Real time quasiparticle tunneling measurements on an illuminated quantumcapacitance detector

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Electron Beam Lithography by
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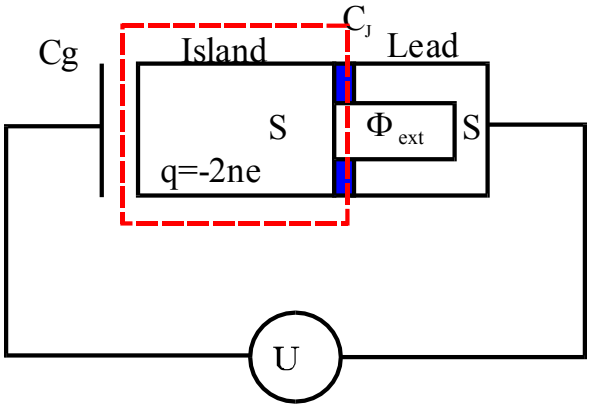
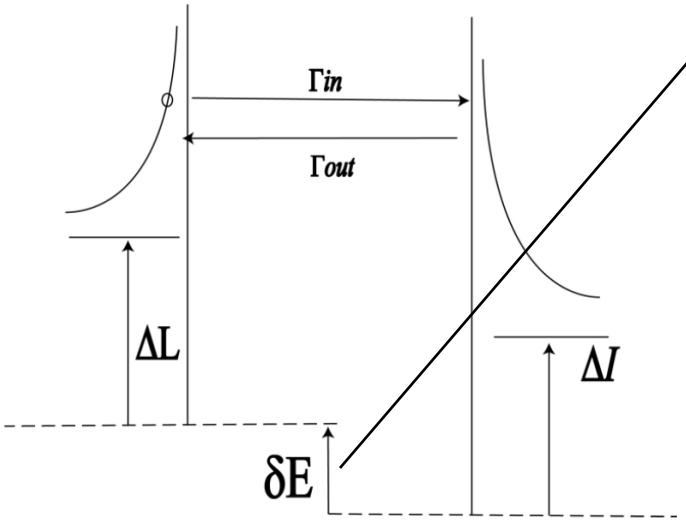
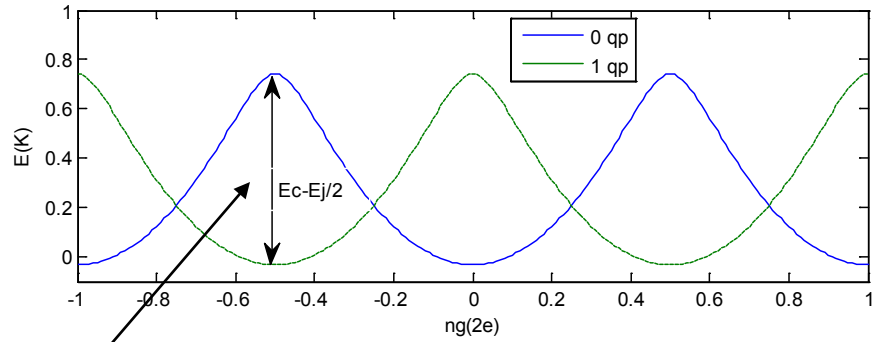
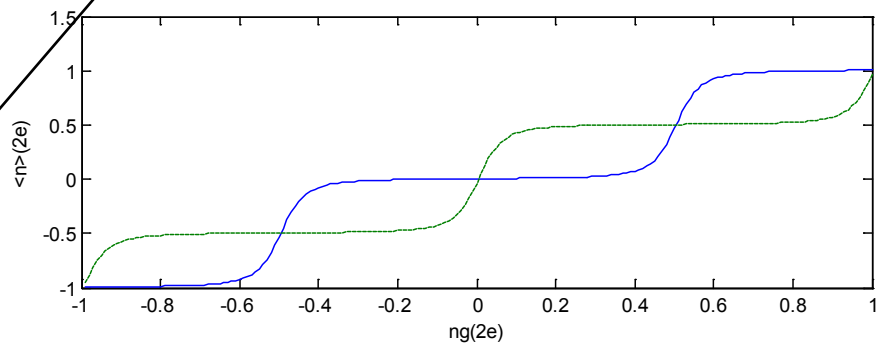
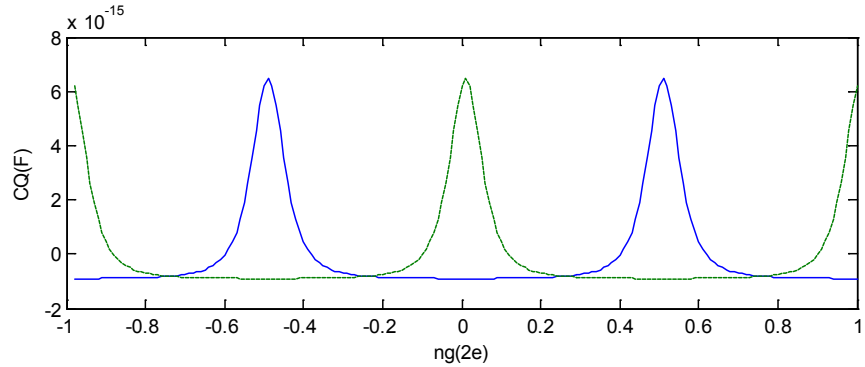
Single Cooper-pair Box (SCB)



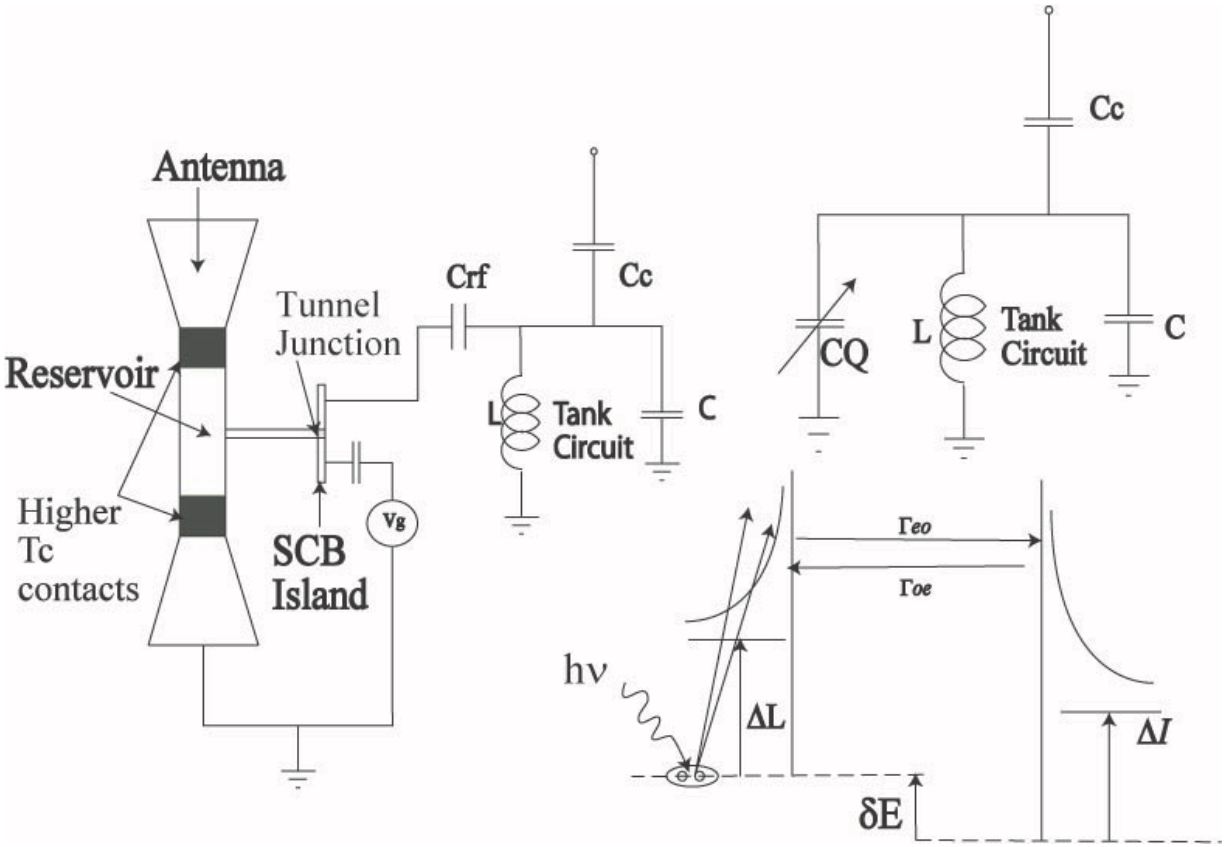






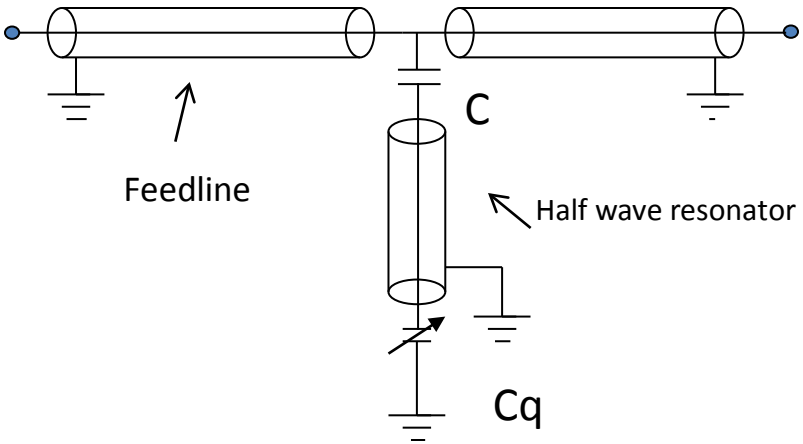


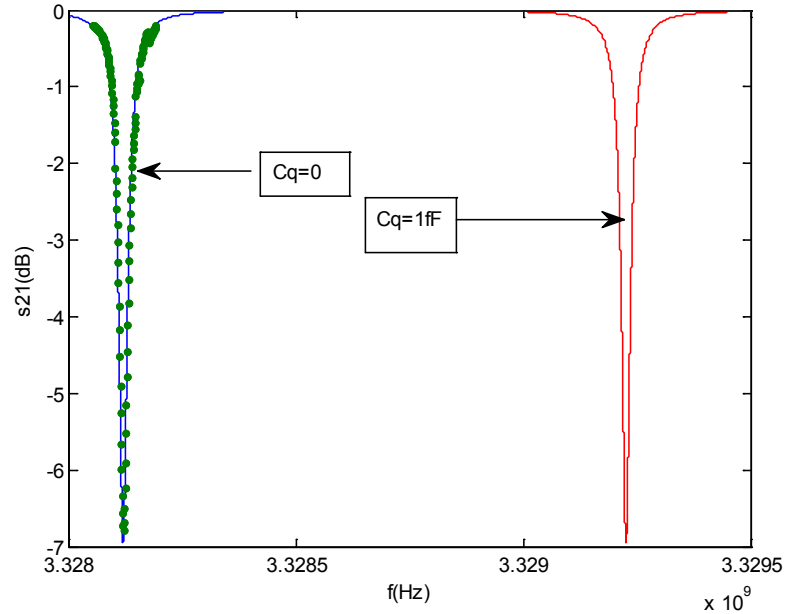
The Quantum Capacitance Detector



- Radiation coupled by an antenna breaks Cooper pairs in the reservoir (absorber)
- Quasiparticles tunnel onto the island with a rate Γ_{in} proportional to the quasiparticle density in the reservoir
- Quasiparticles tunnel out of the island with a rate Γ_{out} independent of the number of quasiparticles in the reservoir
- At steady state the probability of a quasiparticle being present in the island is given by $Po(Nqp)=\Gamma in/(\Gamma in+\Gamma out,)$
- The resulting change in the average capacitance will be $C_Q=(4E_C/E_J)(C_g^2/C_\Sigma)Po(Nqp)$
- *This change in capacitance will produce a phase shift* $\delta\Phi\sim 2C_Q/(\omega_o Z_o C_C^2)$

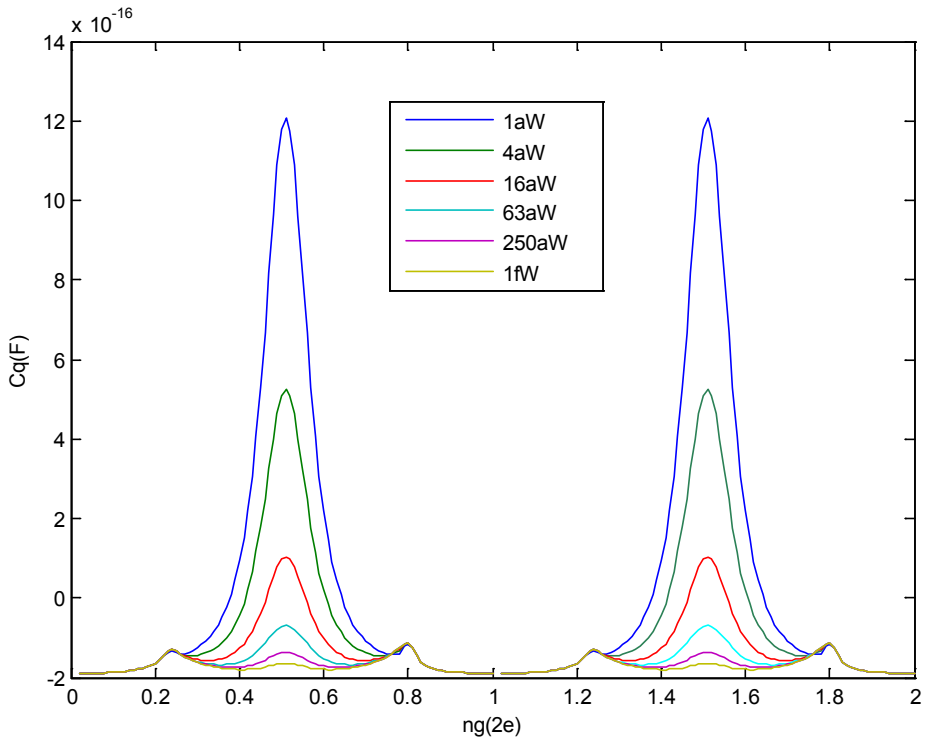
Measurement Technique

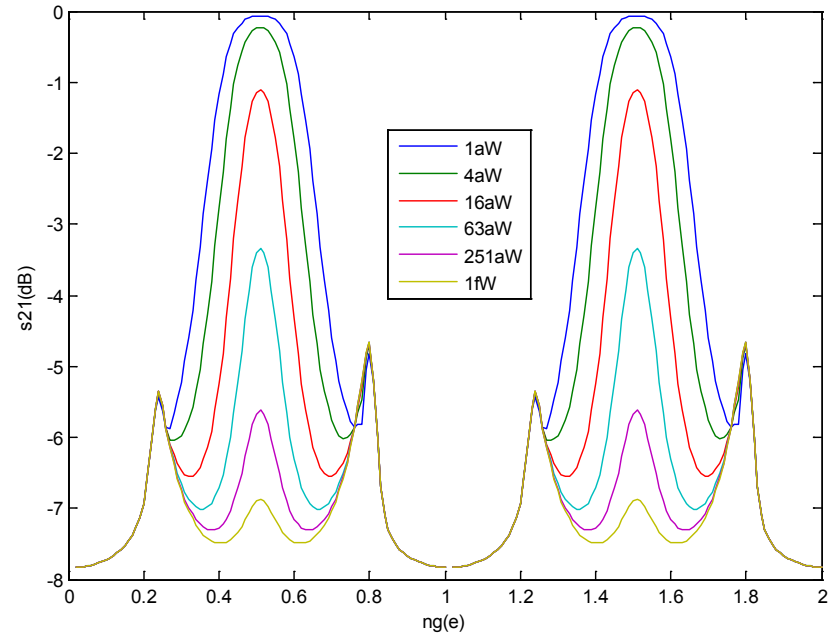




- λ/2 resonator capacitively coupled to a feedline
- SCB is the variable capacitor at the end of resonator
- Change in resonance frequency due to change in quantum capacitance should be large (1MHz)
- Single pixel resonator (green dots)
- Resonance frequency = 3.328118 GHz
- Qi = 220000; Qc= 360000; Qt=136000

Simulated response

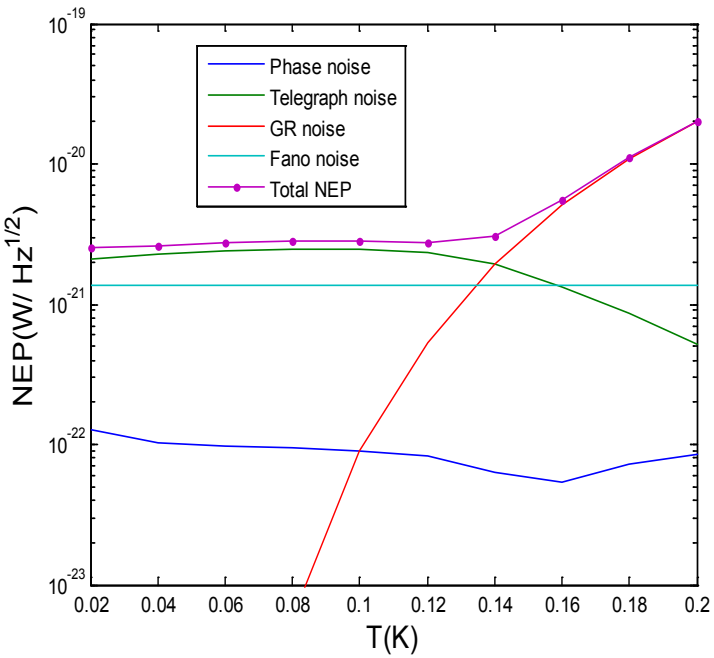


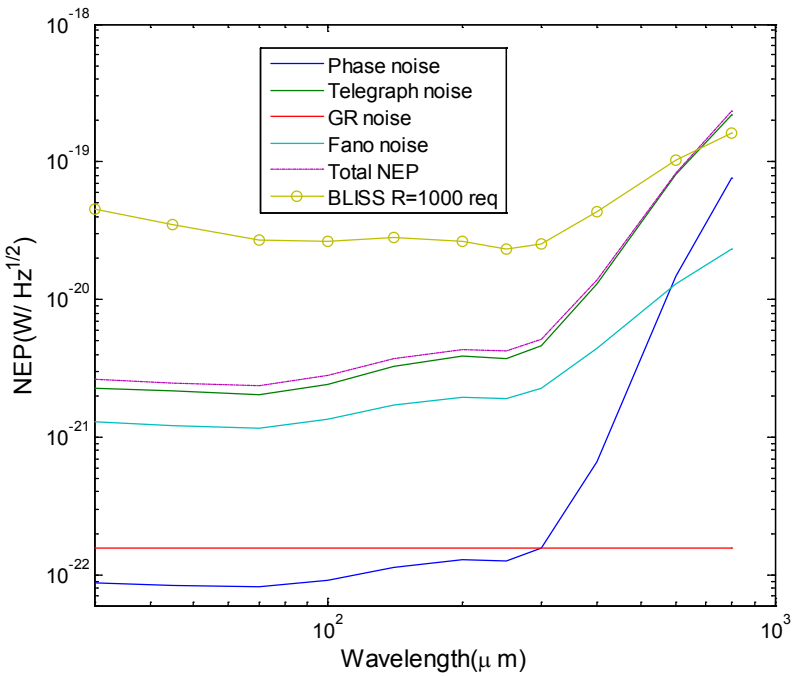


- SCB capacitance x gate voltage (in units of Cooper Pair charge) for different coupled optical signal power

- transmission through feedline x gate voltage (in units of Cooper Pair charge) for different coupled optical signal power

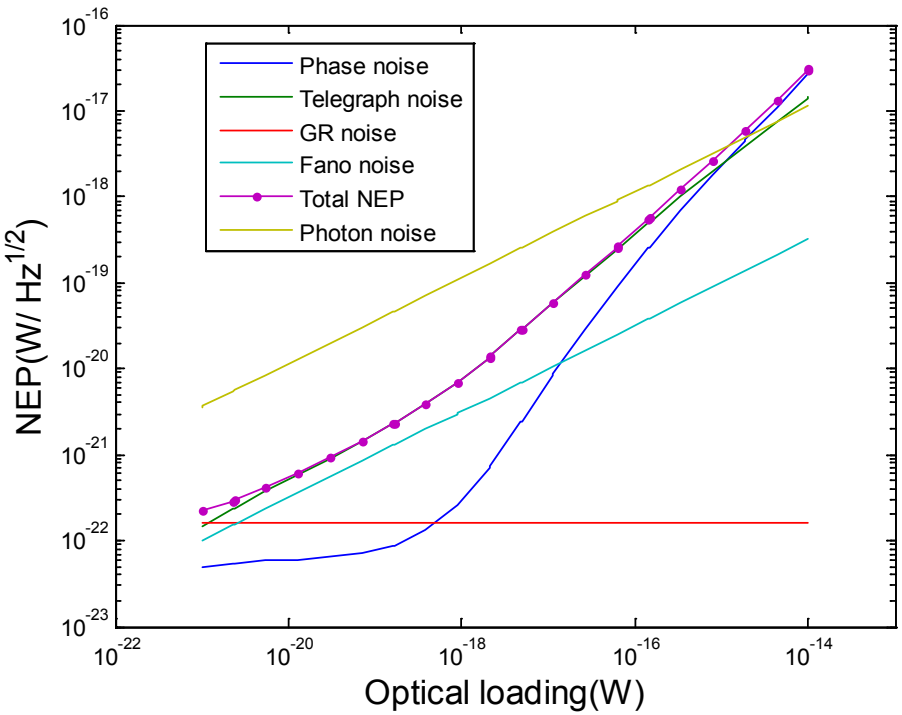
Theoretical Sensitivity





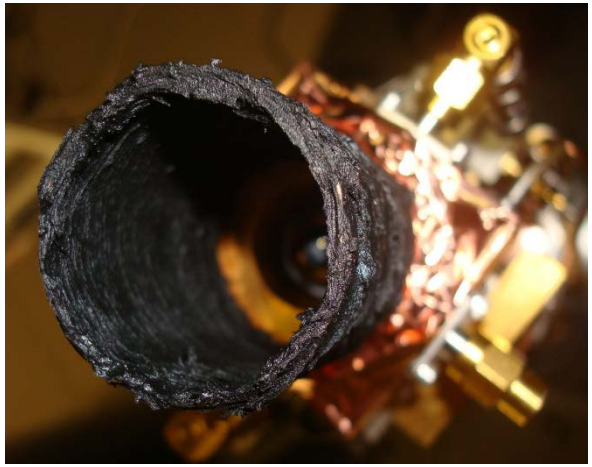
Left: NEPs from various noise sources calculated for devices optimized for λ =100μm, optical loading 10^{-19} W and R=1000 as a function of temperature. Right: NEPs of various noise sources as a function of wavelength as compared to the requirements for a spectrometer with R=1000 and the expected optical loading at L2 for a cold (4.2K) telecope . The operating temperature was chosen to be 0.1K at which the GR noise contribution is negligible.

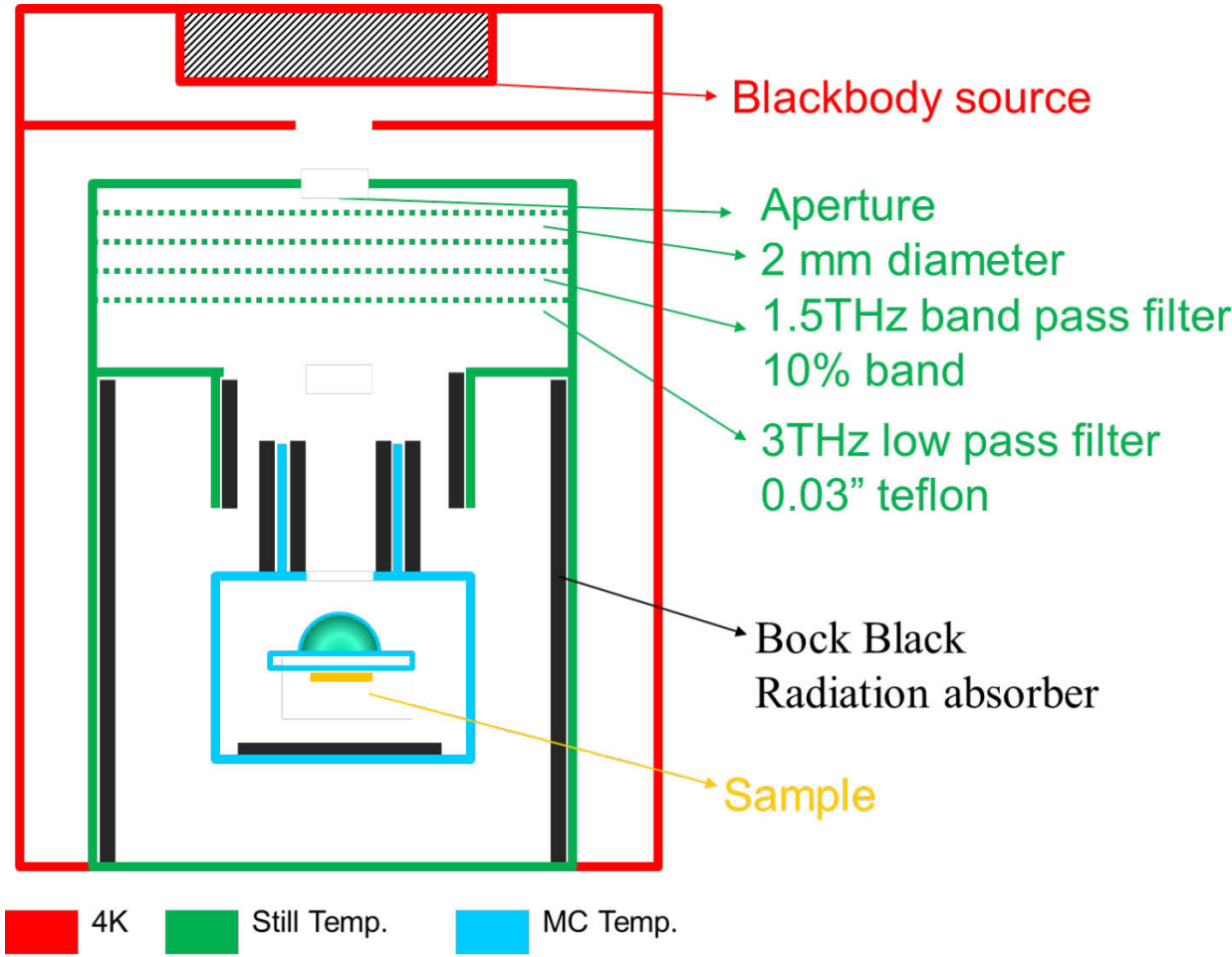
Theoretical Sensitivity vs. Signal Power



- *Detector is background limited over a wide range of operation*

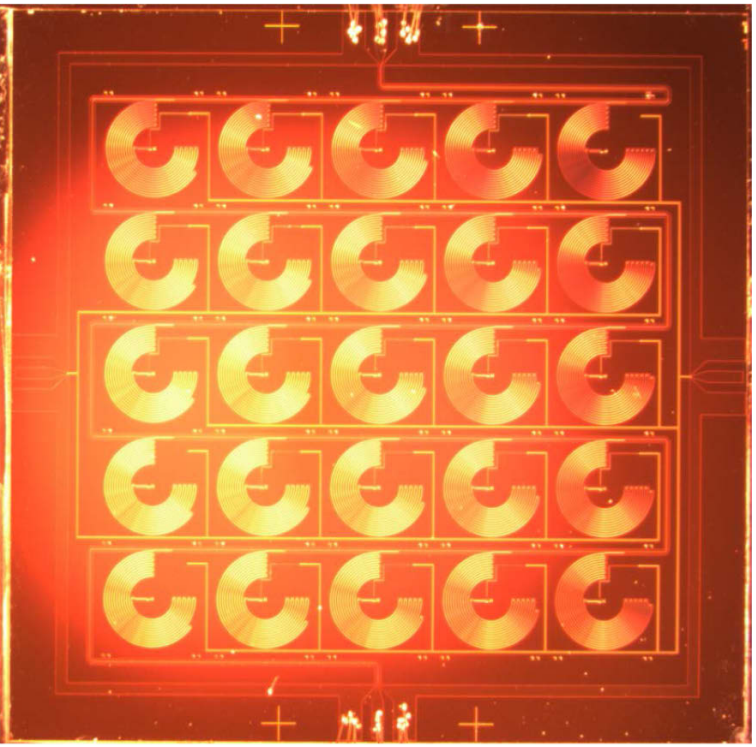
Experimental Setup

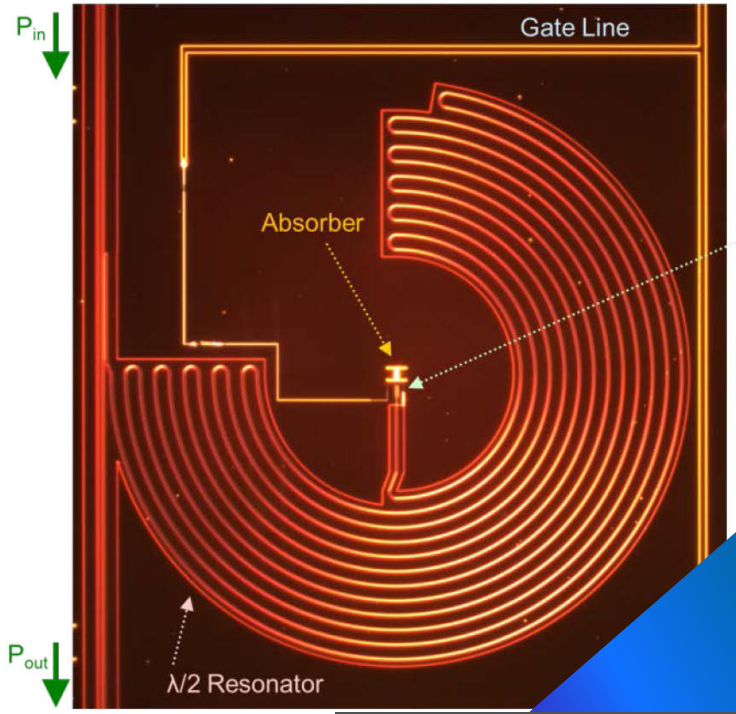


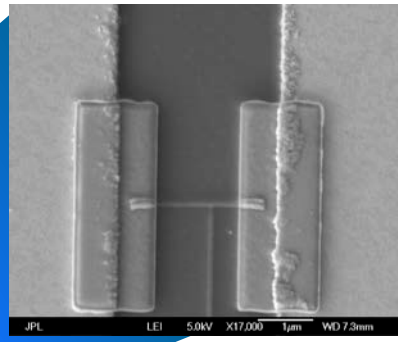


- Black body source and filters provide 1.5THz radiation from 4.2 – 40 K. Bock Black absorbs stray 4K radiation

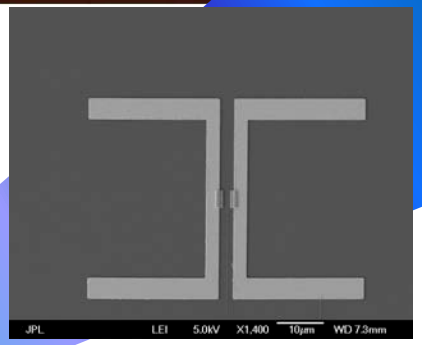
Quantum Capacitance Detector: 5x5 Array



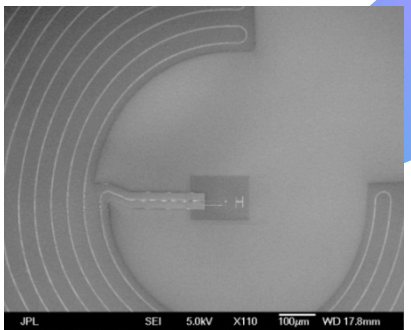




Nb plugs

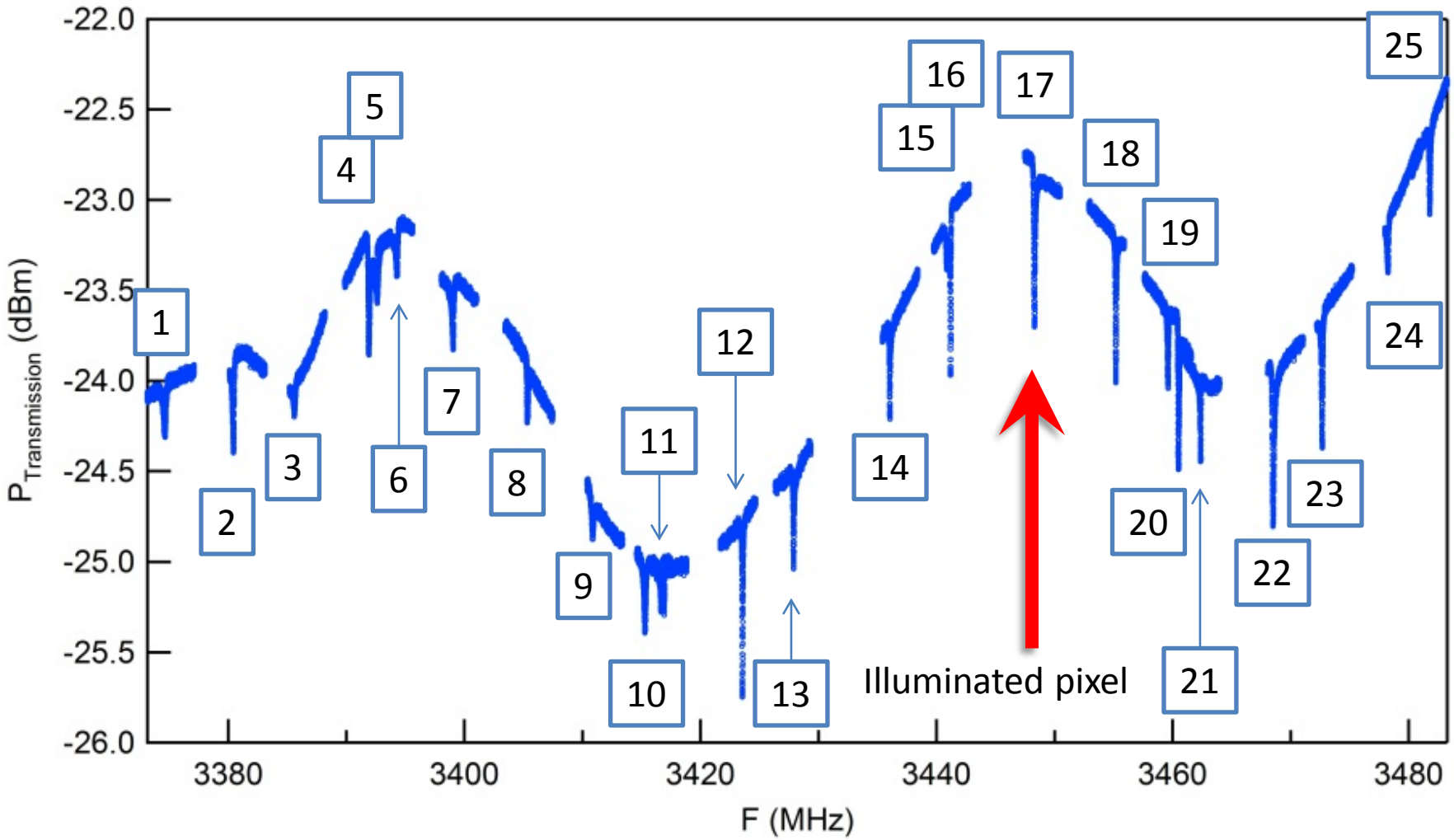


Au absorber



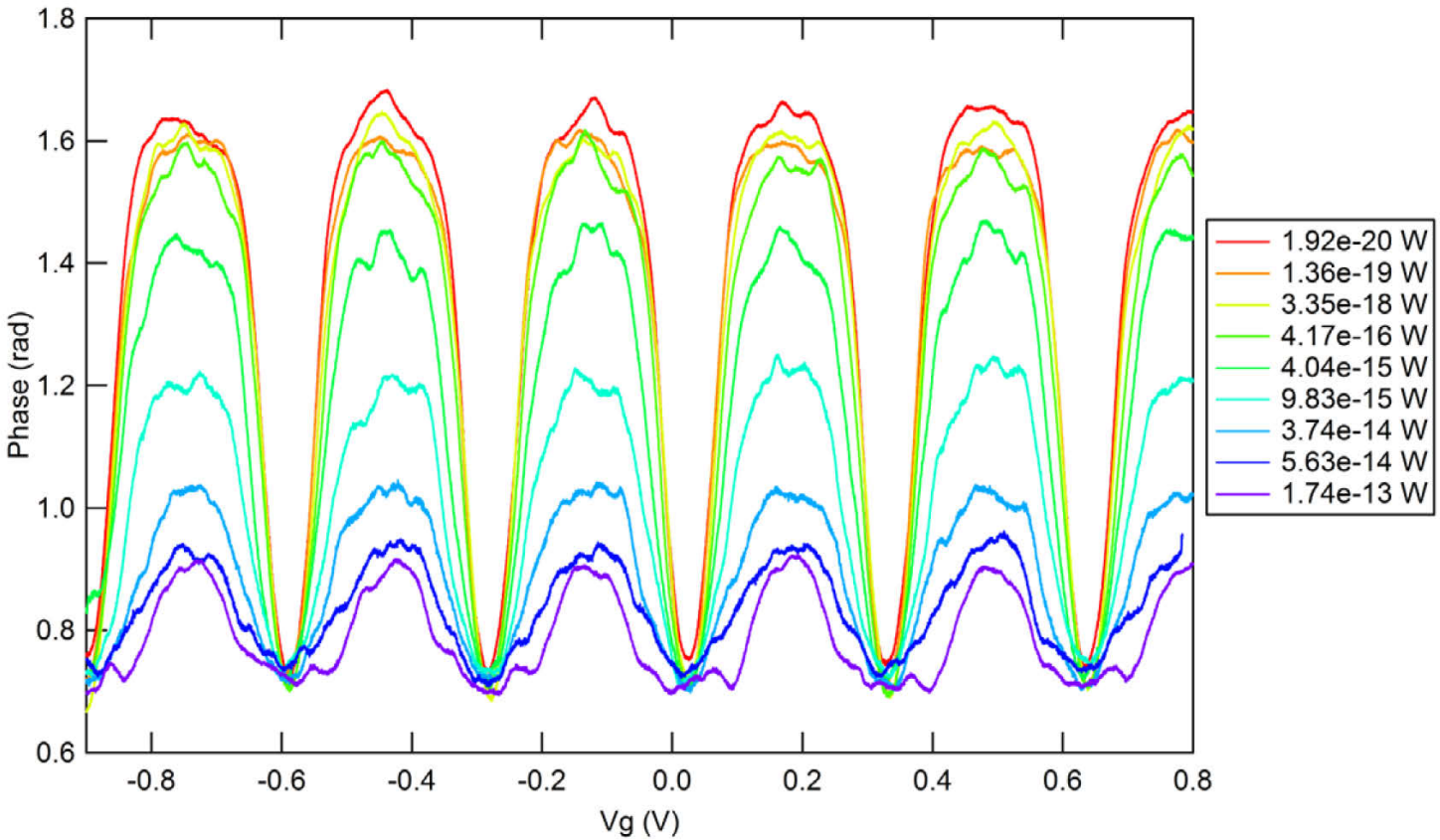
Only center device
Illuminated by lens.
Each device has a slightly
Different resonance frequency.

Resonances

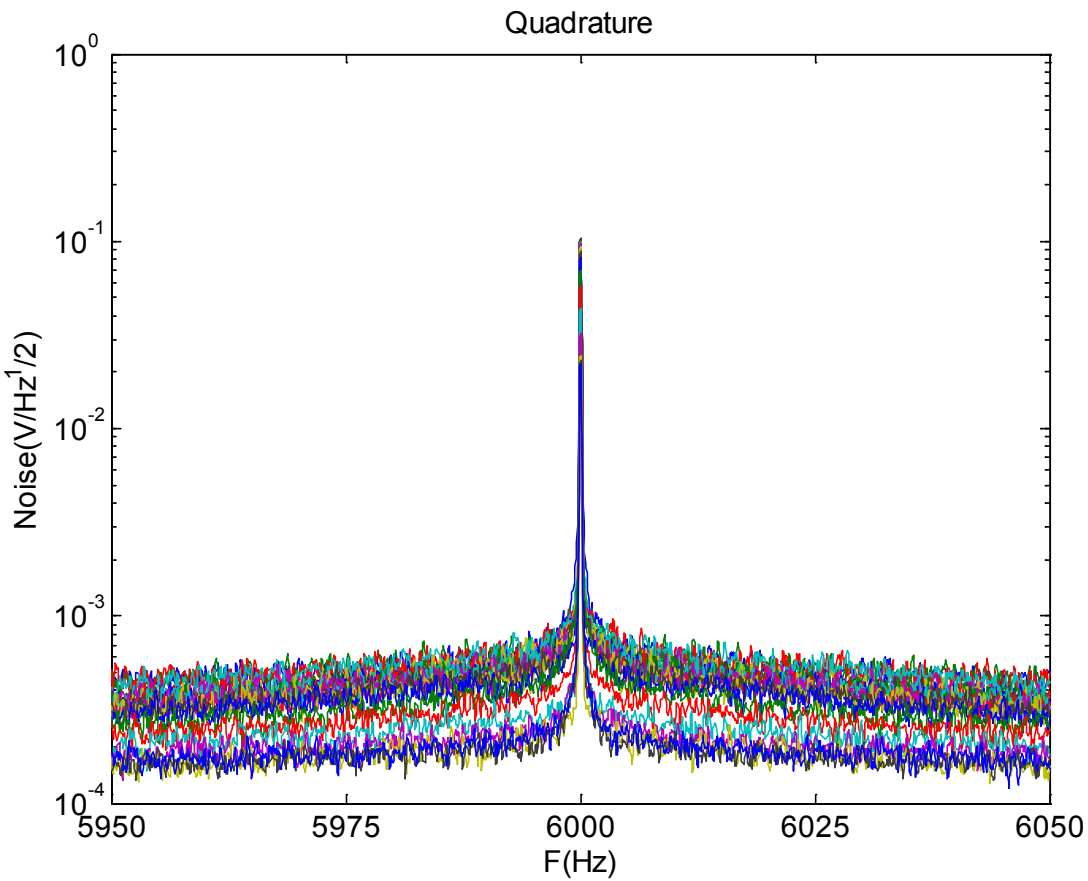


Plot of all 25 resonances, with various depths and non-uniform spacing
Likely coupling between resonators – working on bridges form gp to gp to cut down coupling

Phase shift x gate voltage as a function of black body source temperature

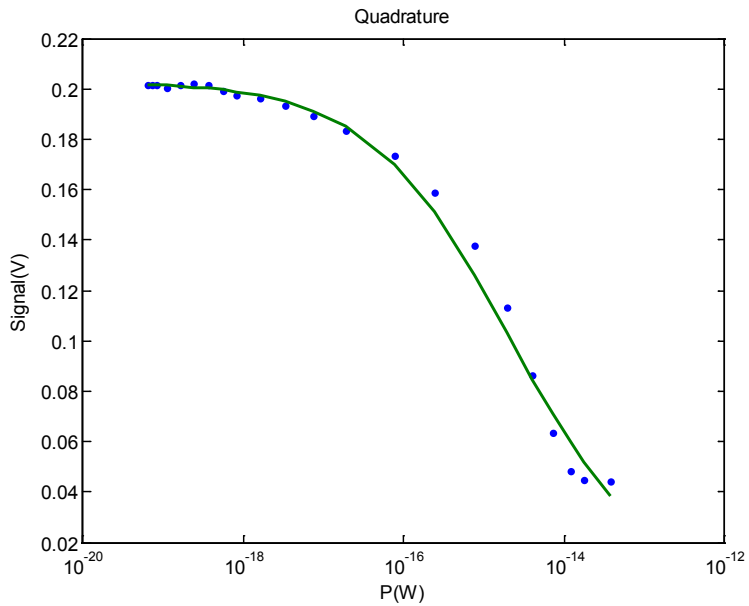


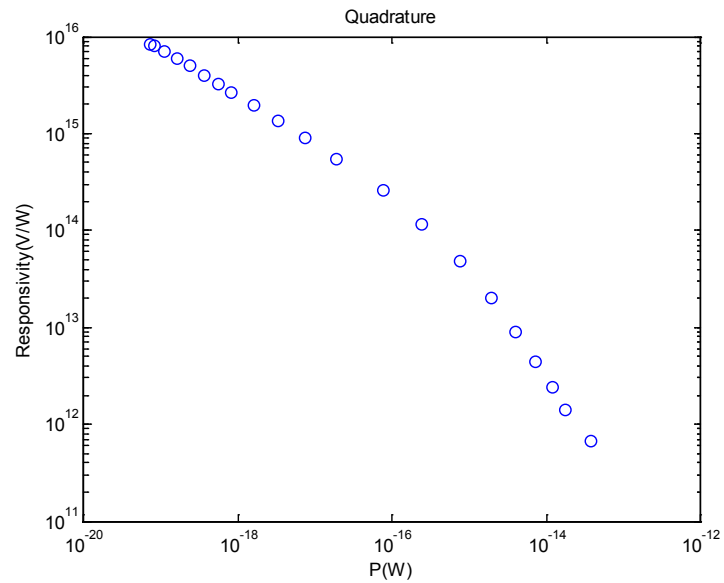
Spectrum analyzer response



Gate voltage swept at 1kHz, spanning 6 peaks
Peak at 6kHz is the signal

Response and responsivity

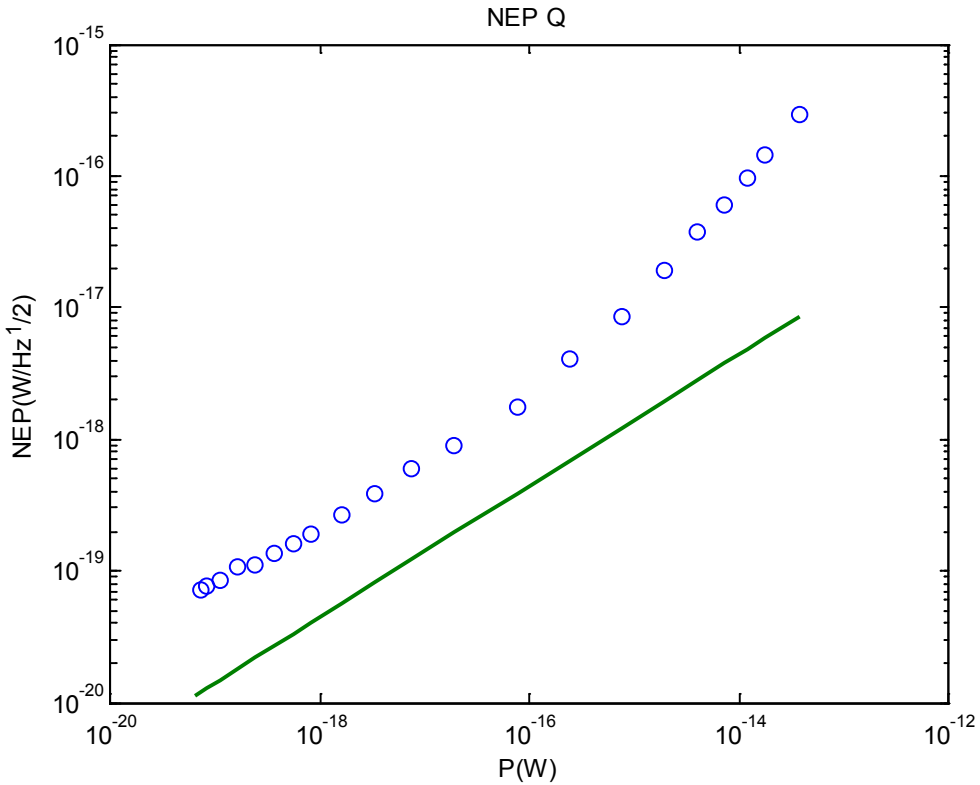




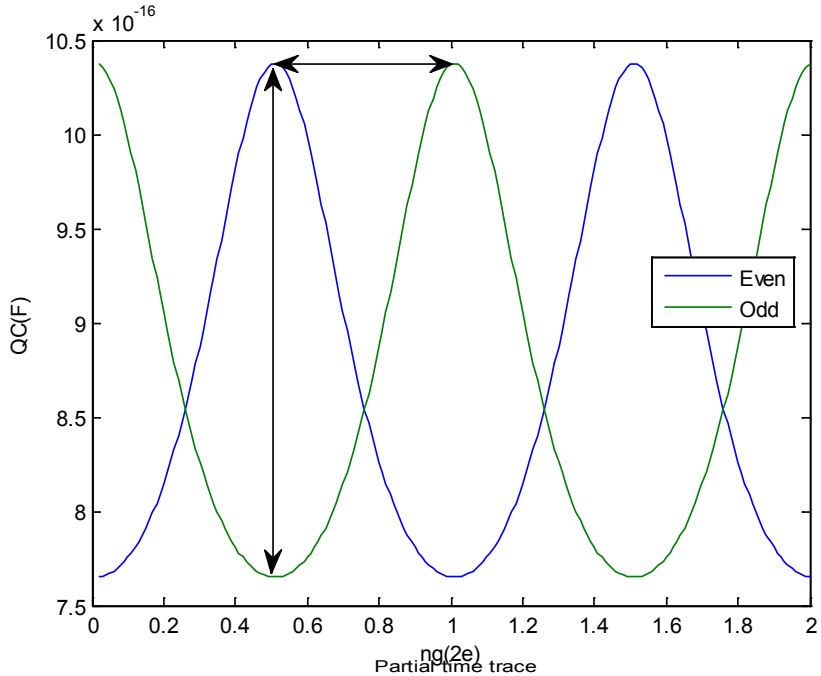
Amplitude of 6KHz peak as a function of optical signal power.
Fit comes from simulation of device based on telegraph noise measurements

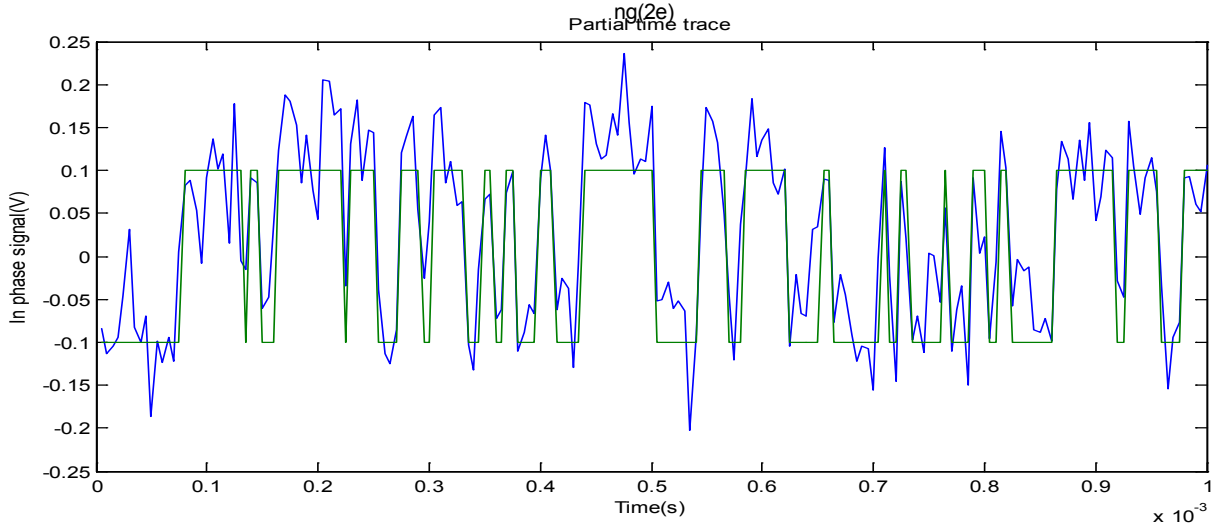
Responsivity dR/dP

Noise Equivalent Power

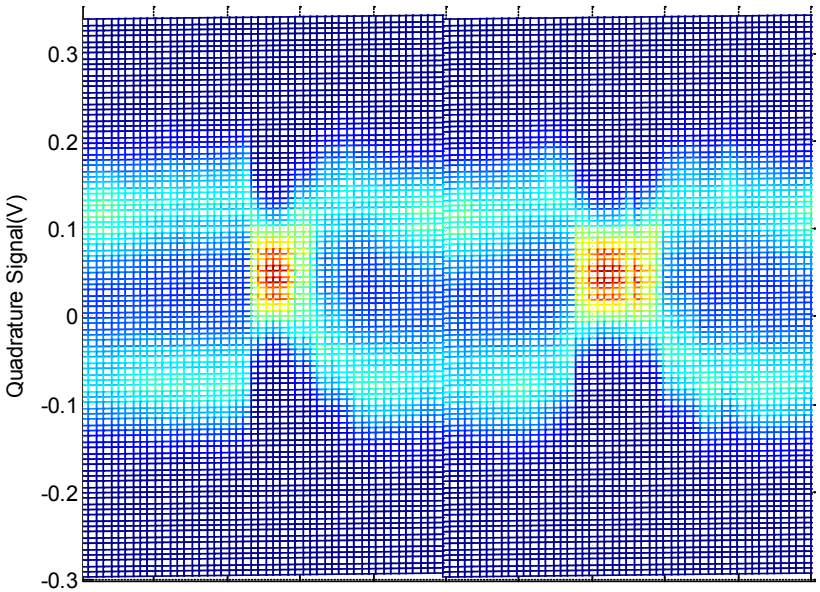


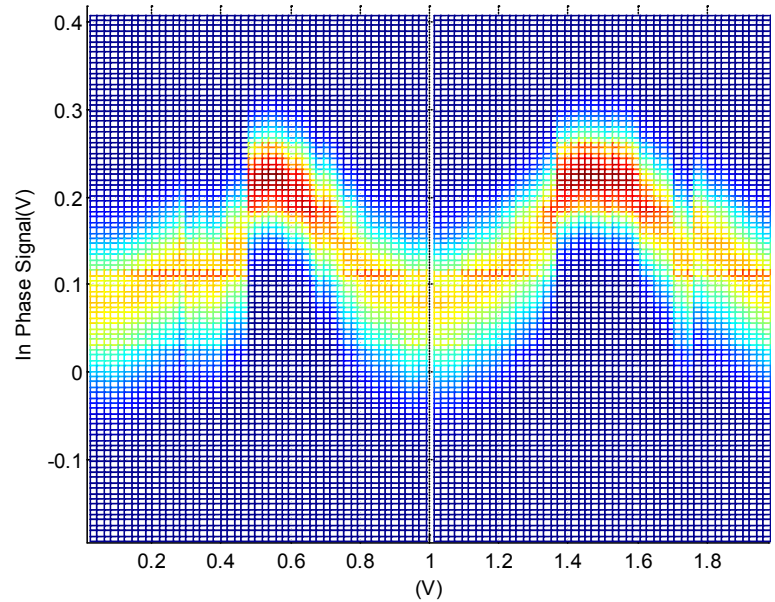
Real time measurement – telegraph noise

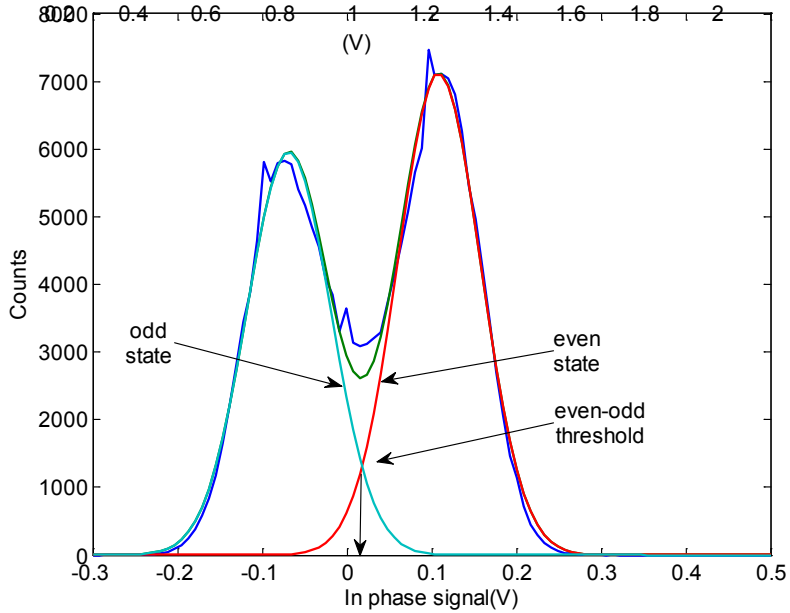




Telegraph noise histograms as a function of gate voltage

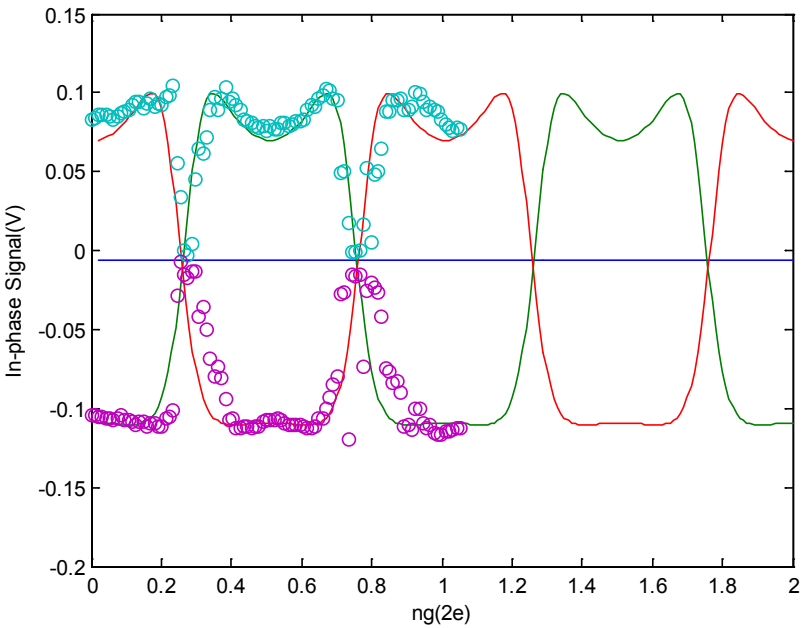


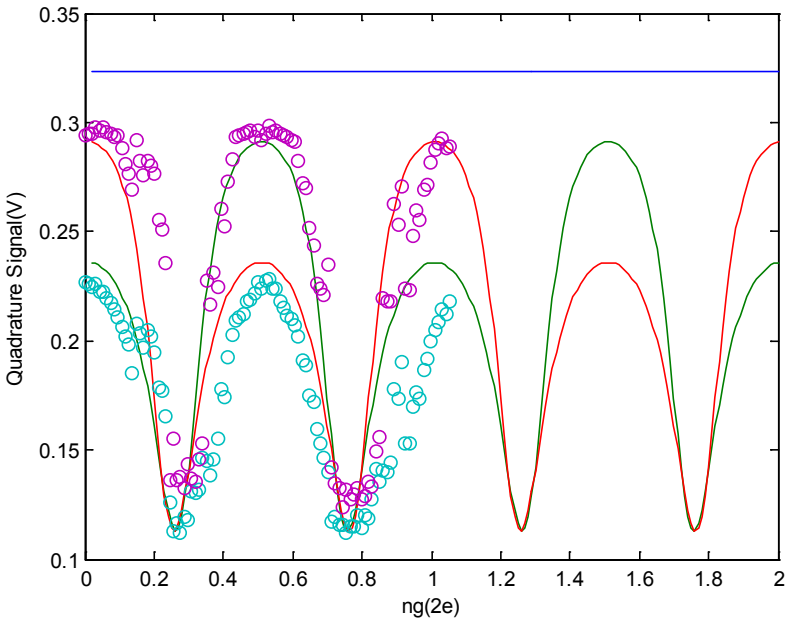




- Histogram peaks trace even and odd state traces
- Histograms fit by two gaussian

In phase and quadrature transmitted signal fits

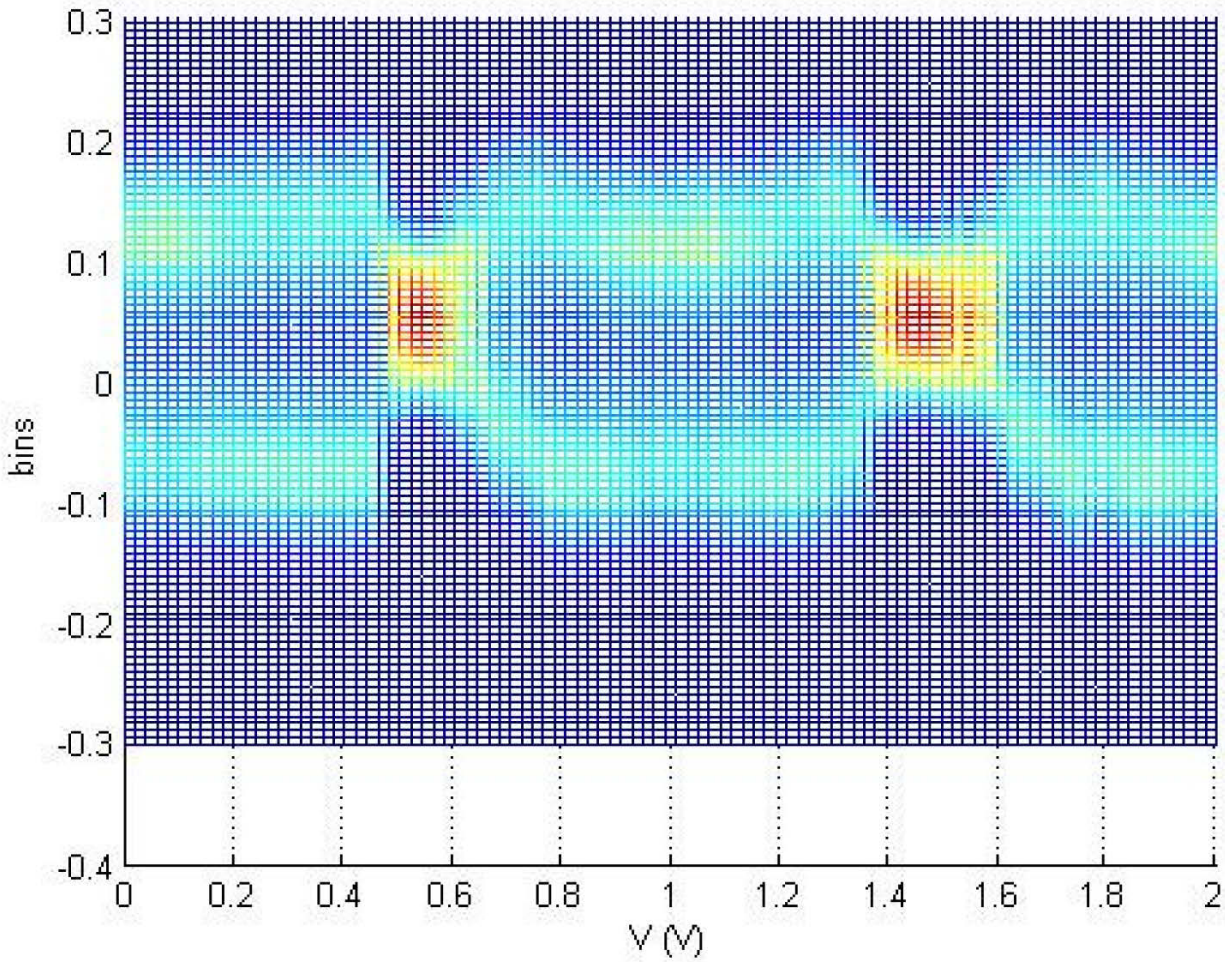




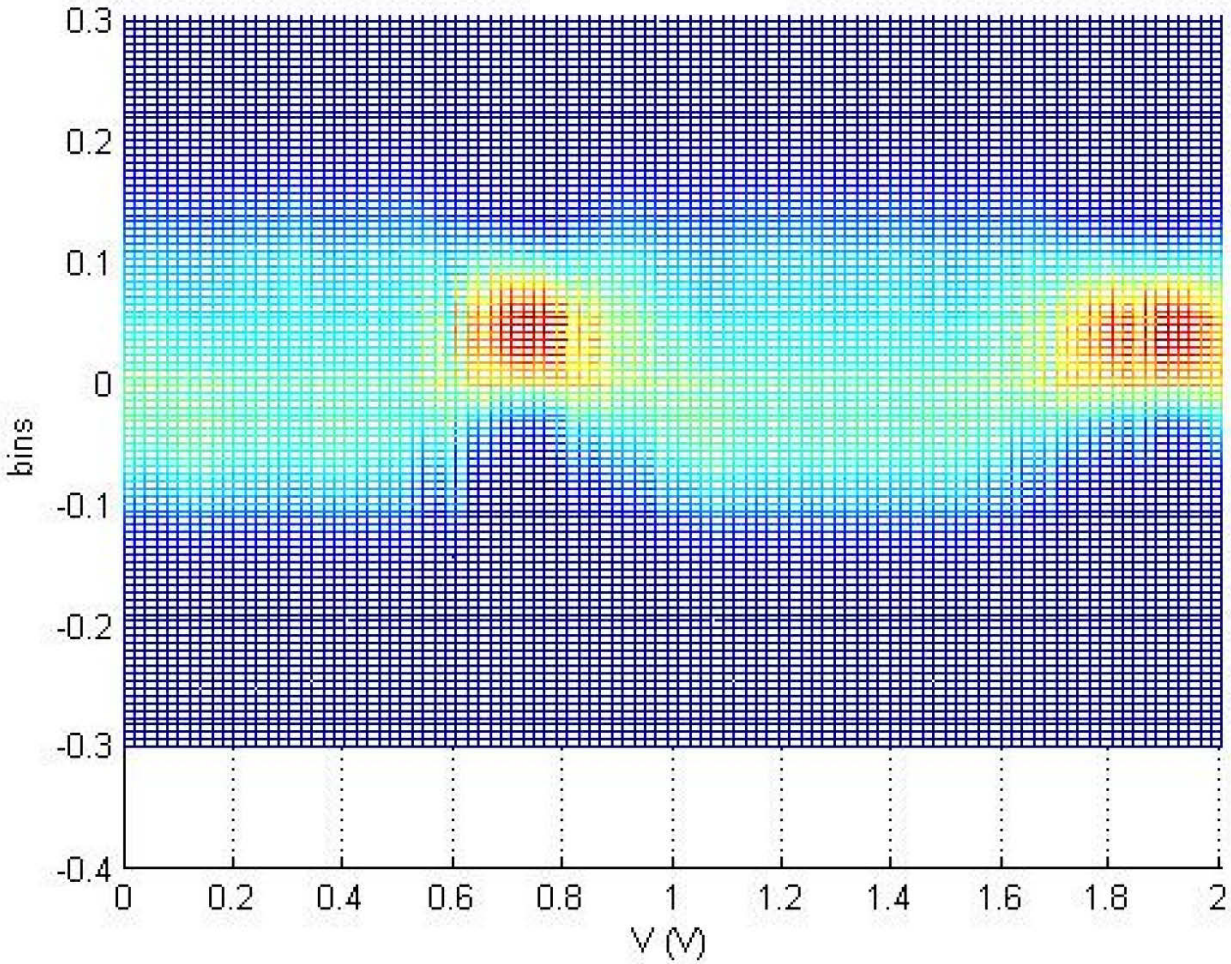
- Fits yield several parameters :
- Ec=5.51K, Ej=1.4K, Cg= 1.26fF, Cj=0.55fF
- From Ej and superconducting gap we extract Rn=7.5kOhm

Measurements as a function of black body temperature and sample temperature

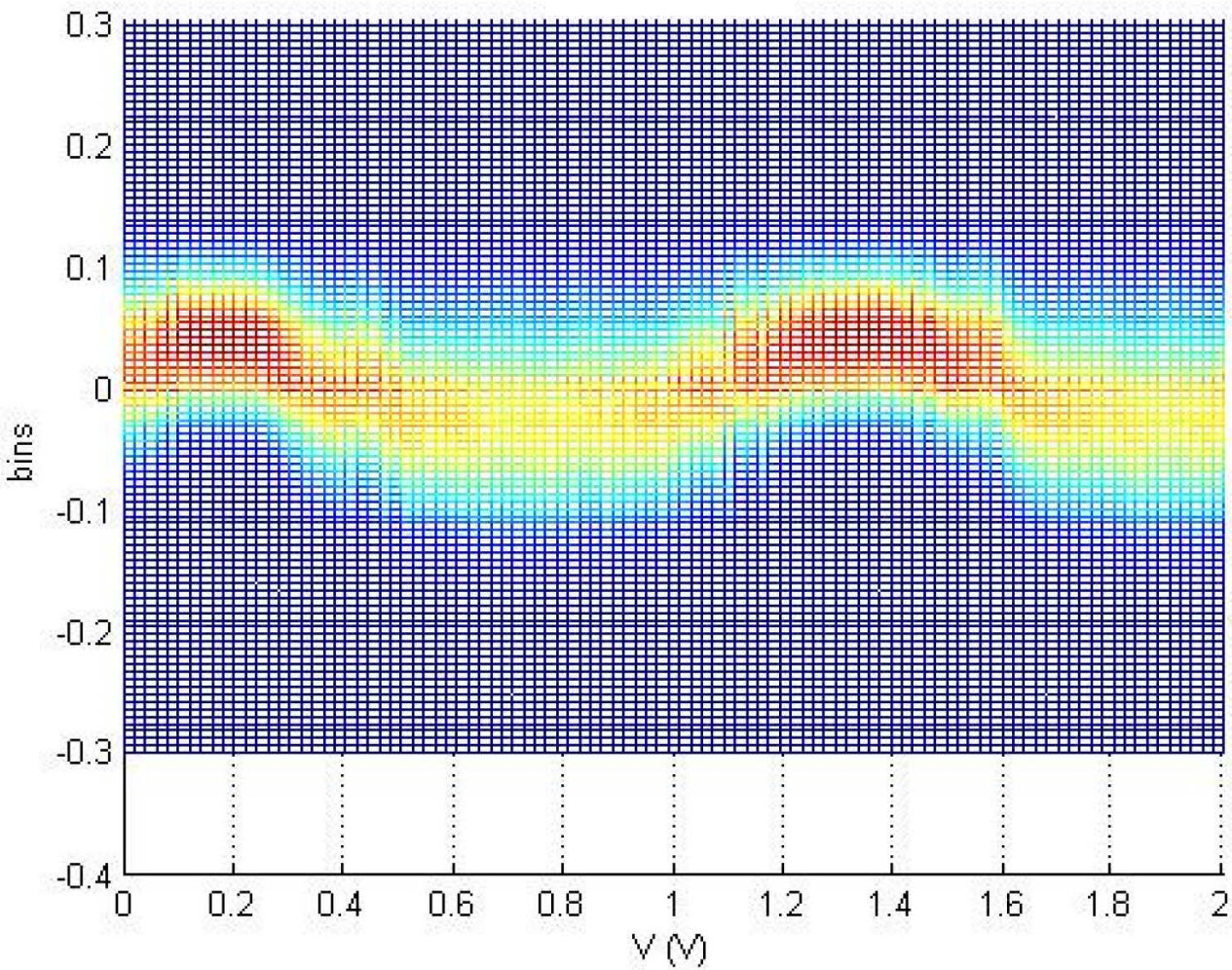
$2x10^{-20}W$



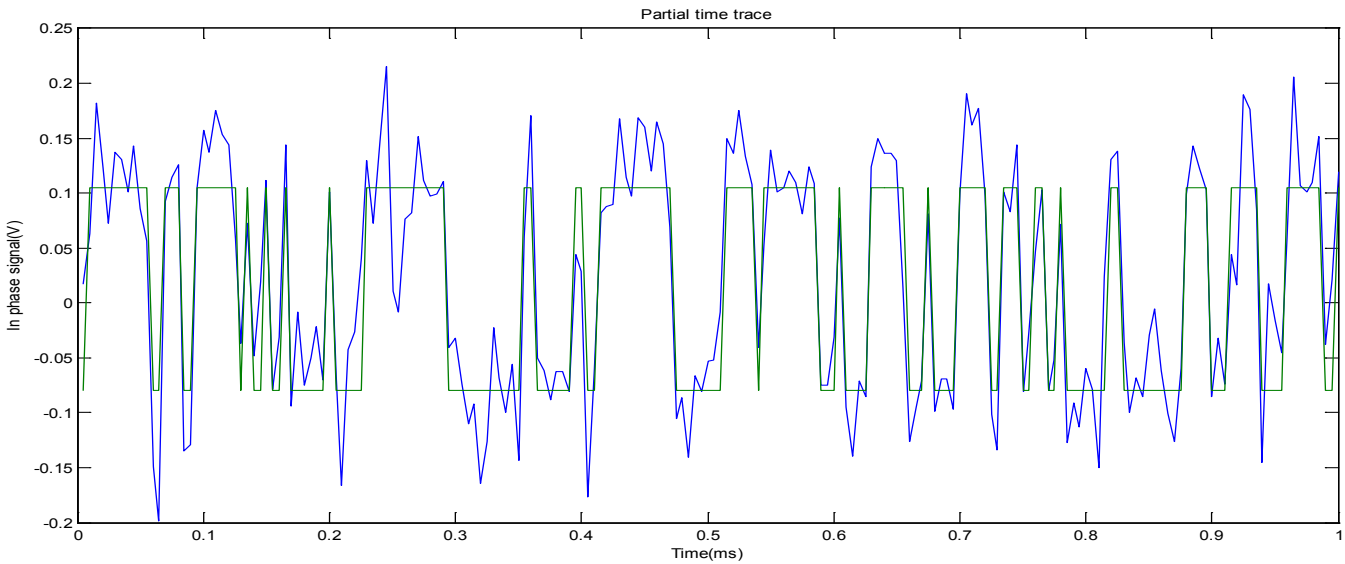
9.7x10^{-15}W

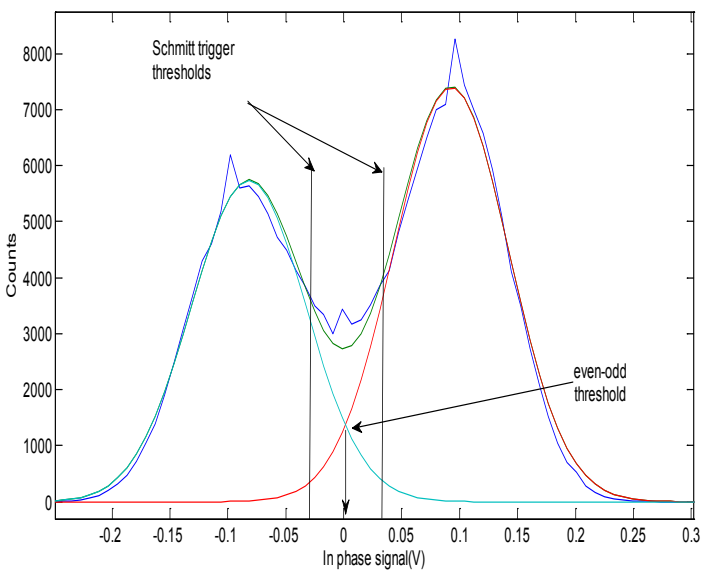


5.6×10^{-14}W



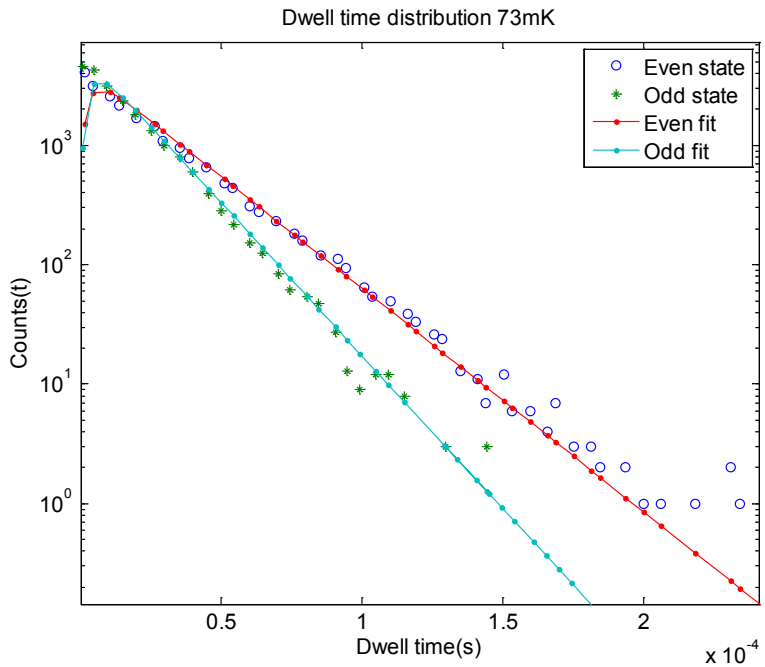
Real time measurement – telegraph noise

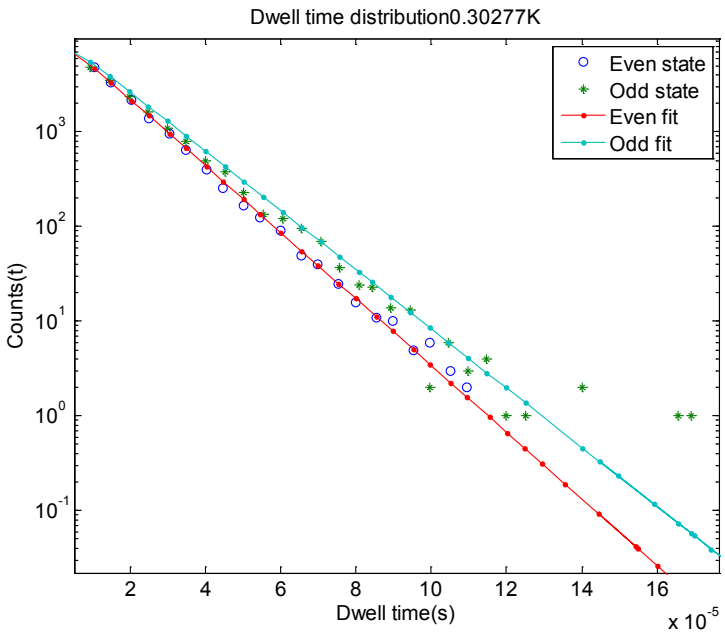




- Apply Schmitt trigger algorithm
- Measure dwell time distribution in even and odd state

Dwell time distribution – temperature dependence

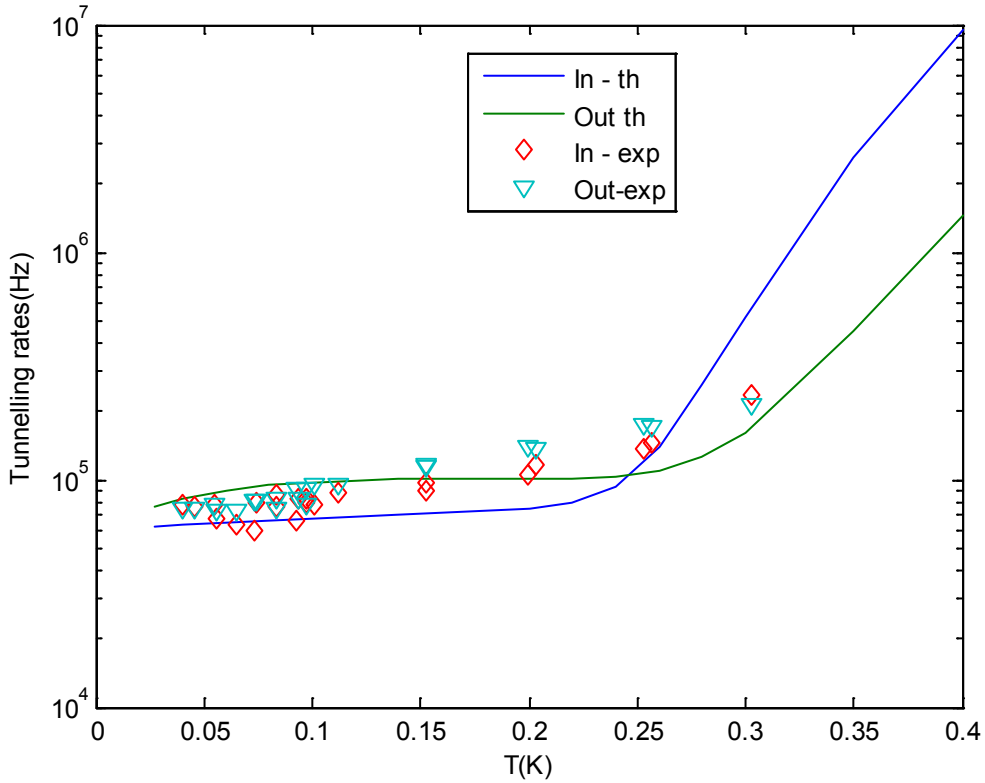




- Tunneling rates comparable to measurement time $1/\Gamma_{DET}$
- Apply procedure by Naaman and Aumentado -PRL **96**, 100201 (2006)
- Fit curves to

$$h \propto e^{-\frac{1}{2}\lambda t} \sinh\left(\frac{\theta t}{2}\right), \qquad \theta = \sqrt{\lambda^2 - 4\Gamma_{IN}\Gamma_{DET}} \qquad \lambda = \Gamma_{DET} + \Gamma_{IN} + \Gamma_{OUT},$$

Temperature dependence of tunneling rates



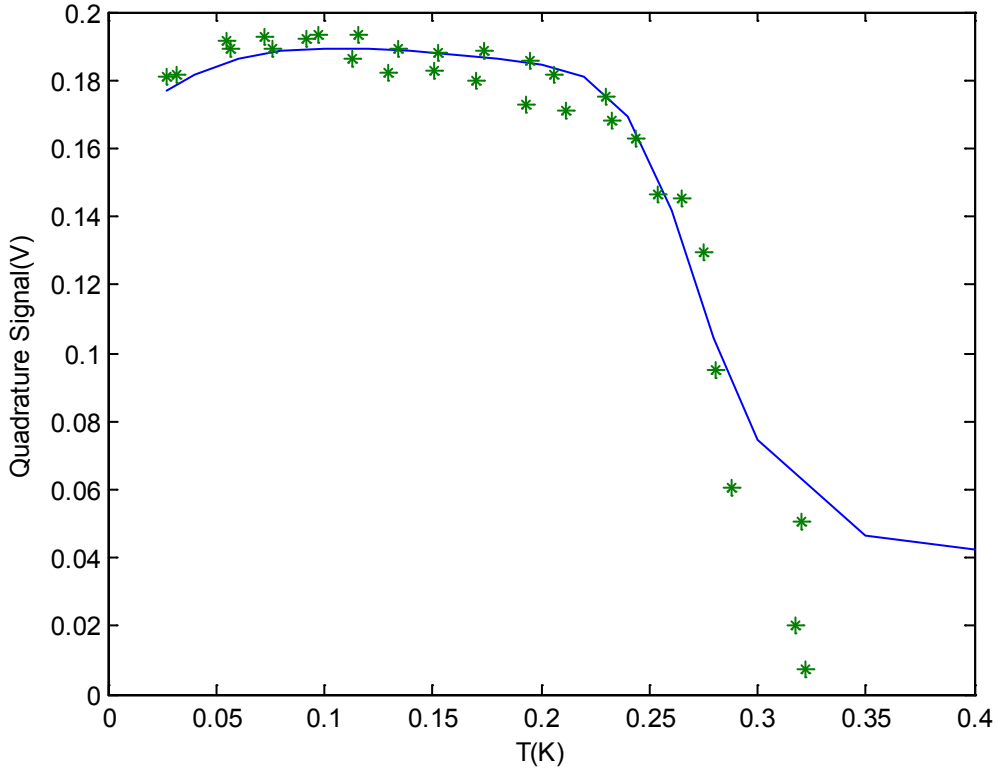
Shaw et al. PRB **79** , 144511 (2009)

1890 μm^3/qp

$$\Gamma_{IN} = n_{qp} \frac{G_N}{e^2} \frac{e^{\Delta_L/kT}}{V_L N_L} \int_{\max(\Delta_I - \delta E, \Delta_L)}^{\infty} dE \frac{E(E+\delta E) - \Delta_L \Delta_I}{\sqrt{((E+\delta E)^2 - \Delta_I^2)(E^2 - \Delta_L^2)}} e^{-E/kT}$$

- low temperature flat part -> residual number of quasiparticles = 35 qp/μm^3
- comparable to the results of de Visser et al. PRL 106 , 167004 (2011) - qp/μm^3

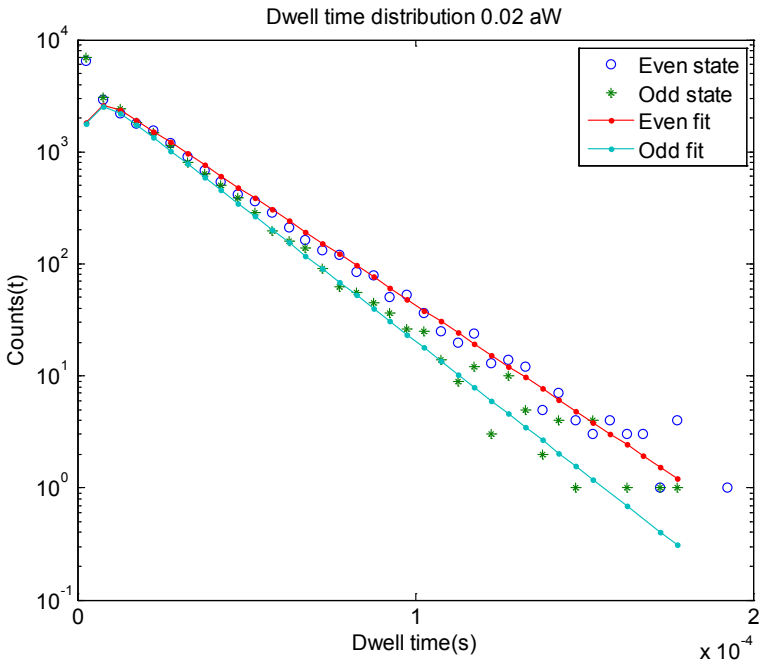
Response x temperature - fit

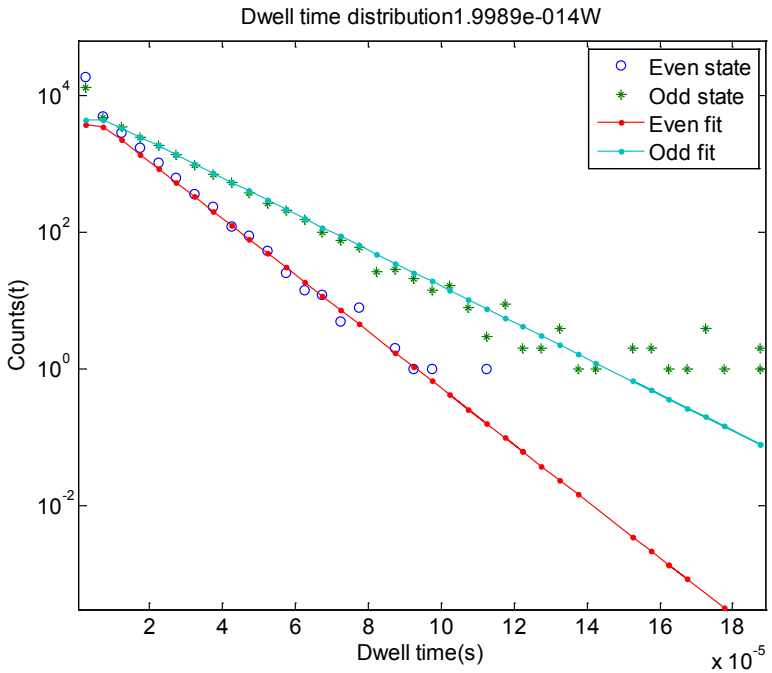


$$R = \frac{\Gamma_{OUT}}{\Gamma_{OUT} + \Gamma_{IN}} A_{EVEN}$$

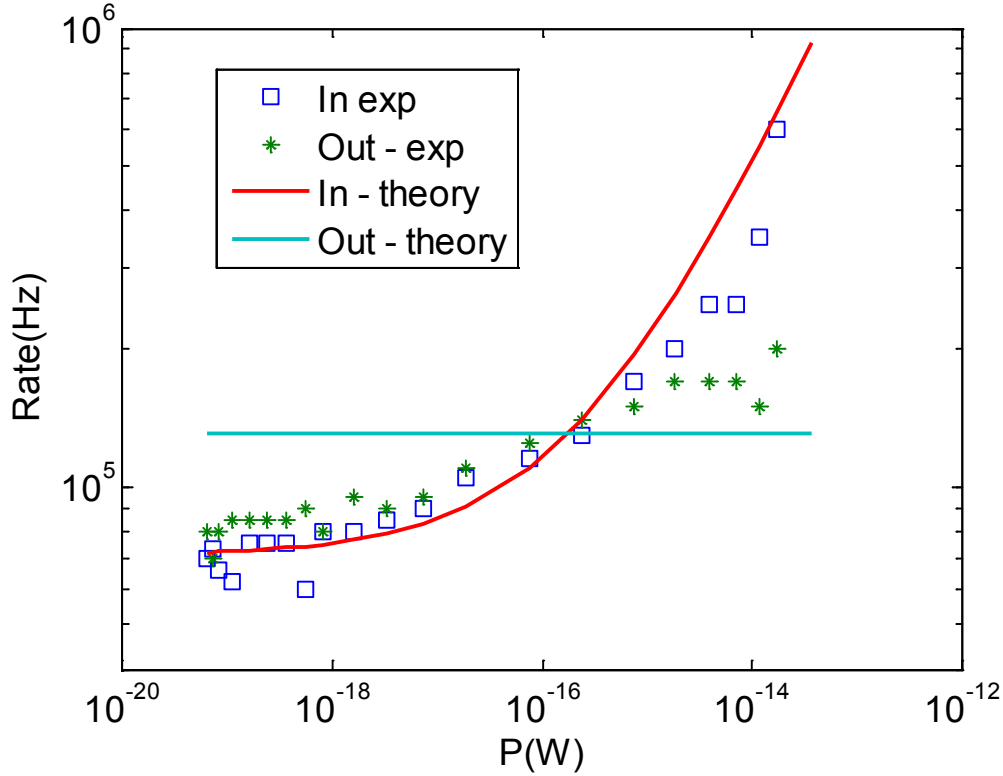
- A_{EVEN} is the amplitude of the completely unpoisoned quantum capacitance response
- Assuming the amplitude of the completely poisoned state to be nearly zero

Dwell time distribution – optical power dependence

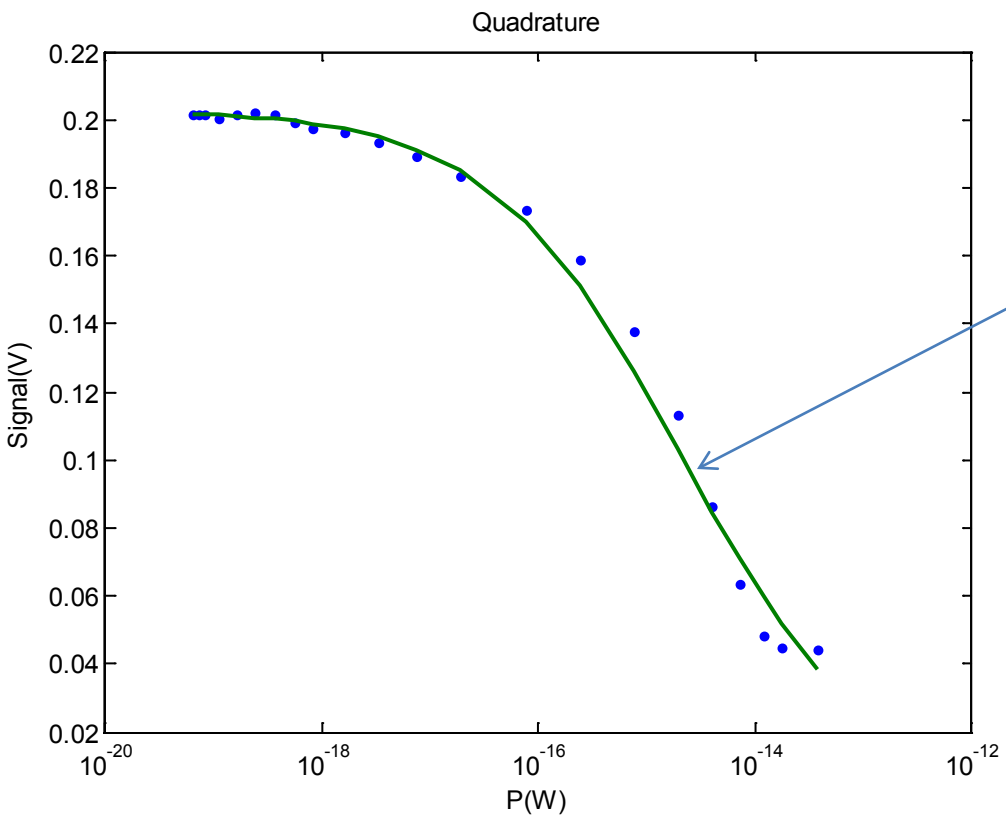




Optical power dependence of tunneling rates



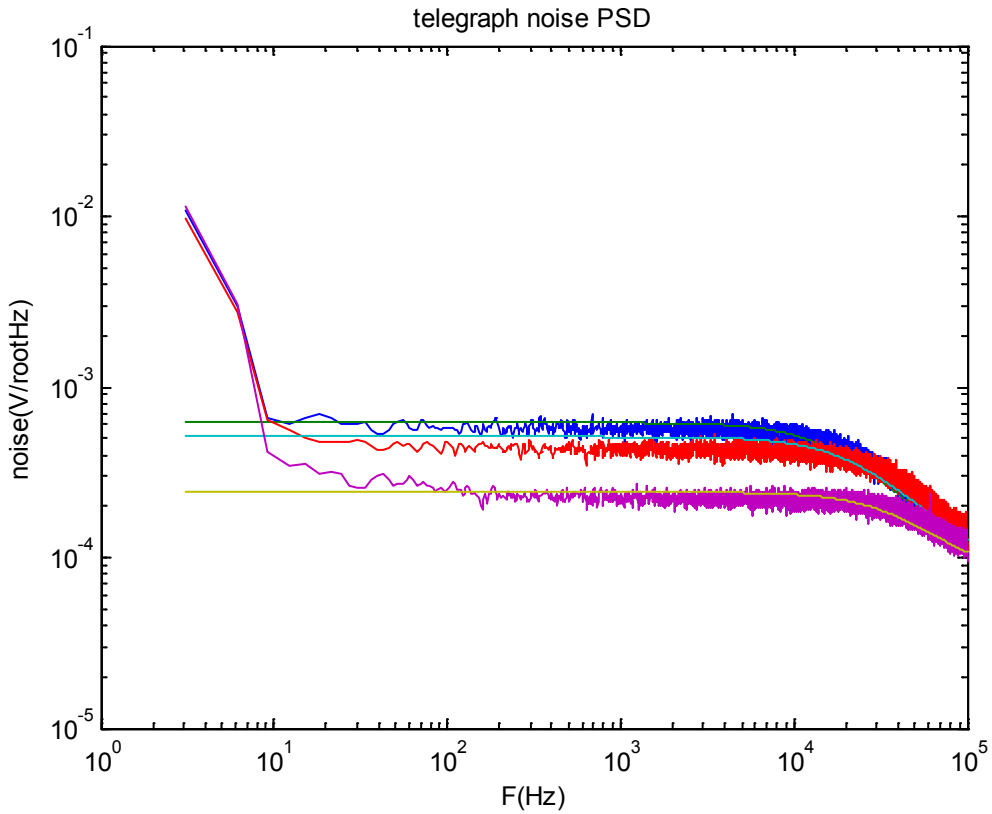
Response fit using tunneling rates



$$R = \frac{\Gamma_{OUT}}{\Gamma_{OUT} + \Gamma_{IN}} A_{EVEN}$$

- Fit is used in NEP calculation

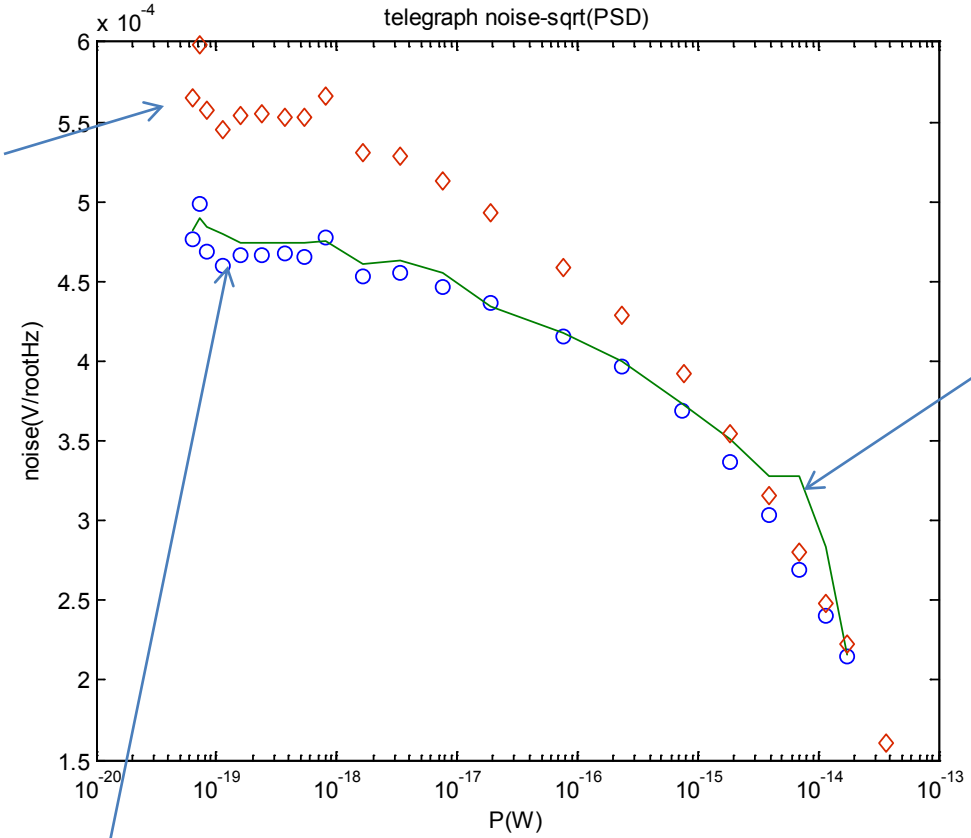
Telegraph noise power spectrum density



- PSD from time series noise comparable to measured noise
- As predicted is the major noise source (> phase noise due to offset charges, > amplifier noise)

Telegraph noise power spectrum density

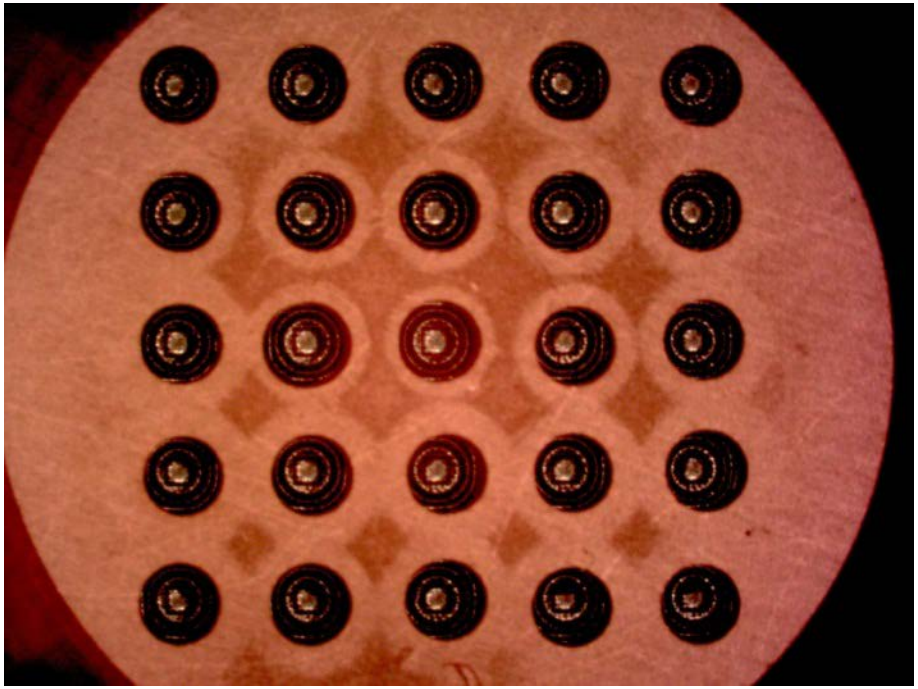
From spectrum analyzer



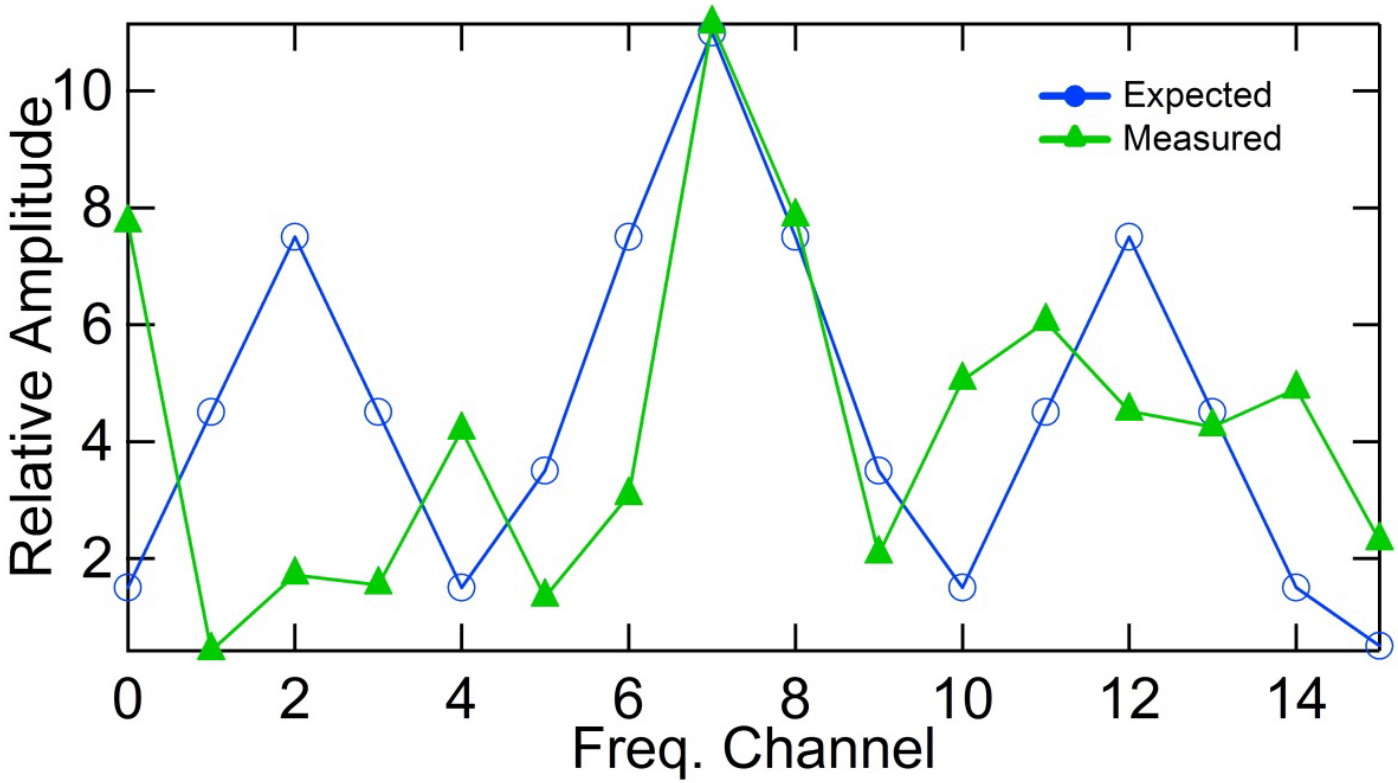
$$\sqrt{S_V(f)} = 2\pi\Delta V^2 \frac{\Gamma_{IN}\Gamma_{OUT}/\Gamma_\Sigma}{\Gamma_\Sigma^2 + (2\pi f)^2}$$

- Telegraph noise agrees with theoretical prediction (a factor of pi too high) using rates obtained from fits
- As predicted is the major noise source (> phase noise due to offset charges, > amplifier noise)

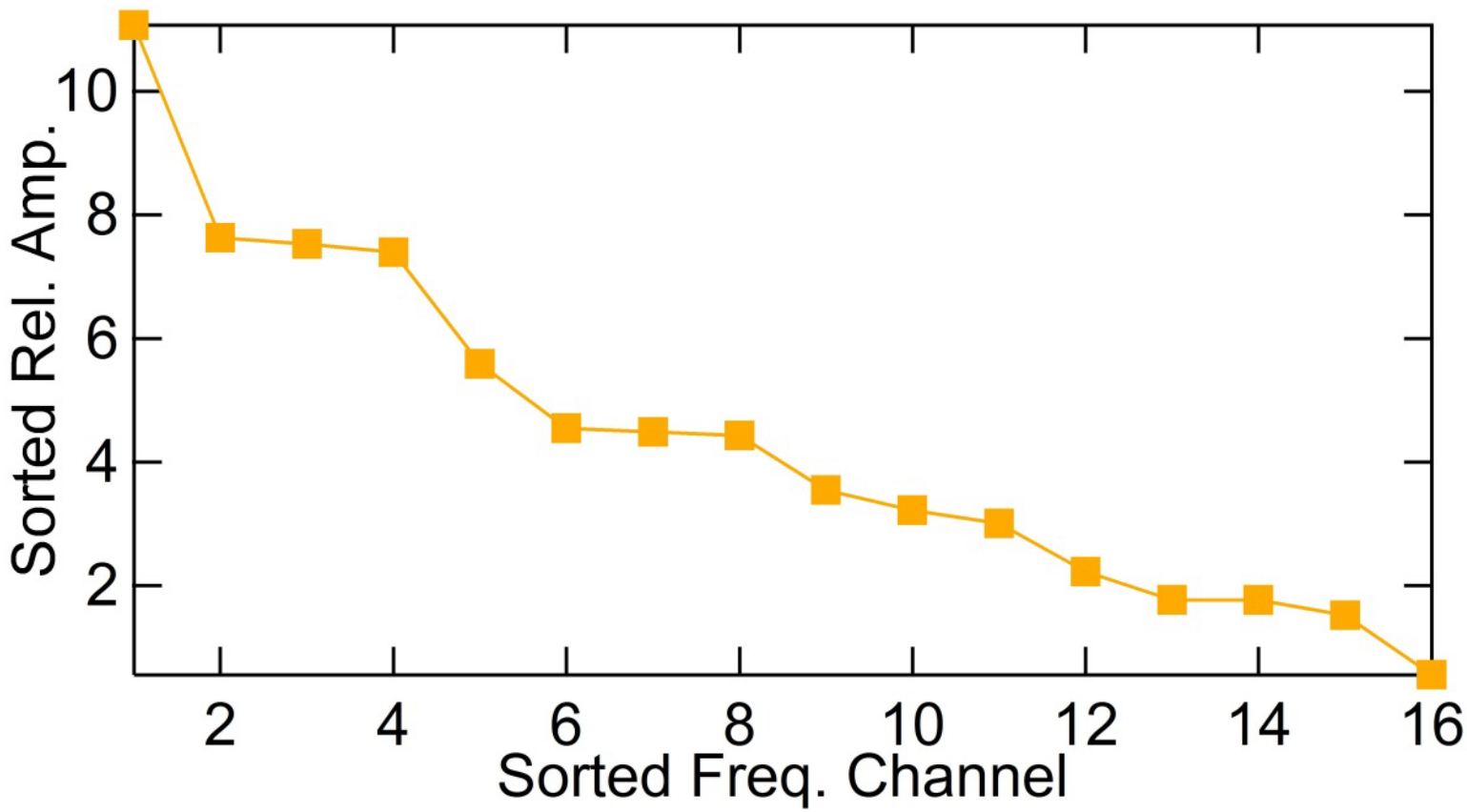
Fresnel lens array



Fresnel lens array



Fresnel lens array



Conclusion

- Achieved $7 \times 10^{-20} W/Hz^{1/2}$ at $9 \times 10^{-20} W$ with 200µm wavelength
- Telegraph noise measurements provide additional information
- Improvements
  - Improve resonator response
    - redesigned resonators better, but not ideal (need bridges?)
  - Lower number of residual quasiparticles
    - increase island gap with respect to reservoir
    - better shielding/ filtering
  - Improve antenna and quasiparticle trapping
- Fresnel lens development progressing well