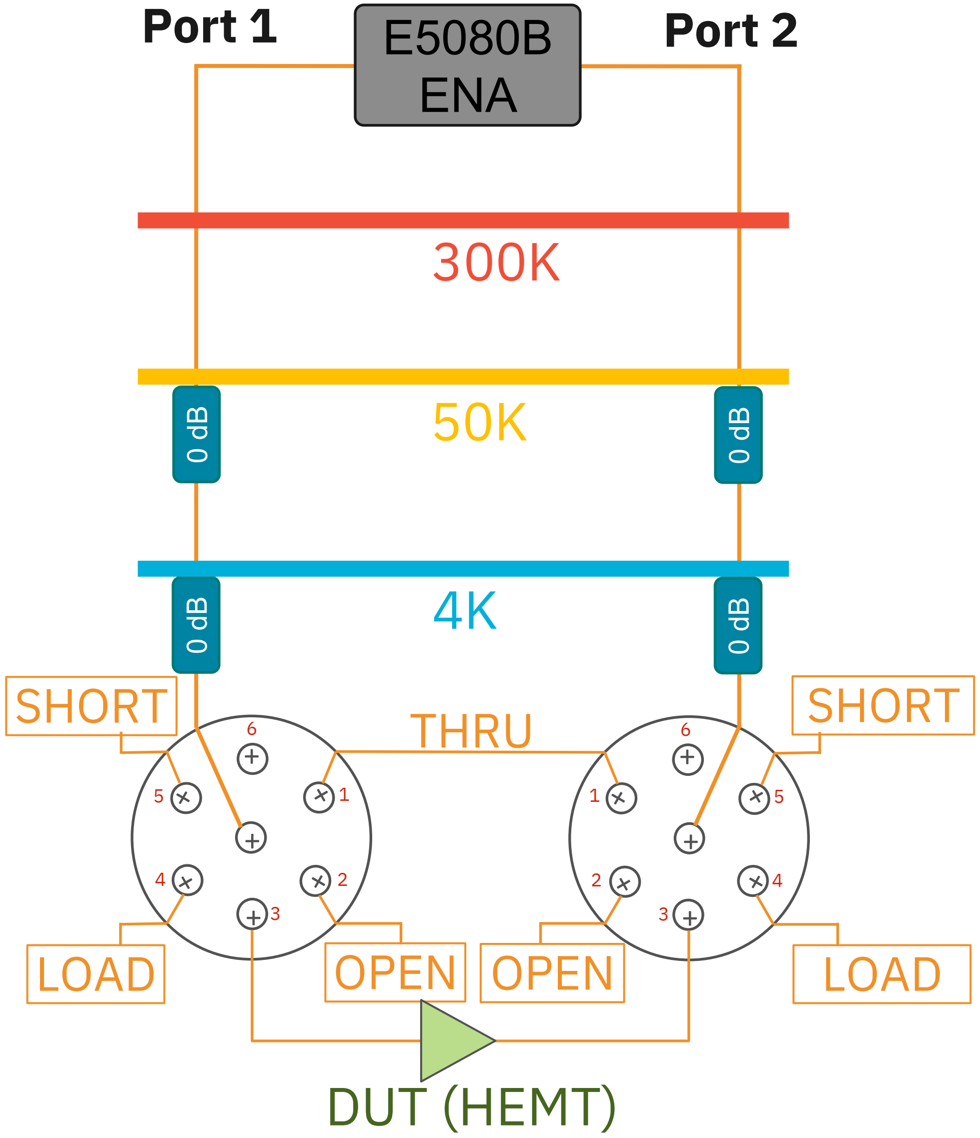


Measured Parameters

- Common specifications on commercial data sheets
  - Room temperature S-parameters and OP1dB compression
  - Gain and Noise figure at room and cryogenic temperatures
  - Power consumption
- Uncommon specifications
  - Cryogenic S-parameter and OP1dB compression

Cryogenic S-Parameter Calibration

- SOLT standards
- Basic calibration in ENA
- Measure each standard individually



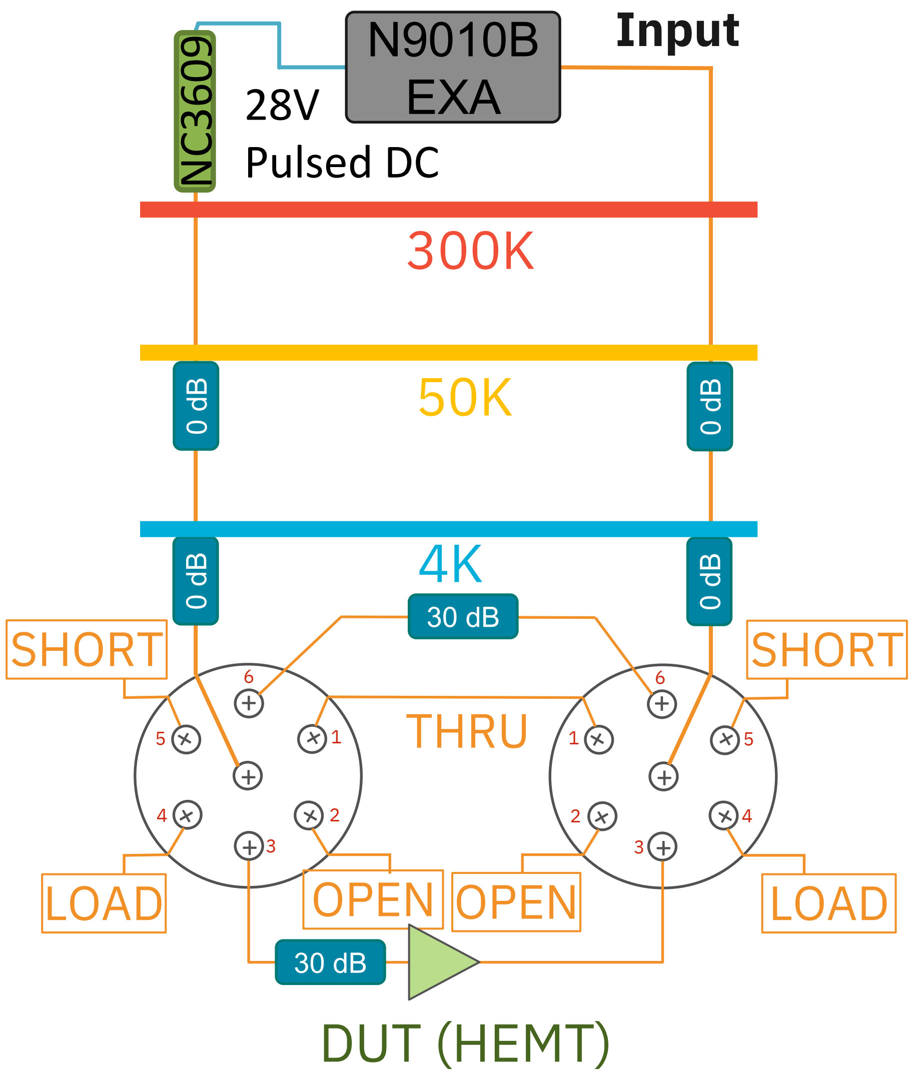
Noise Temperature Calibration

ENR: >40 dB

Cold Attenuator: 30 dB

Cable Loss: 2 – 6 dB

- Calibrate the input of the SA
- Measure the THRU Loss with VNA
- Calibrate and measure attenuator
- Generate loss comp tables
- Apply loss comp with measured temperature

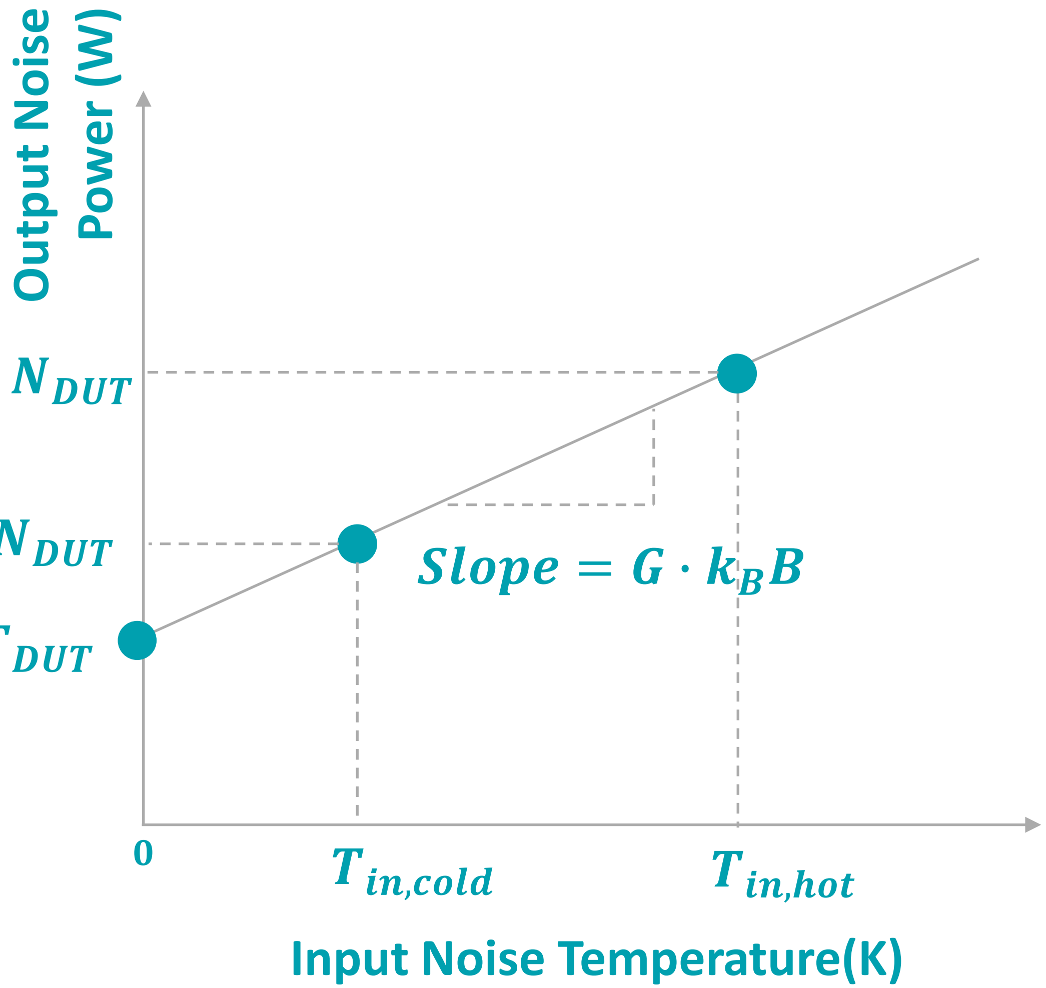


Y Factor Method

$$N_{out,hot} = G \cdot k_B B \cdot T_{hot} + N_{DUT}$$

$$N_{out,cold} = G \cdot k_B B \cdot T_{cold} + N_{DUT}$$

$$N_{DUT} = G \cdot k_B B \cdot T_{DUT}$$



$$Y = \frac{N_{out,hot}}{N_{out,cold}}$$

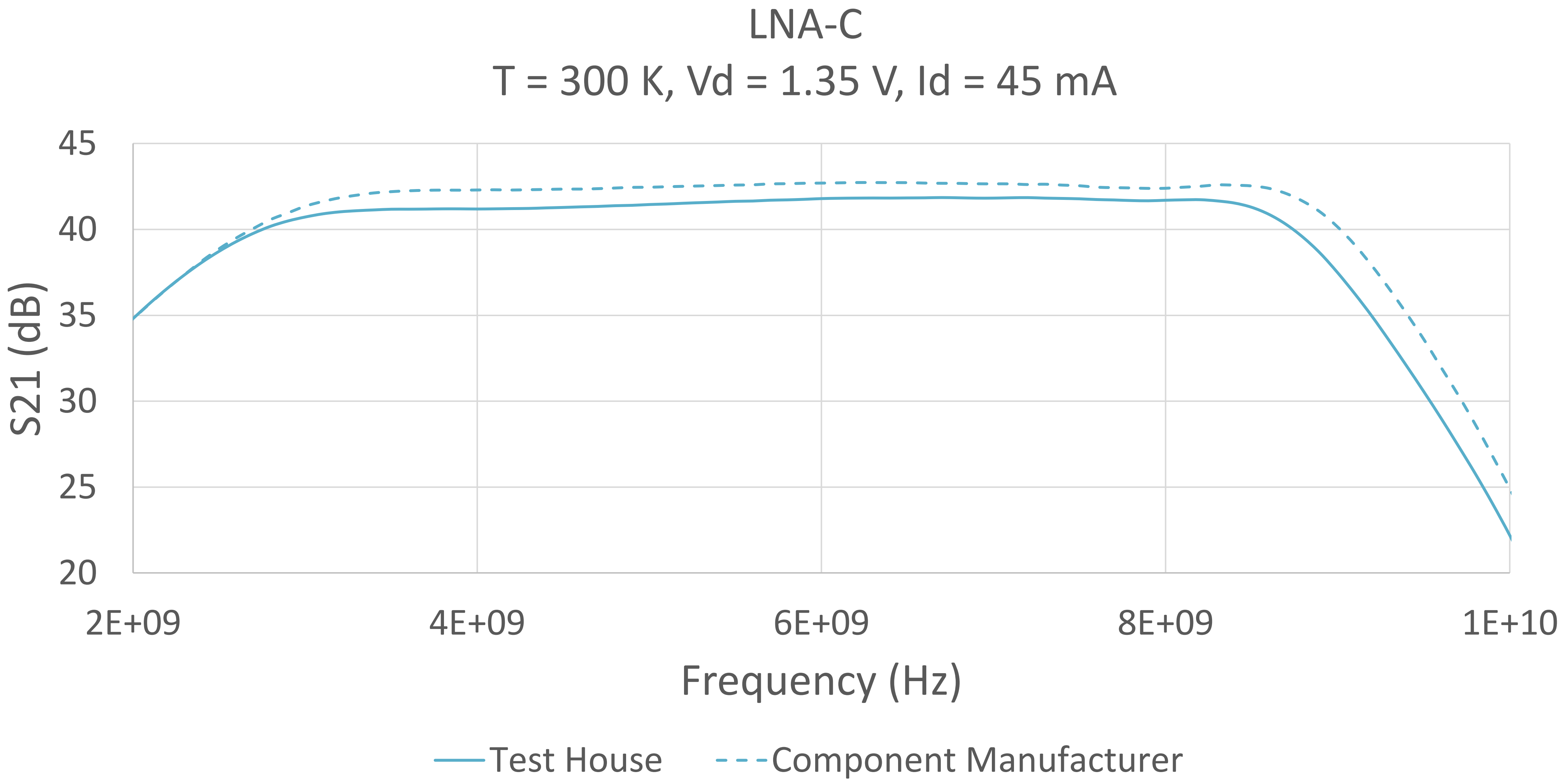
$$T_{DUT} = \frac{T_{hot} - Y \cdot T_{cold}}{Y - 1}$$

Noise Temperature Model

- Input noise has three components
- For hot noise N_S should be large, source noise dominates
- For cold noise L_A should be large, attenuator noise dominates
- Cable noise should be comparably small to be negligible

$$N_{in} = \underbrace{\frac{1}{L_A L_{cable}} N_S}_{\text{Source Noise}} + \underbrace{\frac{1}{L_A} N_{cable}}_{\text{Cable Noise}} + \underbrace{\left(1 - \frac{1}{L_A}\right) k_B T_A B}_{\text{Attenuator Noise}}$$

LNA-C Room Temperature



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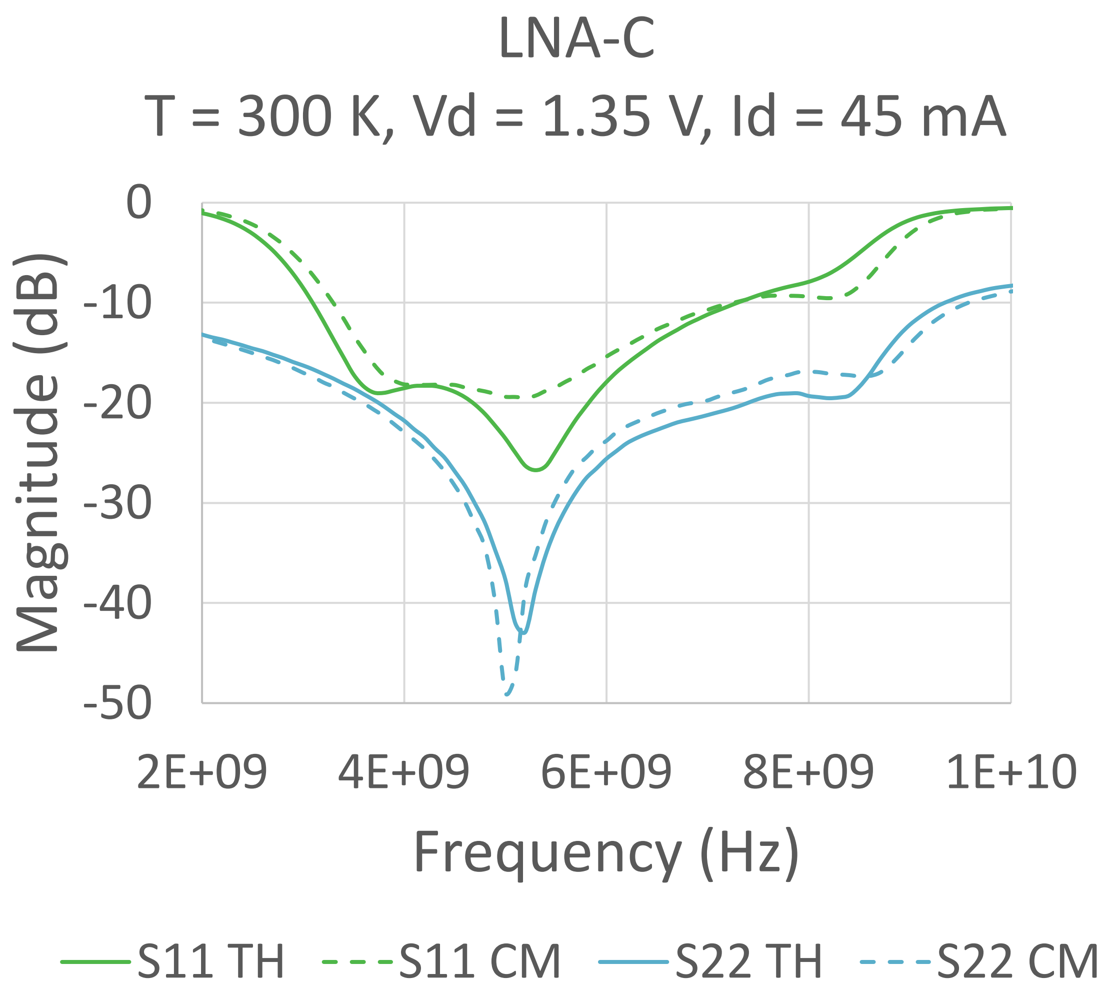

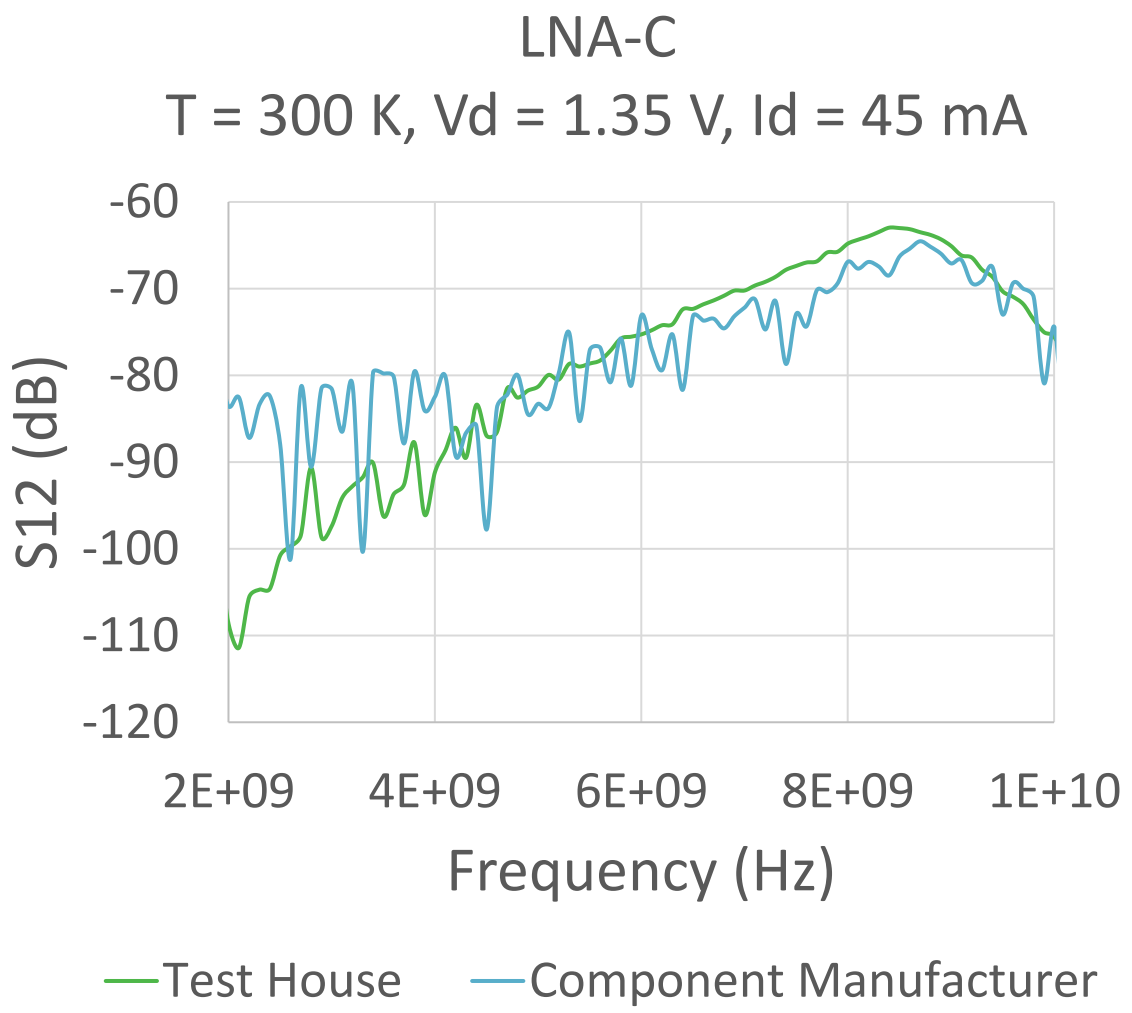

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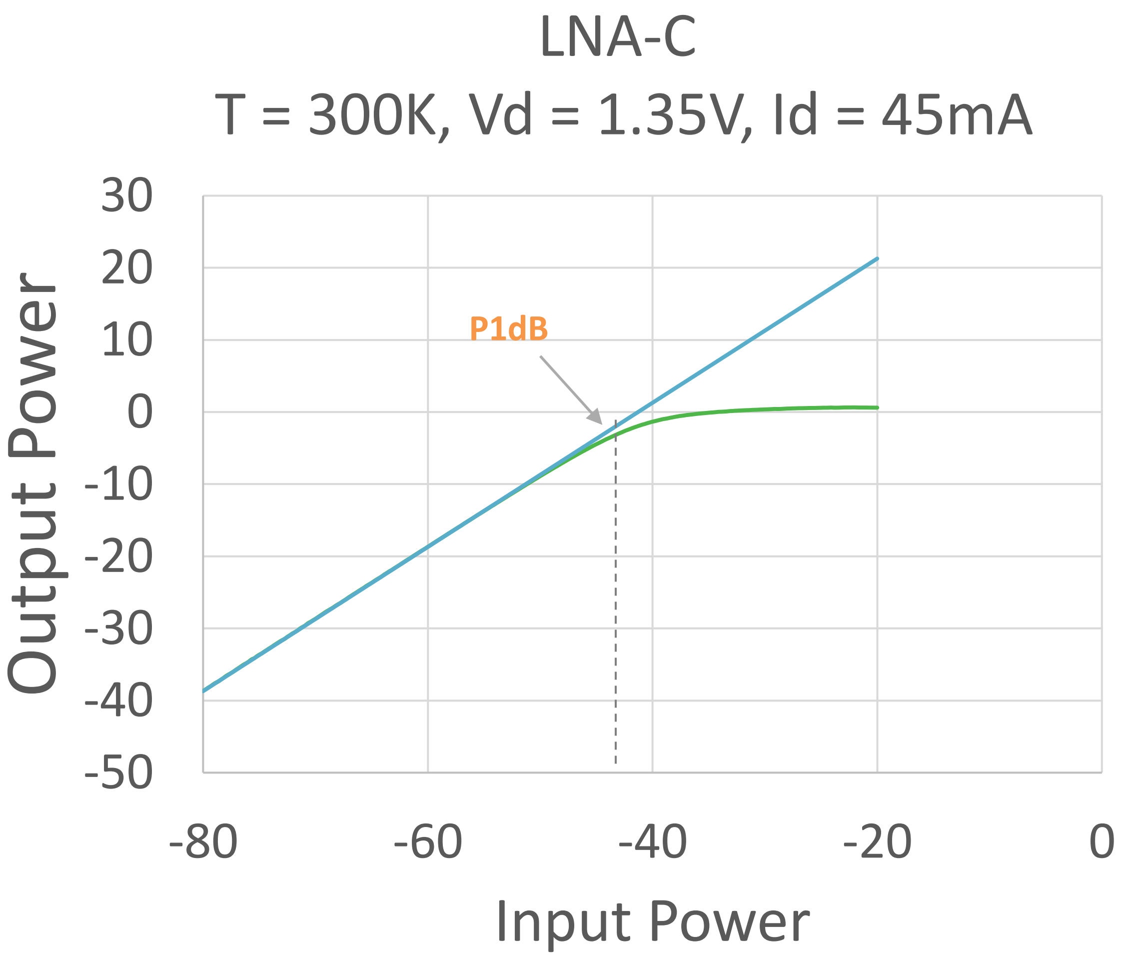

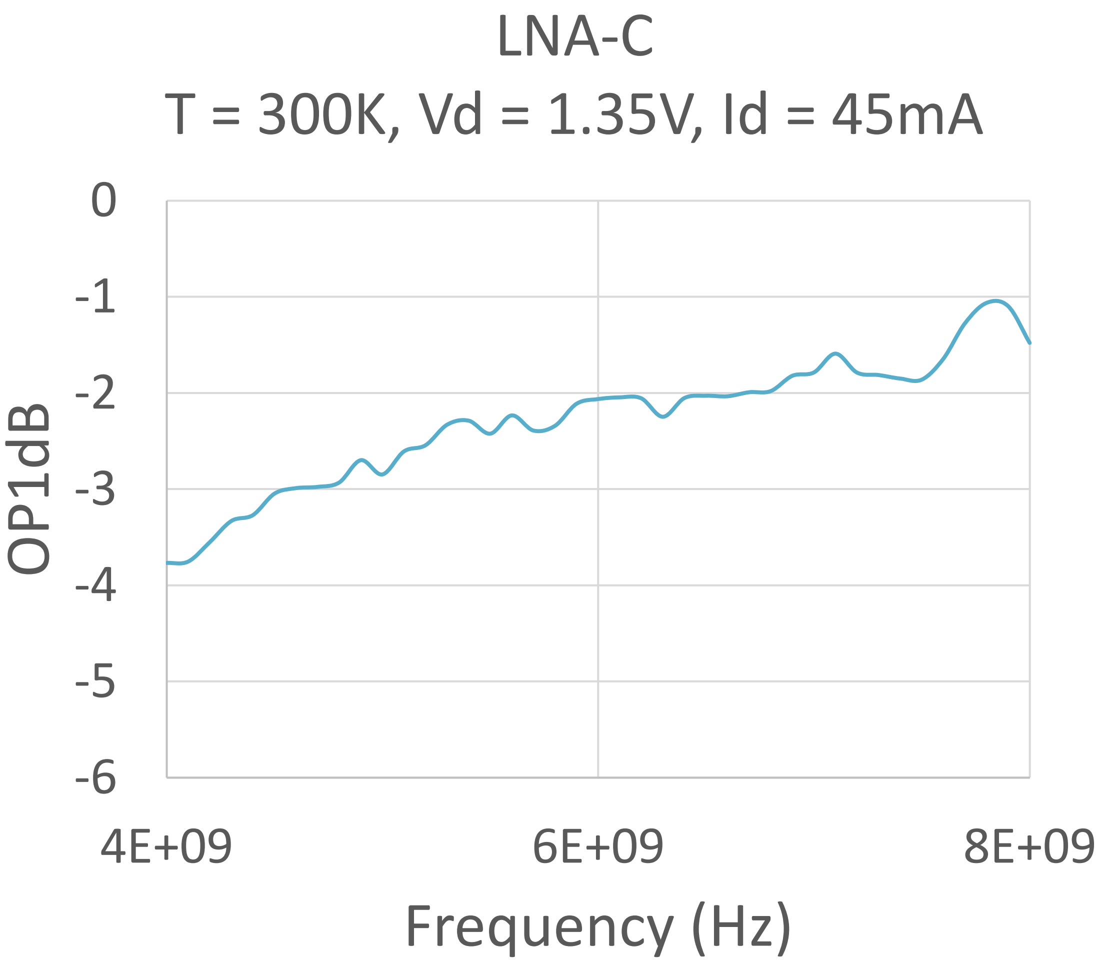

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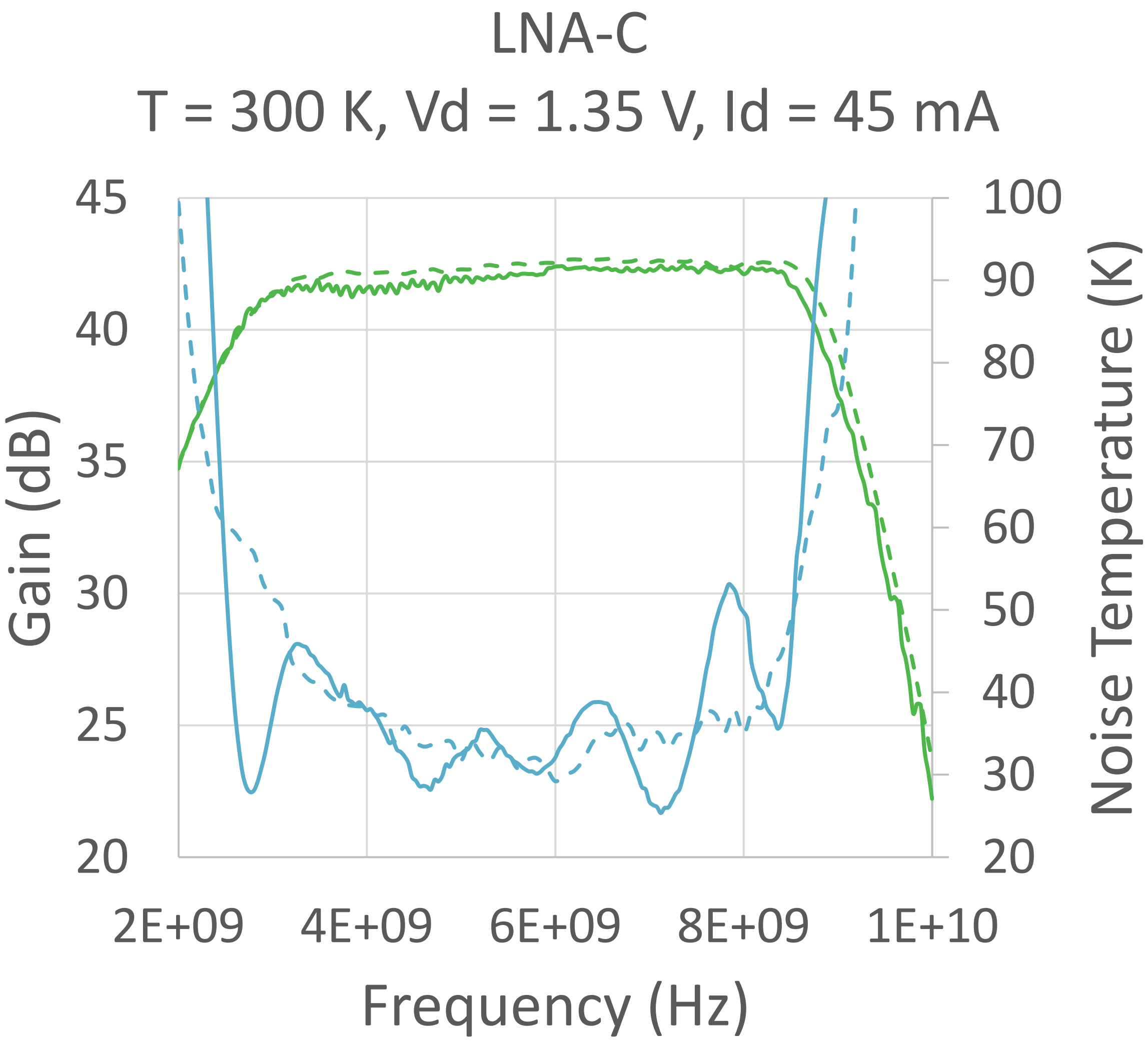
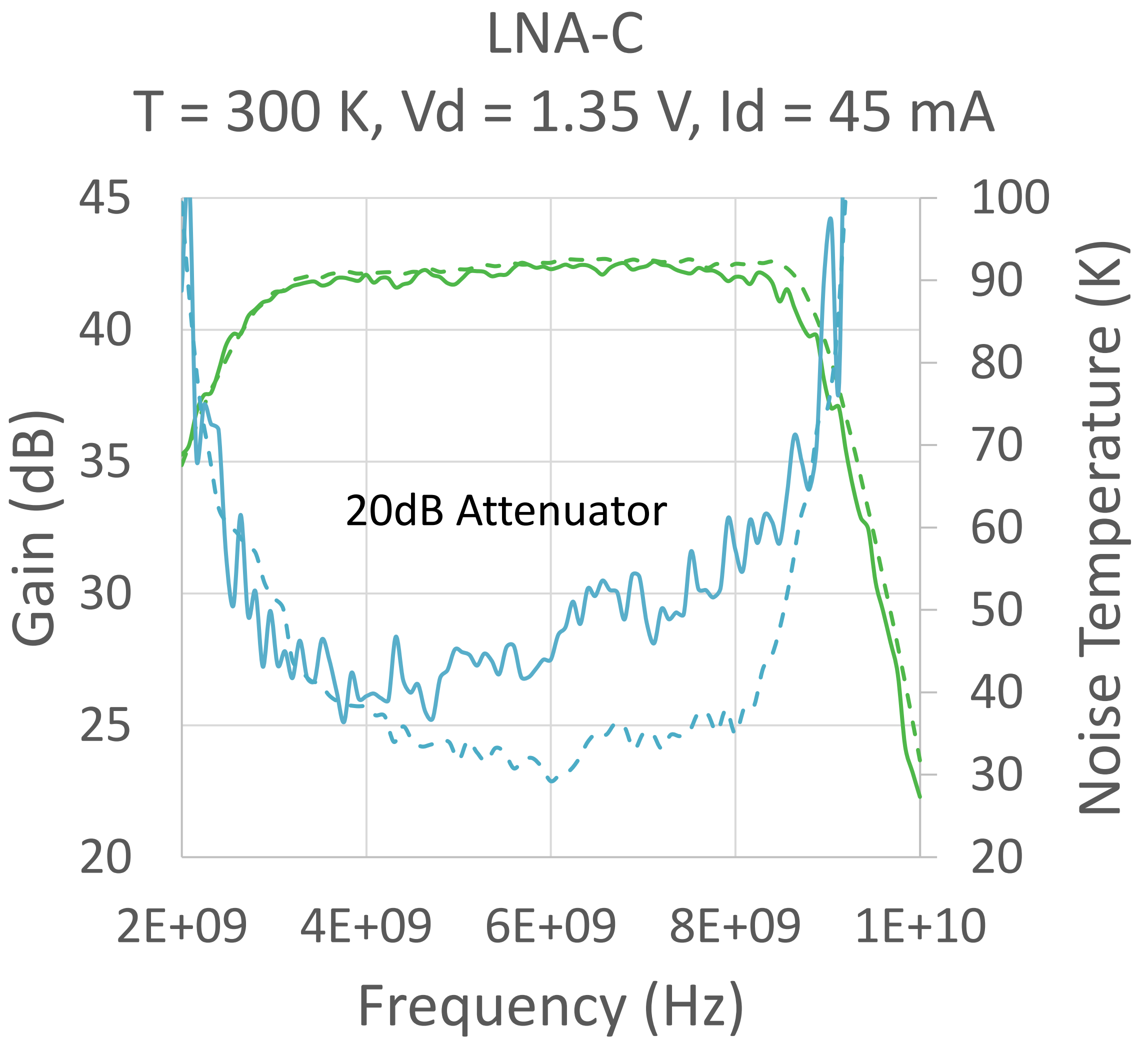
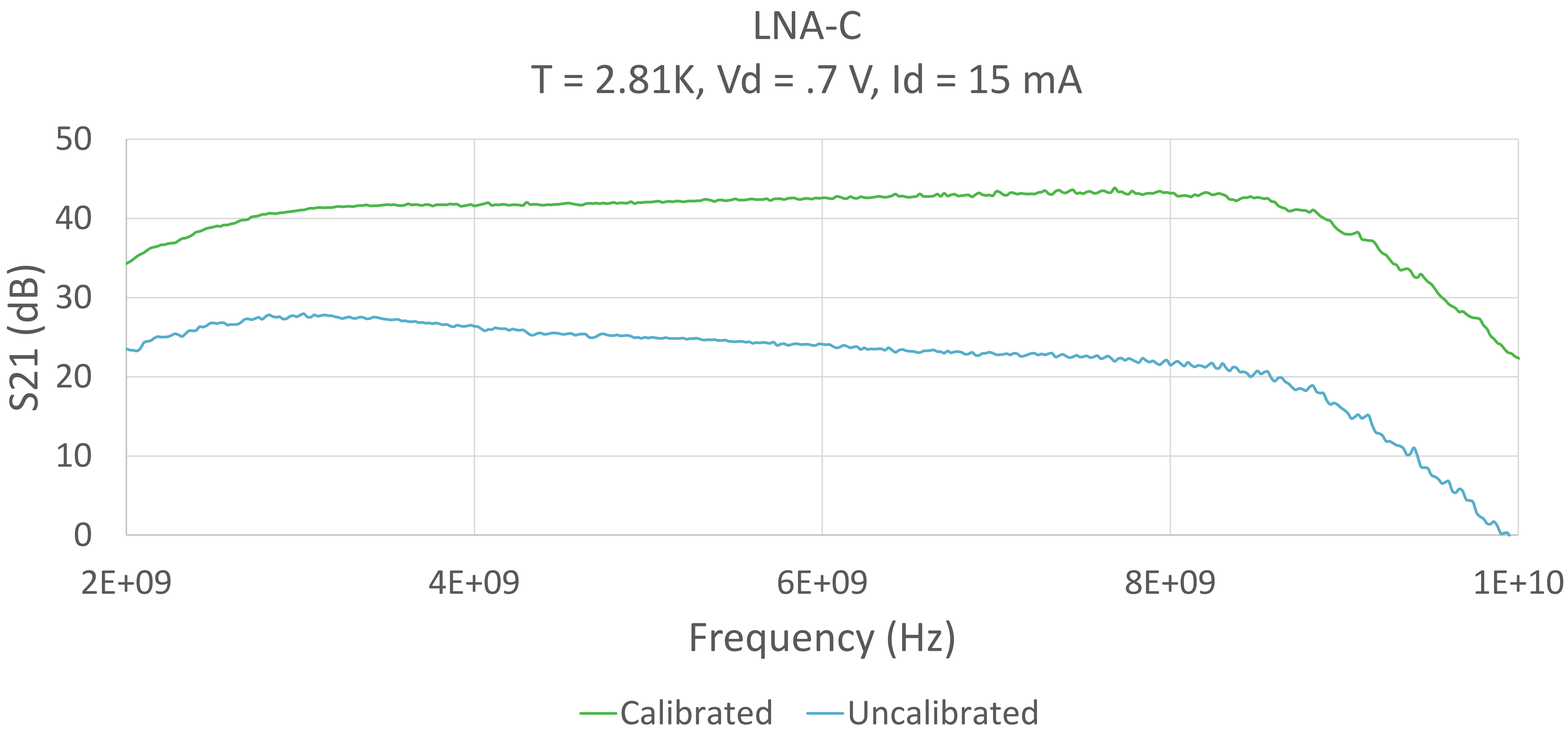




Test House Gain — Manufacturer Gain — Test House Noise — Manufacturer Noise

LNA-C Cryogenic Temperature



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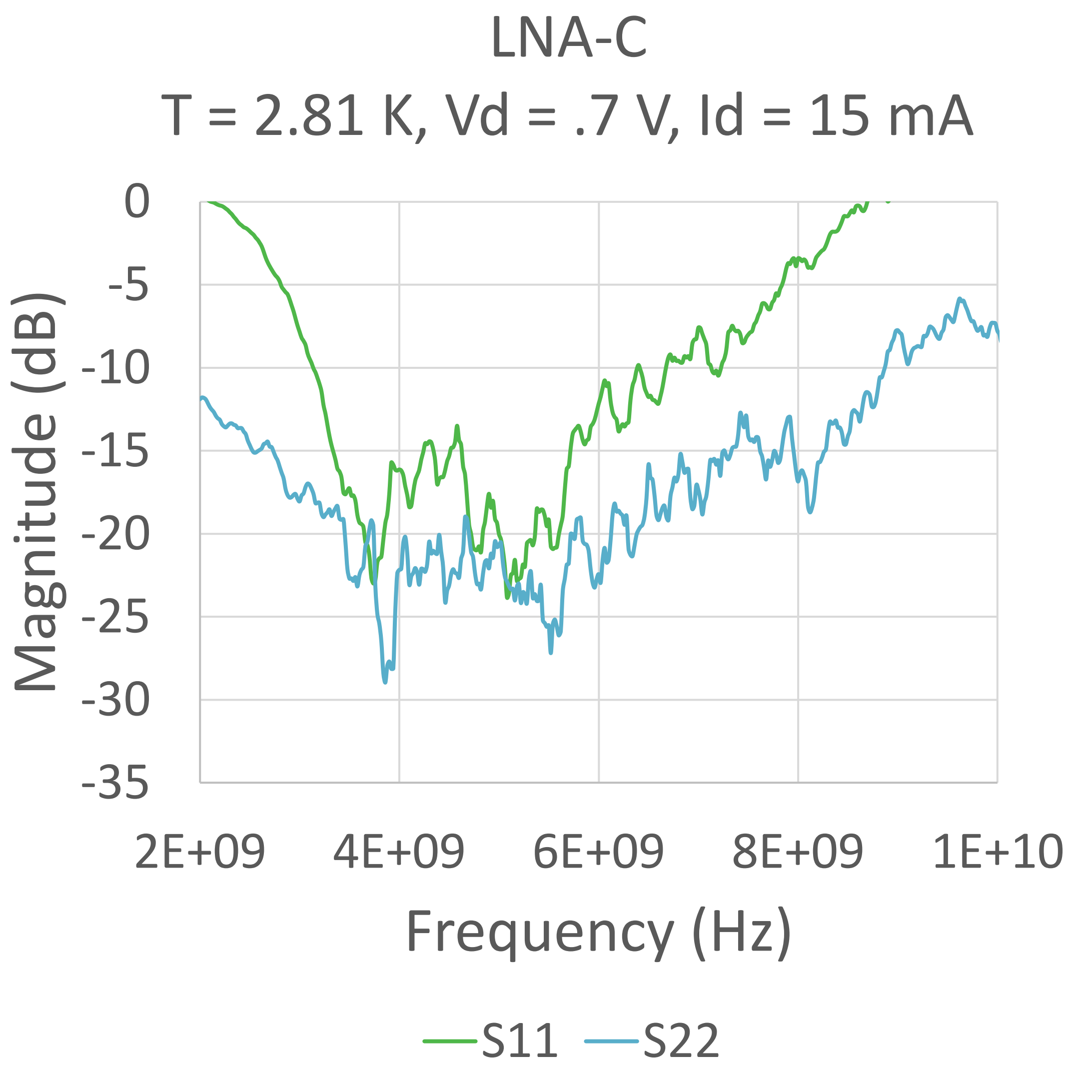

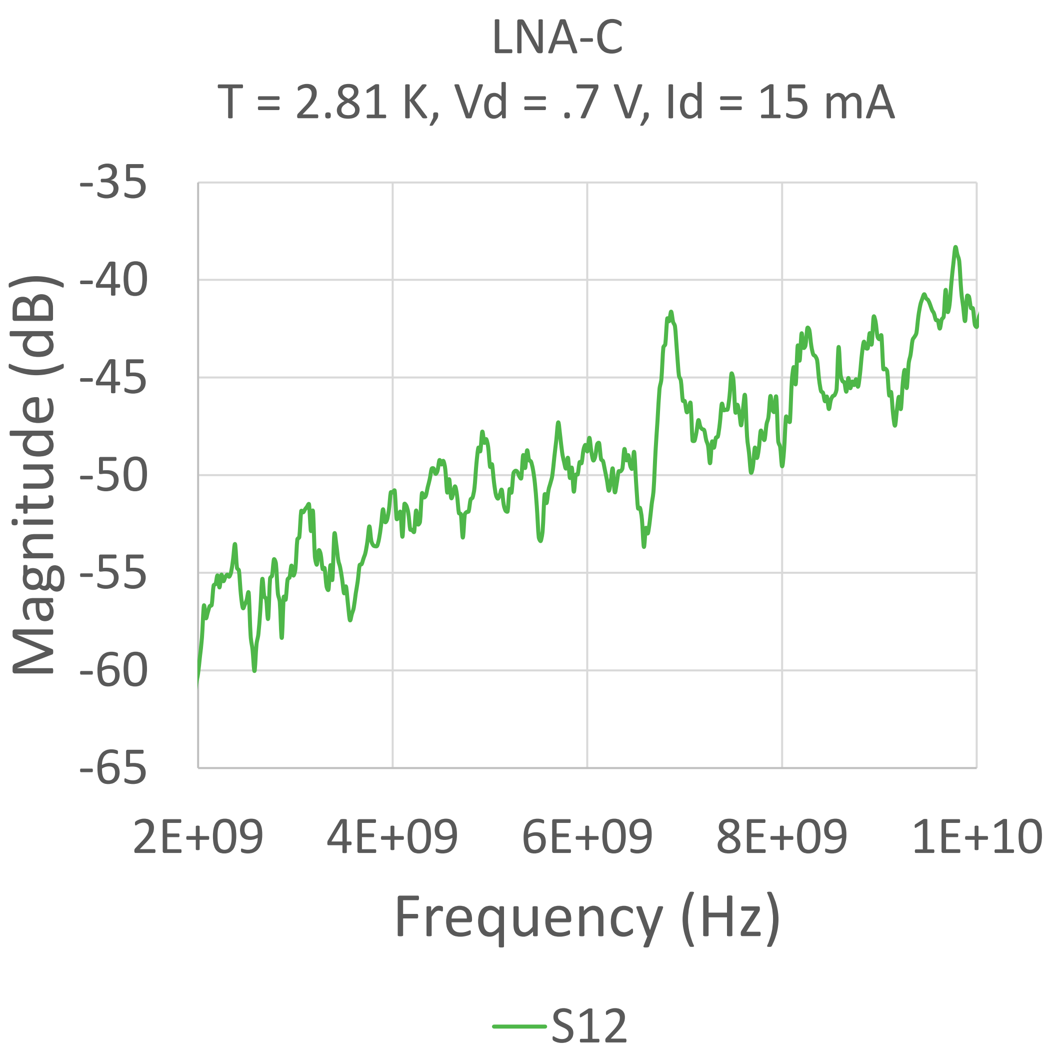

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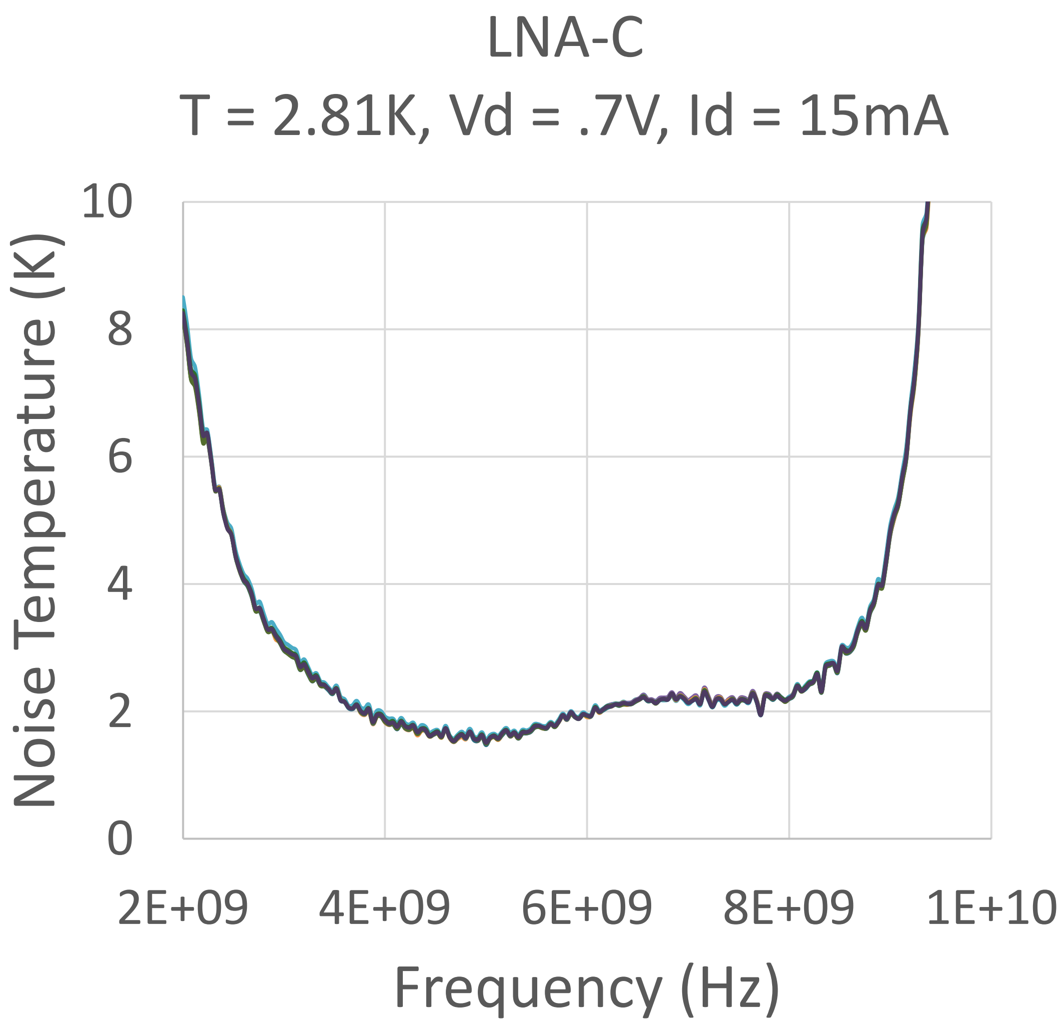

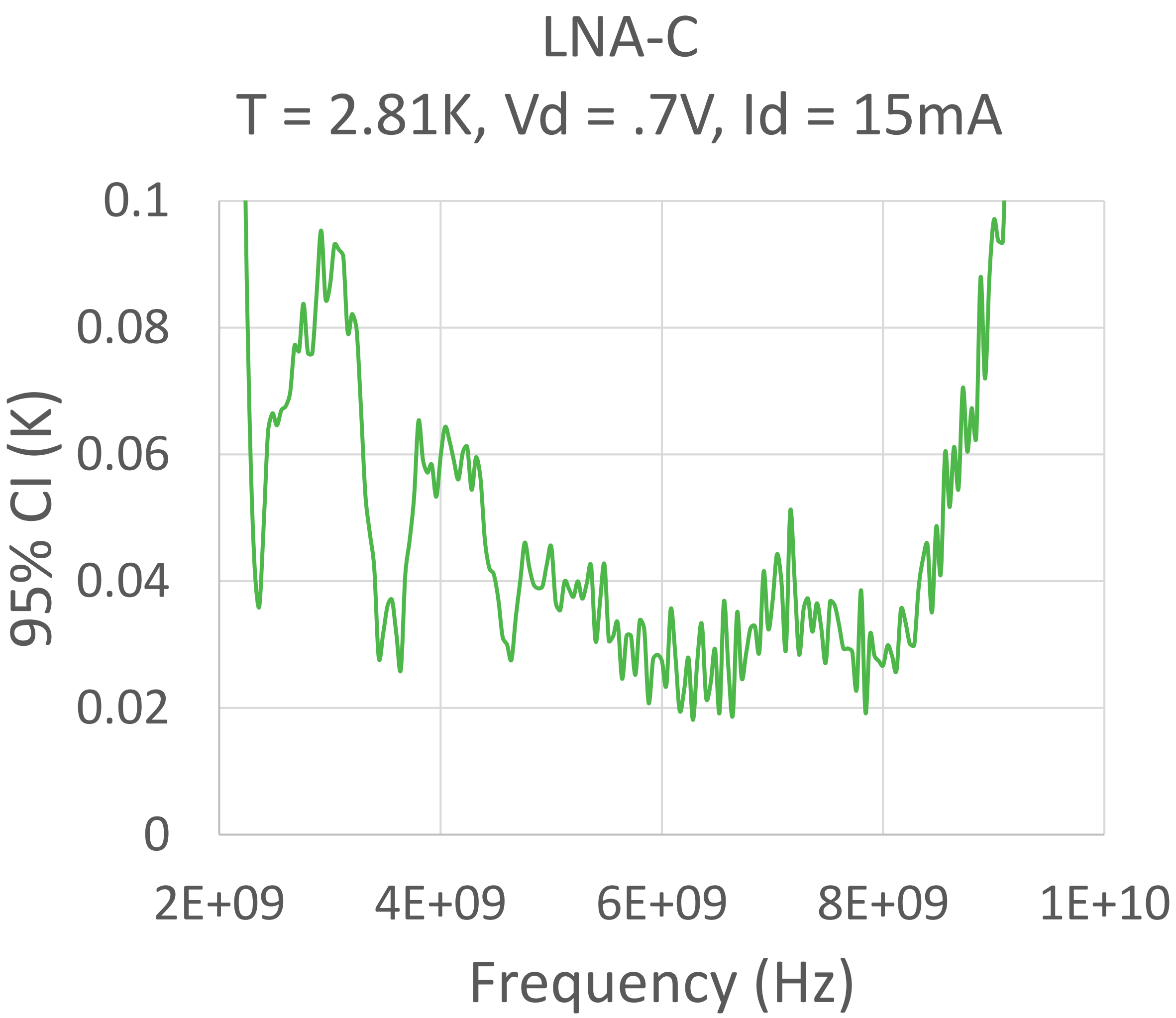

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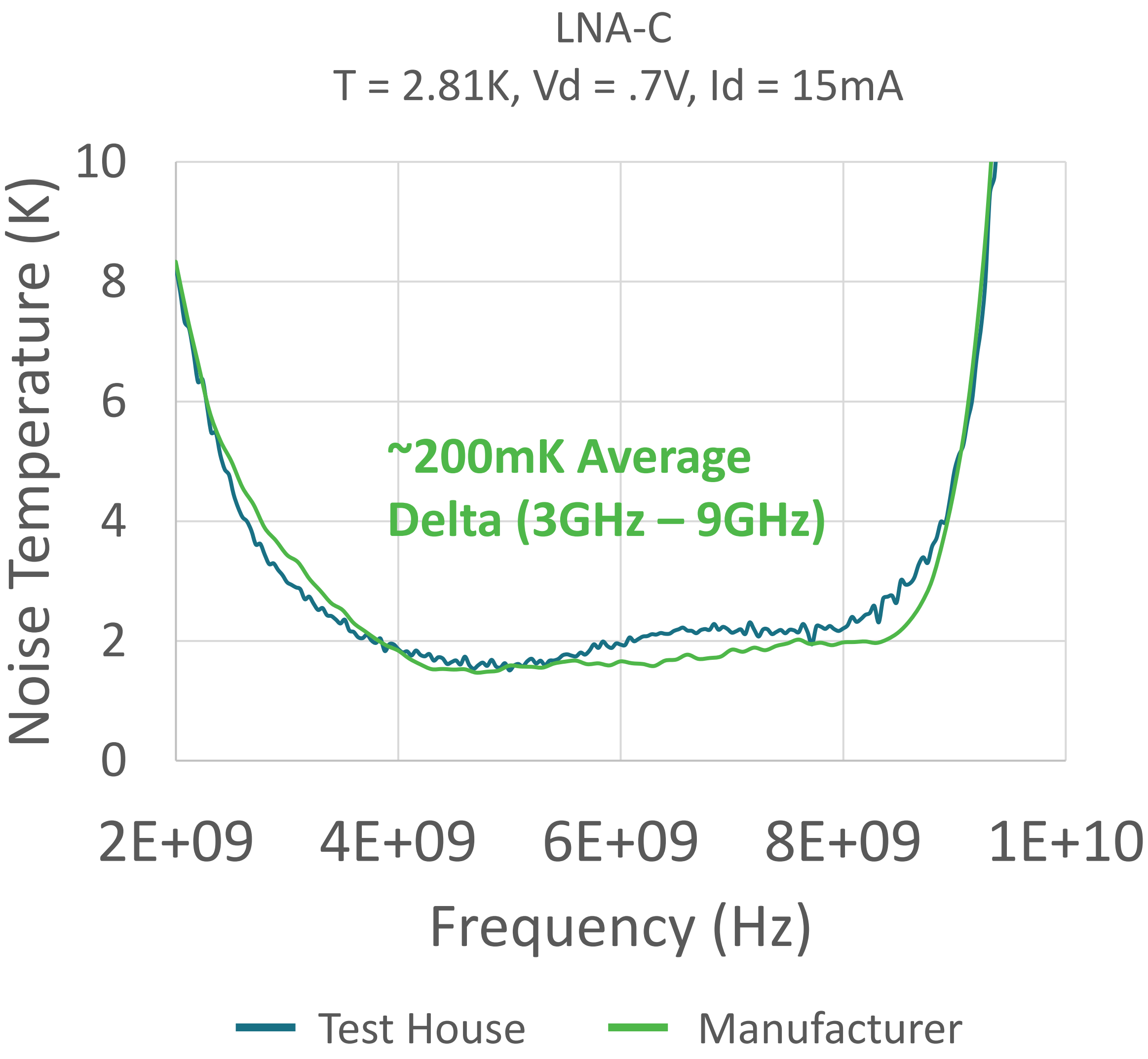
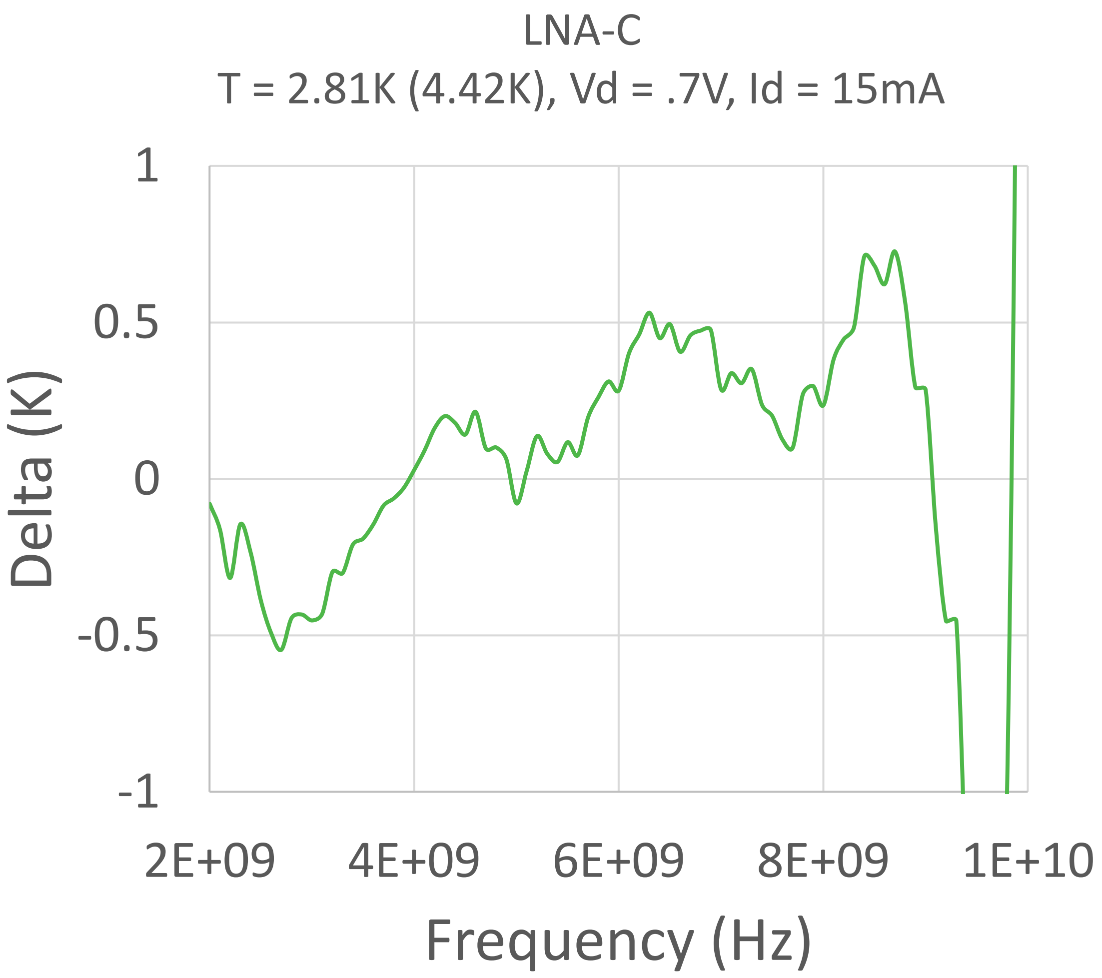
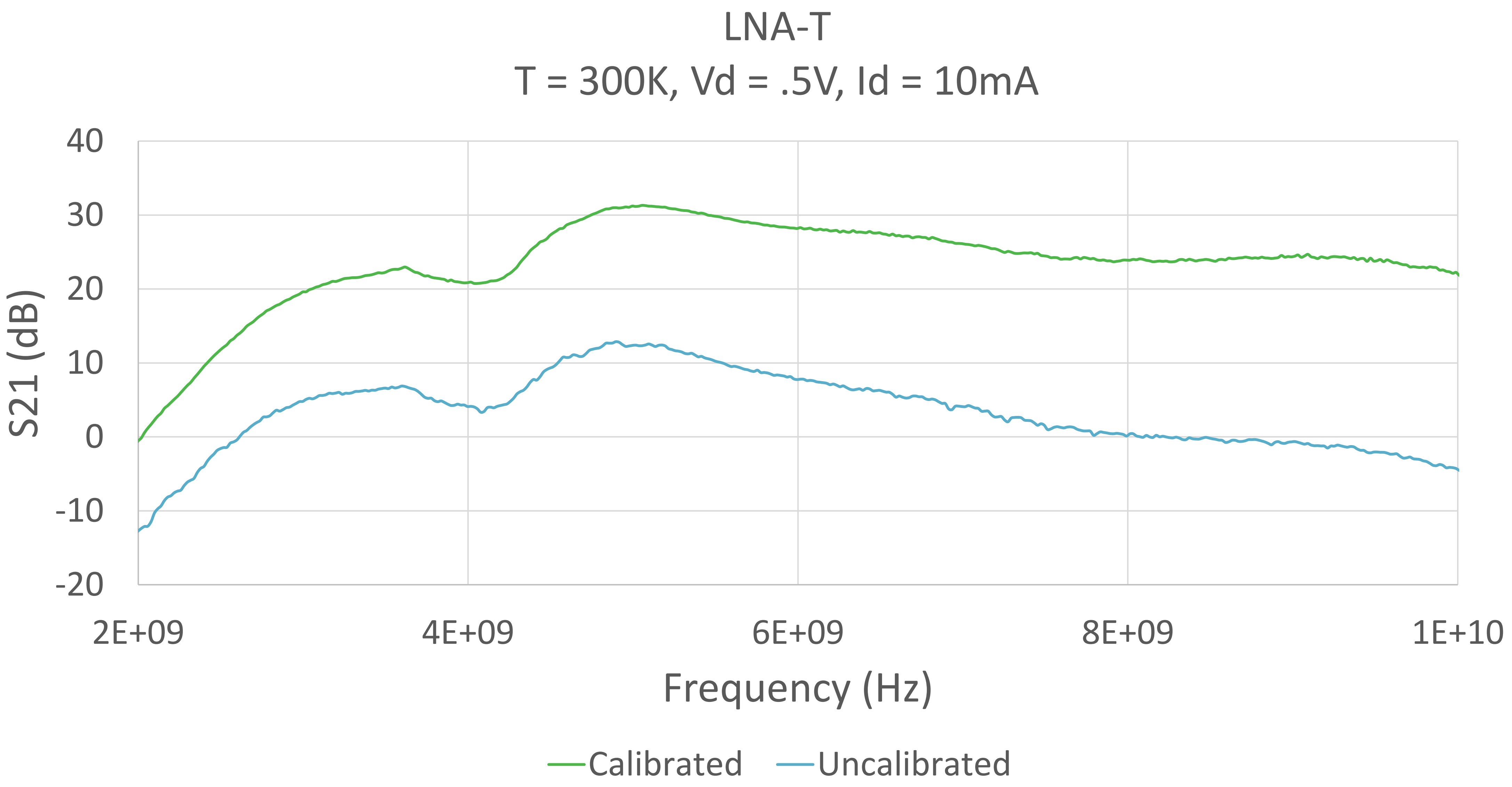
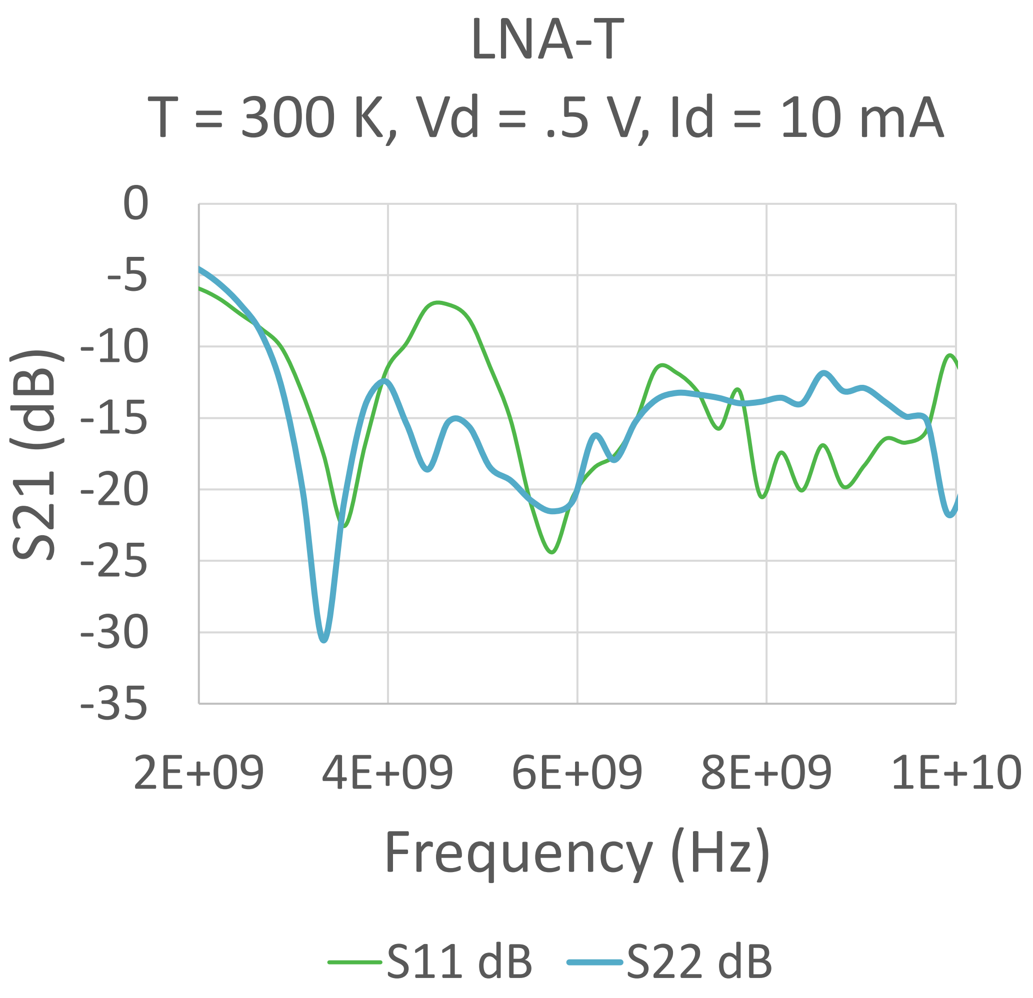


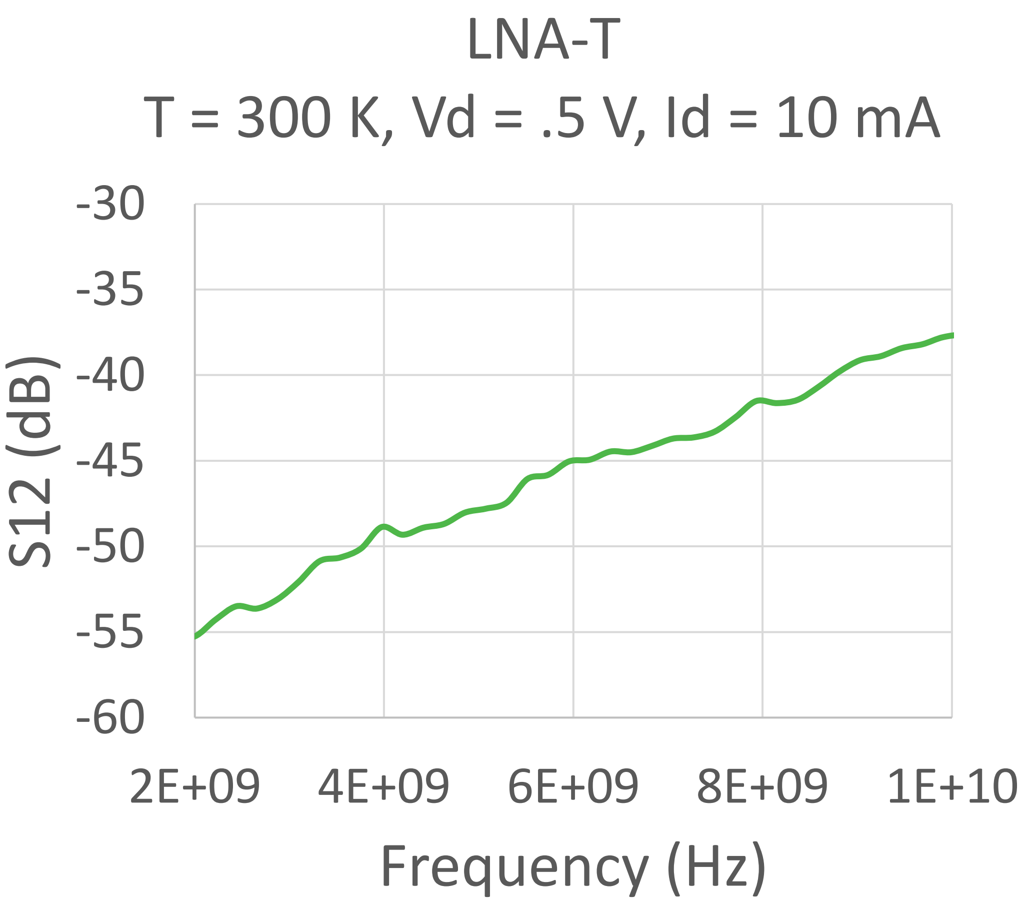


LNA-T Room Temperature

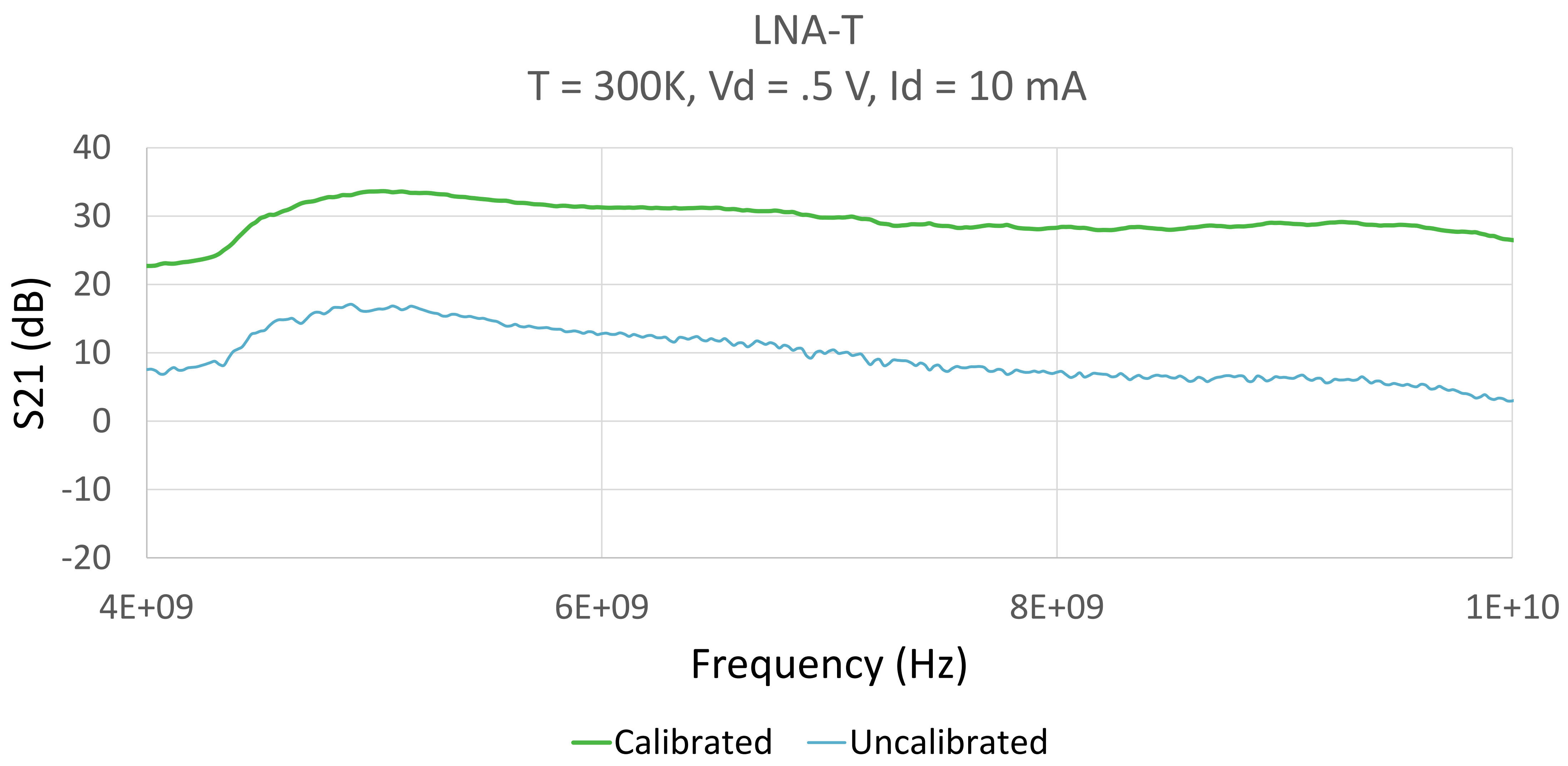


LNA-T Room Temperature

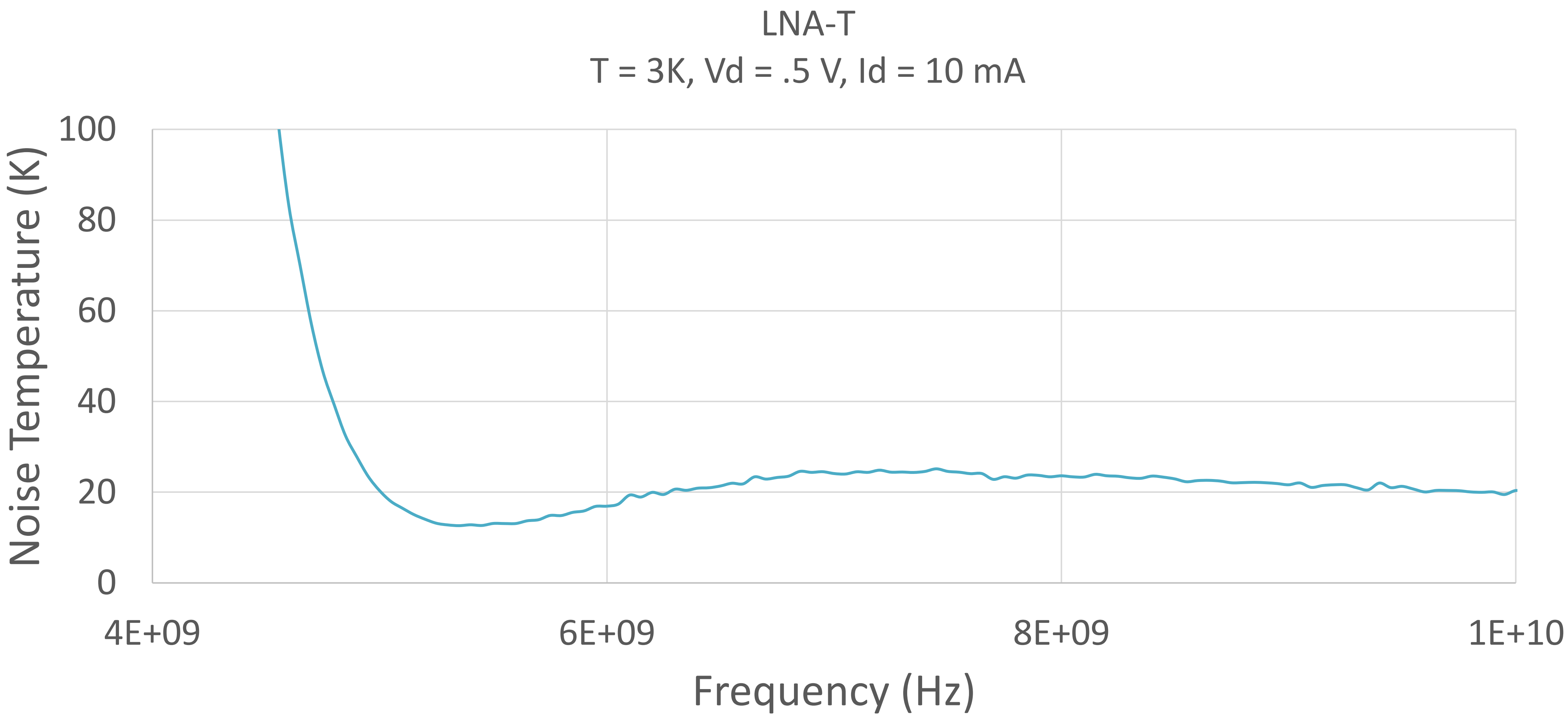




LNA-T Cryogenic Temperature



LNA-T Cryogenic Temperature

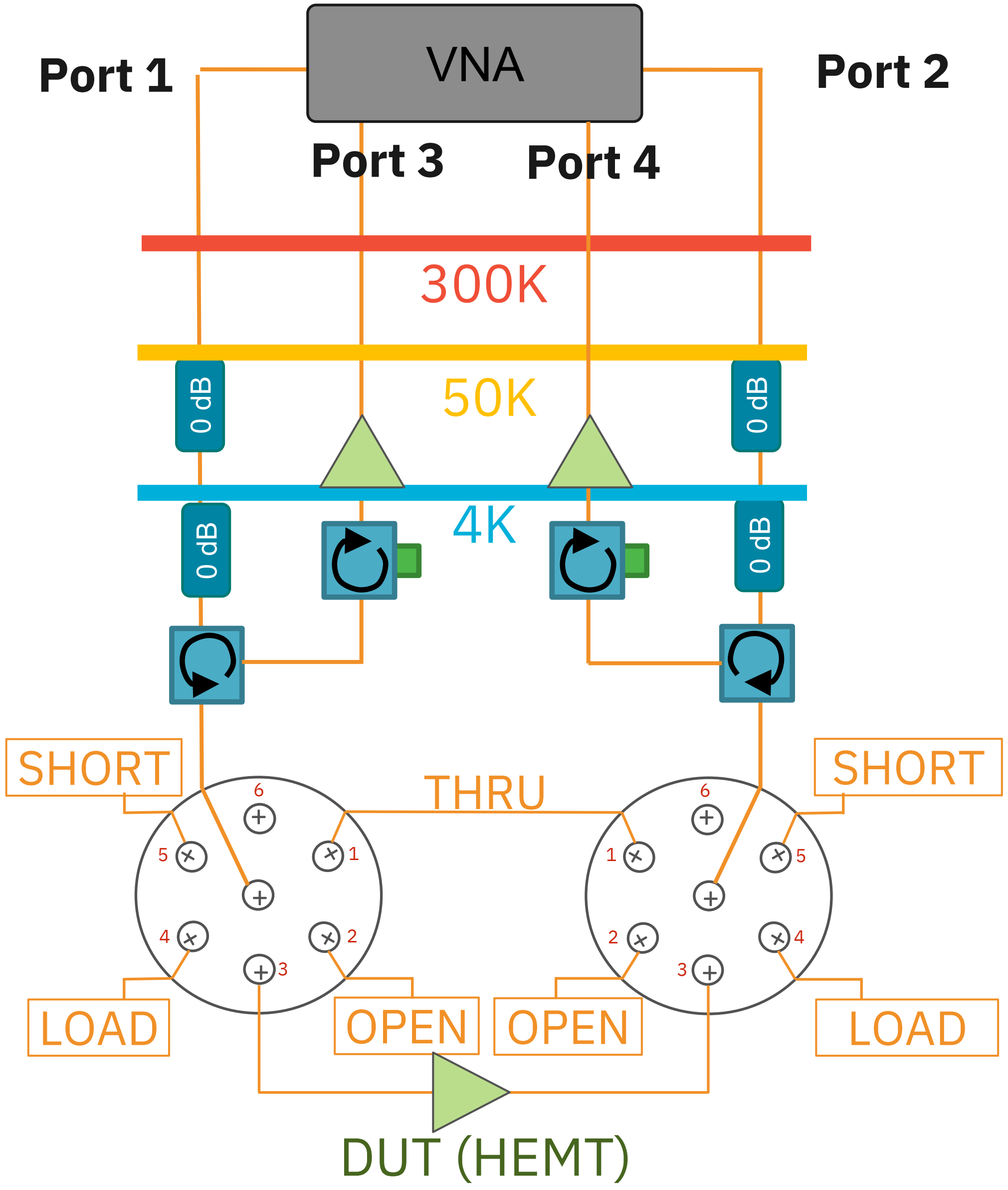


Measurement Errors

- Differing bias voltages due to lead resistance
- Low SNR for S11, S12, and S22 without amplification
- Impedance mismatch of ENR at room temperature
- Cable noise neglected rather than calibrated
- Temperature gradient from attenuator to sensor

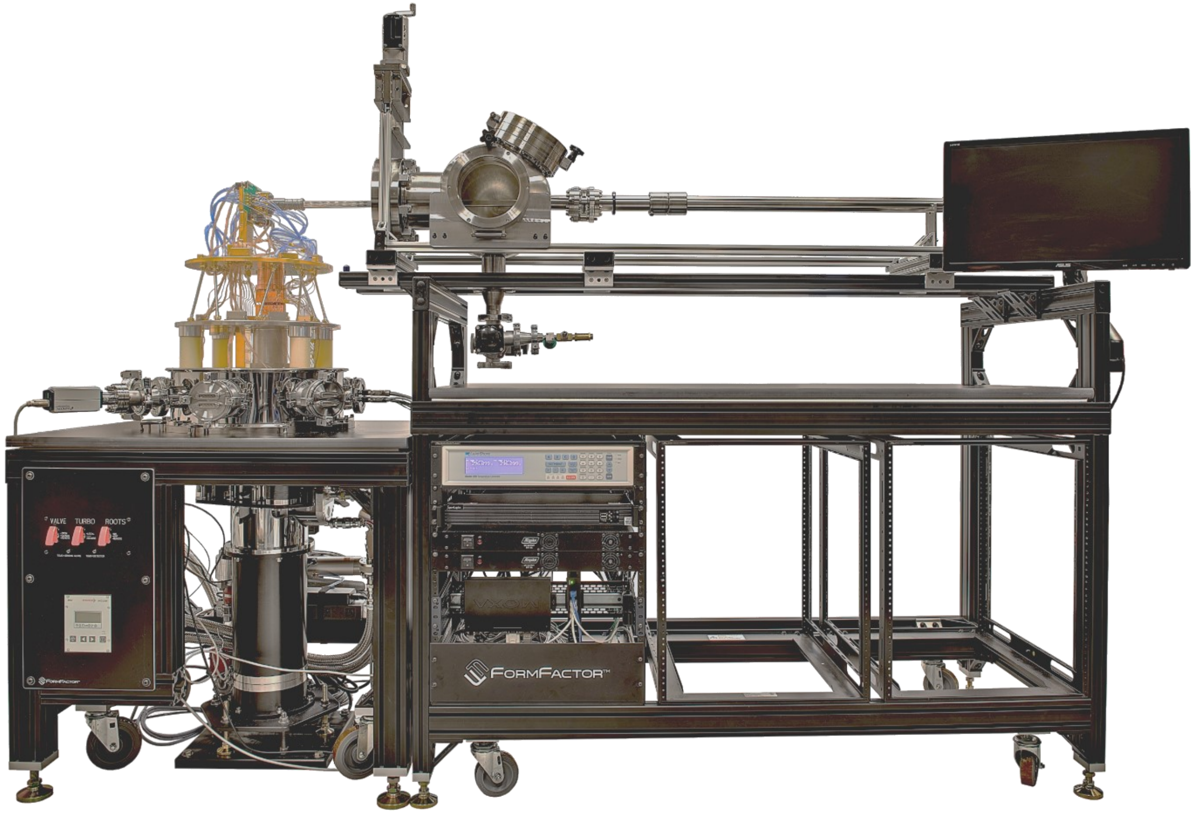
4 Port Calibration

- Circulate output signals to ports 3 and 4
- Amplify output signals
- Better SNR on calibration and S11, S12, and S22
- More complex and more expensive



Reliability Testing

- Rapid thermal cycling
- Periodic functional tests
- 20+ thermal cycles from 300K to 4K
- Functional test every 5
- Observe degradation over many cycles

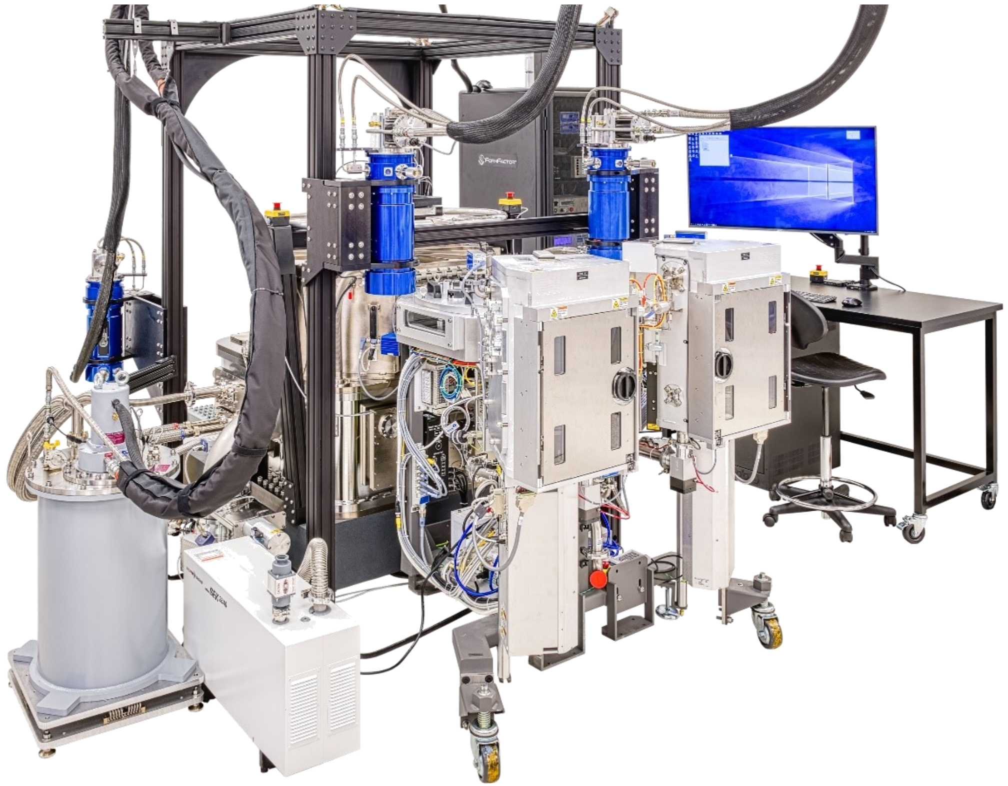


Integration Testing

- Full Qubit Control and Readout
- Well characterized baseline
- Swap out test components to measure change
- Measurement Parameters
  - Resonator Spectroscopy
  - Dispersive Shift
  - Qubit Spectroscopy
  - Rabi Oscillations
  - T1 and T2 Times

Scaling to Production

- Maximize sample space, minimize cycle times
- Single cooldown S-parameter and Noise Temperature
- Automate calibration and measurement sequence
- Test MMIC devices at wafer scale



Conclusion

- More work to improve cryo S-parameter measurement
- Integrate setup in a higher throughput system
- Setup load-lock or other method for reliability testing
- Call to Action! More workgroups, different components
- Cryogenic circulators and isolators are a good next step