Operation of a superconducting nanowire in two detection modes: KID and SPD

Edward Schroeder†, Philip Mauskopf†*, Hamdi Mani*, Sean Bryan*, Karl Berggren⋆, Di Zhu⋆
†*Department of Physics, Arizona State University*
**School of Earth and Space Exploration, Arizona State University*
⋆*Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology*

Introduction

- Nanowire devices are a promising technology for high S/N imaging arrays for use in astronomy.
- We present the characterization of a superconducting nanowire that can be operated in two detection modes: i) as a kinetic inductance detector (KID) or ii) as a single-photon detector (SPD). We will refer to the collective device as a Superconducting Nanowire Resonator (SNR).
- Two superconducting nanowires developed for use as single-photon detectors (SNSPDs) are embedded as the inductive (L) component in resonant inductor/capacitor (LC) circuits coupled to a microwave transmission line.
- When operated in resonator mode, the detectors are AC biased with tones at their resonant frequencies of 45.85 and 91.81 MHz.
- When operated as an SPD in Geiger mode, the resonators are DC biased through cryogenic bias tees and each photon produces a sharp voltage step followed by a ringdown signal at the resonant frequency of the detector. This signal converted to a standard pulse with an envelop detector.

Apparatus

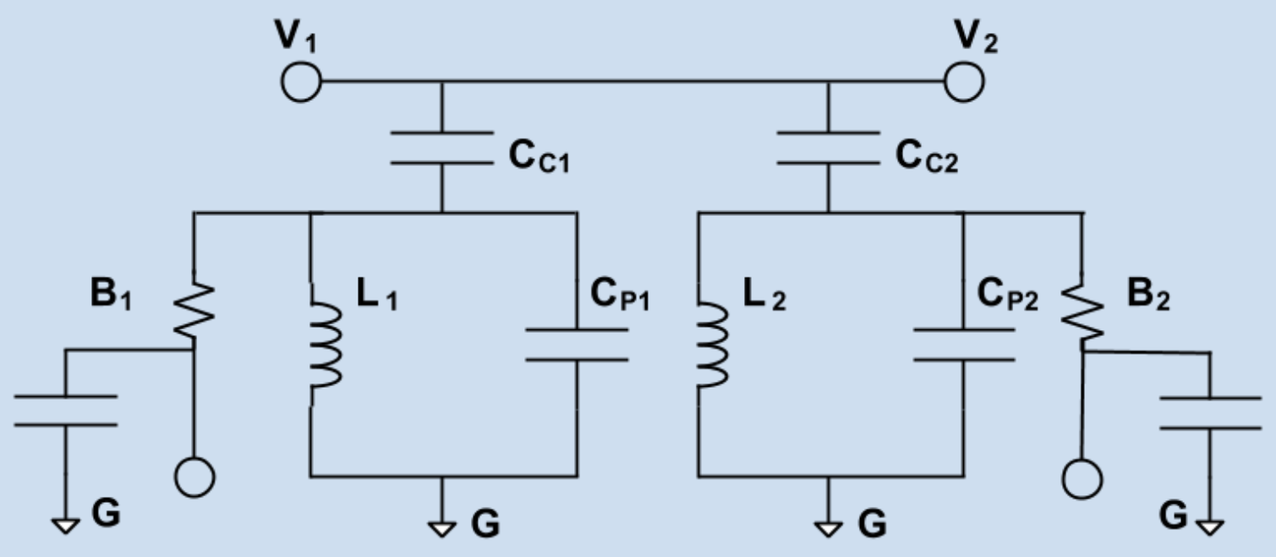

Figure 1: Circuit diagram of two SNRs on the same feedline. V_1 and V_2 are the input and output ports. L_1 and L_2 are the nanowires. C_{C1} and C_{C2} are the coupling capacitors. C_{P1} and C_{P2} are the parallel capacitors. B_1 and B_2 are bias-tees. G is the common ground. A $30dB$ cryogenic low-noise amplifier (LNA) made at ASU is included at the output of the resonator. It has a $4K$ noise temperature.

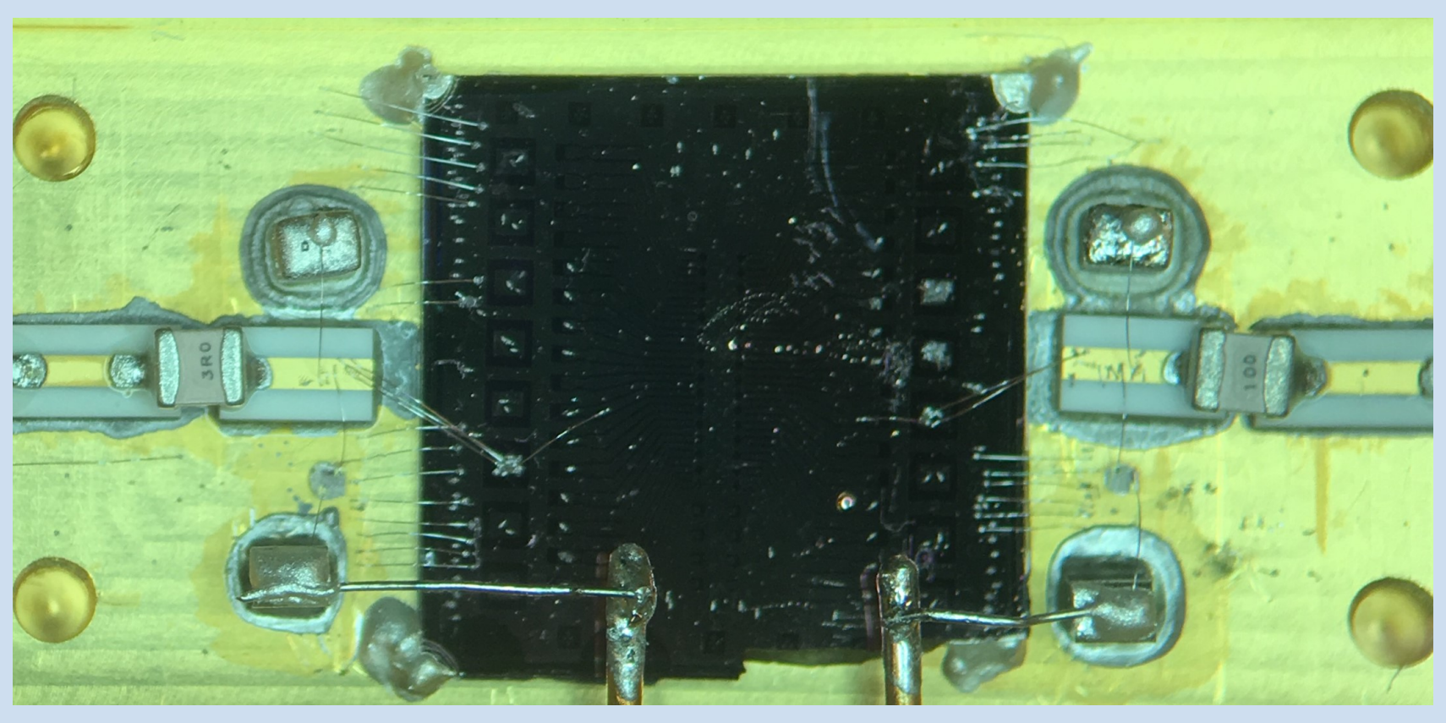

Figure 2: Micro-assembly inside the SNR package. The central chip contains the nanowires and was fabricated at MIT by the Quantum Nanostructures and Nanofabrication Group. The inductances of the nanowires are $L_1 = 731nH$ and $L_2 = 586nH$ for SNR1 and SNR2, respectively. These values are obtained from the experimental values of the resonances. Annunziata et al.[1] present a resourceful analysis of kinetic inductance values in nanowires. Each nanowire has two associated SMD capacitors. For SNR1, $C_{C1} = 3pF$ and $C_{P1} = 1pF$. For SNR2, $C_{C2} = 10pF$ and $C_{P2} = 10pF$. This concept is similar to that proposed by Doerner et al.[2], where instead of SMD capacitors, an interdigital capacitor is used.

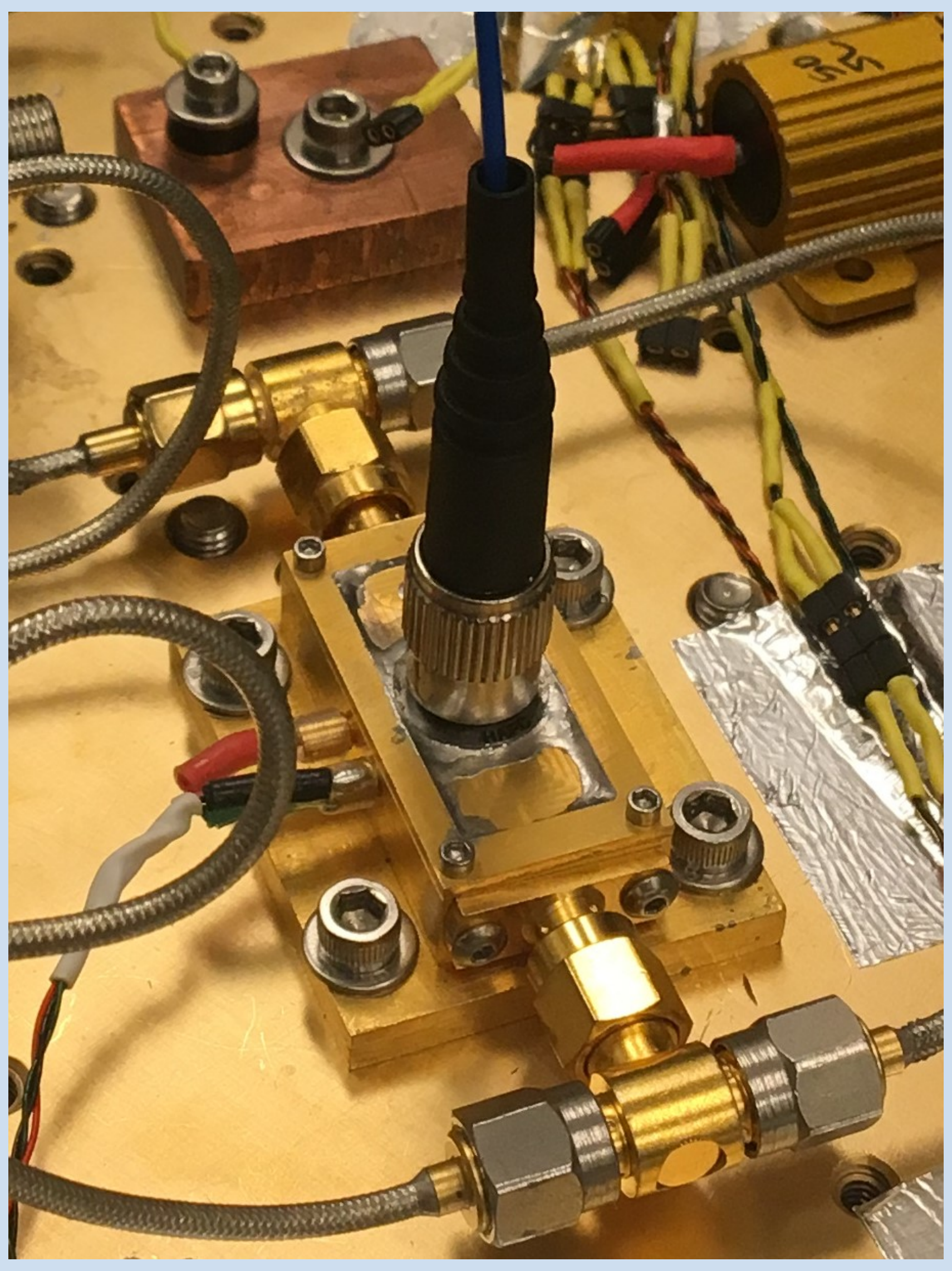

Figure 3: Fiber-coupled SNRs mounted inside the cryostat on the cold-plate.

Resonance Fitting

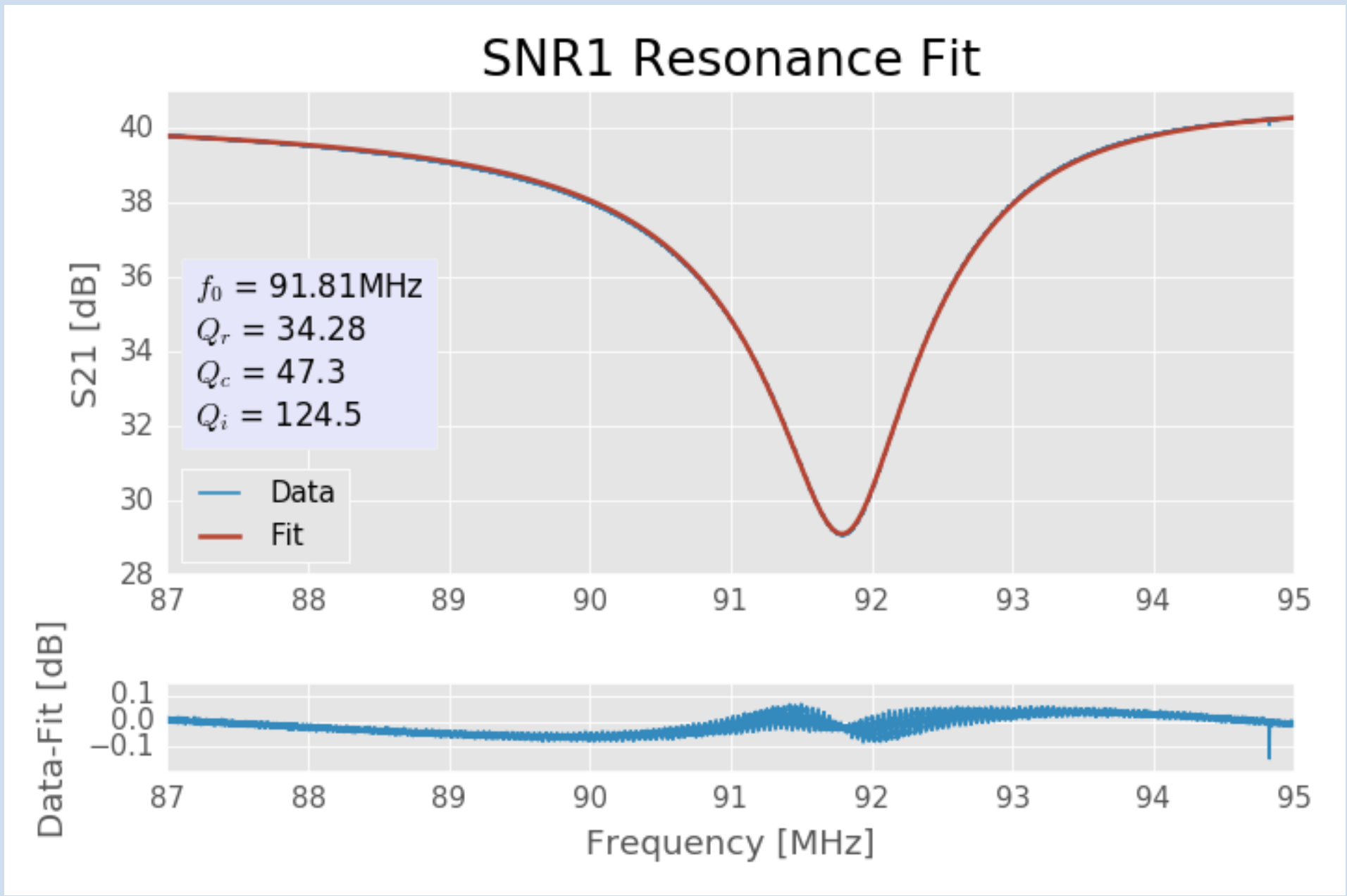

Figure 4: We fit the resonance curve with *emcee* which is a Python code Markov-chain Monte-Carlo (MCMC) method developed at MIT. The fit is consistently within a tenth of a dB. Q_r is limited by the coupling to the transmission line and Q_i is limited by loss in the parallel SMD capacitor.

Resonator Mode

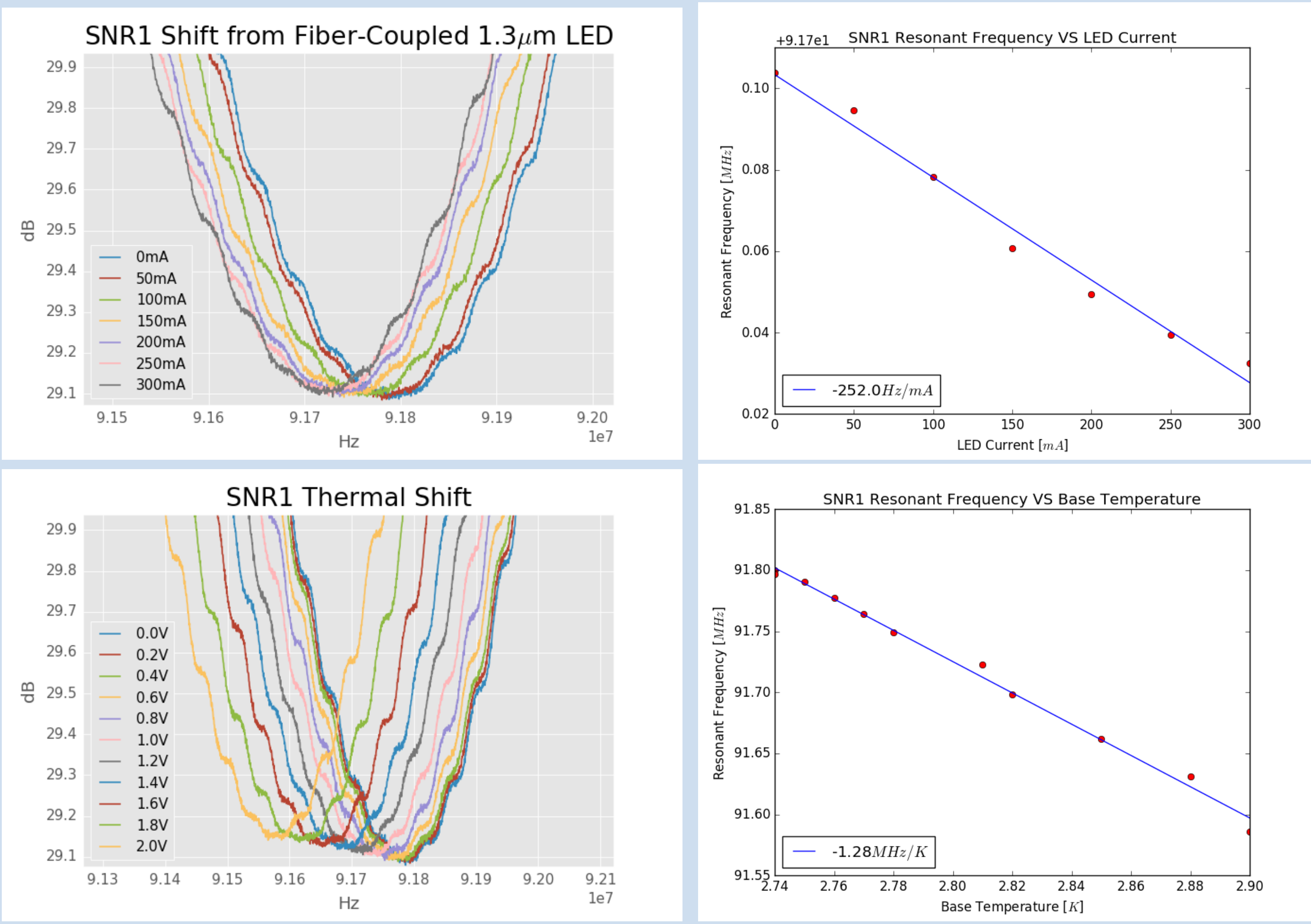

Figure 5: (Upper Left) Zoomed-in resonance shift as a function of LED current. (Upper Right) Linear fit for resonant frequency as a function of LED current. This yields a shift of $252\frac{Hz}{mA}$. (Lower Left) Zoomed-in resonance shift as a function of base temperature. (Lower Right) Linear fit for resonant frequency as a function of base temperature. This yields a shift of $1.28 \times 10^6\frac{Hz}{mA}$.

We measured S_{21} for the resonators as a function of base temperature and at a fixed base temperature $(2.7K)$ as a function of LED current. If we compare the frequency shift of the resonance as a function of LED current with the temperature dependence, we can calculate an effective temperature shift of the quasiparticles as a function of LED current with

$$\delta T = \frac{\Delta T_{base}}{\Delta I_{LED}} = 197\frac{\mu K}{mA}$$

This effective temperature shift is a lower estimate because it assumes that the energy from each photon is distributed evenly throughout the nanowire. In fact, the energy from each photon is deposited locally and creates a hotspot of normal metal around which the current has to flow.

From the measured critical current and critical temperature, we calculated the change in quasiparticles per mA at low temperatures with

$$\frac{\delta N_{qp}}{\delta T} = \frac{N_{qp}}{T}\left(\frac{1}{2} + \frac{\Delta}{kT}\right),$$

where $\Delta \sim 1.764kT_C = 1.29meV$, for $T_C \approx 8.5K$, and $T \approx 2.74K$. $N_{qp} = 1.44 \times 10^5$ is found via analysis of the non-linear kinetic inductance and equating the scaling energy with the condensation energy of the superconductor.

The absorbed power in SNR1 per mA of LED current can be found with

$$P_{abs} = \frac{\delta N_{qp}\Delta}{\eta\tau_{qp}}$$

In NbN HEB detectors, the bandwidth is about $3 - 5GHz$. This corresponds to a time constant of $30 - 50ps$. We will consider a lower bound to the time constant to be $20ps$ and an upper bound to be $1ns$. Assuming a typical value for the production efficiency, $\eta = 0.57$, we find a range of $\boldsymbol{P_{abs} = 2.24 \times 10^{-11} - 1.12 \times 10^{-9}\frac{W}{mA}}$ for SNR1.

Geiger Mode

At a fixed temperature, the detectors were biased with a DC current and illuminated by an LED. The pulses that ring down were rectified with an analog circuit and counted with a frequency counter (Tektronix FCA3100). Using this technique it is not possible to distinguish between pulses from the two detectors.

The detected power can be estimated from the number of pulses per second as a function of LED current (Figure 6, Lower Right) multiplied by the photon energy with

$$P_{abs} = 1591\frac{kHz}{mA} \times h\nu,$$

where h is Planck's constant, and $\nu = 2.31 \times 10^{14}Hz$. This yields $\boldsymbol{P_{abs} = 2.43 \times 10^{-13}\frac{W}{mA}}$. A range for the Internal Quantum Efficiency (IQE) can be determined by comparing the absorbed power per mA in resonator mode to that in Geiger mode:

$$\boldsymbol{IQE = 0.02 - 1.08\%}$$

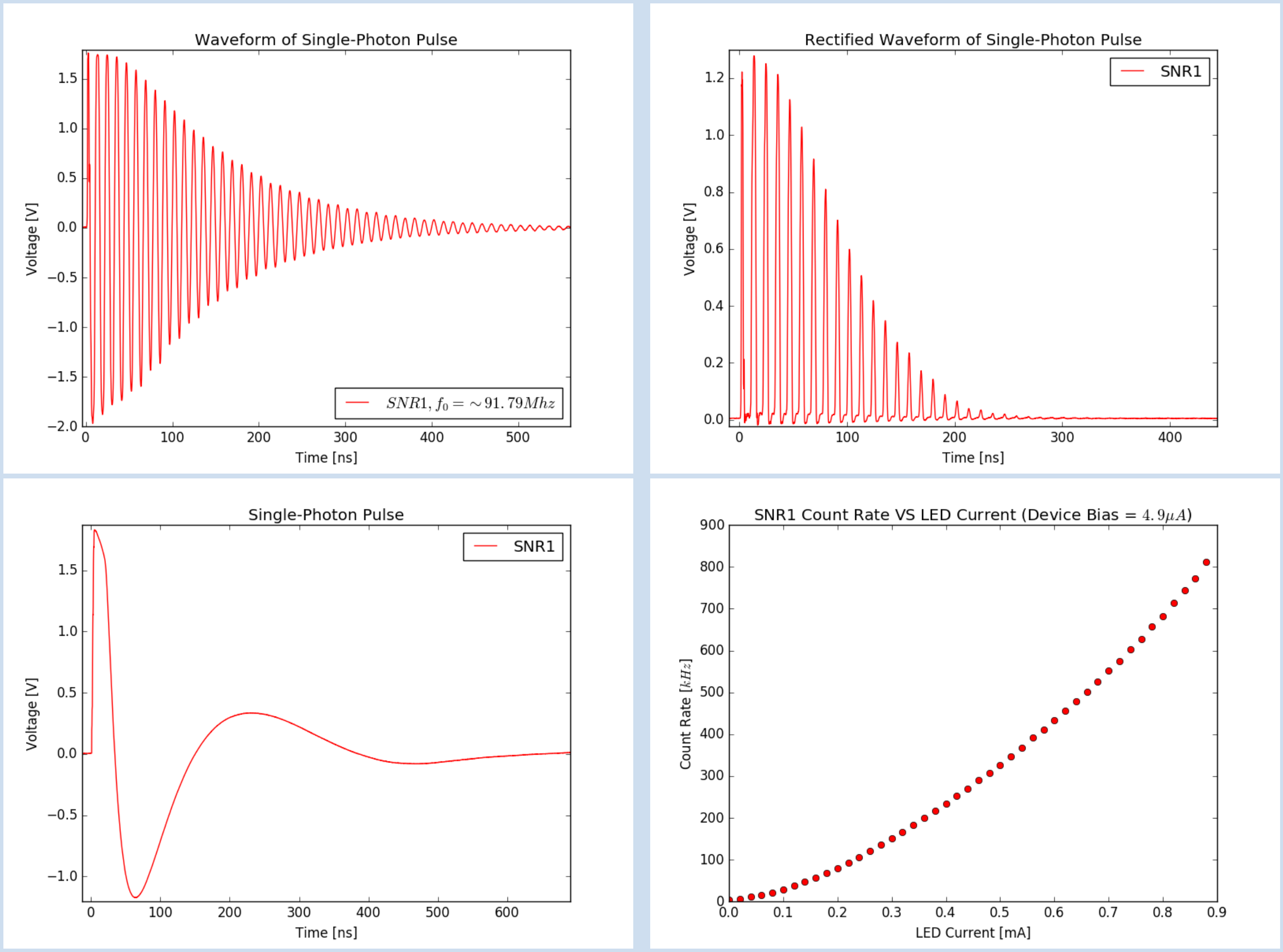

Figure 6: (Upper Left) Amplified waveform produced by a single-photon incident on the nanowire in SNR1 and traveling through the 3pF coupling capacitor. (Upper Right) Rectified waveform produced by a diode. (Lower Left) Filtered pulse produced by an RC-circuit. (Lower Right) Count rate as a function of LED current bias.

The low IQE is likely due to the critical currents for the nanowires being used having lower values than expected for high-quality nanowires. Preparing an SNR with higher quality nanowires should increase the count rate of the nanowires in Geiger mode and therefore increase the IQE.

Outlook

- We will measure the photon noise as a function of incident optical power in resonator mode with a homodyne system.
- We will measure the pulses from the two multiplexed detectors using an FPGA-based readout board that allows real time separation of the two different detector frequencies.

References

[1] A. J. Annunziata, D. F. Santavicca, L. Frunzio, G. Catelani, M. J. Rooks, A. Frydman, and D. E. Prober. Tunable superconducting nanoinductors. *Nanotechnology*, 21:445202, November 2010.

[2] S. Doerner, A. Kuzmin, S. Wuensch, K. Ilin, and M. Siegel. Operation of superconducting nanowire single-photon detectors embedded in lumped-element resonant circuits. *IEEE Transactions on Applied Superconductivity*, 26(3):1–5, April 2016.

[3] P.D. Mauskopf. Transition Edge Sensors and Kinetic Inductance Detectors in Astronomical Instruments. *to appear in PASP*, 2016.