CMB Summer School - MKIDs Lab
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1 Introduction

This should provide a brief, practical hands-on introduction to microwave techniques required for lab testing of Kinetic Inductance Detectors. All the lab work will take place in LL127. Feel free to leave the door propped open.

Warnings:

- Don't tighten SMA connectors with anything except an SMA torque wrench.
- Don't set any microwave equipment to powers above 0 dBm without talking to an instructor first.
- Every SMA-like connector you find in LL127 should be compatible with every other SMA-like connector in this room. But, **do not** mix and match our connectors with hardware in other rooms without talking to an instructor. Not all SMA-like connectors are the same.

2 Resources

- VNA principles, and introduction to microwave techniques `http://literature.cdn.keysight.com/litweb/pdf/5965-7707E.pdf`
- Zmuidzinas 2012. A terse but thorough KID revew. `http://www.annualreviews.org/doi/abs/10.1146/annurev-conmatphys-020911-125022`
- Berry 2014. A recent MKID thesis with a nice background review. `http://orca.cf.ac.uk/71562/1/2014BarryPPhD.pdf`
- Gao 2008. An older MKID thesis with detailed fitting discussion. (And lots of interesting TLS physics.) `http://thesis.library.caltech.edu/2530/1/thesismain_0610.pdf`

3 The Vector Network Analyzer. (Your auto-calibrating IQ-mixer pal who's fun to be with.)

Feel free to skip any parts of this which is redundant with other labs or are obvious to everyone in the group.

1. To get started, set the VNA to display log-magnitude of S21, with a frequency range from 10 MHz to 1 GHz, an output power of 0 dBm, and an IFBW of 30 kHz, and 801 points. Feel free to change these throughout the lab; this is just a starting point.
2. With nothing plugged into the VNA, take a look at the amplitude of S21 and S22. (Note that S12 and S11 are broken on this particular VNA. But, for symmetric circuits S11 and S22 are identical.) Does this make sense?
3. Plug a thin blue $\sim 3\,\mathrm{m}$ cable directly between P1 and P2 on the VNA. Again, look at both S21 and S11 and consider any features you see.
4. Switch the VNA display from log amplitude to a polar plot, showing the real and complex S21 (or I and Q) components of the sweep. By adjusting the frequency span and measuring the fraction of a circle that's covered, estimate the phase velocity of the cable.
5. Use the VNA to measure the value of the mystery attenuator.
6. Place a 50 Ohm terminator on P2. Set the IFBW to 3 kHz. Measure the noise floor of the instrument at 1 GHz.
7. What do you expect to happen to the noise floor if you change the IFBW from 3 kHz to 30 Hz? Check it.
8. What do you expect to happen to the noise floor if you return the IFBW to 3 kHz but average 100 traces? Check it.
9. **Extra (if time permits).** Using a digital multimeter, measure the DC resistance between pins and between each pin to ground in the attenuator. From those measurements, and given that the attenuator is designed to appear as a 50 Ohm load from either direction *when connected to a 50 Ohm load at the other end*, draw a plausible circuit diagram for the attenuator and calculate the expected attenuation. Does this match your microwave measurement?

4 Resonances, bifurcation power.

1. Connect the VNA to the bluefors fridge dark channel as instructed.
2. Starting with an output power of -20 dBm, find a well-isolated and typical looking resonance. (Starting around 2 GHz and moving upward will speed things up.)
3. Estimate the value of Q_r of the resonance by eye. Qualitatively, how do Q_i and Q_c compare for this resonator?

4. Slowly raise the output power of the VNA until you see evidence a frequency shift and distorted S21 sweep due to bifurcation. Switch to a polar (IQ) plot and look for a discontinuity in the IQ sweep. Record this power level.

5 Finding Qs

1. Set the VNA to record 1601 points. Using the VNA save function, record your resonator sweep to a USB key. Record a trace that's around five times the width of your resonator.

2. Transfer the data to a machine running python or data anlysis software of your choice. Plot |S21| vs. frequency and I vs. Q and confirm that it shows what you'd expect.

3. We're now going to fit to the data to measure f0, Qi, Qc. You can do this in several different ways - feel free to try a different one if you prefer.

   Note: you may find you get a decent fit without the baseline removal included in steps 1 and 2. Feel free to try fitting your data without this first and include it only if you need it to get a decent looking fit.

   (a) Baseline removal: excise the region near the resonator (and any other resonators) from the data. Fit |S21| over the remaining region with a low-order polynomial to obtain a (real-valued) baseline function $B(f)$. Divide your I and Q data by $B(f)$ to obtain normalized and gain corrected data.

   (b) Apply the amplitude correction to your resonator data. Plot |S21| and confirm that you've successfully normalized your data.

   (c) Fit the resonator transfer function to the measured device. I suggest fitting $|S21|$ to the absolute value of the following function multiplied by an arbitrary real constant if you've not previously normalized the data. You're welcome to choose your own version. (If you want to try a complex fit to the amplitude and phase of S21, you'll need to add an Exp$[-2\pi(f\tau)+\theta_0]$ term multiplying the form of S21 given below to account for phase, where τ is a cable delay time and θ_0 is a phase offset. You can also independently measure these in the region outside of the resonance and supply them by hand - feel free to let me know if you want to try this.)

$$f_{\text{fit}}(x) = A|S21(x)|$$
$$S21(x) = 1 - \frac{Q_r}{Q_c e^{(-j\phi)}}\left(\frac{1}{1+2jQ_i x}\right)$$
$$x \equiv \frac{f-f_0}{f_0}$$
$$Q_r^{-1} = Q_i^{-1} + Q_c^{-1}$$

   Record your values for Qr, Qc, Qi. Do they agree with your estimates made by eye with the VNA?

4. **Extra (and quite involved)** Given your measured values for Qs and the total attenuation in the cryostat, how does the bifurcation power measured compare to the prediction of `Swenson2013`?

6 Optical response

1. Switch the readout over to the optical channel on the cryostat.
2. Locate a resonance using the VNA. (Note that the resonances are *very* shallow for these devices.)
3. While looking at the resonance on the VNA, remove and replace the flat metal plate in front of the dewar. Wave your hand in front of the window. How would you explain the two time constants visible when moving the metal plate?
4. Using a bucket of liquid nitrogen and a room temperature eccosorb sample, measure the change in frequency of the device to a 300 vs. 77K chop.
5. Calculate the response of the device in frequency units to the change in loading in the previous part.
6. These devices are designed for an optical band that is 25 GHz wide and centered at 150 GHz. If you neglect any losses and assume a single-polarization, single-moded antenna is looking into a beam filling load at 77 and 300K, what responsivity in Hz/Watt do you estimate for these devices?

7 Measuring noise

1. Switch the readout system back to the dark channel.
2. Set up the single-tone readout system as instructed. Using the labview program provided, locate an isolated and reasonably deep resonator.
3. Perform a labview-driven VNA sweep of all channels on the device, as instructed.
4. Perform an IQ resonator sweep using the single-tone system. Adjust the power to find bifurcation, then set the power to be a few dB below that.
5. Using the labview noise recording software provided, record a timestream and measure the noise from the resonator in fractional frequency units.
6. Identify any features present in the on or off resonance spectra.
7. Assuming both the optical and dark devices you've measured are the same, use this noise measurement in combination with the previous response measurement to estimate the NEP of these devices in physical units.

8 f0 vs. T

This should be done at the end of the day when no more data needs to be taken, since it takes a while for the stage to cool back down to base temperature.

1. Record the minima of one resonator on the VNA (which is a pretty good approximation to f_0) and the depth of the resonance.

2. Raise the temperature of the stage in a several increments from base temperature to around 300 mK. Record f_0 and the dip depth at each temperature. Do these behave as you'd expect?

3. **Extra** Compare your data for f_0 vs. T Mattis-Bardeen function to determine a value for T_c. You can either perform an actual fit, or just overplot the M-B curve for various values of T_c and find a resonably close one. (For materials that are less BCS-like, a reasonable fit is hard to achieve.) The approximate formula is given below:

$$\Delta_0 \approx 1.76kT_c$$
$$\frac{\delta f}{f} \approx -\frac{1}{2}e^{-\Delta_0/kT}$$