PYT300

SUMMER INTERNSHIP
PROGRESS REPORT PART-1

Name: ANUSHKA PANDEY

Host Institute: Institut Néel – CNRS, Grenoble, France

Internship Supervisor: ANDREW FEFFERMEN

Home Institution Supervisor: Prof. KEDAR KHARE

Project Title: *Ultra-Coherent Nanomechanical Resonators*

Reporting Period: 14 May'25 – Present

Abstract

This report contains the contributions made throughout the internship towards the project "Ultra Coherent Nanomechanical Resonators" under supervisor Andrew Feffermen at the Ultra Basses Temperatures (UBT) group, Neel Institute, CNRS, Grenoble, France.

1. Introduction

This internship is part of an ongoing research project in the Ultra-Coherent Nanomechanics (UBT) group at Institut Néel, focused on the characterization of high-Q nanomechanical resonators embedded in superconducting circuits. These systems are critical for advances in quantum sensing, hybrid optomechanical devices, and low-loss microwave platforms. My work involves cryogenic measurements, data modeling, and theoretical analysis of mechanical dissipation and optomechanical coupling.

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2. Laboratory Training and Integration

- I received hands-on lab training which included:
    - Familiarization with cryogenic measurement systems (including dilution refrigerators).
    - Exposure to signal generators, network analyzers, and microwave components.
    - Understanding the wiring and filtering needed for low-noise measurements at milliKelvin temperatures.

- This training helped me integrate into the UBT team and participate more effectively in data acquisition sessions.

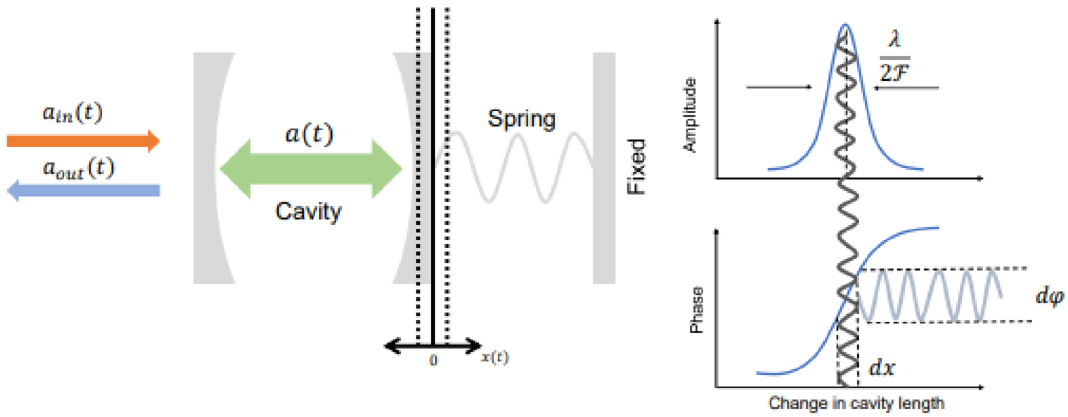


Fig 1 : (left) Schematic showing an optical cavity with a mechanically compliant resonator (right) The small motion of the mechanically compliant mirror induces a large change in the phase of the output signal

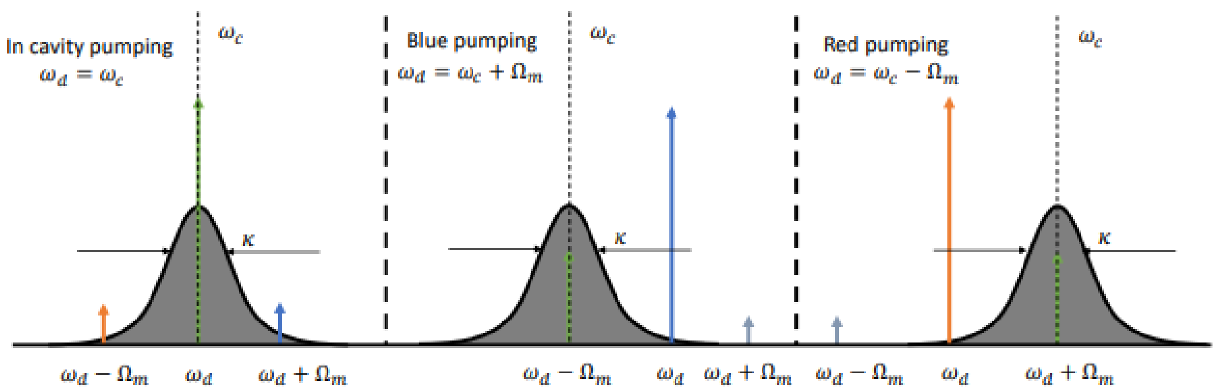
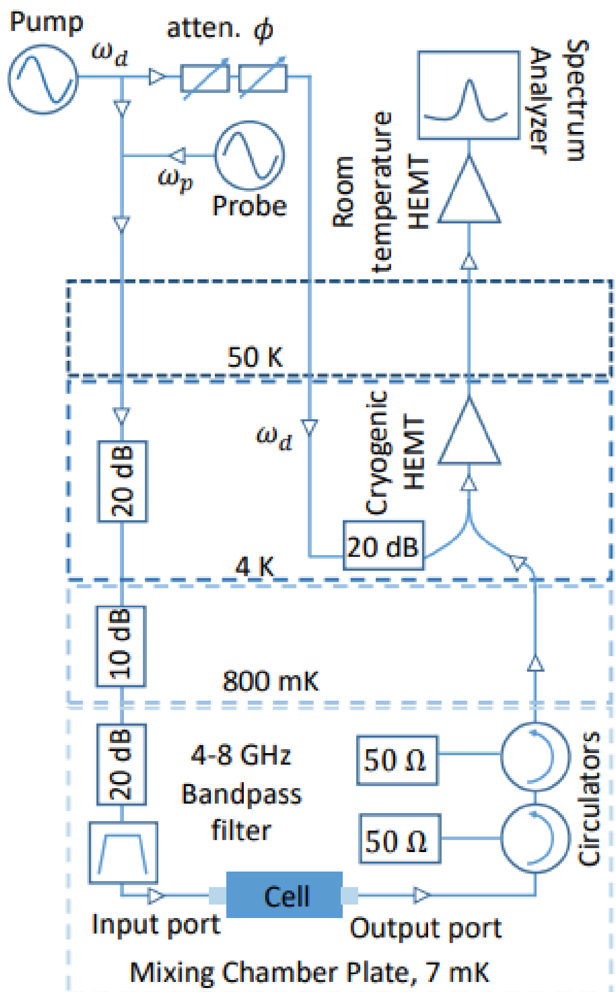
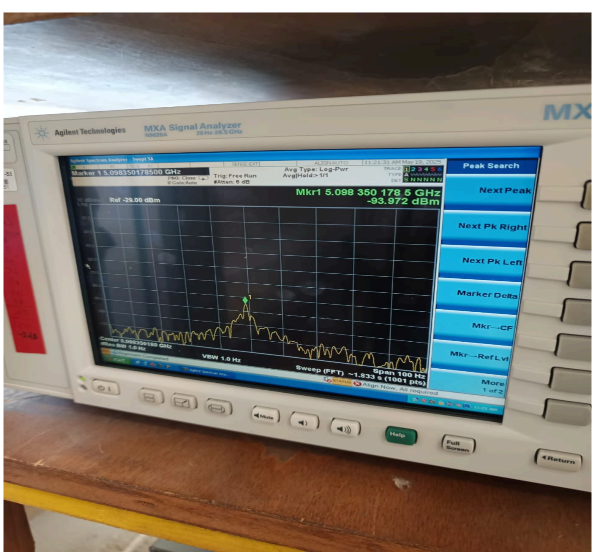


Fig 2: The schematic showing three different pumping schemes (left) incavity pumping (center) Blue pumping and (right) red pumping


Pump
ω_d
atten. ϕ
ω_p
Probe
Room temperature HEMT
Spectrum Analyzer
50 K
ω_d
20 dB
Cryogenic HEMT
20 dB
4 K
10 dB
800 mK
20 dB
4-8 GHz
Bandpass
filter
50 Ω
50 Ω
Circulators
Cell
Input port
Output port
Mixing Chamber Plate, 7 mK


MXA Signal Analyzer
Peak Search
Next Peak
Next Pk Right
Next Pk Left
Marker Delta
Mkr1 5.098 350 178 5 GHz
-93.972 dBm

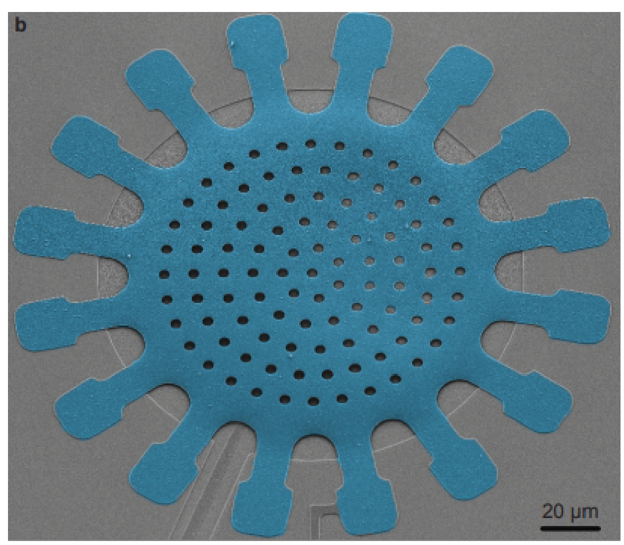
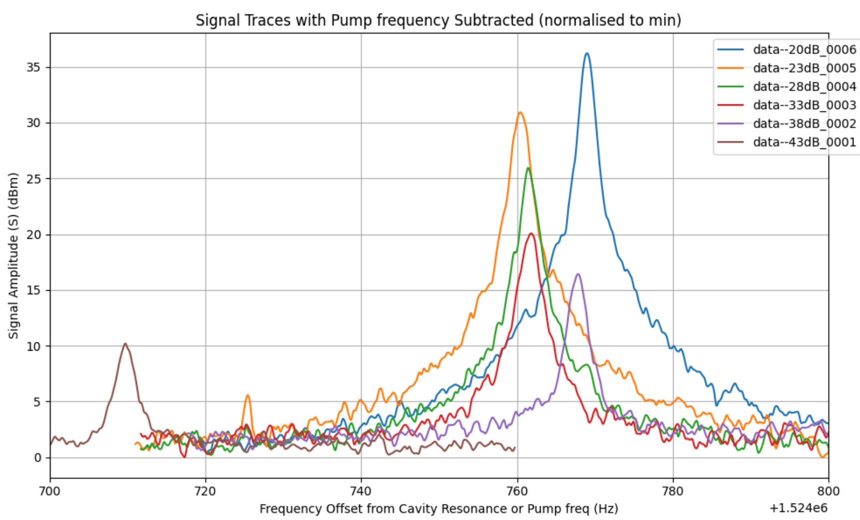

b
20 μm

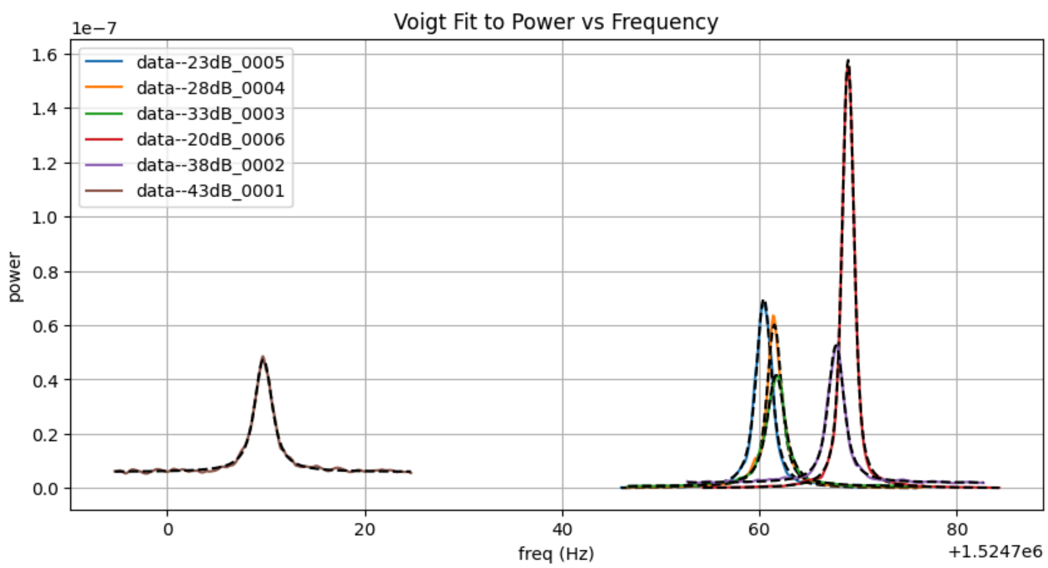
Fig 3 : i) A schematic circuit diagram with spectrum analyzer as measuring instrument ii) FSP spectrum of mechanical sideband in blue pumping $(\omega + \Omega_m)$ iii) A drumhead parallel plate capacitor after releasing the top layer.

3. Work Completed

a) Experimental Data Analysis at Millikelvin Temperatures

- I have been analyzing mechanical response measurements for two nanomechanical devices with resonance frequencies of 5.1 GHz and 5.973 GHz.

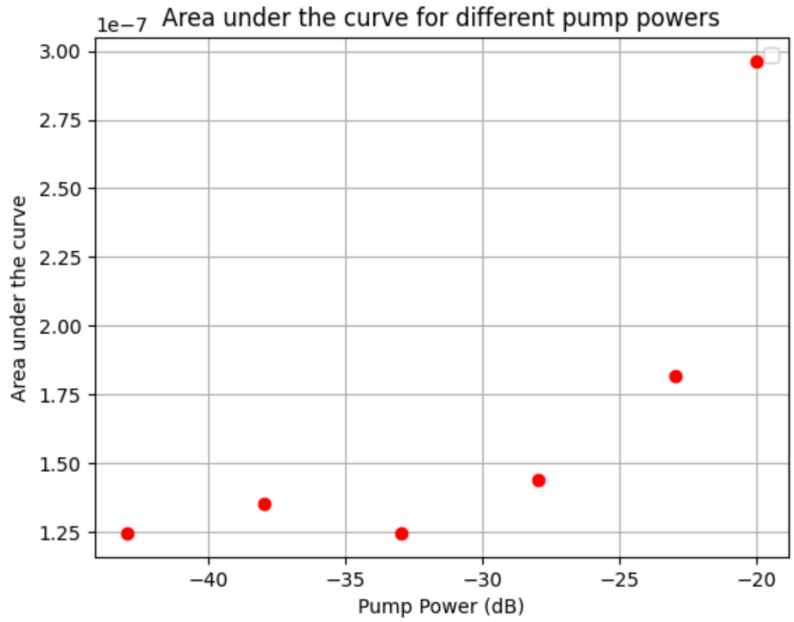




- The devices were probed at 212 mK and 12 mK, using a cryogenic setup to observe high-Q mechanical modes and their thermal response.
- I performed curve fitting using Voigt profiles to accurately extract key mechanical parameters:
    - Resonance frequency shifts under different experimental conditions.
    - Linewidth (Γ_m) which relates directly to the mechanical quality factor.
    - Amplitude of the spectral peaks.
- In particular, the Voigt profile was used to model broader line shapes and account for Gaussian broadening and gives convolution of lorentzian and gaussian filters present in the FSP.

$$V(\omega; \Gamma, \sigma_{\mathrm{RBW}}) \equiv \int_{-\infty}^{+\infty} \frac{\Gamma}{\pi(\omega'^2 + \Gamma^2)} \times e^{-\frac{(\omega-\omega')^2}{2\sigma_{\mathrm{RBW}}^2}} \, d\omega'$$

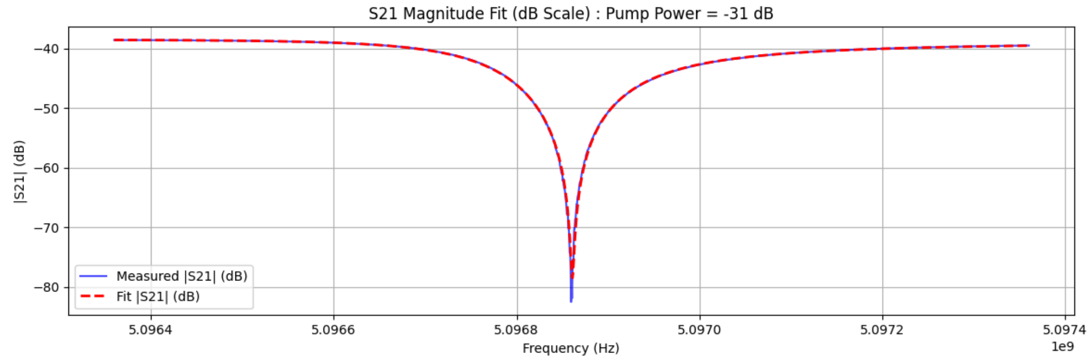
- Calculated the area under the Lorentzian curve, which corresponds to the integrated mechanical power spectral density and is critical for understanding energy dissipation.

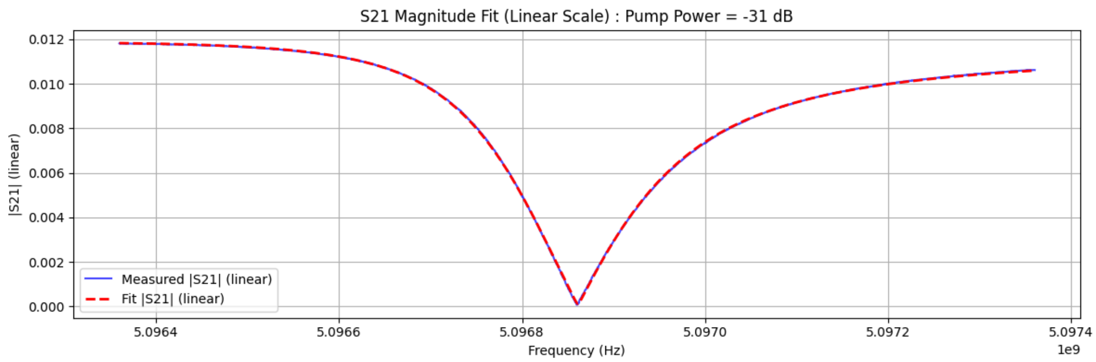


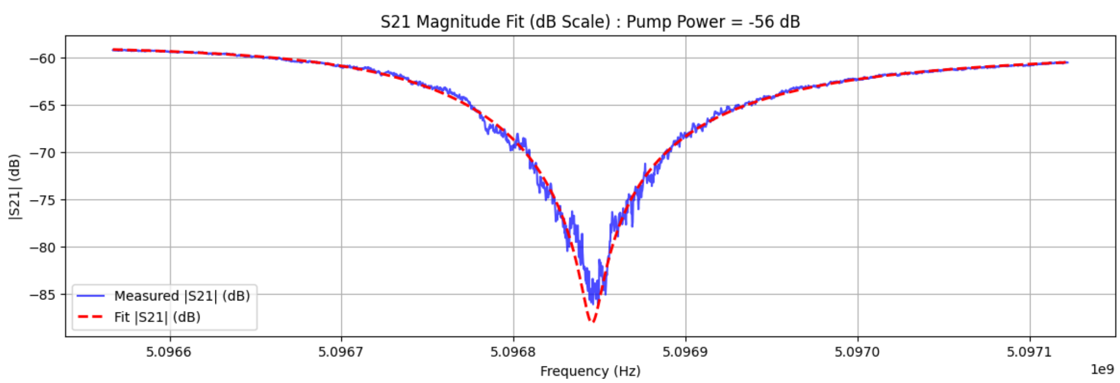
b) Damping Characterization

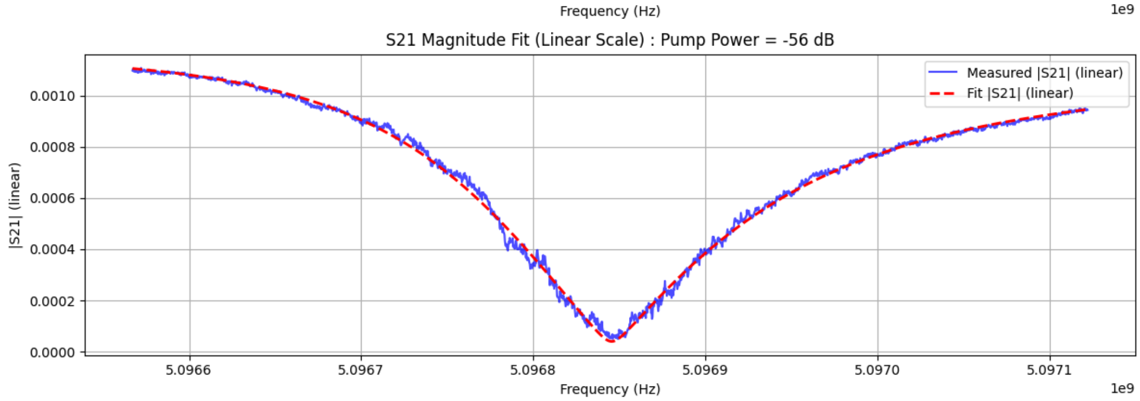
- From the spectral data, I extracted both internal damping (Γ_{int}) and external damping (Γ_{ext}) by fitting transmission S21 measurements according to following equation:

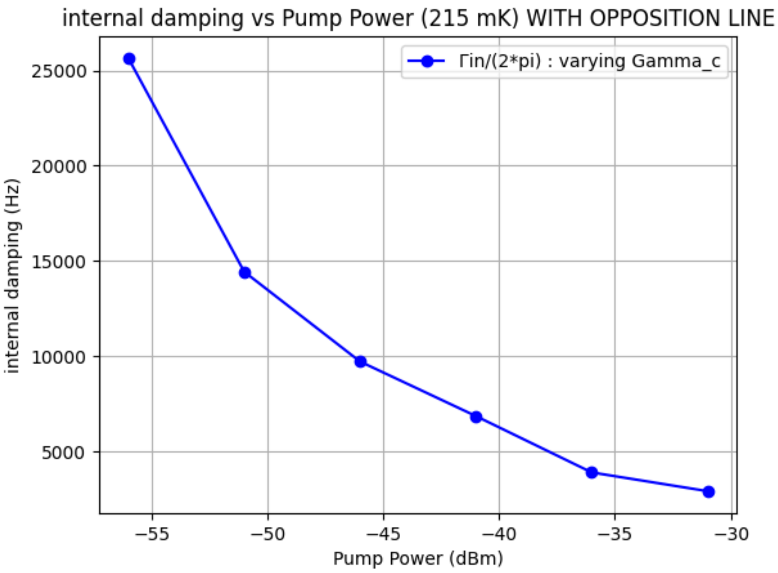
$$S_{21} = 1 - \frac{\frac{Q_0}{Qc} - 2i\frac{\Delta\omega}{\omega}}{1 + 2iQ_0\frac{\omega - \omega_0}{\omega_0}}$$

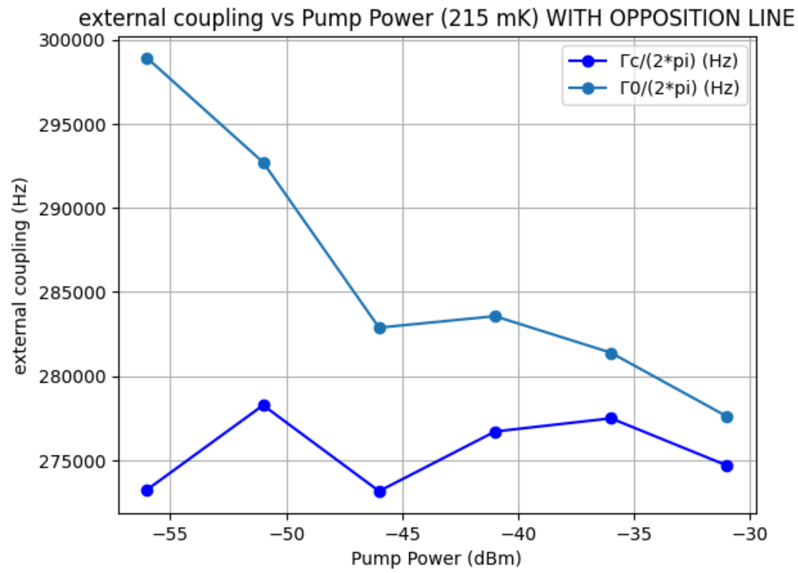

S21 Magnitude Fit (dB Scale) : Pump Power = -31 dB
|S21| (dB)
−40
−50
−60
−70
−80
5.0964
5.0966
5.0968
5.0970
5.0972
5.0974
1e9
Frequency (Hz)
Measured |S21| (dB)
Fit |S21| (dB)

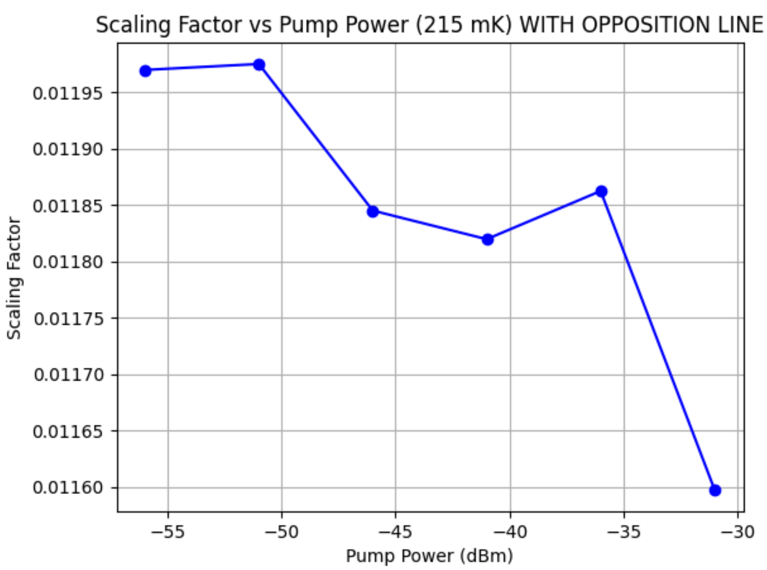

S21 Magnitude Fit (Linear Scale) : Pump Power = -31 dB
|S21| (linear)
0.012
0.010
0.008
0.006
0.004
0.002
0.000
5.0964
5.0966
5.0968
5.0970
5.0972
5.0974
1e9
Frequency (Hz)
Measured |S21| (linear)
Fit |S21| (linear)

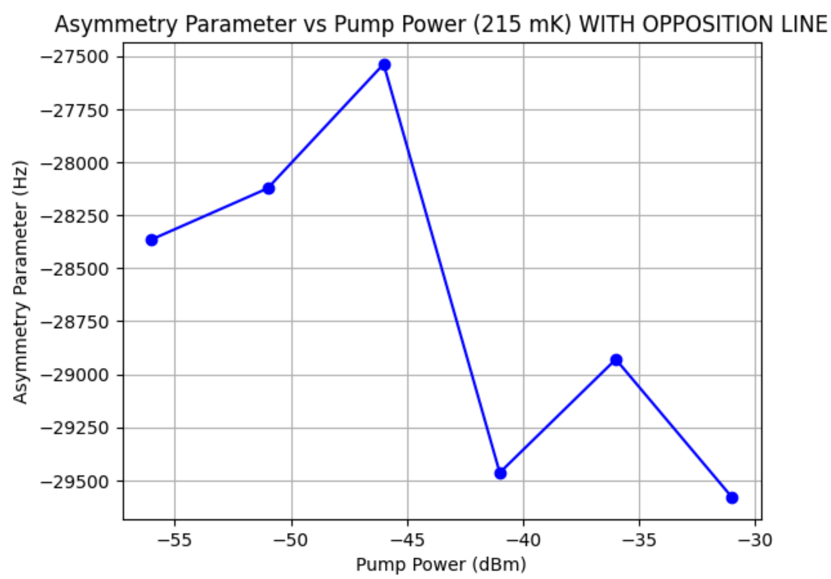

S21 Magnitude Fit (dB Scale) : Pump Power = -56 dB
|S21| (dB)
−60
−65
−70
−75
−80
−85
5.0966
5.0967
5.0968
5.0969
5.0970
5.0971
1e9
Frequency (Hz)
Measured |S21| (dB)
Fit |S21| (dB)


S21 Magnitude Fit (Linear Scale) : Pump Power = -56 dB
|S21| (linear)
0.0010
0.0008
0.0006
0.0004
0.0002
0.0000
5.0966
5.0967
5.0968
5.0969
5.0970
5.0971
1e9
Frequency (Hz)
Measured |S21| (linear)
Fit |S21| (linear)

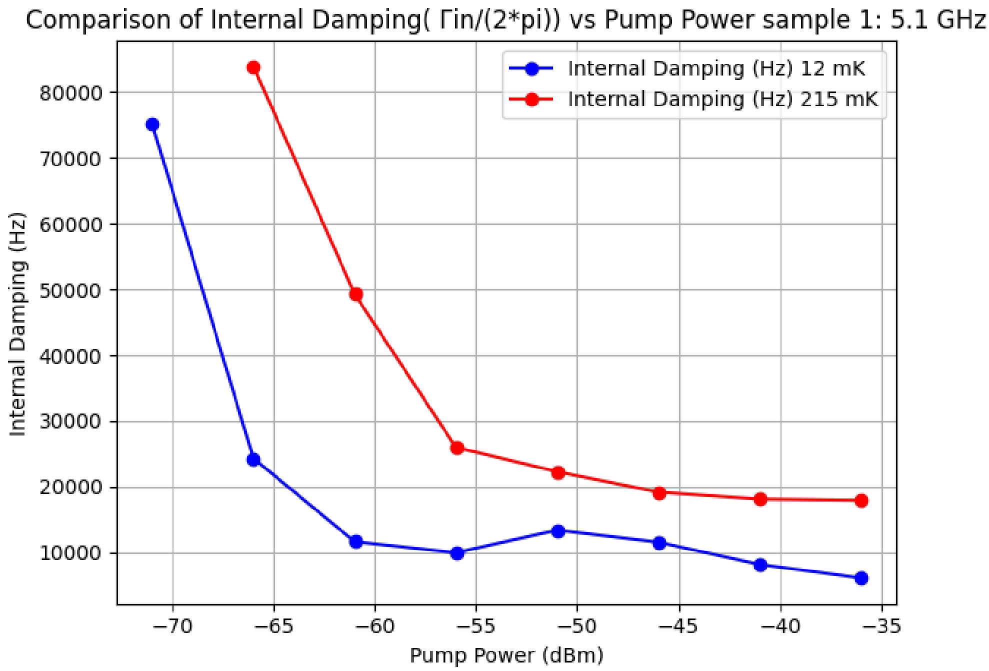


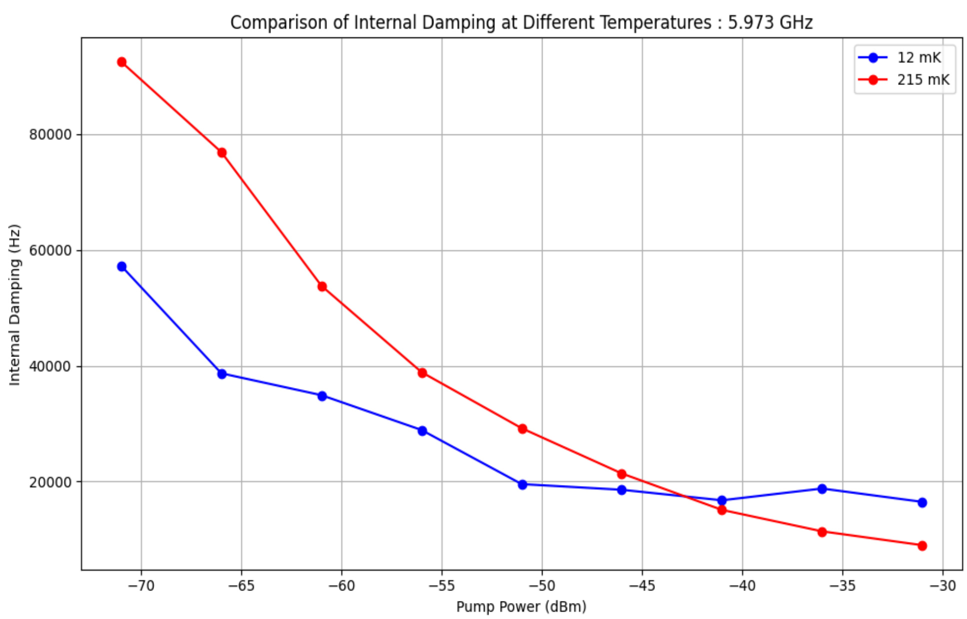






- This was done for both devices at two temperatures 12mK and 215 mK, helping to map how environmental and structural factors influence mechanical losses.





c) Optomechanical Noise Spectrum Analysis

- A significant part of my work involved understanding and applying optomechanical theory to interpret the device's output signal.

- Specifically, I studied the derivation of the position noise spectrum $S_x(\omega)$

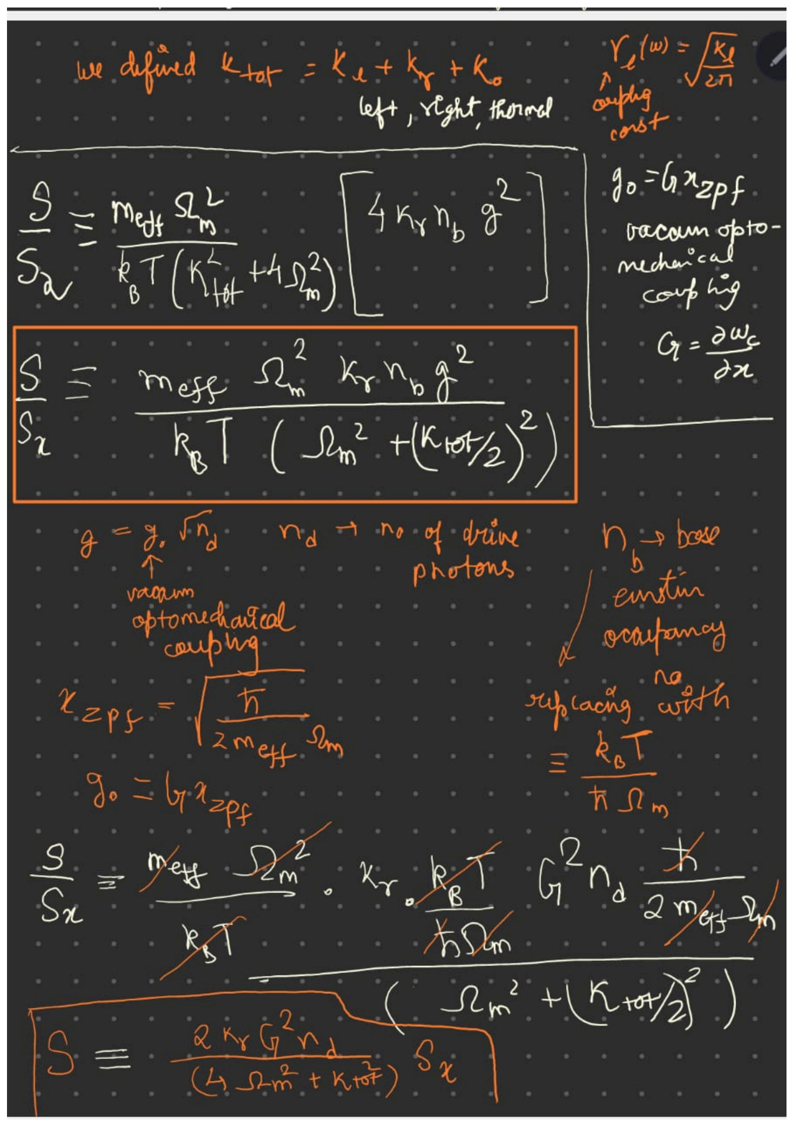
$$S = \frac{16\Gamma_m \kappa_r n_b g^2}{\Gamma_m^2 + 4(\omega_c - \omega - \Omega_m)^2} \frac{1}{\kappa_{total}^2 + 4\Omega_m^2} + \frac{16\Gamma_m \kappa_r g^2 (n_b + 1)}{\Gamma_m^2 + 4(\omega - \omega_c - \Omega_m)^2} \frac{1}{\kappa_{total}^2 + 4\Omega_m^2} \tag{2.93}$$

  under the *green pumping* scheme from Sumit Kumar’s thesis, focusing on Eq. 2.93.

- I derived and verified the conversion factor between $S_x(\omega)$

$$S_x[\omega] \approx \frac{k_b T}{m_{eff}\Omega_m^2} \frac{\Gamma_m}{[(\omega - \Omega_m)^2 + (\Gamma_m/2)^2]}$$

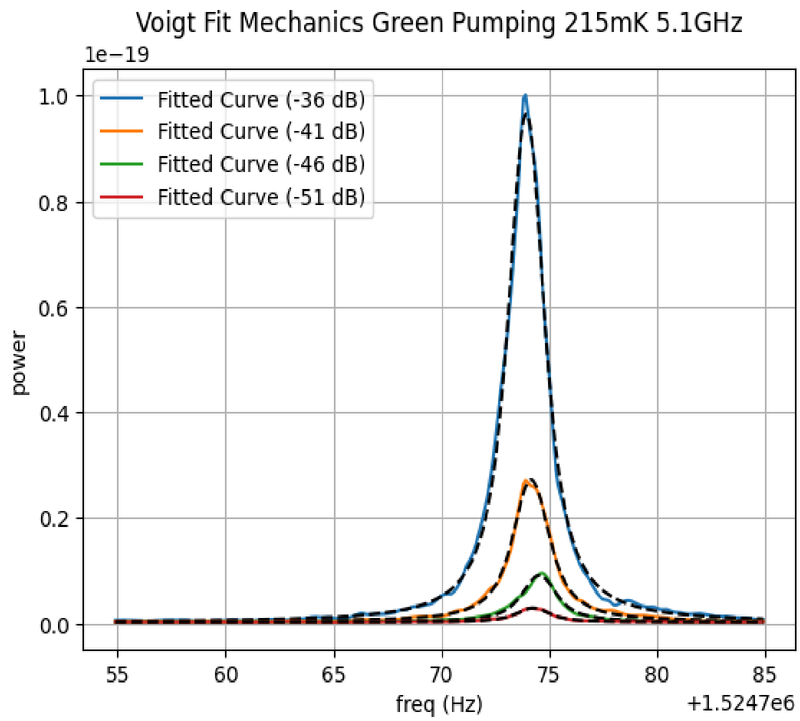
  and the output voltage spectrum detected in our measurement chain.

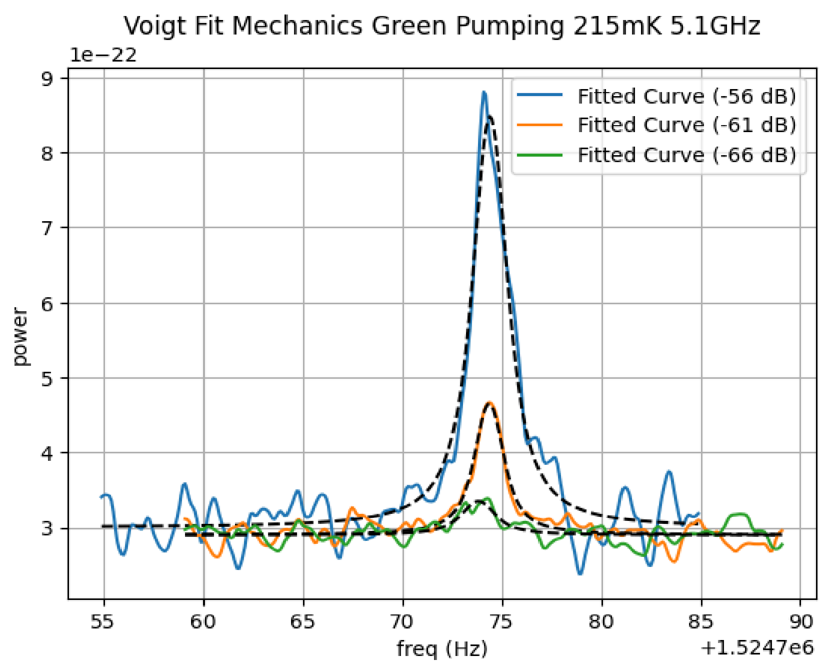


d) Determine whether the area of Sx depends on pump power

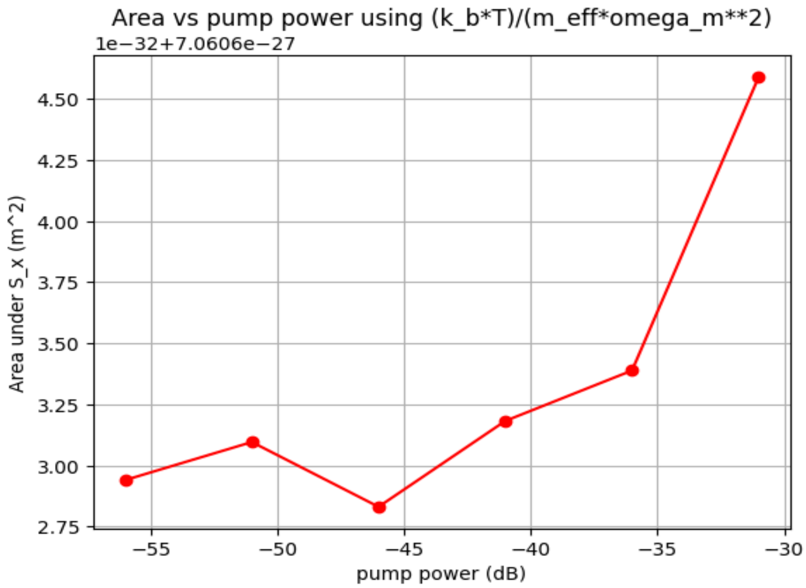
- This required accounting for system-specific factors such as:
  - Amplifier gain

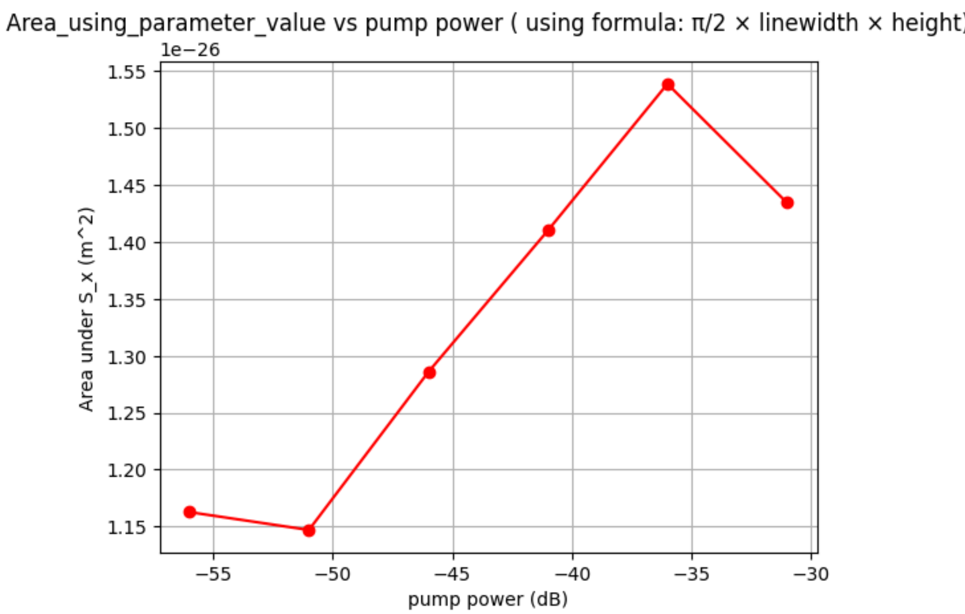
- ○ Filtering effects from the Field Spectrum Processor (FSP), modeled as a Gaussian convolution





- We tried to verify our result by calculating variance of position using equipartition method :





3. Literature Review

To support this work, I reviewed the following key references:

- **Youssefi et al. (2023)** – *A squeezed mechanical oscillator with millisecond quantum decoherence*, *Nature Physics*.
  [DOI: 10.1038/s41567-023-02135-y]
  Demonstrates high-fidelity ground-state preparation and squeezing using a superconducting optomechanical system.

- **Capelle et al. (2020)** – *Probing a Two-Level System Bath via the Frequency Shift of an Off-Resonantly Driven Cavity*, *Phys. Rev. Applied*.
  [DOI: 10.1103/PhysRevApplied.13.034022]
  Provides a model for TLS-induced loss and frequency shifts under off-resonant pumping.

- **Geerlings et al. (2012)** – *Improving the quality factor of microwave compact resonators by optimizing their geometrical parameters*, *Appl. Phys. Lett.*
  [DOI: 10.1063/1.4710520]
  Crucial for interpreting S21 data and correcting for impedance mismatch in transmission measurements.

- **[Vacuum-gap Capacitor Paper]** – *Compact superconducting vacuum-gap capacitors with low microwave loss and high mechanical coherence for scalable quantum circuits*.
  (Presumed Melville et al. or similar) Discusses the design of capacitive elements with high mechanical and microwave coherence, relevant for integration in scalable cryogenic quantum circuits.

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4. Additional Activities

i) Machine-Tool Safety Training

- I will attend the **machine-tool safety session** organized by the Cryogenics Service on **Friday, June 20** in the mechanical workshop.
- This session is mandatory for using the **self-service machine-tool park** and will enhance my understanding of hands-on hardware preparation, mechanical assembly, and lab safety protocols.

- Attended seminars on:

    - *Microwave-optical transduction with barium titanate*
    - *Single-electron interferometry and time-resolved EM sensing*
    - *Even & Odd denominator quantum Hall interferometry in bilayer graphene*

These seminars helped me contextualize my project within the broader scope of condensed matter and quantum physics.

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5. Future Plans

- Transition from transmission configuration to termination at one end as per the figure below.

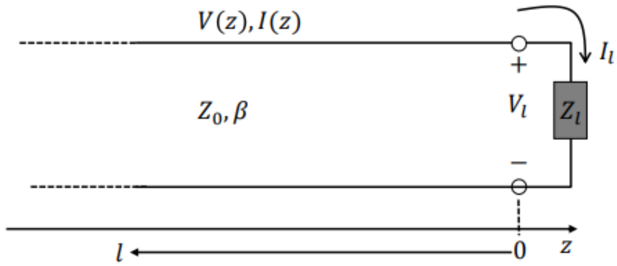

FIGURE 3.11: A transmission line terminated in a load impedance Z_l)

- Run new cooling cycles to study power- and temperature-dependent mechanics.
- Possibly contribute to internal documentation or publications based on data analysis.

6. Reflections

This internship is giving me a deep, hands-on understanding of nanomechanics at ultra-low temperatures and the real-world complexities of optomechanical experiments. The work has strengthened both my technical foundation and research motivation in the field of condensed matter and quantum devices.