# A cross-talk mitigation technique for FDM readout system in the SAFARI instrument

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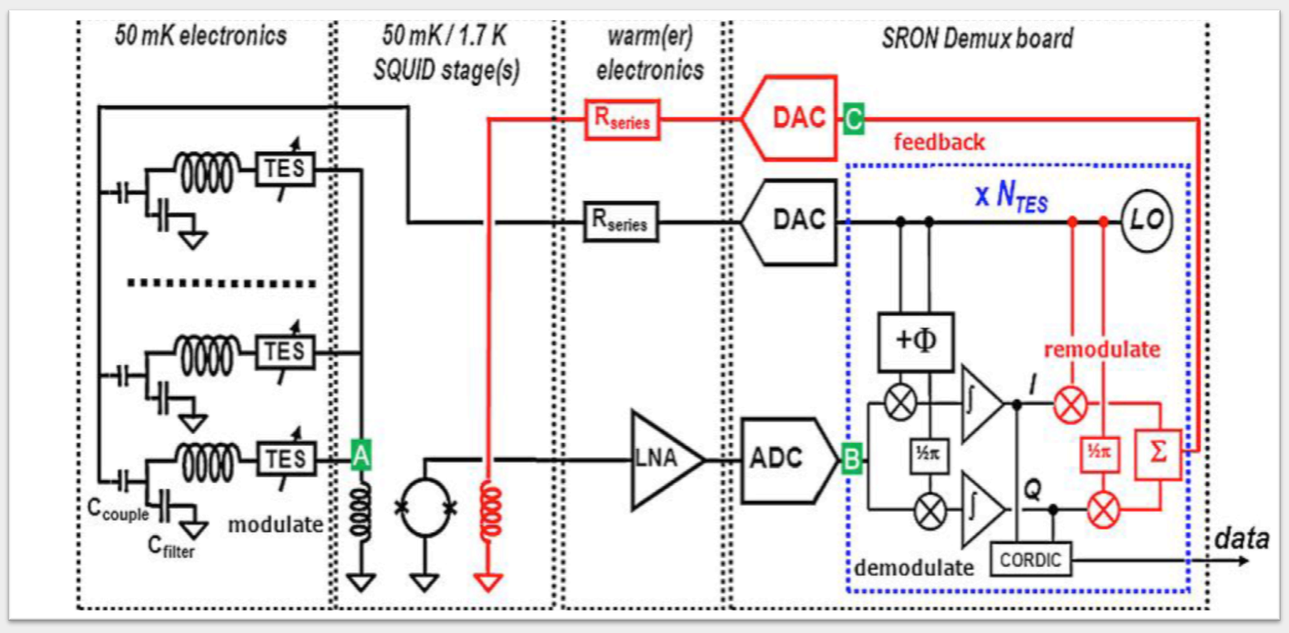
## Introduction

The SAFARI instrument is a diffraction grating and FTS spectrometer on board of the SPICA space observatory, designed to achieve the highest-ever sensitivity for line emission in a wide far-infrared wavelength. It will employ sensitive TES (Transition Edge Sensor) bolometer arrays with nearly 4000 pixels with an NEP of 0.2 aW/√Hz. Frequency Division Multiplexing (FDM) will be used to read out these bolometers. Under FDM each TES is in series with an LC resonator and then in parallel with other pixels. The detectors share a bias line and are readout by a single SQUID amplifier. Each detector is biased at a particular frequency equal to the resonance frequency of the LC it is in series with. The signal at the TES modulates the amplitude of the carrier signal, which is retrieved when demodulated. The current baseline is to have multiple FDM readout channels, each capable of reading out around 160 pixels with bias frequency range between 1-4 MHz and 16 kHz spacing. This frequency spacing causes substantial electrical cross talk under high optical loading of the detectors. Under these operating conditions the resistance of the detector are high, thereby broadening the electrical bandwidth. As a result the amount of the current that leaks into the neighboring pixels is not negligible and in order to determine the optical power on each pixel the resistances of the neighboring pixels and their corresponding bias currents needs to be considered at the same time. Here we discuss carrier leakage and present a method to calculate the resistance and the current of each pixel in the whole array, despite large carrier.

## FDM readout circuit

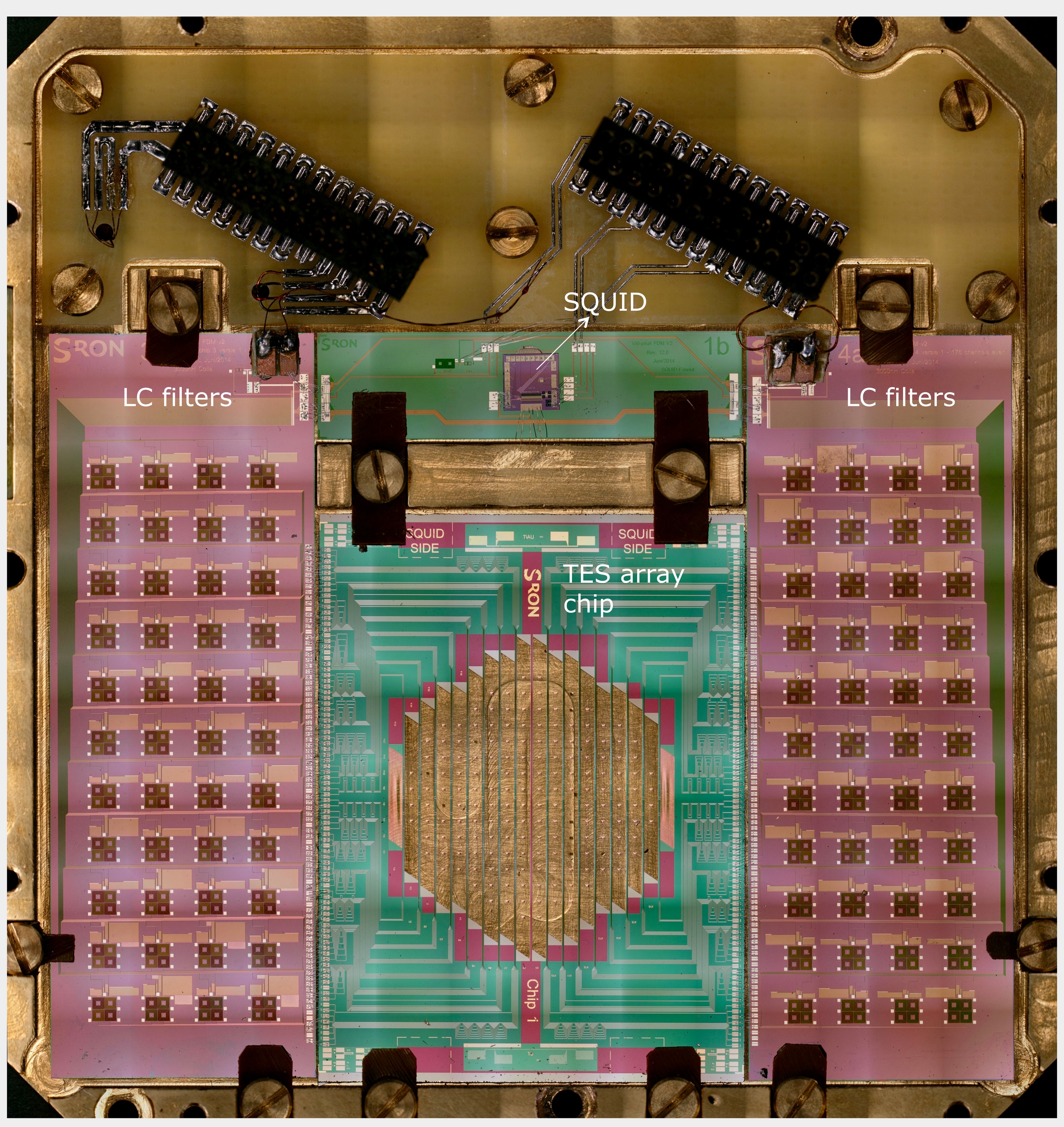
- FDM applies a set of sinusoidal AC carriers to bias the TES detectors in their set points, which are amplitude modulated when the detectors are heated by the radiating power.
- The detectors are separated in frequency by placing them in series with LC resonators of specific frequencies. It allows the readout of multiple TES pixels by one SQUID.
- The TES currents are added in the summing point and picked up by the SQUID, furthered amplified and digitized.
- This signal is then demodulated, resulting in the quadrature *I* and *Q*.
- The I and Q signals are remodulated and combined to provide a feed back to improve the linearity and dynamic range of the SQUID.




## FDM readout setup

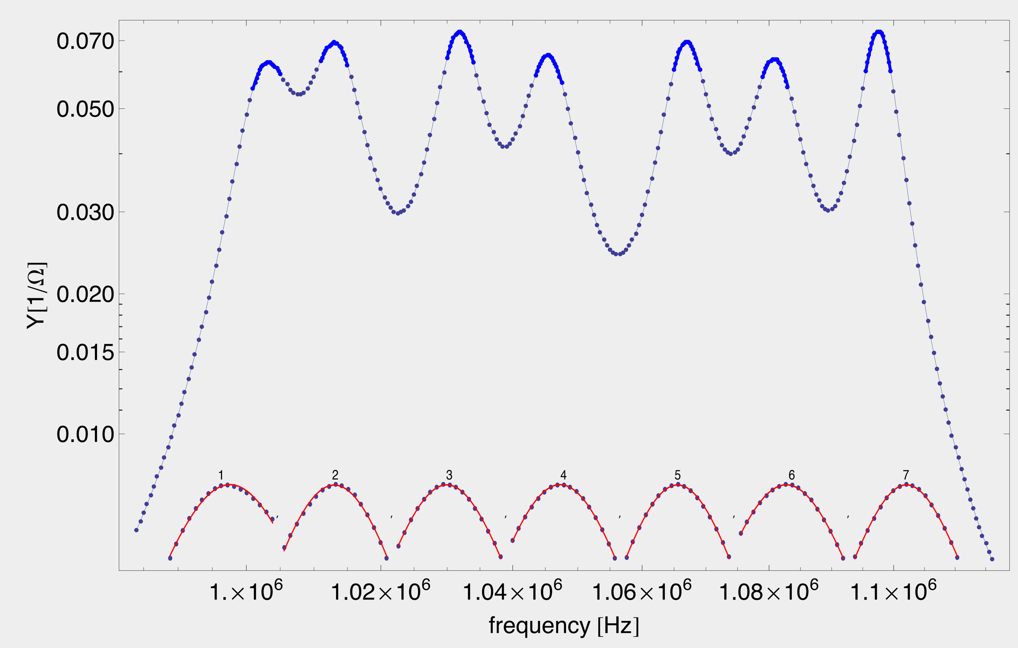
- We use a 176-channel FDM readout system
- Bias frequency range is 1-3.8 MHz.
- Frequency separation is about 16 kHz.
- L in LC resonators are nominally 3 μH.
- This is the current baseline for SAFARI readout demonstration.
- Ti/Au TES bilayer, Tc around 105 mK
- Normal state resistances are between 100-200 mΩ

**For details see:**
R.A. Hijmering et al, "Readout of a 176 pixel FDM system for SAFARI TES arrays," Proc. SPIE 9914, 99141C (4 August 2016);

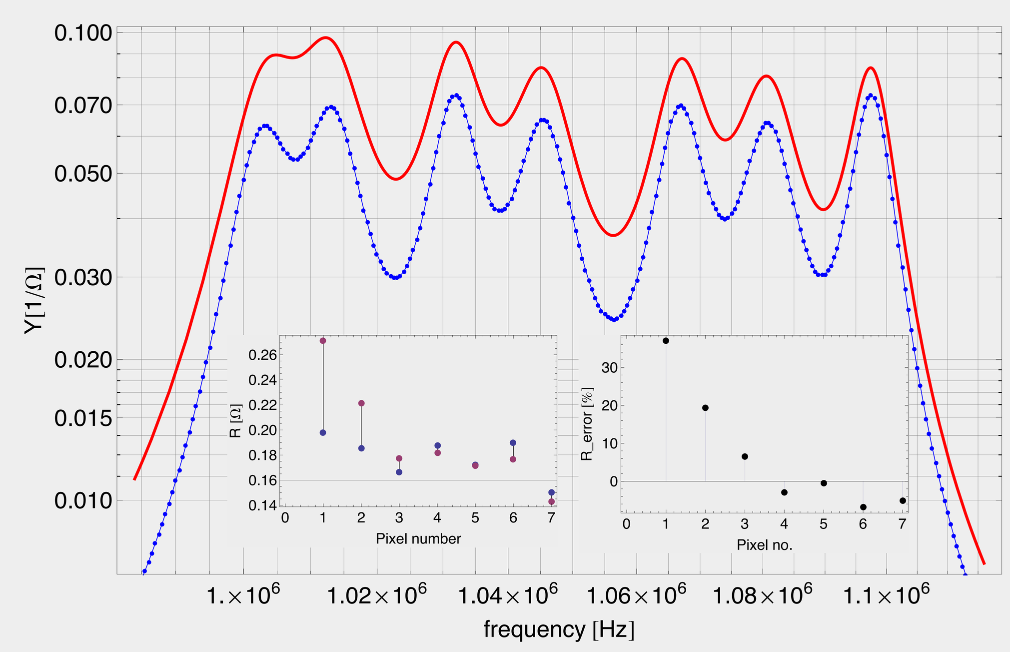



## Mitigating Carrier Leakage

- To demonstrate the problem with carrier leakage we model 7 resonators between 1-1.1 MHz with 16±3 kHz spacing.
- We assume all TESes are heavily loaded and have resistances of 175±25 mΩ close to the normal state.
- Below is the real part of the total current as a function of frequency.

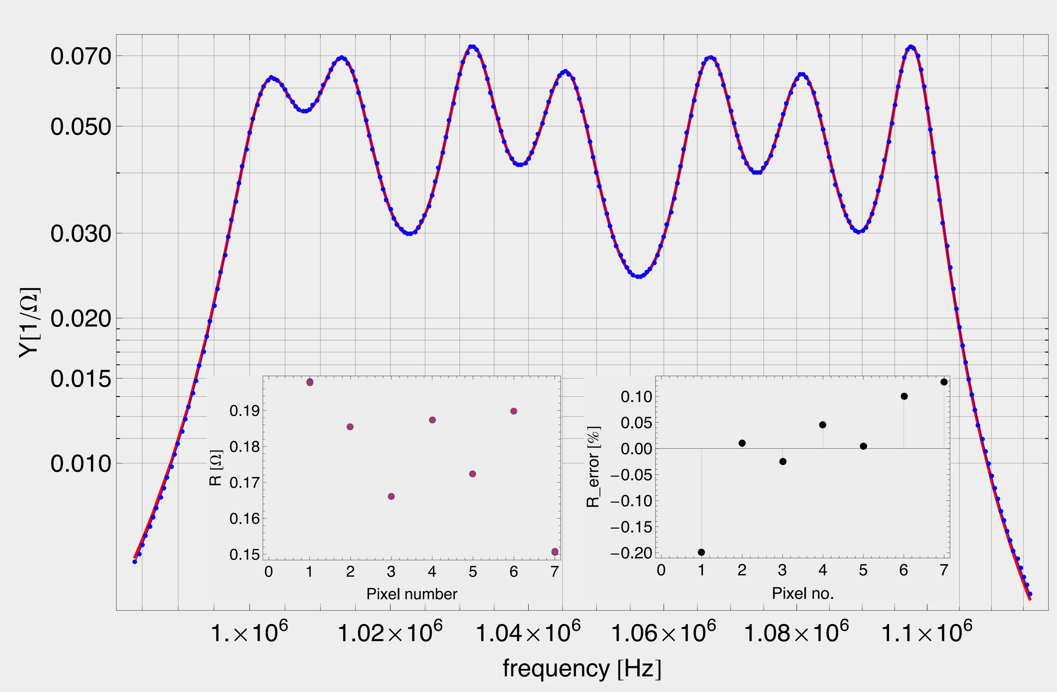



- The peaks are easily identified and the R's are estimated by fitting a Lorentzian to every peak and extract the Q's.
- However the estimated R's would produce the following current (Red), which is very much different than what we started with (in blue).
- There is also a rather large difference between the calculated R's and the actual values due to the large carrier leakage (inset below).



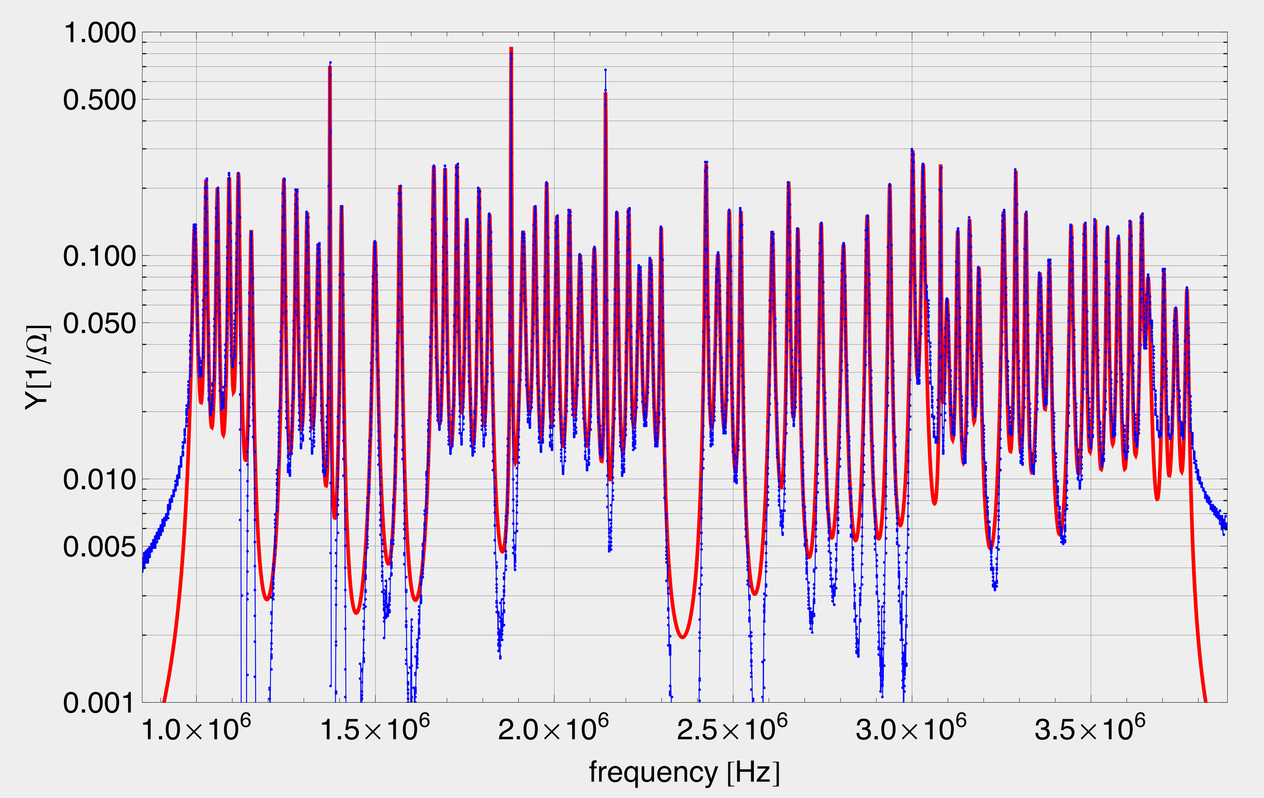

Despite the presence of large carrier leakage it is possible to extract the exact resistance of each TES by the following method:

1. First estimate the R's by fitting a Lorentzian to each peak as we did above.
2. Estimate each R by Fitting a Lorentzian again but this time use all the other R's to create a baseline for the Lorentzian to add on.
3. The new set of R's are much closer to the actual values that what we had in the first step so we update the R's and repeat step 2.
4. After 5 iterations the estimated R's converge to the actual values. As shown below the calculated real part of the current as a function frequency (Red) is exactly the same as the actual current that we started with (in blue). The R's and the errors are shown in the inset.

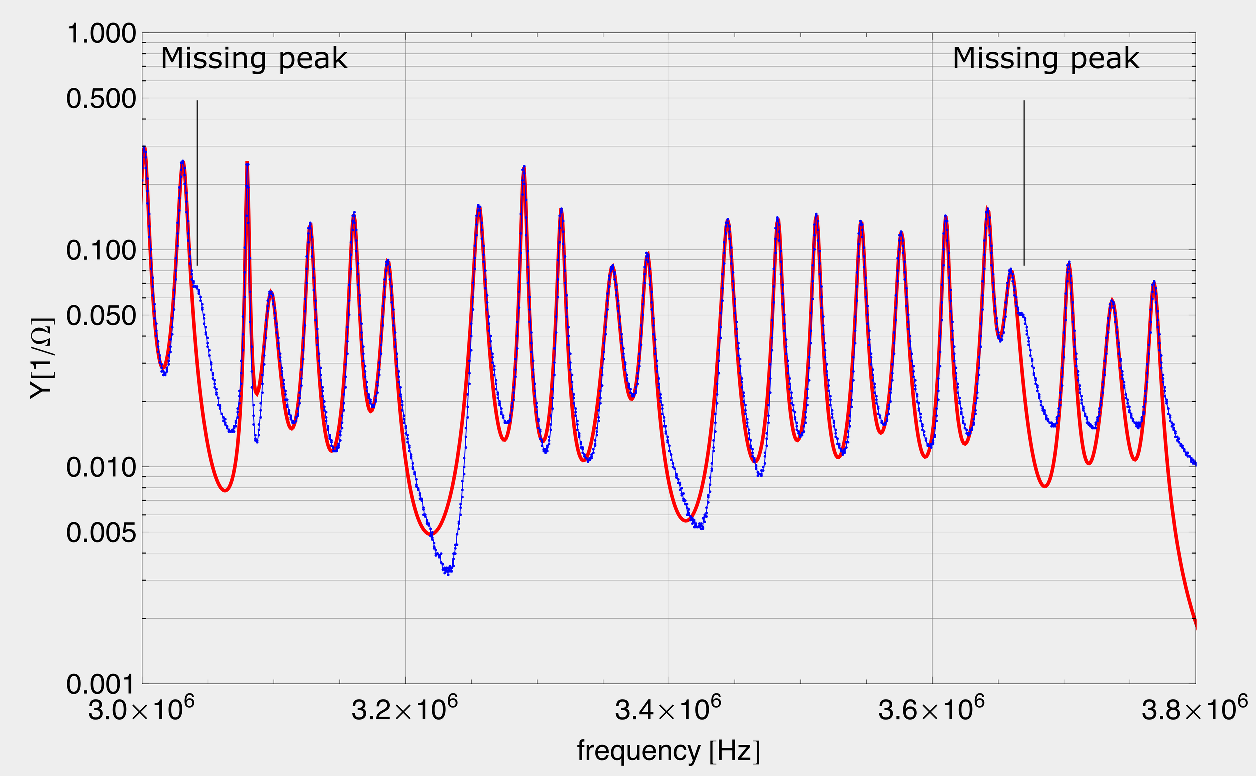



## Applying the method

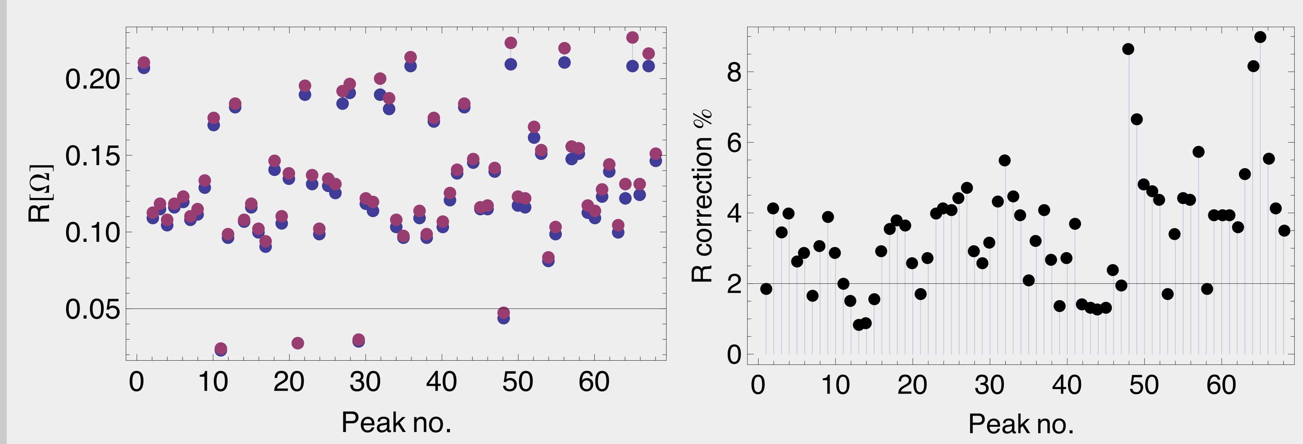
- We applied This technique to estimate the Rn of the TESes in our setup. In this experiment we had half the chip wired, which includes 70 resonators with mostly around 32 kHz frequency spacing and occasionally multiples of that. Below is the measured data (blue) and the estimated curves when all TESes are in normal state.




- We could identify 68 resonance peaks and missed 2 since they were very close to their neighbors. Obviously in these areas we deviate from the measured data.




- The mismatch between measured and calculated data at low currents can be due to the error in the phase correction to extract the real part of the complex current.
- It can also be due to other kind of cross talk such as parasitic common inductance that is ignored here but can be included.
- Below are the first estimate of R's in red and the outcome after iterations in blue for each resonator. The corrections after iterations in percentage is also plotted in black.




- As we see the corrections here are below 10% since the spacings are 32 kHz or multiple of that. The correction is expected to become much larger when full array with 16 kHz spacing is measured and estimated with this method.

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