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Electro-Mechanical Tuning of High-Q Bulk Acoustic Phonon Modes at Cryogenic Temperatures

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We investigate the electromechanical properties of quartz bulk acoustic wave resonators at extreme cryogenic temperatures. By applying a DC bias voltage, we demonstrate broad frequency tuning of high-Q phonon modes in a quartz bulk acoustic wave cavity at cryogenic temperatures of 4 K and 20 mK. More than 100 line-widths of tuning of the resonance peak without any degradation in loaded quality factor, which are as high as 1.73×10^9 , is seen for high order overtone modes. For all modes and temperatures the observed coefficient of frequency tuning is ≈ 3.5 mHz/V per overtone number n corresponding to a maximum of 255.5 mHz/V for the $n = 73$ overtone mode. No degradation in the quality factor is observed for any value of applied biasing field.

Low loss systems have found numerous applications as time-keeping devices as well as sensors, due to their long coherence times and high sensitivity. Although, in addition to high quality factors, many applications require a degree of frequency tunability. For example; frequency tuning is needed in clock applications to lock a low phase noise device to an external stable resonance

or an atomic transition¹⁻⁵, or in detection systems where the frequency of a detectors target signal is unknown^{6,7}. However, it has been recognised that achieving both high tunability while maintaining high quality factors is extremely difficult both for electromagnetic and mechanical systems. In photonic applications this can be solved by changing geometry of the resonant system with mechanical actuators. In mechanical systems however, a geometrical tuning solution is almost impossible to realise without compromising losses. A lossless tuning mechanism for such mechanical resonators would be desirable as these devices may be more suitable than their optical counterparts for certain applications requiring lower frequency operation. In this work, we demonstrate highly stable electromechanical tuning of an acoustic quartz resonator, preserving the resonators extremely high quality factors.

Quartz bulk acoustic wave (BAW) resonators are primarily used in precision frequency and metrology applications as ultra-stable timing references, thanks to their extraordinarily high acoustic quality factors and frequency stability. For applications of these resonators that require locking to an external reference source, a traditional method of frequency tuning is to employ a tunable capacitor in the form of a varactor that can shift the resonant frequency by a few Hertz. The main drawbacks of this method are a low tuning range, additional noise due to the active component and an inability to work at cryogenic temperatures.

Another solution is to exploit the same piezoelectric coupling that is used to excite and read out the BAW modes, in order to change the geometry of the acoustic cavity. With efficient decoupling of the tuning and readout subsystems, this allows one to achieve broad frequency tunability without compromising system quality factors. Importantly, such a tuning mechanism is of great benefit when we consider the stable operation of quartz BAW resonators in a sub-Kelvin environment, where their performance significantly improves. Here

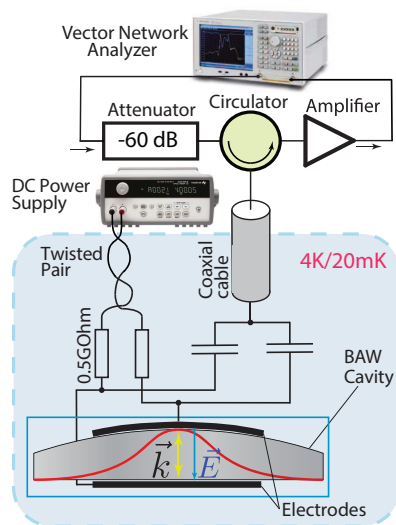


FIG. 1. Experimental setup for the excitation of acoustic modes in the quartz BAW resonator.

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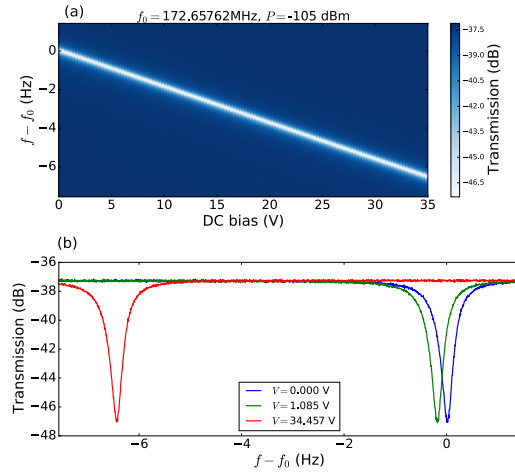


FIG. 2. Signal transmission through the experiment centred on the 55th overtone (173 MHz) mode of the quartz BAW at $T = 4$ K. (a) Density plot shows the system frequency response for varying applied bias field (b) Plotted traces show the transmission for different applied voltages.

they are known to exhibit an increase in acoustic quality factor (Q) to as high as tens of billions, with a maximum reported⁸ $Q \times f$ product of 7.8×10^{16} Hz.

The design of a mechanism to tune low loss cryogenic acoustic resonators, such as the quartz BAW, without degradation to Q and without the need for spatially inefficient and thermally taxing components such as actuators, is highly motivated. Many applications such as quantum acoustics^{9–13}, development of ultra-stable cryogenic quartz oscillators¹⁴, as well as detection experiments searching for new physics such as dark matter or gravitational waves^{6,7,15–18}; benefit from increased sensitivity due to large Q s and effective resonator mode mass. Further benefit can also be found due to the low thermal noise provided by a cryogenic operating environment. Preserving quality factors while also introducing a degree of frequency tuning at cryogenic temperatures would be highly desirable to these applications. Additionally, the performance and characteristics of quartz BAW resonators operating at sub-Kelvin temperatures is relatively unexplored. This stark contrast to the well documented study of such resonators at room temperature motivates further investigation into system behaviours and device performance in the sub-Kelvin cryogenic regime.

Previously, the loss mechanisms in quartz BAW resonators at both 4 K and milli-Kelvin was studied^{19–23}, along with the relationship between mode frequency and temperature. In these studies it was shown that the intrinsic losses in quartz BAWs are caused by

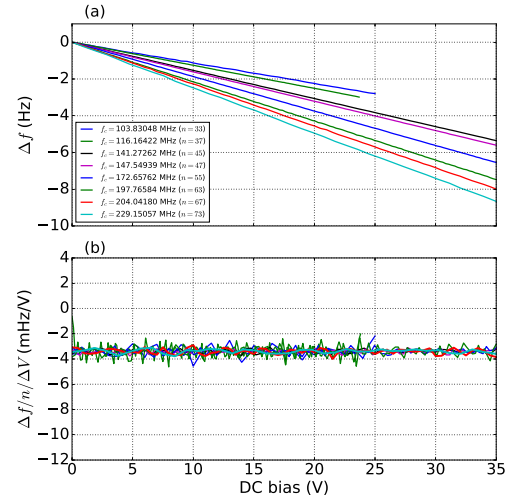


FIG. 3. Plotted traces show the measured frequency tuning of eight quartz BAW overtone modes at $T = 4$ K for a varying applied bias field. (a) frequency of the resonators maximum response as a function of applied bias. (b) Frequency change normalised to mode number n per change in applied bias for the same eight overtone modes.

different physical mechanisms, depending on the crystal temperature T . These mechanisms can be characterised by the identification of different scaling relationships between Q , T and the crystal's acoustic drive mode frequency f . It was shown that while the macroscopic Akheiser model²⁴ dictates acoustic losses at room temperature, losses at cryogenic temperatures are described by the scattering of acoustic phonons with thermal phonons in accordance with the Landau-Rumer theory of dissipation²⁵. As the crystal is cooled to lower temperatures the thermal phonon distribution becomes less populated, generally leading to far better quality factors. This increase to acoustic mode Q also allows for more energy to be stored in the crystal, resulting in the observation of non-linear effects for a much lower threshold drive power. From these previous investigations into the relationship between mode frequency and losses, we can conclude that mechanical behaviour of quartz BAW resonators at cryogenic temperatures is non-trivial when compared to room temperatures.

In this work however, the relationship between external electric field and mode frequency is investigated, providing a different channel for studying these resonator systems. The broad frequency tuning capability of the quartz BAW resonator is demonstrated by making use of the piezoelectric effect to tune multiple phonon modes across a significant region of frequency space. The

tuning mechanism is explored at both 4 K and 20 mK in order to confirm the technologies suitability as an ideal platform in the development of next generation low loss cryogenic resonator systems, primarily for fundamental physics tests.

A quartz plate 30 mm in diameter and 1 mm thick featuring an SC-cut²⁶ crystal axis with a plano-convex²⁷ surface was chosen for this work. The SC-cut axis of the quartz lattice allows for acoustic modes with better frequency stability and isolation from mechanical stresses, when compared to alternative axis cuts. The plano-convex surface concentrates the bulk phonon distribution to the center of the crystal, reducing anchoring losses and improving acoustic quality factors.

This crystal was situated in a copper vacuum enclosure that was placed into a dilution refrigerator where it was subject to a stabilised environment temperature T of either 4 K or 20 mK. Acoustic modes of the quartz plate were excited by a signal supplied via microwave cables with capacitive DC blocks. These lines connect to two almost flat electrodes separated from the resonator crystal plate surface. The supplied microwave signal then couples to acoustic resonances in the crystal bulk via the piezoelectric effect. The set-up is displayed schematically in figure 1.

The crystal's resonant modes were observed by measuring the amplified reflection signal off the resonator with a vector network analyser (VNA) stabilized by a hydrogen maser. The use of a circulator was employed to isolate the reflected signal from the input source. In this configuration the reflected signal off the quartz can be amplified and measured as the S_{21} transmission as seen by the VNA. The BAW excitation power is kept extremely low (-105 dBm) in order to avoid any inherent non-linear effects exhibited by the crystal at low temperatures.

The piezoelectric coupling can be further exploited by applying an external DC electric bias field to the crystal in order to vary its bulk thickness, thus linearly shifting the resonant frequency of the acoustic modes. This can be thought of as the acoustic analogue of changing the length between the end mirrors in an optical Fabry-Perot cavity. To this end, an external power supply was connected to the electrodes so that an adjustable DC voltage would allow tuning of the resonator. Two cold $500\text{ M}\Omega$ resistances were used to isolate the power supply from the resonator in order to minimise loading of the resonator's intrinsic quality factor. Decoupling capacitors were used to separate the signal feeding lines and the ground from the external high voltage applied to the device.

To explore the frequency tuning of the device the BAW cavity was held in the dilution refrigerator where it was subject to a stable external environment temperature of $T = 4\text{ K}$. An external DC voltage supply was ramped in discrete stabilized steps from an initial value V_0 to a maximum of 67 V, applying a linearly varying static electric field to the quartz crystal. At each step the

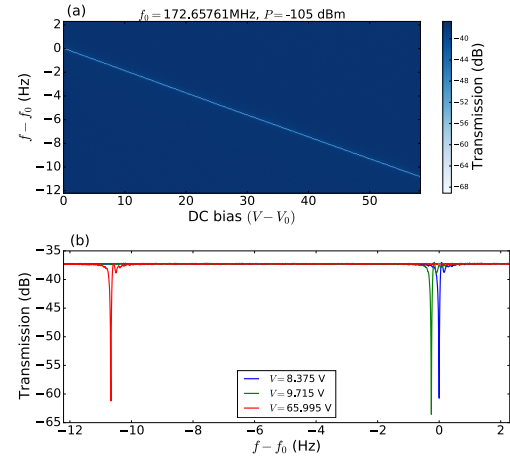


FIG. 4. Signal transmission through the experiment centred on the 55th overtone (173 MHz) mode of the quartz BAW at $T = 20\text{ mK}$. (a) Density plot shows the system frequency response for varying applied bias field (b) Plotted traces show the transmission for different applied voltages.

crystal response was measured with extremely narrow frequency resolution centred around a specific mode of the resonator. An IF bandwidth of 1 Hz was utilised, minimising the excitation signal sweep rate and allowing for ring-down effects to settle.

Eight various overtone modes were monitored with resonant frequencies ranging from 104 MHz to 229 MHz. In all cases consistent linear tuning of the corresponding frequency was observed, with no noticeable changes to the Lorentzian resonance shape or loaded quality factor, an example is given in figure 2 where the initial bias field value V_0 is 0 V.

The change in frequency for all modes was found to strictly obey a $\Delta f \propto n$ dependence where n is the overtone number. This relationship is clearly seen in figure 3. This suggests that as is the case with this device at room temperature; applied electric field creates a strain across the crystal via the piezoelectric effect, changing the thickness of the quartz plate and in turn affecting the resonant condition in the bulk as $f \propto \frac{n}{L}$ where L is the length of the acoustic cavity. The relationship can be quantitatively described by a tuning coefficient of $\approx 3.5\text{ mHzV}^{-1}n^{-1}$.

In order to further these investigations; the above experiments were then repeated at the dilution refrigerators base temperature of 20 mK to determine if the same bulk thickness tuning mechanism can be sustained in a sub-Kelvin regime, where the quartz resonator is known to exhibit strong non-linear effects²⁸. In all cases across the same overtone modes, as seen in figure 5, similar

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linear tuning proportional to the acoustic mode number was observed. The same $\approx 3.5 \text{ mHzV}^{-1}n^{-1}$ tuning coefficient was extracted from these results where V_0 was set to $\approx 5 \text{ V}$ in order to overcome an observed voltage suppression in superconducting DC feed lines. These results confirm consistent electromechanical coupling of the the crystal to electrically induced strain fields at extremely low cryogenic temperatures.

The highest magnitude of frequency tuning achieved was a 16.4 Hz shift of the $n = 73$, 229 MHz mode at 4 K when biased across a $\approx 67 \text{ V}$ range. This corresponds to a controllable linear frequency shift of more than 30 line-widths of the resonant mode ($Q_{\text{loaded}}^{(n=73)} \approx 5.41 \times 10^8$), compressing the quartz crystal plate by $\approx 0.75 \text{ \AA}$ or 15% of the quartz unit cell, assuming ideal phonon trapping. However, for higher Q modes the relative frequency shift is more substantial. For example the $n = 55$, 172.6 MHz mode at 20 mK, as depicted in figure 4, shifted 10.8 Hz under a similar applied voltage range, with $Q_{\text{loaded}}^{(n=55)} \approx 1.73 \times 10^9$. This corresponds to a frequency shift of 127 line-widths. A summary of all the experimental findings is given in table I.

67 V was the maximum potential difference attainable in this work due to the current suitable equipment on hand, in principle larger bias fields are possible in order to demonstrate further tuning of the resonator. However, at some point extremely large strain fields will be at risk of damaging the quartz crystal plate. A qualitative argument can be given in order to estimate the critical magnitude of strain field that could be applied before risk of elastic deformation. By considering the reported bulk modulus of regular cut quartz at 4 K as 38.75 GPa²⁹, as well as the apparent elastic limit of 41 MPa³⁰, we determine a maximum bulk deformation of the quartz BAW of 1.15 μm . Such strain applied to the longitudinal direction of the crystal would correspond to a 240 kHz shift of the resonant frequency of the $n = 73$ mode, however this would require a large voltage of 950 kV. This argument does not consider the rotation of the crystallographic axis to the SC cut orientation that is utilised in this work, as well as considering phonon trapping of the curved crystal surface. However, it does highlight that potentially much higher strain fields could be applied to demonstrate further tuning without any permanent damage to the crystal.

While linear tuning may be a highly expected result for a room temperature device; it is of interest to quantify the rate, as well as observing such linear tuning, in a cryogenic environment. It has been demonstrated that the dominant electromechanical behaviour of these devices at such temperatures can greatly differ from the known mechanisms at room temperature. A combination of processes such as thermal phonon scattering, impurity site interactions and non-linear acoustic phonon mixing, all contribute in order to generate different behaviours for varying temperature. As a result of these regime changes, even the most simple of crystal behaviours at room temperature must be experimentally verified

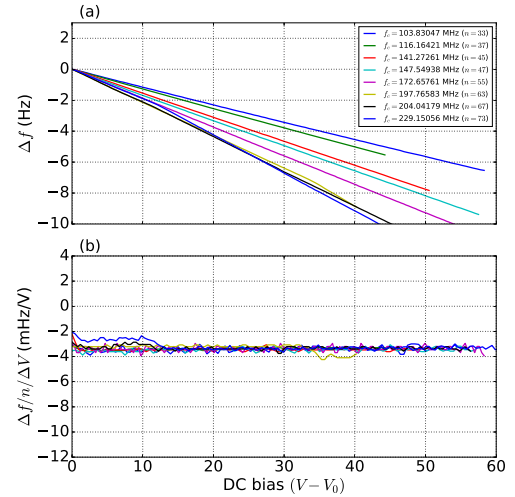


FIG. 5. Plotted traces show the measured frequency tuning of eight quartz BAW overtone modes at $T = 20 \text{ mK}$ for a varying applied bias field. (a) frequency of the resonators maximum response as a function of applied bias. (b) Frequency change normalised to mode number n per change in applied bias for the same eight overtone modes.

under cryogenic conditions. Through the verification we present here it is shown that quasi-static linear piezoelectricity is well defined across the crystal bulk in the cryogenic regime.

Comparing the performance of the presented device and tuning mechanism to other acoustic resonators, it is seen that smaller nano-mechanical flexural resonators are capable of greater frequency tuning whilst maintaining relatively good quality factors³¹. Such a typical device³² exhibits 17 000 line-widths of tuning at mode center frequency $f_0 = 6.5 \text{ MHz}$ with quality factor 0.34×10^6 , thanks to an actuated applied stress tuning mechanism. However, the extremely low effective mode mass of these nano-scale resonators, as well as the inability to tune the device at cryogenic temperatures, makes them poor candidates for fundamental physics tests.

Thin-film and high overtone bulk acoustic wave resonators (FBAR/HBAR) are from the same family as the quartz BAW resonator and can be frequency tuned by changing the material dimensions or adding passive components much the same as quartz BAWs³³. These devices are typically micrometer-scale and designed for GHz frequency operation. Frequency tuning at the expense of quality factor can be gained by manufacturing FBAR resonators from ferroelectric materials, allowing the device to be tuned via an external electric field. A competitive HBAR resonator for example³⁴

n	f_n (MHz)	$T = 4$ K		$T = 20$ mK	
		Δf_n (Hz)	$V_{\max} - V_0$ (V)	Δf_n (Hz)	$V_{\max} - V_0$ (V)
33	103.83	2.79	25.0	6.53	58.29
37	116.16	2.99	25.0	5.86	44.25
45	141.27	5.35	35.0	8.02	56.5
47	147.55	5.60	35.0	9.46	57.5
55	172.66	6.54	35.0	10.80	58.0
63	197.77	7.47	35.0	12.02	40.2
67	204.04	7.99	35.0	13.17	56.35
73	229.15	16.43	67.0	14.48	57.17

TABLE I. Summary of results for the tuning of all 8 overtone modes of the quartz BAW. The net frequency tuning of a mode resonance f_n is denoted by Δf_n . The maximum applied bias field in each case is $V_{\max} - V_0$ where V_0 is an offset in order to overcome suppression effects associated with superconducting DC bias lines.

demonstrates ≈ 5 line-widths of tuning at $f_0 = 1.5$ GHz with a maximum maintained quality factor of 130. Centimetre-scale mechanical resonators, such as gravitational wave detector test masses³⁵, are ideal for fundamental physics tests due to their exceptionally high quality factors and cryogenic operating environment, however it is rare for such devices to display any degree of frequency tuning. The quartz BAW architecture thus provides competitive tuning ranges when compared to other resonators of the BAW family, with the added benefit of consistent linear tuning at cryogenic temperatures, as well as large effective mode mass and extraordinarily high quality factors. The combination of these traits make the quartz BAW device extremely suitable for precision tests of fundamental physics.

To summarise, we have performed an investigation into the electro-mechanical properties of a quartz crystal BAW resonator in the sub-Kelvin regime, where we have observed a maximum of more than 100 line-widths of tuning of an acoustic resonance with no reduction to Q or change in mode shape. We have further shown that this tuning mechanism is consistently linear and stable across a broad temperature range. The degree of tuning observed was completely limited by the equipment on hand, and the consistency of our results suggest that even further frequency tuning is indeed possible.

Many recent experiments that utilise these devices or similar resonators would significantly benefit from such frequency tuning. Precision experiments that use mechanical resonators to search for the small modulating signatures induced by ultra light dark matter^{6,18,36,37} could utilise such frequency tuning in order to exclude a larger region of dark matter parameter space without sacrificing any sensitivity. This would bring mechanical resonator dark matter experiments in-line with the broad band frequency tuning capabilities of world leading cavity based searches such as ORGAN³⁸ and ADMX³⁹. High frequency gravitational wave search experiments¹⁷ could make use of this tuning mechanism in order to use advanced detection techniques such as cross correlation of the output of two identical quartz BAW detectors tuned to the same frequency. Such

a system would be capable of probing a stochastic background of high frequency gravitational radiation⁴⁰. This work presents an important step towards the stable operation of quartz crystal resonators at sub-Kelvin temperatures, where they have been known to display various instabilities and offer technical challenges^{41,42}. These investigations will aid in the development of highly tunable mechanical resonators for cryogenic operation, providing the tools required to perform high fidelity metrology, prepare mechanical systems for quantum ground state operation, and search for new physics with unparalleled sensitivity.

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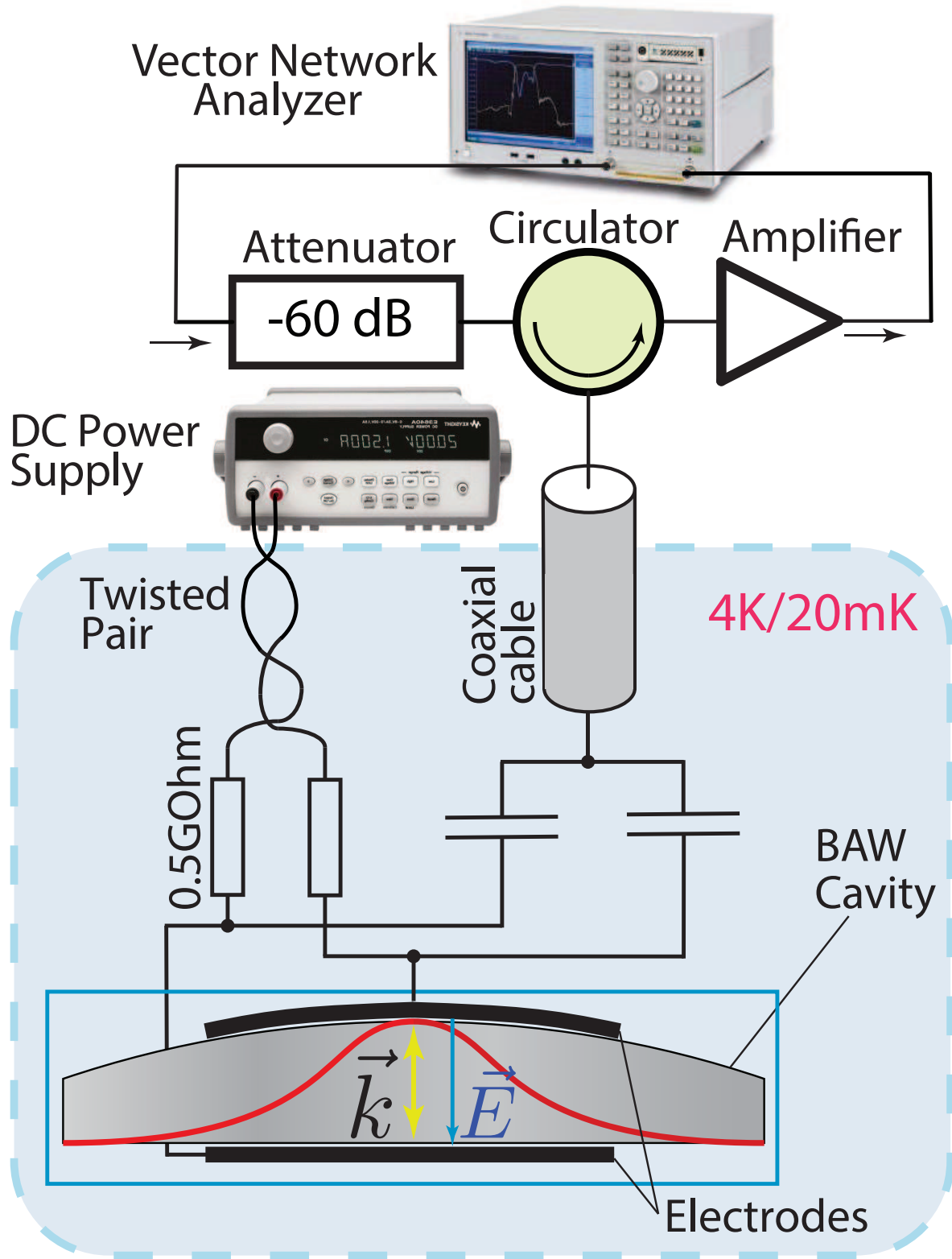
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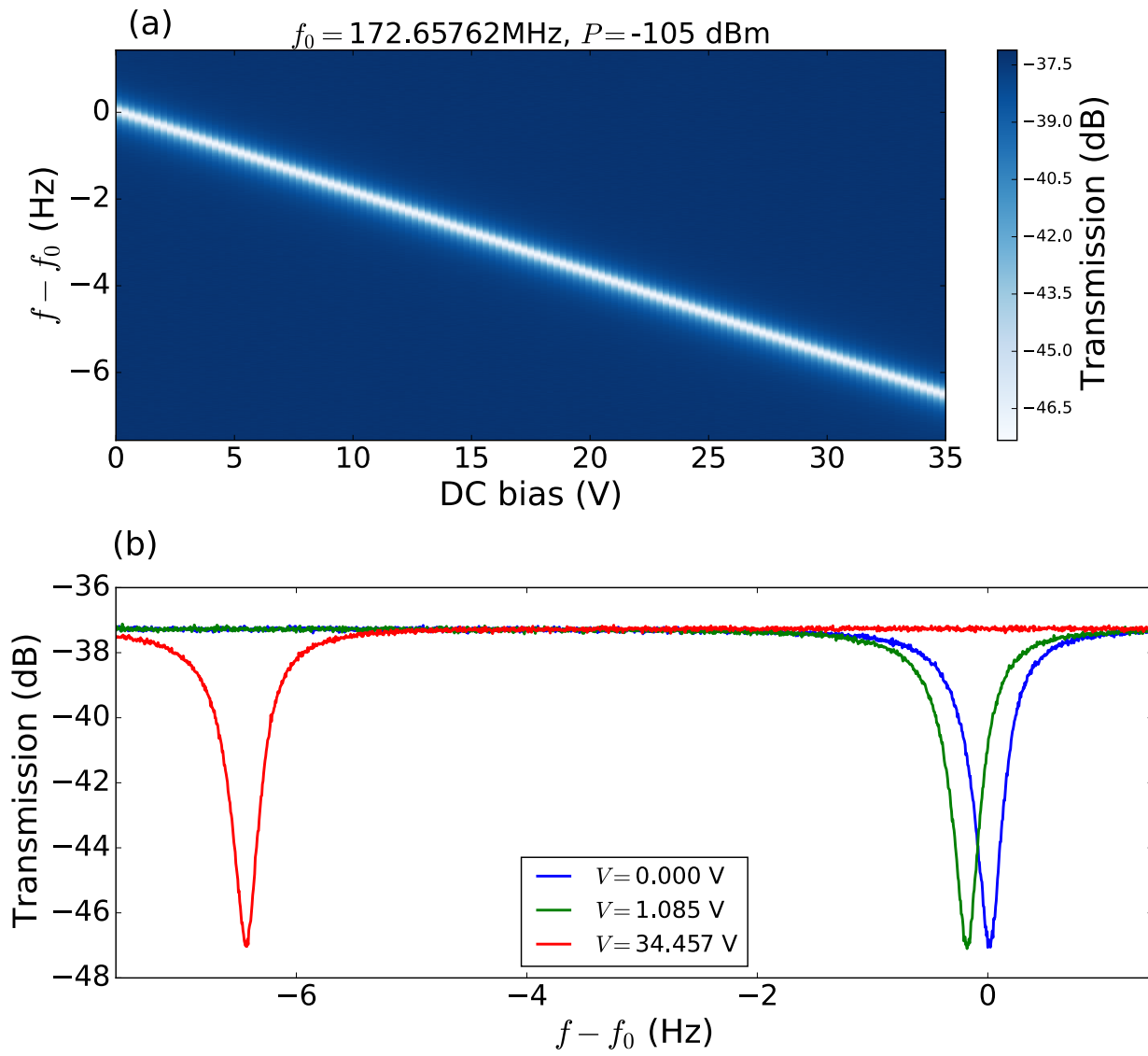
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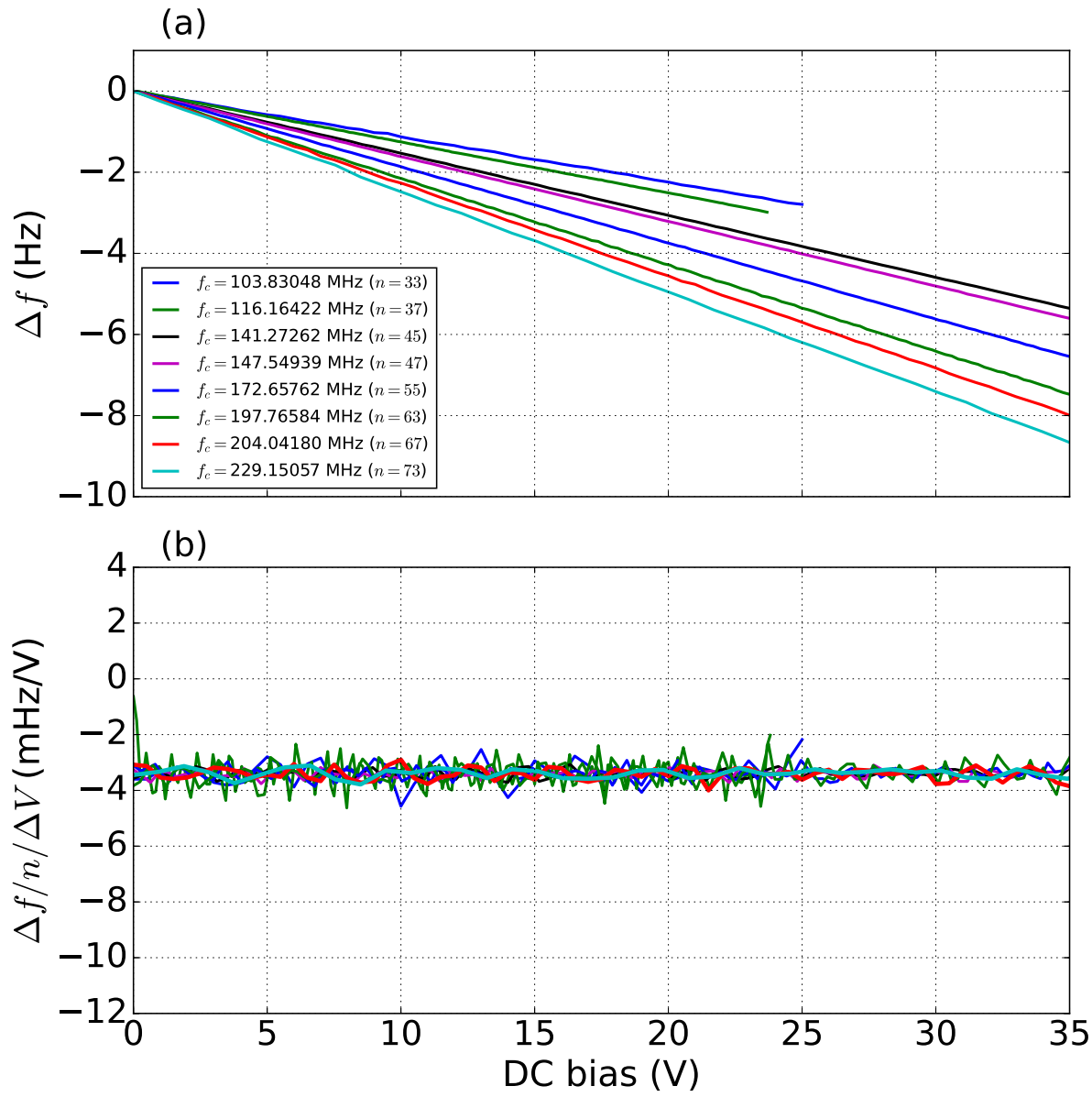
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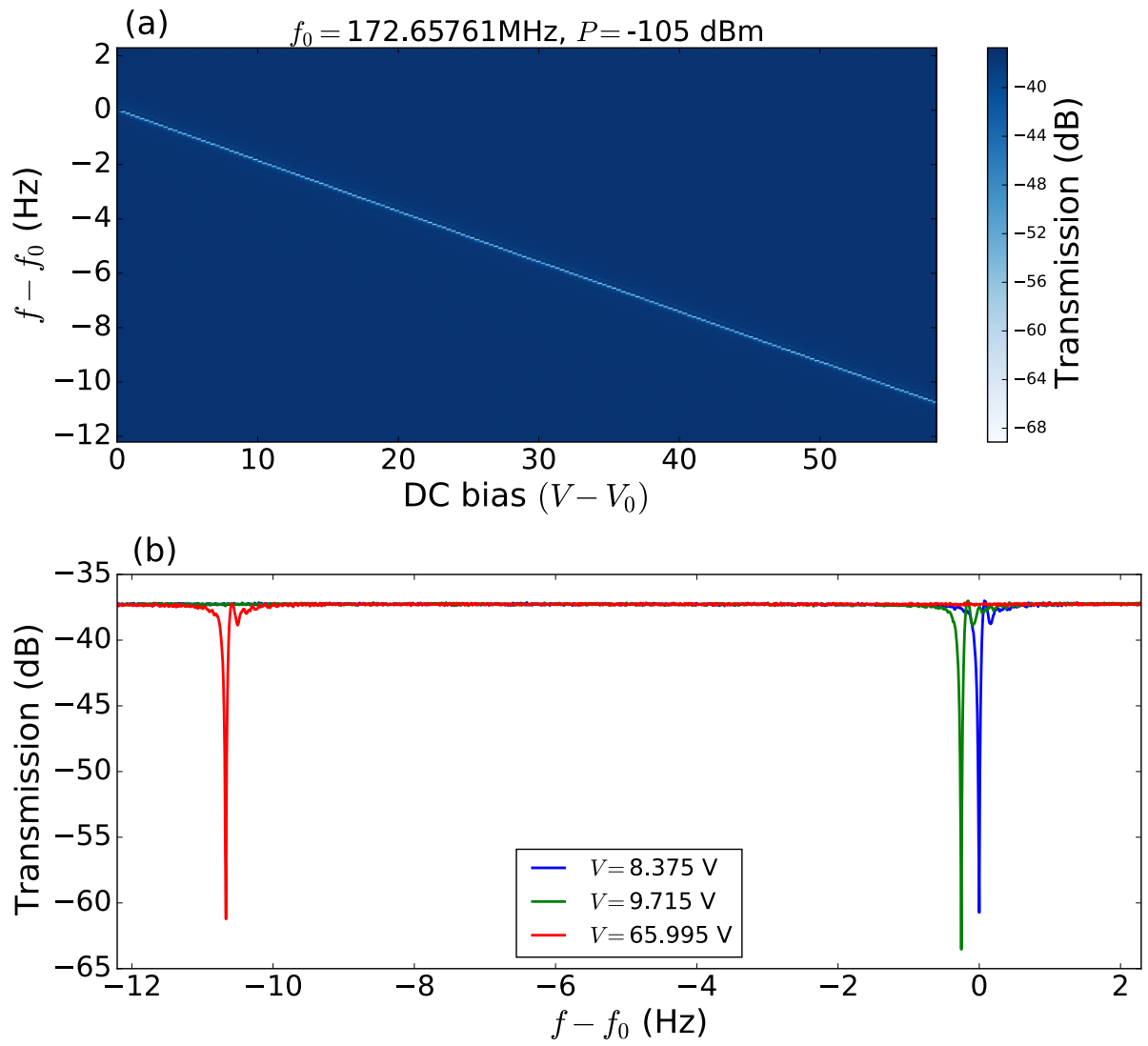
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