NICA Optical testing summary

This memo provides a summary of the optical testing carried out at Cardiff on the current 2mm NICA chips from the array mask version V1.5

Method: The optical and electrical NEP of the chip is measured using two separate methods. In both methods the resonant frequency is defined by finding the maximum in the phase slope of the centered IQ data (max $d\phi/df$). Sweeps are performed around the resonant frequency for varying optical power, or, fridge (chip) temperature. The whole process is controlled by Labview in both cases and follows the following procedures

Electrical NEP:

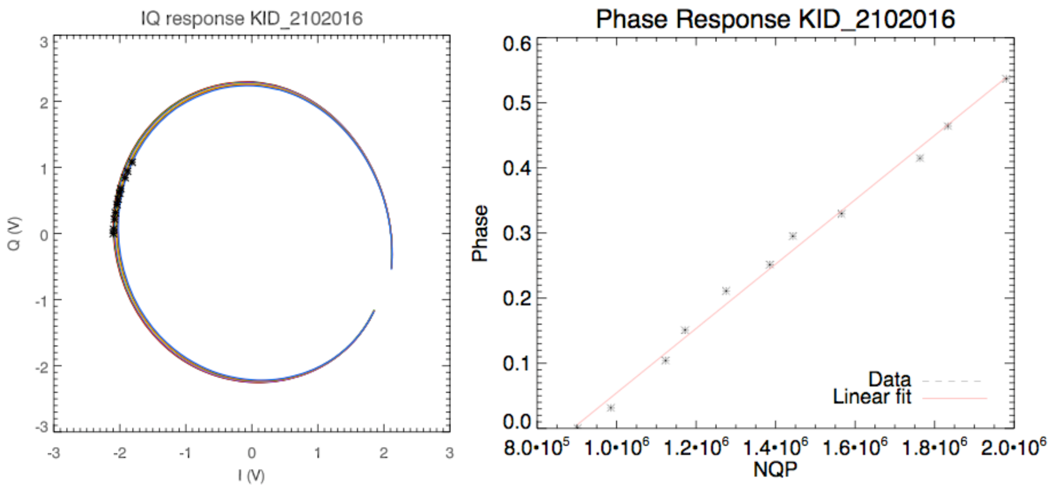
1) Perform a predefined sweep that contains the entire resonant feature in the IQ plane.
2) Centre the IQ data so that the centre of the IQ circle lays on the origin of the IQ plane
3) Calculate and unwrap the phase ($\tan\phi=Q/I$ data is unwrapped to avoid a jump of π in the phase data).
4) Calculate $d\phi/df$ and set the signal generator to f0 (F0=max $d\phi/df$)
5) Pulse an infra-red LED a number of times while sampling the detector time-stream (DAQ triggered on LED pulse). This data is used for quasi-particle lifetime measurements. Current 2mm setup does not perform this step and the quasi-partical lifetime is measures using high energy particle hits seen on the detector.
6) Measure 25 one-second time-streams with the signal generator set to F0.
7) Measure 25 one-second time-streams with the signal generator set off F0 (usually set to lowest frequency in the IQ sweep data).
8) Repeat for all predefined resonator sweeps and input power / attenuation levels.
9) Increase the fridge temperature using a PID control and repeat steps 1-8. The increase in temperature is user defined. The loop continues until the maximum user defined temperature has been reached.

Optical NEP

1) Set the fridge to a temperature a few mK above the base temperature (usually 220 mK for this system). Throughout the process of changing blackbody power the fridge is held at this slightly elevated temperature using a PID control so that Cooper pairs are only broken by radiation and not varying chip temperature.
2) Warm the blackbody to its highest temperature (200K)
3) Perform a predefined sweep that contains the entire resonant feature in the IQ plane.
4) Centre the IQ data so that the centre of the IQ circle lays on the origin of the IQ plane.
5) Calculate and unwrap the phase ($\tan\phi=Q/I$). Data is unwrapped to avoid a jump of π in the phase data).
6) Measure 25 one-second time-streams with the signal generator set to F0.

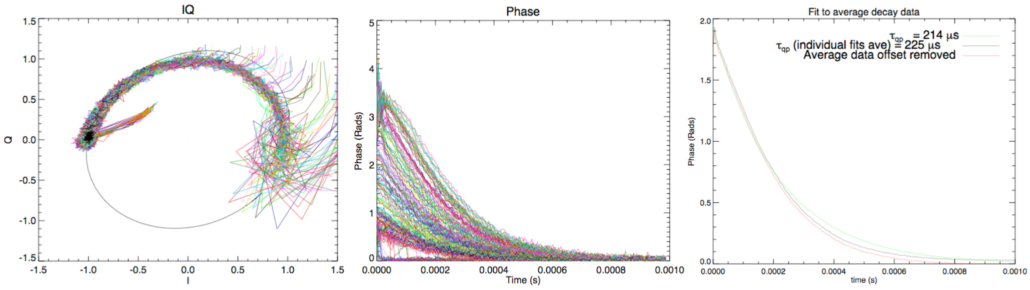
7) Measure 25 one-second time-streams with the signal generator set off F0 (usually set to lowest frequency in the IQ sweep data).
8) Repeat for all predefined resonator sweeps and input power / attenuation levels.
9) Wait for the blackbody to cool by a predefined amount then repeat steps 1-8. The saved data is stamped with the blackbody temperature at the time it was take. This approach should be fine as the blackbody is very slow (5 hours to cool from 200 to 4K)

The two routines above provide us with all the experimental information we need to calculate both electrical and optical NEP. The electrical NEP can be calculated using Mattis-Bardeen theory. This essentially tells us the change in quasi-particle density with change in temperature for a given material (Aluminium in our case). First the responsivity of the detector must be found. This is done by calculating the changing phase angle of f0 as the detector warms up. With the material volume, type and temperature known this can be converted into a plot of number of quasi-particles (Nqp) vs phase angle (ϕ) An example is sown below.



The IQ response data is rotated so that the f0 point at the base temperature lays on the Q axis, points marked * are f0 at the base temperature. The same approach can be used for calculating the amplitude response by fitting NQP to Amplitude (amplitude = $(I^2+Q^2)^{0.5}$) .

We also need to know the quasi-particle life-time (τ_{qp}). In this case this was done by measuring the detector relaxation time after it was perturbed after being struck by a high energy particle. This effect was noticed when looking at the time-streams of LEKID resonators and noticing that, on average, the detector was responding to an event one every two minutes or so. This event (assumed to be a particle causing a “phonon shower in the substrate) seemed to co-inside with the quasi-particle lifetime measured when the detector was illuminated by an LED pulse. The current setup with a 2mm filter stack in front of the chip does not allow the IR radiation of the LED (mounted in front of the chip carrier) to enter the chip carrier and so the particle hit method was used in this case. Below is a set of plots demonstrating this effect.



Fitting to the phase data of individual hits and then averaging we measure τ_{qp} to be of order 215-225 μs at the fridge base temperature of 211mK.

The phase or amplitude noise is measured by looking at the IQ time-stream data. The data is shifted and rotated as it was for the sweep data so that the IQ circle is centered on the origin with the resonance point on the Q axis. The phase noise is then calculated by converting the IQ time-streams into a phase time-stream (phase = Atan(Q/I) and taking an FFT of each of the 25 one-second on resonance time-streams. The FFT data is then averaged and usually converted into dBc for analysis. The same approach is used for the amplitude data (amplitude = $(I^2+Q^2)^{0.5}$) . It is worth noting that using this method can allow some of the phase noise to "slide" into the amplitude noise if the IQ Mixer is not well calibrated.

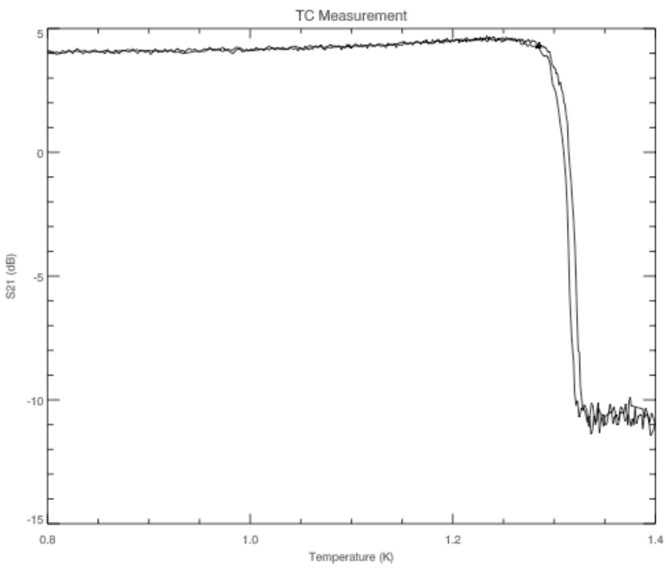
With the response, phase or amplitude noise and τ_{qp} known the electrical NEP can be calculated using the following equations set out in Ben Mazine's thesis.

$$NEP^2 = S_x\left[\frac{\eta\tau_{qp}}{\Delta}\frac{dx}{dN_{qp}}\right]^{-2}\left(1+\omega^2\tau_{qp}^2\right)\left(1+\omega^2\tau_{RD}^2\right)$$

Here S_x is the phase or amplitude noise spectral density (rads^2/Hz), η is the Fano factor, τ_{qp} is the quasi-particle lifetime, τ_{RD} is the detector ring-down time, ω is the readout frequency and Δ is the Cooper pair binding energy which can be calculated using the following:

$$\Delta = \frac{3.5K_BT_c}{2}$$

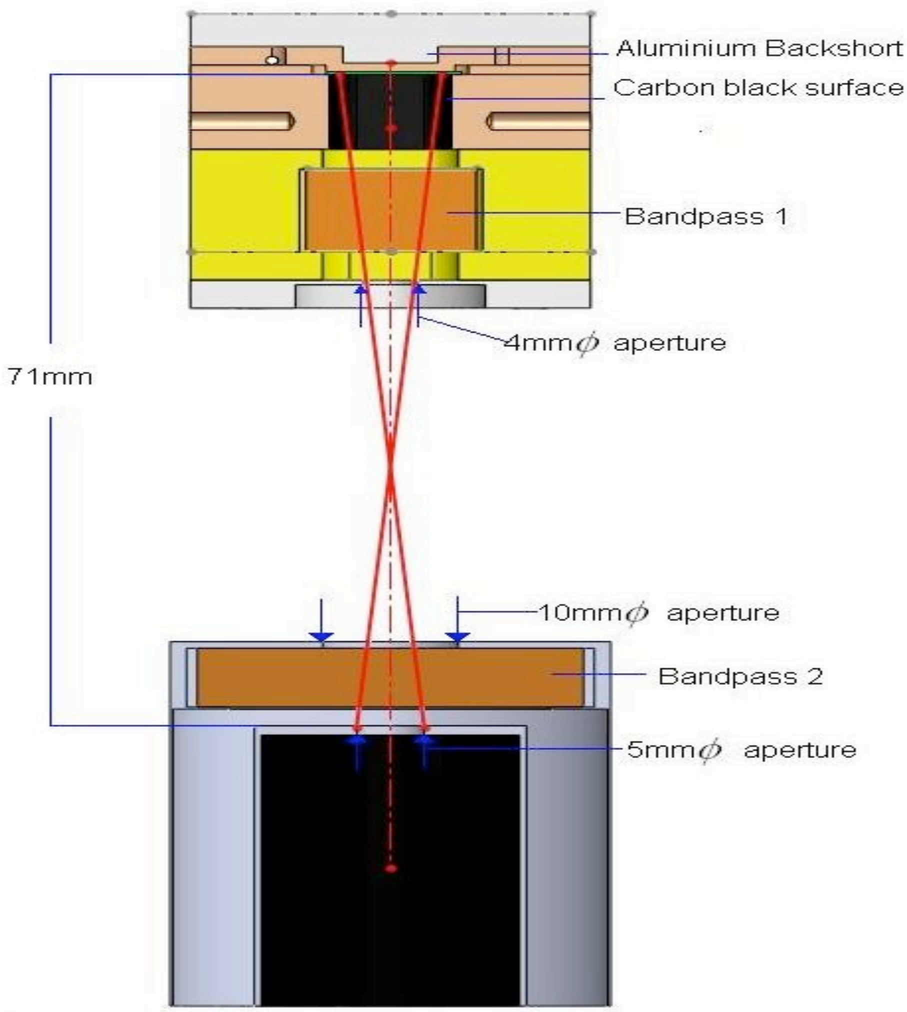
Here K_B is the Bolzman constant and T_c is the transition temperature. It is worth noting that due to an exponential component in the quasi-particle density calculation from Mattis-Bardeen theory the electrical NEP calculation has a strong dependence on Δ and hence T_c. The plot below show a measurement for T_c for this chip by looking at S21 of a fixed tone away from any resonances as the chip warms up. Here we see S21 rapidly reduce as we pass through the transition.



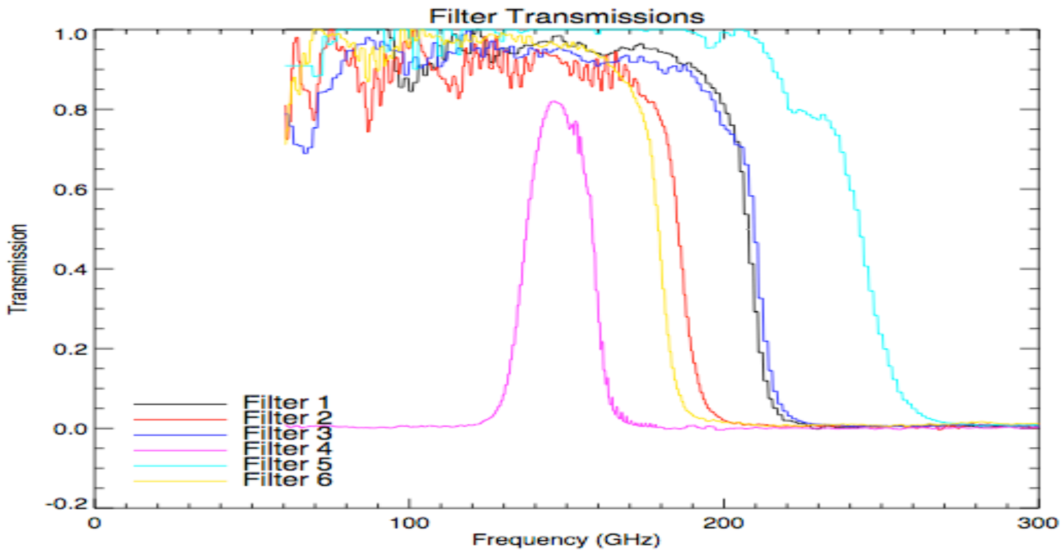
Transition temperature measurement of the chip. Here we pass through T_c twice – once warming and then once cooling producing some hysteresis in the transition curve

Optical Setup

For measuring the optical response of the LEKID the entire chip is optically loaded using a calibrated blackbody with varying temperature. A schematic of the setup is shown below:



The power from the blackbody is limited by the first aperture of diameter 5mm. Directly in front of the blackbody is a set of filters which collectively make up band-pass 2. This band-pass limits the out of band power incident on the fridge to limit the radiation loading on the sample stage. Before entering the chip holder the blackbody radiation is stopped down by a 4mm aperture. The purpose of this aperture is to reject beams that would other wise be incident on the inside blackened walls of the sample holder and risk being reflected on to the chip this is demonstrated by the ray tracing red lines. The blackbody radiation then passes through a second set of 3 filters that form band-pass 1. This band-pass defines the band of interest. The filter transmission profiles are shown below:



Filter transmissions for the 6 filters between the blackbody and the chip. Filters 1,5 and 6 are place directly in front of the blackbody (Bandpass 2) and filters 2,3 and 4 form bandpass 1.

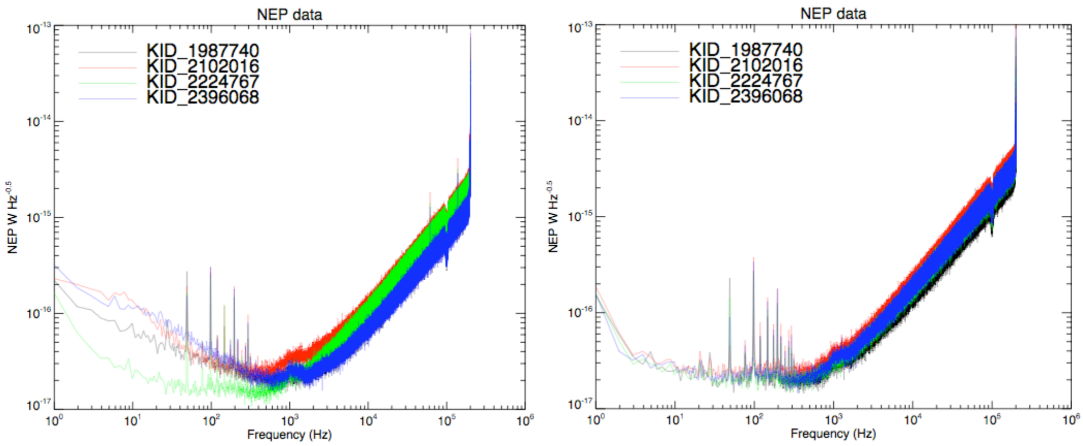
The 4mm aperture has led to some concern about diffraction of the 2mm source. However we can calculate the expected first minima of an Airy pattern using the following:

$$q_1 = 1.22\frac{R\lambda}{2a}$$

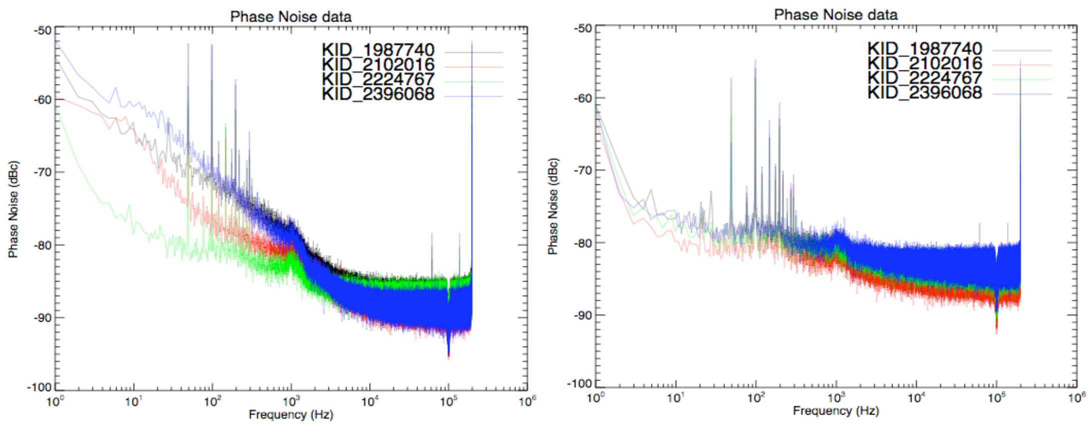
Where R ≈ distance to the chip from the aperture, a is the radius of the aperture and λ is wavelength. The distance from the aperture to the chip surface is 22mm therefore this places the first minima at around 13mm. The total chip size is only 10mm and the LEKIDs occupy approximately a 6 x 4 mm area in the centre of the chip. Therefore diffraction should not be a problem. For completion the first minima from diffraction from the source aperture 5mm over the distance to the 4mm aperture (R≈50mm) is approximately 25mm.

Electrical NEP results.

A few runs were performed to establish the best electrical NEP and it was found that the highest readout power was not necessarily the best in terms of low noise. In addition to this it was found that the electrical NEPs were more consistent between resonators for an optimum readout power. This can be seen in the two plots below:



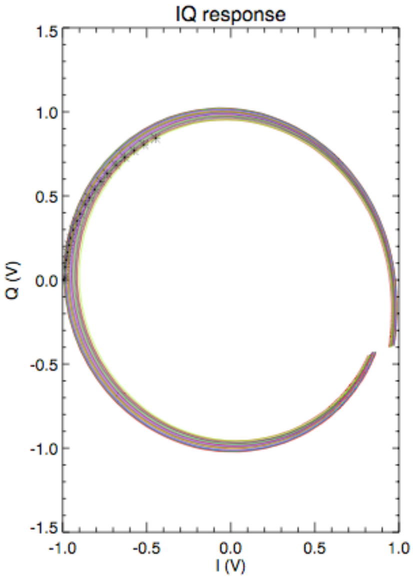
Left: Electrical NEP plots for 4 resonators with 60dB of input attenuation. Right: Electrical NEP plots for the same 4 resonators with 64dB of input attenuation.

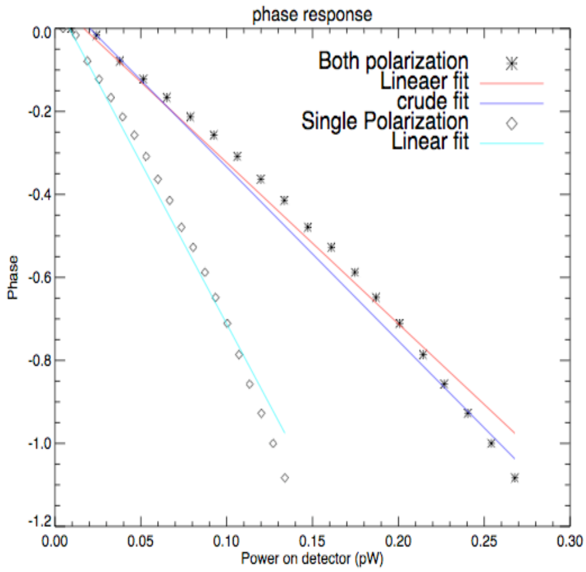


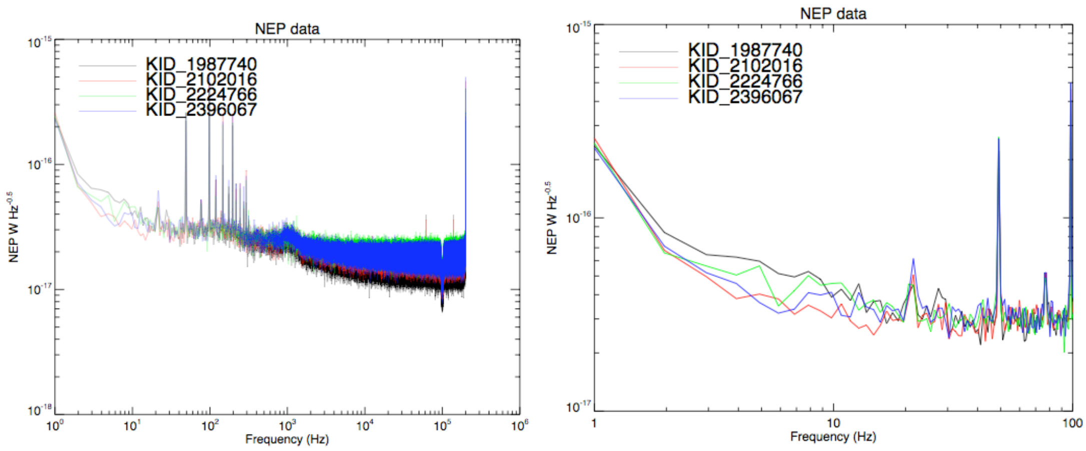
Left: Phase noise plots for 4 resonators with 60dB of input attenuation. Right: Phase Noise plots for the same 4 resonators with 64dB of input attenuation.

Optical NEP Results

The optical NEP is calculated in the same manner as the electrical NEP with regards to the handling of the IQ data. However the responsivity is measured this time by looking at the shift in f0 with changing optical power from the blackbody. This is demonstrated in the two plots below. The optical NEP is then calculated by multiplying the phase or amplitude response by the phase or amplitude noise sprectra. The plots below do not contain any roll-off calculations from resonator ring-down and quasi-particle lifetime. This will lead to a rise in NEP at higher frequencies as seen in the electrical NEP calculations. The lower frequencies (1-10 HZ) that we are interested are un-effected by this modification.





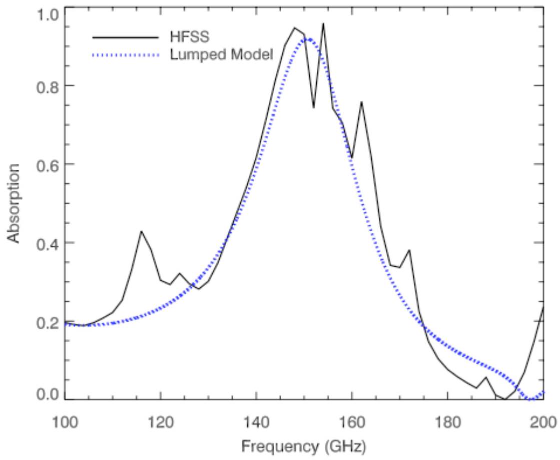


Left optical NEPs across entire spectrum measured. Right: Same plot zoomed in on low frequencies

Results verification

The average electrical NEP at 2Hz for the four resonators was $5.29 \times 10^{-17} W/Hz^{0.5}$ and the average optical NEP at 2Hz = $7.21 \times 10^{-17} W/Hz^{0.5}$

This implies and absorption efficiency of 70%. The meander is mainly sensitive to a single polarization however we have tests performed at Grenoble show that we get 20% cross-polarization. The filter stack we use defines a narrower band than the filter stack that will be used on the telescope. HFSS and analytical simulations suggests that we should expect around 70-80% absorption in a single polarization, the modeled absorption plot is shown below:



Taking the upper limit of 80% absorption in this narrow band along with the 20% cross polarization we should expect a total optical efficiency of around 50% this leaves a discrepancy of 20% too much power absorbed in our optical NEP measurements. Possible reasons for this:

1) The sheet resistance is higher than we expect leading to better absorption
2) The quasi-particle lifetime is longer than we measure (data for τ_{qp} was taken on a previous chip fabricated from the same film but measured with lower readout power).
3) Δ is higher than we calculate. As mentioned before the electrical NEP measurements has a strong dependence on Δ which is usually increased in thin aluminium films.
4) The Fano factor changes for thin films. Not sure about the theory behind the number 0.57 which is used as standard for aluminium films.
5) Film volume used in electrical NEP measurements. Film maybe thinner than 40nm this would also affect point 1.

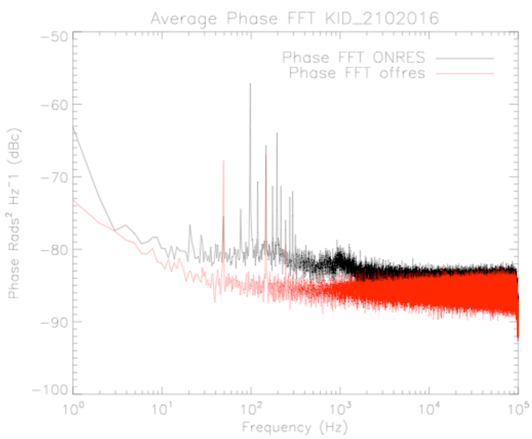
Conclusion

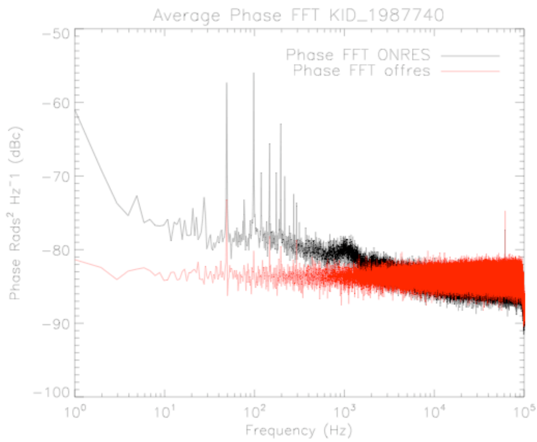
NEP

The performance of these resonators is approaching the required NEP for background limited detection at IRAM. However these measurements were taken under much less optical loading than we would expect at the telescope (optical load typically 0.1-0.3 pW).

Phase Noise

The phase noise we measure is not bad and is approaching the value we measure off resonance in some resonators. In others we see a clear difference on and off resonance. Either way there is still some ground to gain here (maybe 5-10 dBc) possibly by looking at other substrates (Sapphire) or reducing the surface to total volume E field ratio in the capacitor by spacing the fingers further apart. Below shows the phase noise for two resonators on and off resonance.





<u>Responsivity</u>

We should certainly look in to increasing the responsivity of the LEKID. At the moment the meander has a high geometrical inductance. Reducing this will increase the responsivity. We could possibly look in to thinner films also. This would increase the Kinetic Inductance to geometrical inductance ratio increasing responsivity. However we should approach this with caution as thinner films will have lower Qs and will be affected more by optical loading.

<u>Absorption.</u>

The absorption across the entire IRAM 2mm band is only around 40% of a single polarization ignoring the gain we get from the cross-pol only around 20%. More resistive materials will help this and there are also preliminary deigns for a meander that will absorb in both polarizations.

<u>Amplitude readout</u>

The LEKID design we are currently testing show no improvement in NEP when measuring using an amplitude readout. This may be due to the low Q factors (QL typically around 50000) or the fact that we are operating at low frequencies. The amplitude readout works on the fact that an increase in quasi-particles increases losses in the film changing the amplitude of S21. However these losses have a dependence on frequency becoming larger at higher frequencies. This may be the reason for poor amplitude response and could bee addressed by reducing C or L to operate at higher frequencies but this needs to be investigated.

<u>Ways forward</u>

It seems that we are making quite good progress with this design and addressing the issues above leaves us a lot of parameters to adjust to improve the overall NEP without adding much complication from a design and fabrication point of view.