Many researchers employ low temperatures in their optical cavity experiments to reduce phonon broadening and enable material observations inaccessible at room temperature. For researchers studying optical cavities, there are experimental considerations that extend beyond simply achieving cryogenic temperatures. Factors such as temperature stability, ultra-low vibrations and accelerations, and the demands of sustaining a cryogenic environment for days, weeks, or even months deserve heightened importance when working at low temperatures. We consider two experiments which were configured to perform cavity physics at cryogenic temperatures, and we also discuss recent advances in closed-cycle technology which will reduce the barrier to entry of performing low temperature optical cavity experiments.
Optical Cavity Physics: Mitigating Thermal and Vibrational Noise

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INTRODUCTION

Optical cavities are resonators allowing light to circulate within the structure and then emit at a specific frequency or wavelength depending upon the parameters of the cavity. These structures enable control of the optical emission properties of materials placed inside them. Cavities can provide optical gain, stabilize the spectral width of lasers, and influence the spontaneous emission rate. Optical microcavities are attractive for studying the fundamental physics of the interaction between materials with electromagnetic radiation and are promising for precision measurement science and quantum information processing.

Efforts to further enhance cavity performance will need to take advantage of vibration isolation technology optimized for a high-performance cryogenic environment. While the trends toward closed-cycle preclude the expense and hassle of working with liquid cryogens, limits in the existing technology introduce challenges for these measurements. We consider two experiments which were intricately configured to mitigate these issues, and we also discuss recent advances in closed-cycle vibration isolation technology which should allow for less demanding construction to achieve high-performance cryogenic optical cavity setups.

Cryogenic cooling of an optical cavity is a necessary step for improving cavity performance and experimental success.

Cavity performance depends strongly on several factors which include the Q-factor, input coupling loss, and internal loss. Each of these factors can benefit from cryogenic cooling to temperatures of ~4K, increased temperature stability, and decreased mechanical vibrations and accelerations [1-4, 8].

Optical resonators (cavities) may take on a variety of form factors experimentally depending upon the intended application. Cavities are commonly implemented for laser frequency stabilization (an example cavity is schematically shown in Figure 1a). These cavity stabilized laser systems are powerful tools for precision measurement science that can probe nature at the quantum mechanical level. For a laser operating in the visible region, if the frequency instability could be reduced to $10^{-18}$, the resulting laser linewidths would be a few mHz, yielding a new generation of precision measurements. Maintaining a stable operating temperature while also minimizing mechanical vibrations and accelerations is critical. Cavities are also being implemented in fiber optic based quantum networks to enhance the emission properties of color centers (a simplified fiber-optic cavity scheme is shown in Figure 1b). The success of these quantum information experiments based on entanglement physics is directly related to the probability of a color center emitting into the resonant zero phonon line. At room temperature, the ambient thermal energy excites many phonons and the probability of zero-phonon transition is close to zero. Cryogenic cooling is critical for reducing the phonon population and simultaneous vibration reduction (maintaining RMS displacements < 0.5nm) is necessary for enhancing the probability of zero-phonon line emission for successful quantum information processing [1, 4].

Figure 1: a) A free-space laser coupled crystal is shown, where the monolithic crystal with Bragg reflective coatings is the cavity. b) A fiber-coupled laser cavity is formed by the reflective back side of the sample and a mirror coated concave optical fiber-tip.
Cryogenic cooling of an optical cavity is a necessary step for improving cavity performance and experimental success. Researchers have recently favored closed-cycle cryogenic solutions due to the high cost of liquid helium, as well as advances in technologies that provide low vibration, high temperature stability closed-cycle options. In the sections below, we discuss two examples of custom engineered setups that illustrate the time and care that goes into designing a suitable cryogenic platform for enhancing cavity performance. We then discuss recent technological developments which can drastically simplify the setup of a closed-cycle cryogenic optical cavity experiment. [3, 4]

**CRYOGENIC CONSIDERATIONS**

**Benefits of Cryogenic Measurements**

Cryogenic cooling of an optical cavity can improve cavity length stability, Q-factor (optical quality factor), optical finesse, input coupling losses, and internal losses. [1-4] Reducing the operating temperature to ~4K offers several advantages. The thermal noise (thermal reservoir) is reduced, which results in fewer phonon modes. As the number of phonon modes decreases, the lifetime of emitters increases and the probability of emission into the zero-phonon line is enhanced, which is critical for quantum information experiments.

\[
\frac{\Delta L}{L} = \alpha_L \Delta T
\]

where \( L \) is the length, \( \Delta L \) is the fluctuation in length, \( T \) is the temperature, and \( \alpha_L \) is the linear CTE for the system. [7] To understand the ramifications of this, we consider the specific case of Zhang et. al. in which they study a 6cm long silicon cavity with reflective end coatings; at 4K the CTE is approximately \( 2 \times 10^{-11}/K \). If we assume baseline cryocooler fluctuations of 100mK, this results in a frequency instability of \( 10^{-13} \) which is well above the thermal noise floor of \( 4 \times 10^{-17} \). [3] Given this example, it is clear that one must carefully consider how to improve the thermal stability of a cryocooled platform to realize the benefits of cryogenics.

Additionally, the coefficient of thermal expansion (CTE) decreases rapidly near absolute zero. This means that any temperature instability in the system results in a much smaller change in the mirror separation, and therefore, the output linewidth is more stable. Lastly, the Q-factor (quality factor) of the resonator is increased at cryogenic temperatures due to reduced dissipation and decoherence of the observable oscillatory states in the optical cavity.

**Challenges of Cryogenic Measurements**

Several experimental paradigms have been developed to operate optical resonators at cryogenic temperatures. Traditionally, cryogenic cooled cavity systems have made use of liquid helium to reach <4K temperatures, however, the ever increasing cost and reduced availability of liquid helium have necessitated new approaches. While closed-cycle cryocoolers preclude the expense and hassle of using liquid cryogens, the inherent temperature instability and vibrations of the cryocooler must be accounted for with additional mechanical and thermal engineering.

**Thermal Stability**

The thermal stability at the base temperature of a cryocooler is on the order of hundreds of mK. These fluctuations in the absolute temperature of the system can affect the cavity performance through the contraction and expansion of materials. Consider the cavity length, we can intuitively postulate that thermal and vibrational stability are critical due to the coefficient of thermal expansion and relative mirror displacements, respectively. The sensitivity of the cavity to thermal fluctuations, in its simplest form, can be written:

There are two parallel strategies for reducing thermal fluctuations. One strategy is to use low-loss coating materials and dopants that reduce the losses resulting from thermal fluctuations, however, research is still ongoing in this area. [8] The other strategy is to suppress the temperature fluctuations using passive radiation shielding, actively controlled radiation shields, and engineering the thermal path with materials having high heat capacity at cryogenic temperatures.

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The team of Zhang et al. engineered a thermal path using a custom support structure for the sample chamber that utilized a radiation shield cooled to 30K by the first stage of the cryocooler, an actively controlled shield at 3.5K, a passive shield at 3.75K, and a metal alloy thermal filter to passively damp temperature fluctuations from the cryocooler’s second stage. Each layer of shielding is separated by a thermally resistive material. Furthermore, the support structure for the silicon cavity itself has three nested layers connecting it to the cold plate that further increase the thermal path and damp fluctuations in temperature from the cryocooler (see Figure 2a). This method successfully suppressed temperature fluctuations inherent to the closed-cycle cryocooler to the µK range which was below the thermal noise floor (see Figure 2 for additional details on the thermal path). [3] Further improvements to temperature stability could be made with the addition of an actively stabilized 30K radiation shield to further reduce radiative heat load fluctuations on the inner radiation shields.

Both Gifford-McMahon and pulse tube closed-cycle cryocoolers generate RMS vibrations in the micron range and accelerations on the order of 0.1g (g=9.8m/s²). Vibrations and accelerations of this magnitude cause significant distortions to the cavity geometry that limit the minimum linewidths. The sensitivity of the cavity to vibrations and accelerations depends upon the cavity geometry, and in general, a longer cavity is more sensitive to vibrations. The cavity support structure should be designed with a sufficiently high resonant frequency to limit the impact of vibrations and accelerations. Therefore, in order to implement a closed-cycle cryocooler, one must carefully design an auxiliary vibration isolation scheme.

The team of Zhang et al. engineered a split base plate allowing the cryocooler to be mounted separately from the sample platform. To further mitigate vibrations, the sample platform itself was mounted on an active vibration isolation table (see Figure 3a). [3] When considering the monolithic Si cavity studied by Zhang et al., one is primarily concerned with accelerations from mechanical vibrations that cause the cavity to be displaced from the incident free space coupled laser beam. Lateral accelerations lower the Q and finesse, and vertical accelerations cause instabilities in the incident beam angle that lead to transverse offsets. Zhang et al. determined that the maximum intensity of the accelerations in the PSD spectrum should be less than $10^{-9}$ g²/Hz so vibrational noise does not limit the minimum linewidth. [3] Figure 3b shows the effectiveness of the mechanical isolation by measuring the sample platform accelerations with the closed-cycle cryocooler on (black line) and off (red line).
The basic optical fiber cavity setup can be described by the representative schematic in Figure 1b. In this type of cavity, RMS displacements between the fiber and the sample larger than ~0.15nm will cause observable frequency shifts and lower the finesse of the cavity. To mitigate vibrations, this group implemented a cryogenic compatible passive vibration isolation platform with three-axis attenuation. The vibration isolation stage was directly bolted to the cryostat cold plate, and the cavity was mounted atop the vibration isolation stage. The isolation stage has a stiff spring design (on the order of $10^4$ N/m) which results in a high cut-off frequency and can also support the mass of the nanopositioners plus sample.

Although the split base plate design allows mounting the chamber on an active vibration isolation table, the geometric constraints of the design mean the center of mass of the setup is not in the middle of the active isolation table. This necessitates manually balancing the setup by adding weights at different locations on the active isolation table. Moreover, at the start of each experiment, the balancing weights need to be adjusted and verified.

The custom engineered experimental setup shown in Figures 2-3 allowed Zhang et al. to demonstrate the first 4K silicon cavity cooled by a closed-cycle cryostat that achieved a fractional frequency instability of $1 \times 10^{-16}$. Given the base cryogenic platform already has built-in design features to reduce the sample chamber vibrations to <10nm and reduce temperature fluctuations to <10mK, the impressive experimental result was enabled by careful analysis of the mechanical and thermal design, requiring collaboration with the commercial entity to create a custom solution.

The team of Hanson et al. [4] engineered a custom solution to mechanically isolate the sample and fiber cavity in their pursuit of enhancing nitrogen vacancy center emission for quantum information processing experiments (see Figure 4).
The impact of cryocooler induced mechanical vibrations on the cavity performance was further mitigated by carefully timing the cavity linewidth detection to occur in-between pulses of the mechanically driven cryocooler. The custom engineered experimental configuration shown in Figure 4 yielded a tunable, high-finesse Fabry-Perot microcavity with an embedded diamond membrane which ultimately reached finesse values of $F \approx 12,000$ at 11 K. The measured finesse range for diamond films varied from 4000 to 15,000 and scaled with decreasing optical cavity length ($\lambda/2$). The demonstrated 0.48 nm RMS length stability provided a 13-fold increase in the nitrogen vacancy ZPL (zero phonon line) photon emission and is a significant step forward in improving the success probability of quantum information experiments.

AN IDEAL CRYOGENIC PLATFORM FOR OPTICAL CAVITIES

The cryogenic optical cavity case studies discussed above are impressive examples of the custom engineering efforts required to achieve enhanced optical cavity performance. The common engineering goal of these two experimental setups was to implement appropriate strategies to mitigate thermal instabilities and mechanical vibrations introduced by a closed-cycle cryocooler. Given the ever-increasing costs of liquid helium and the complexity of implementing homebuilt solutions, serious consideration should be given to leveraging an optimized closed-cycle cryogenic solution for optical cavity experiments.

Design Considerations

A cavity-optimized cryocooled platform would have integrated vibration damping technology to damp vibrations across a wide frequency range (<1Hz up to tens of kHz). The platform should provide a stable, high inertia reference frame with low accelerations for the optical cavity experiment. Such a platform would also provide for ultra-low RMS displacements between two objects on the platform (e.g. mirrors of the cavity). The base temperature of the system should be near liquid helium temperatures to significantly reduce the thermal noise compared to room temperature. This ideal cryogenic platform should also have a room temperature stage for mounting optics, a radiation shield for mitigating thermal loads and improving temperature stability, and a 4K sample platform with ample space for the addition of passive and active radiation shields.

Electrical connections should be thermally lagged to reduce heat loads and should have sufficient stress relief to prevent vibration transmission to the sample. The system would have integrated temperature control software that makes it simple to add active temperature stabilization and passive radiation shield temperature monitoring. A schematic overview of such a platform is shown in Figure 5.

Moreover, the ideal platform should have multi-stage passive vibration isolation that attenuates noise less than 1Hz in directions perpendicular to and in the plane of the platform. The mechanical isolation strategy would incorporate negative-stiffness springs below the three temperature stages (Figure 5). The design of the various
temperature regions should be thermally isolated but mechanically linked so they form a single, high inertial reference frame. The following equation defines the damping of the negative-stiffness spring:

\[ n_s \frac{K}{K_s} = n_s \left( \frac{f_s}{f} \right)^2 \]

Where \( n_s \) is the damping factor, \( K_s \) is the spring stiffness, \( K \) is the reduced net stiffness, \( f_s \) is the natural system frequency, and \( f \) is the reduced stiffness natural frequency. Mechanical damping can be greatly enhanced with this type of negative stiffness mechanism (NSM) isolation system. For example, consider the mechanical isolation normal to the sample platform, if we assume a natural spring frequency of 5Hz, and the NSM’s natural frequency is 0.5Hz, the resulting damping factor is 100 times.

To preserve the low-profile tabletop geometry of the system and avoid the use of conventional long extension springs, frequencies on the low end of the spectrum can be attenuated using a compact suspension method similar to that implemented for mirrors in gravitational wave detectors such as LIGO. When scaled down for an optical table, the proposed technology would be capable of achieving a platform resonance of 0.5Hz, which means that the sample environment is largely insensitive to heavy machinery, road traffic, microtremors, lab equipment, and other low frequency mechanical noise. Frequencies up to the kHz range are primarily attenuated by an additional stage in the mechanical support structure of the platform. When desired, the high Q-factor of the fundamental platform resonance could be suppressed through magnetic damping. While floating, the platform height could be manually leveled with electronic control knobs to account for uneven mass loads and to optimize the platform resonance frequency and associated attenuation profile.

**Testing Results**

We present measurement results on a new closed-cycle cryogenic platform with high inertia and low accelerations. First, the low frequency accelerations ranging from 0-200Hz are measured. The platform was excited with a driven broadband signal and the platform’s mechanical response was measured with a high sensitivity accelerometer. The platform attenuates vibrational frequencies above 0.85Hz as shown in the transmissibility curve shown in Figure 6b. Frequencies above 2Hz are attenuated by more than a factor of 10. Signals are very well attenuated in a range of \( \sim0.8Hz \) to \( \sim200Hz \) with up to 50db attenuation. The results compare favorably with the low-noise requirements for larger cavities, where maximum intensity in the measured acceleration PSD should be below \( 10^{-6} \text{ g/} \sqrt{\text{Hz}} \) (see Figure 3b). Considering typical cavity lengths, this level of vibrational stability is expected to reduce the fractional instabilities in precision cavity stabilized lasers (see Figures 3b, 6). We discuss the high frequency mechanical characterization results in the next section.
High Frequency Performance Data

To further evaluate the high frequency characteristics of this new platform, we installed an optical cavity capable of measuring the high frequency accelerations and also RMS displacements. A simple optical cavity was formed between an AFM cantilever and an optical fiber as shown in Figure 7. The experimental setup is similar to the optical fiber cavity case discussed in Figure 1b and can be evaluated using the Fabry-Perot formalism. This characterization setup can be used to implement the intrinsic contact noise (ICN) method of characterization. [9] Importantly, the ICN measures the noise of the entire measurement loop including the AFM components and not just the vibrationally isolated cryogenic platform. Therefore, the ICN provides an upper bound on the expected high frequency performance of the platform as there may be noise contributions from the remainder of the experimental setup.

The experimental results of the ICN measurement are shown in Figure 8. The Q-factor for the resonator at 295K was 251 and at < 90K improved to 35,198. Since the ICN measures the entire experimental setup, it will show all noise frequencies and resonances over the measured frequency range (in our case 0 Hz to 100 kHz), including contributions from the AFM. As shown in Figure 8b, the absolute voltage signal remains below 200mV between 0-60kHz. The 200mV signal corresponds to a 0.4nm RMS displacement. This result demonstrates sufficient noise isolation for fiber coupled optical cavities and shows promise for analogous optomechanical devices. This closed-cycle cryogenic platform warrants further consideration for researchers attempting to enhance optical cavity performance with cryogenics while avoiding the expense and hassle of liquid helium.

Figure 7: A schematic representation of the Fabry-Perot cavity used for the intrinsic contact noise (ICN) measurement. The optical cavity is formed between the Si cantilever (Budget Sensors Multi75Al-G; f=75kHz, C=3 N/m, L=225um) of the AFM and the optical fiber. The ICN measures the noise response of the complete experimental setup which includes noise sources from the AFM.

Figure 8: High frequency vibration characterization of the new platform with fully integrated mechanical isolation. Top graph (a) is the thermal peak for the Si cantilever with the cryocooler on. The bottom graph (b) is the Intrinsic Contact Noise spectrum with the cryocooler on. The measured noise is below 200mV which translates to RMS displacements < 0.4nm based on standard calibration factors for the AFM used to make the measurement.
CONCLUSIONS

Optical cavity design and performance is advancing rapidly, and further improvements in performance require high stability cryogenic environments. We discussed examples of two research groups who developed homebuilt, custom engineered cryogenic setups. Both examples required careful consideration of the mechanical and thermal design. These considerations required extensive experimental characterization of the setup itself prior to making any measurements with the cavity.

The physics community now has access to recent developments in low temperature, high inertia, low acceleration platforms that greatly simplify the setup of an optical cavity. We presented the acceleration and intrinsic contact noise characterization results from one such platform to demonstrate the broad range frequency response. These new systems significantly reduce consumable costs and the time required to setup an optical cavity experiment. Researchers can now quickly achieve their ideal experimental environment and focus their efforts on cavity design and new physics.

REFERENCES

1. Markus Aspelmeyer, Tobias J. Kippenberg, and Florian Marquardt, Cavity Optomechanics Rev. Mod. Phys. 86, 1391

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