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Superconducting Titanium Nitride lumped element microwave resonators

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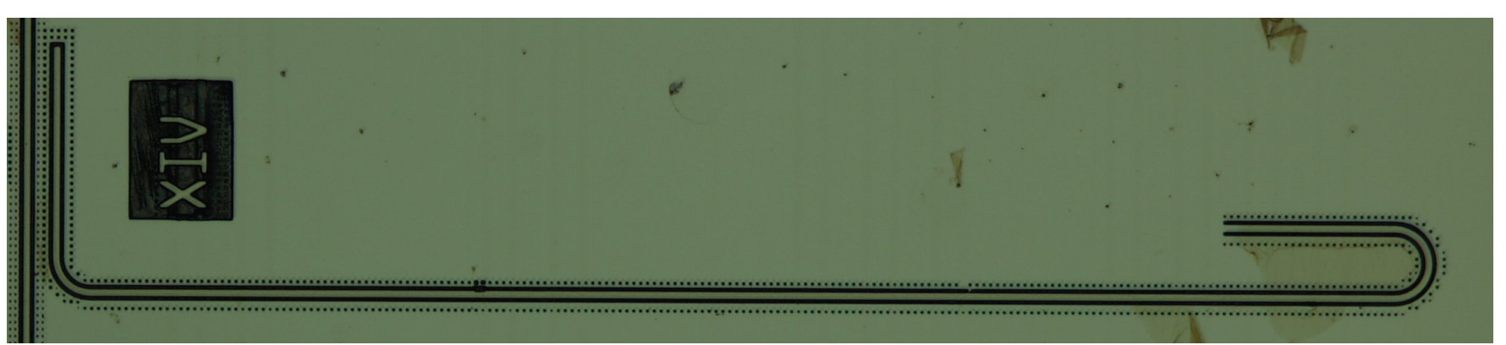
Abstract

Superconducting resonators are of great interest for microwave kinetic inductance detectors and quantum architecture. Not only can they be used for the state readout of a qubit, but also for other purposes, for example as a quantum bus. For these purposes resonators with high quality factors and robust against magnetic field fluctuations would be useful. In the past changes in frequency and quality factor depending on the applied magnetic field and magnetic field history have been observed[1]. In our work we fabricate resonators made out of titanium nitride for which very high quality factors (about one million at single photon levels) have been demonstrated[2]. Furthermore we investigate the behaviour of quarter wavelength and lumped element resonators with a magnetic field applied at temperatures down to 300 mK. We determine all the parameters (quality factor, resonance frequency and coupling strength) using a circle fit considering both quadratures.

Thin film resonators

Superconducting resonators can be realized by transmission line (such as quarter or half wavelength resonators) or lumped element LC resonators. Transmission line resonators simply consist of a superconducting line which can be either shorted to ground ($\frac{\lambda}{4}$) or open ended ($\frac{\lambda}{2}$-resonator). Lumped LCs consist of an inductor and a capacitor in either a parallel or series circuit.



Micrograph image of a quarter wavelength resonator coupled to a feedline (left). The brighter regions are TiN, the darker ones substrate. The small dark points are flux traps.

The resonance frequency of a $\frac{\lambda}{4}$-resonator is:

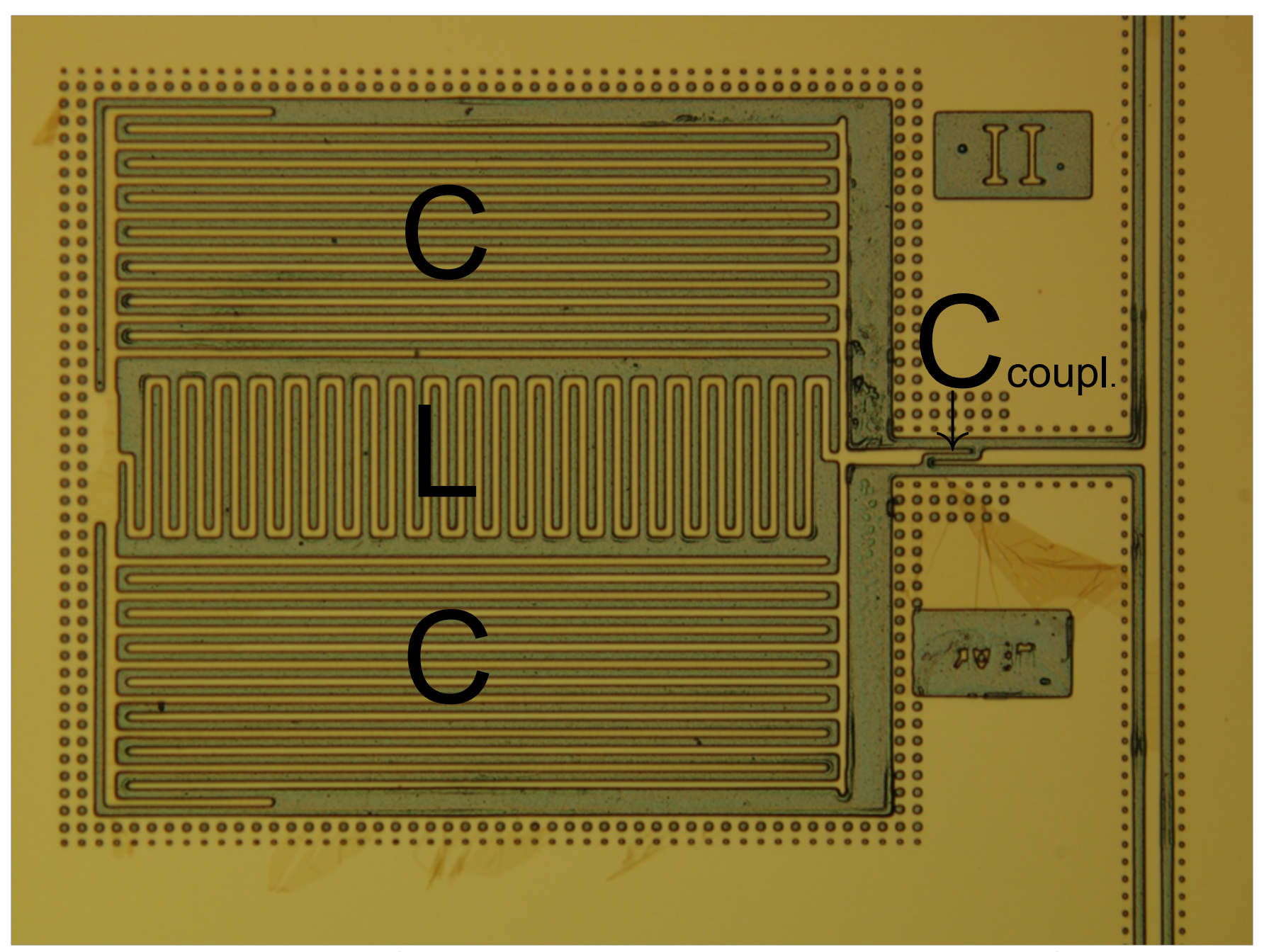
$$f_r = \frac{c}{4l\sqrt{\epsilon_{\text{eff}}}}$$

where c is the light velocity and

$$\epsilon_{\text{eff}} \approx \frac{1+\epsilon_{\text{substrate}}}{2}$$

For a lumped element resonator the resonance frequency is determined by

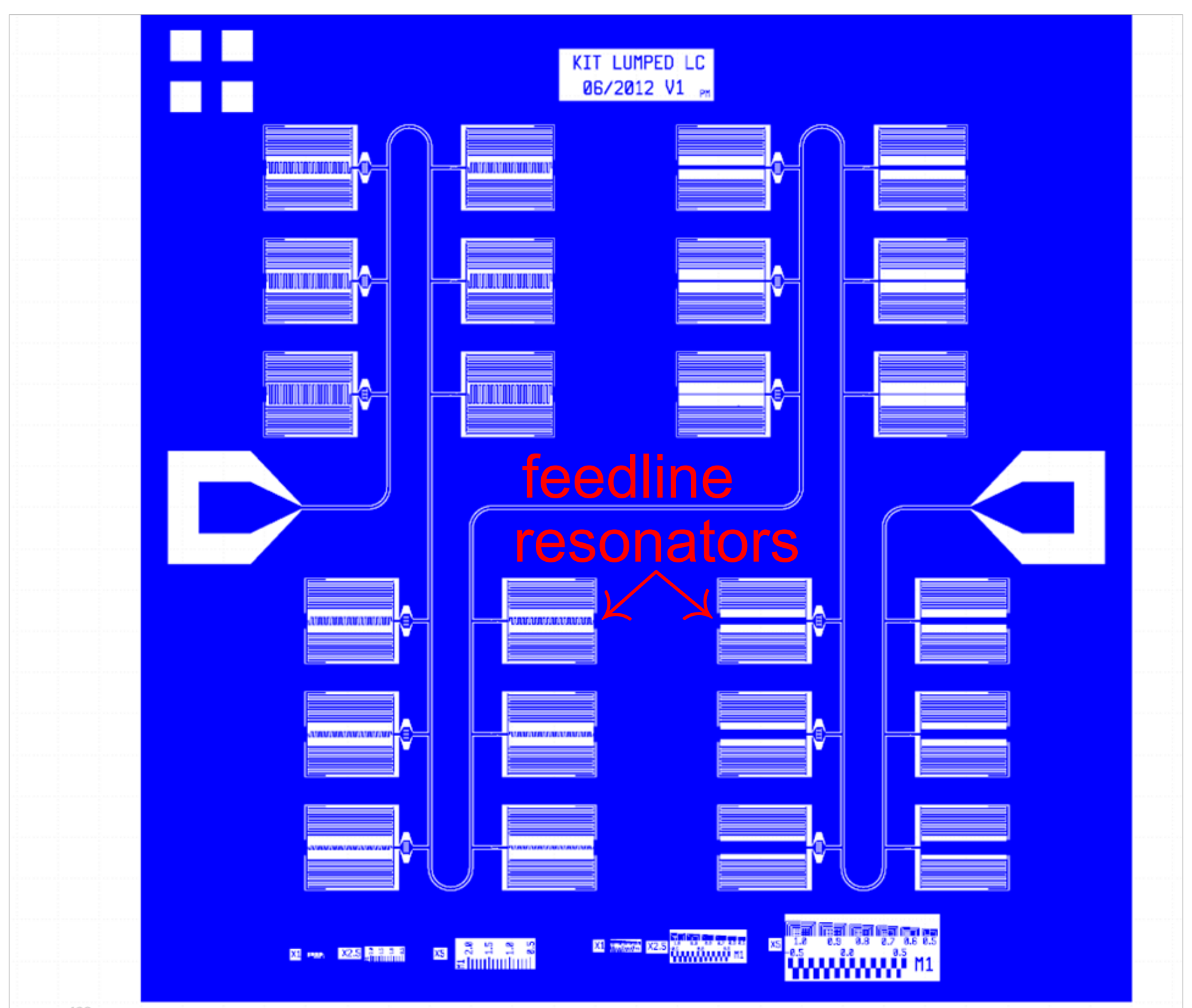
$$f_r = \frac{1}{2\pi\sqrt{LC}}$$



Micrograph image of a lumped element resonator with flux traps consisting of a meandered inductance and two finger capacitors coupled to a feedline. The golden regions are TiN, the darker ones substrate.

Fabrication process

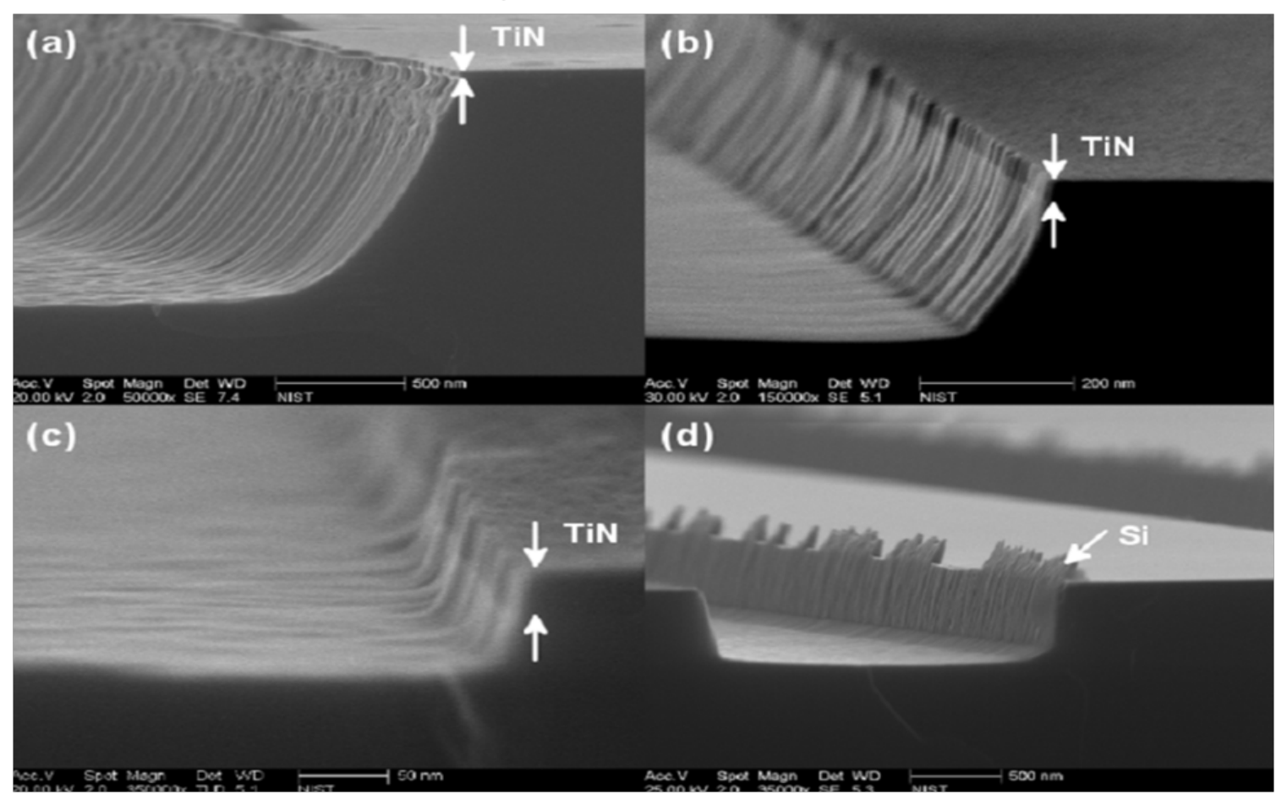
At first we designed some resonator arrays with L-Edit, calculating the resonance frequencies using Sonnet.
In the design on the right 24 resonators with twelve different resonance frequencies are coupled to the feedline. The calculated resonance frequencies range equidistantly from 4-12 GHz. We use two different coupling strengths Q_{C1}=5k and Q_{C2}=100k.



Resonator chip design with 24 resonators coupled to a feedline. The blue regions show superconductor

Fabrication steps

- 50nm of TiN deposited on an intrinsic silicon wafer
- Chromium reticle made using laser lithography
- Photoresist-coated TiN chips UV-illuminated with a mask aligner
- Developing the exposed photo resist
- TiN removed with fluorine etching, using SF_6



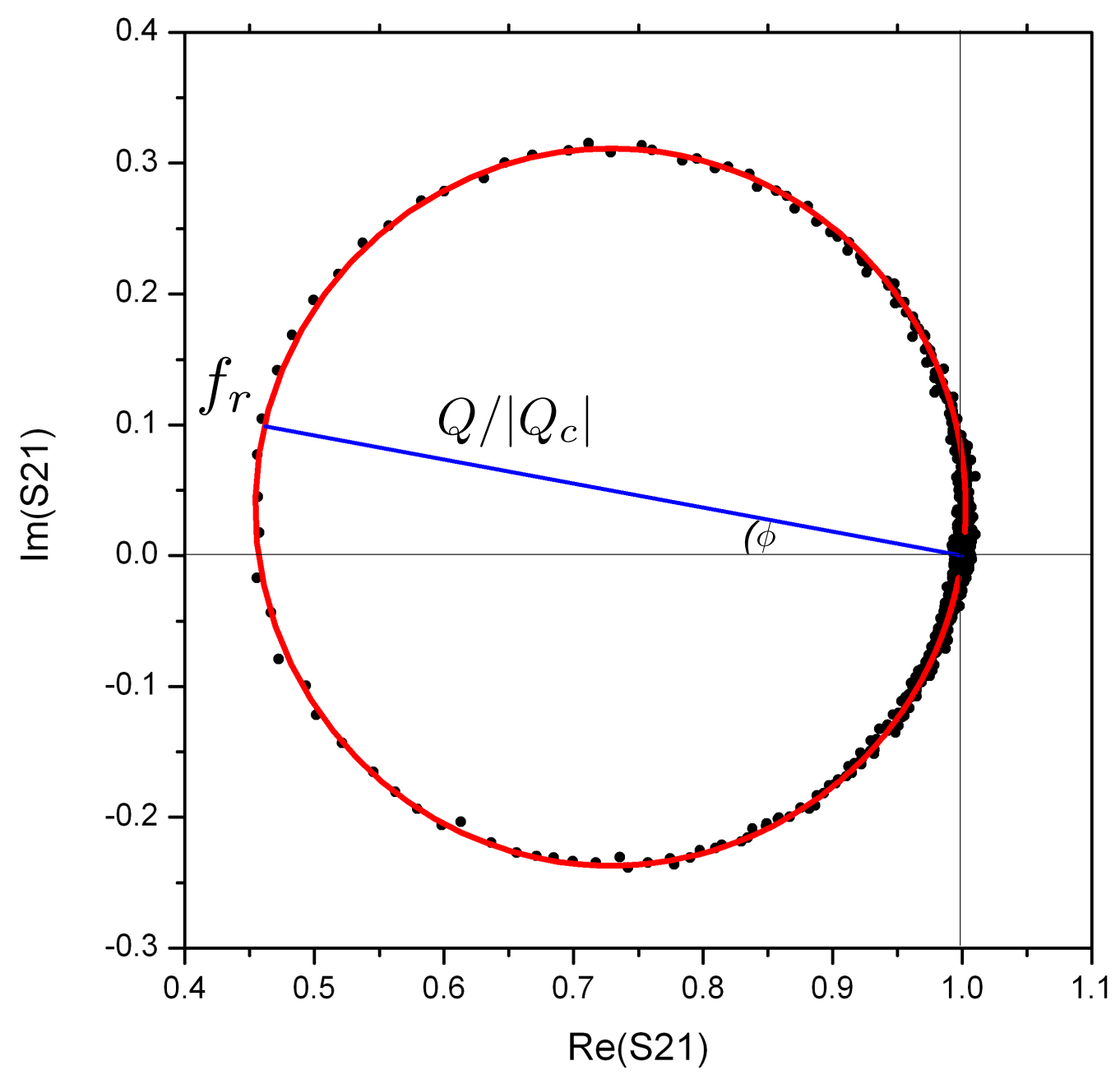
SEM pictures of different samples (a) Trenched F-etch (b) Trenched Cl-etch (c) Non trenched Cl-etch (d) Trenched ion-milled with redeposited Si [2]

Measurement

For calculating the quality factor we plot the transmission spectrum of a resonator on the complex plane. The data points form a circle which can be mathematically described by:

$$S_{21} = a\left(1 - \frac{\frac{Q_r}{|Q_c|}e^{i\phi}}{1+2iQ_r\frac{f-f_r}{f_r}}\right)$$

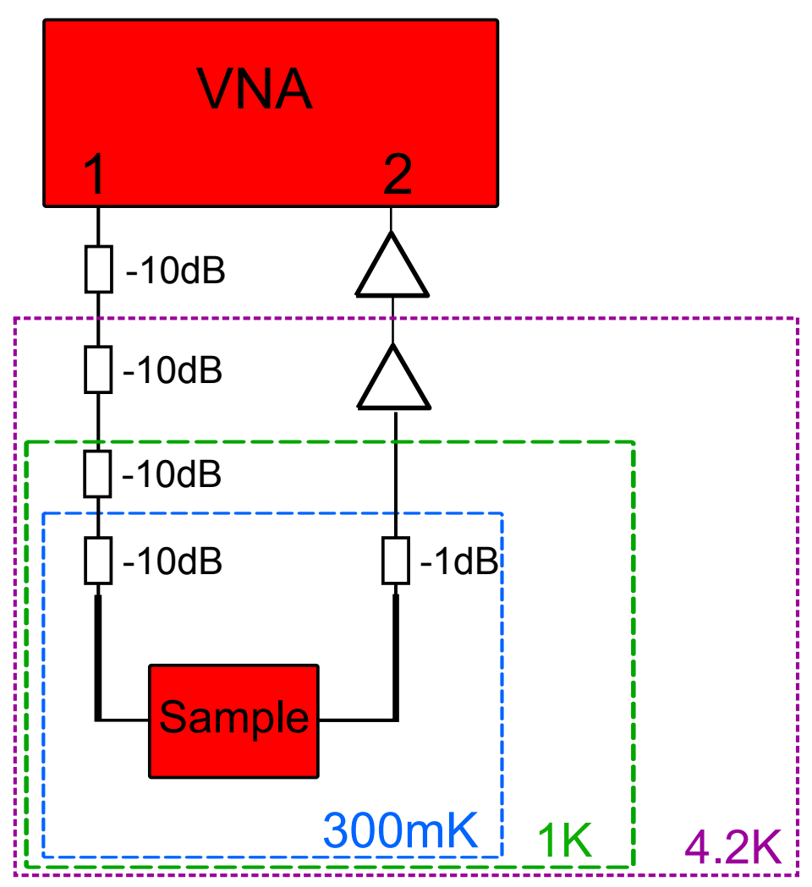
where a is a complex prefactor, f_r the resonance frequency, Q_r the total quality factor, Q_c the coupling quality factor with its phase ϕ
After eliminating the prefactor a we fit a circle to the data. An advantage of this method is that both amplitude and phase instead of just the amplitude is used.

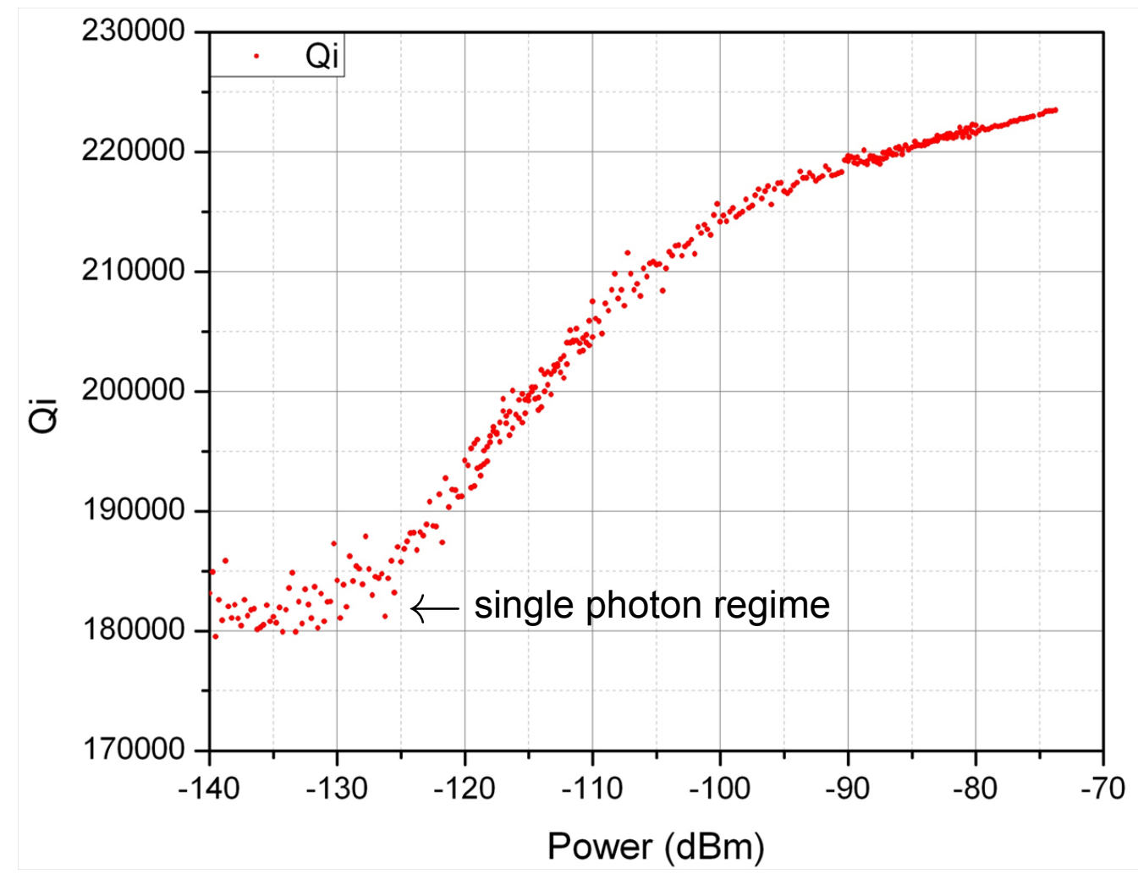


The black points correspond to the measured data after eliminating the prefactor. The red line is the fitted circle.

For our measurements we use a He3 refridgerator to reach temperatures down to 300 mK. Two microwave cables connected to a Vector Network Analyzer are attached to the sample.

The picture on the right shows the power dependence of the quality factor. One reason for the loss in superconducting resonators is the coupling to parasitic two level systems (TLS) in the substrate and thin film interfaces. With increasing power these TLSs saturate and therefore the quality factor increases as the picture ilustrates.





The figure left shows a scheme of the setup with its different temperature stages and the microwave attenuation and amplification chain. The picture on the right shows the power dependence of the quality factor at 300mK.

Outlook

In the future we want to study the relation of frequency and magnetic field and also the temperature dependence of our resonators with magnetic fields applied.
We plan on taking noise data as well.

References

[1] Bothner et al., Phys. Rev. B 86, 2012
[2] Sandberg et al., Appl. Phys. Lett. 100, 2012