Quantum capacitance detector – progress report FY12

P.M. Echternach
K.J. Stone
K. Megerian
J. Bueno*, N. Llombart**
P. K. Day, C.M. Bradford
D. Wilson

Jet Propulsion Laboratory, California Institute of Technology

Electron Beam Lithography by
Richard E.Muller

* present address: Space Research Organization of the Netherlands, Utretch, The Netherlands
** present address: Delft University of Technology, Delft, Netherlands

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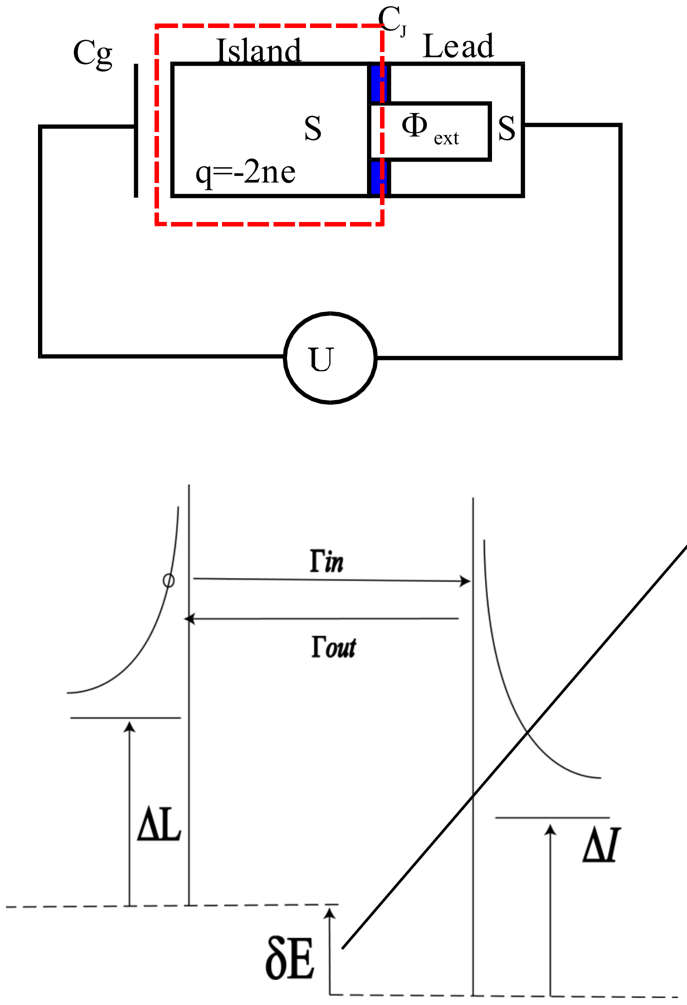
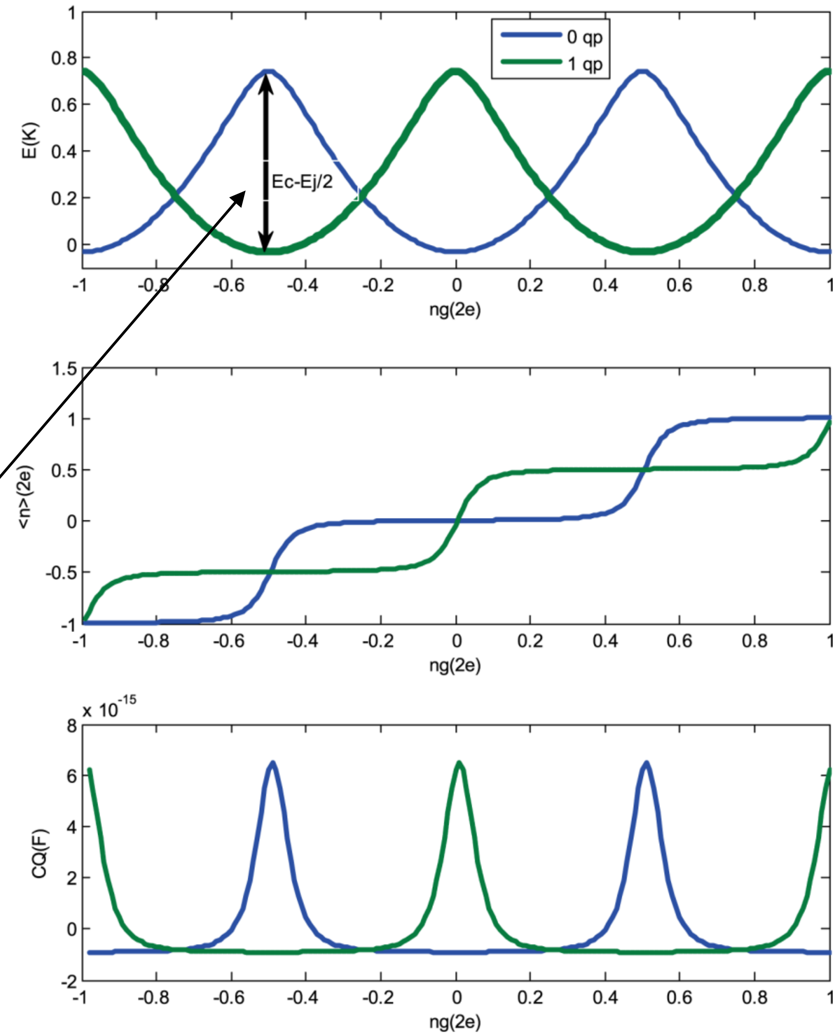
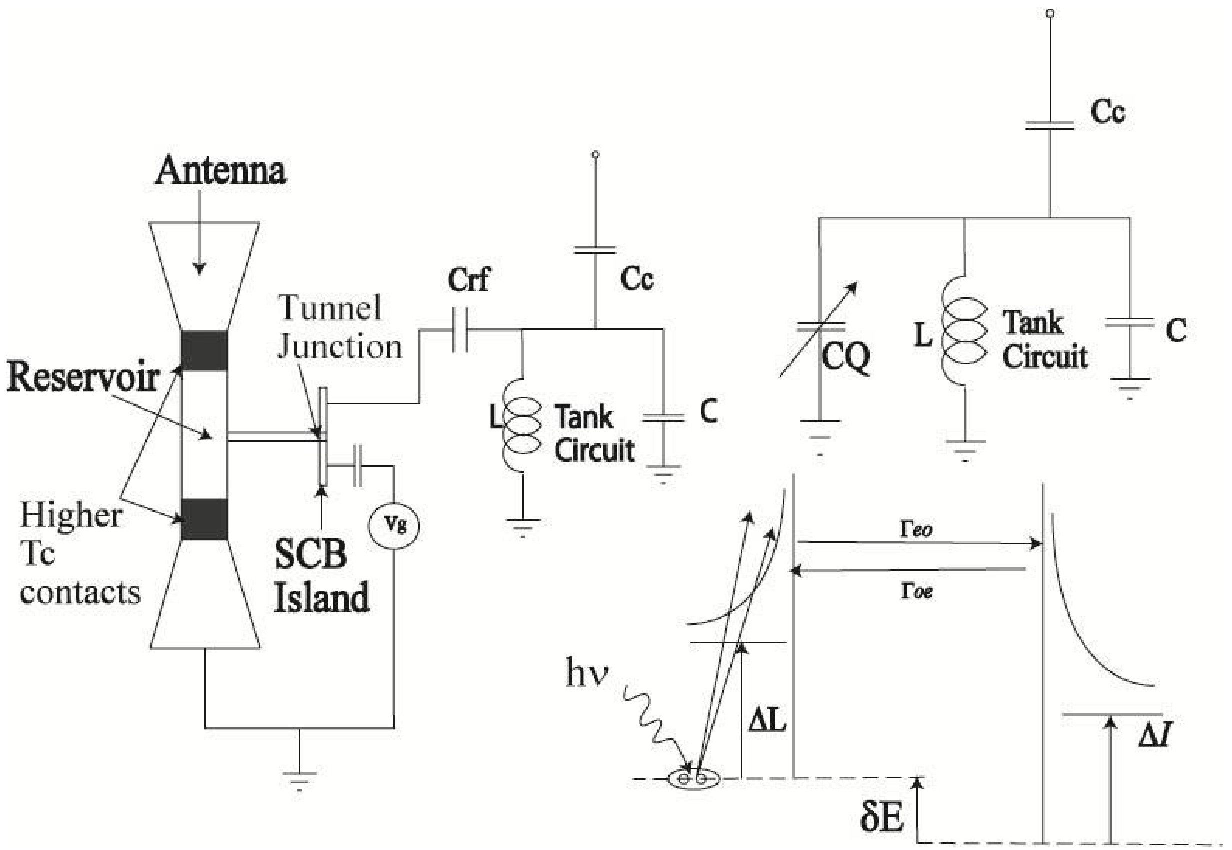
Single Cooper-pair Box (SCB)



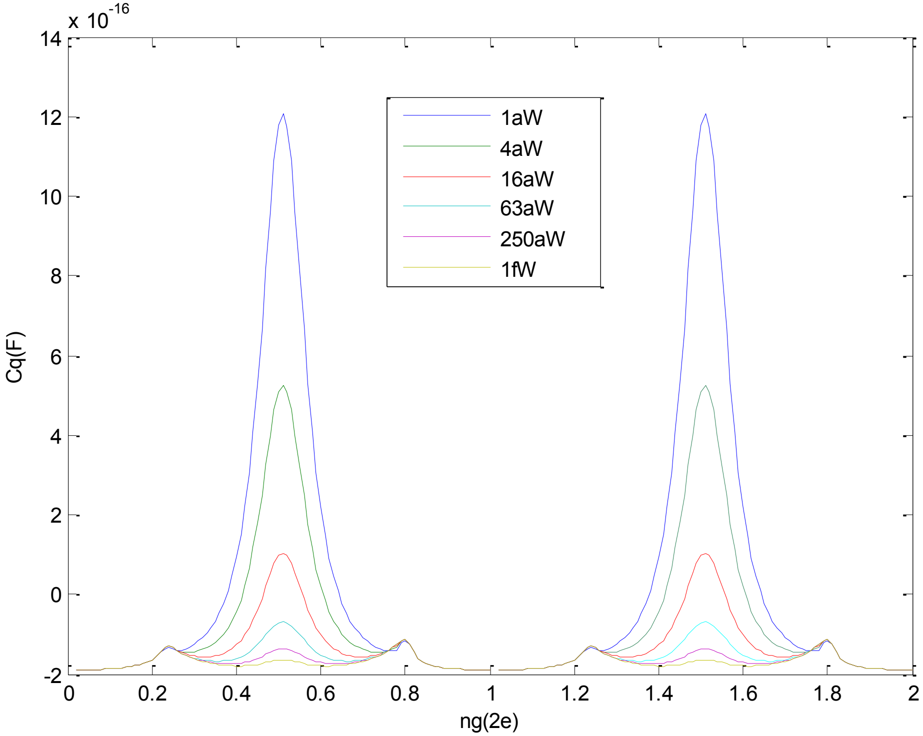


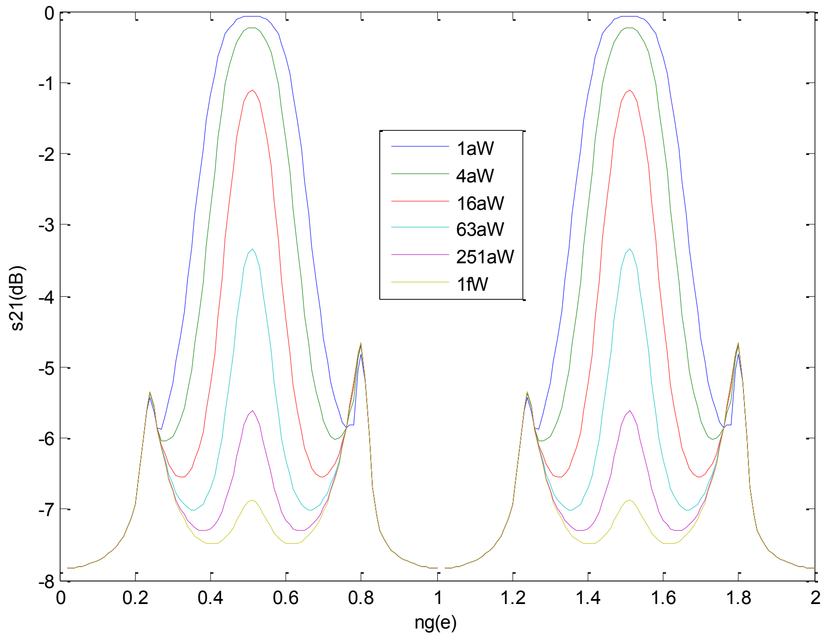
The Quantum Capacitance Detector



- 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* $\delta\Phi\sim 2C_Q/(\omega_o Z_o C_C^2)$

Simulated response

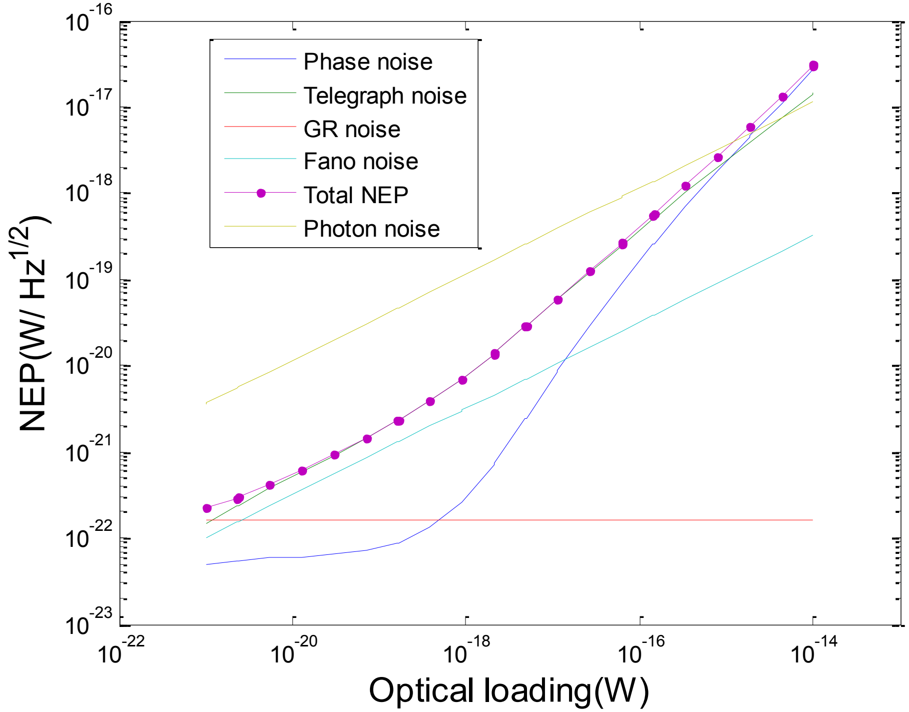




- SCB capacitance x gate voltage (in units of Cooper Pair charge) for different coupled optical signal power

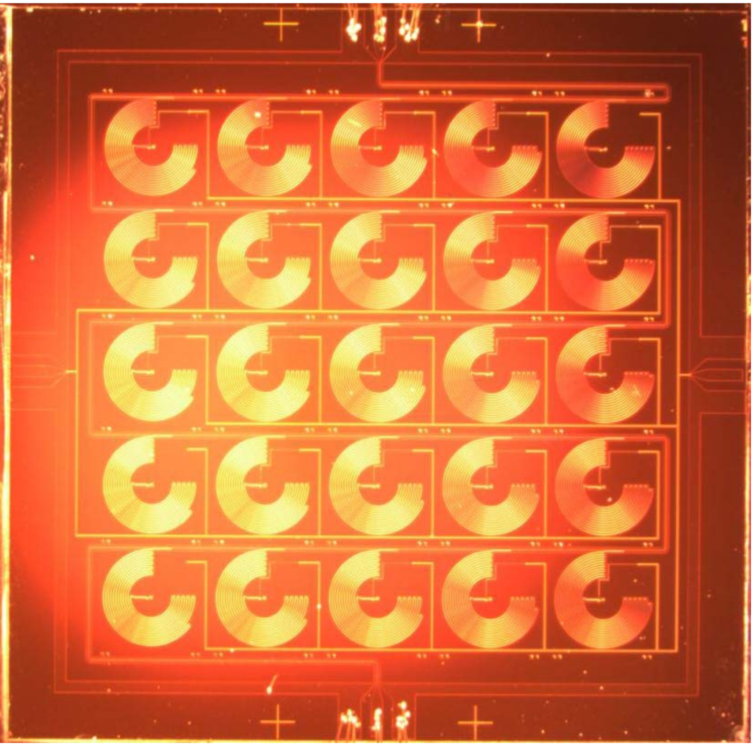
- transmission through feedline x gate voltage (in units of Cooper Pair charge) for different coupled optical signal power

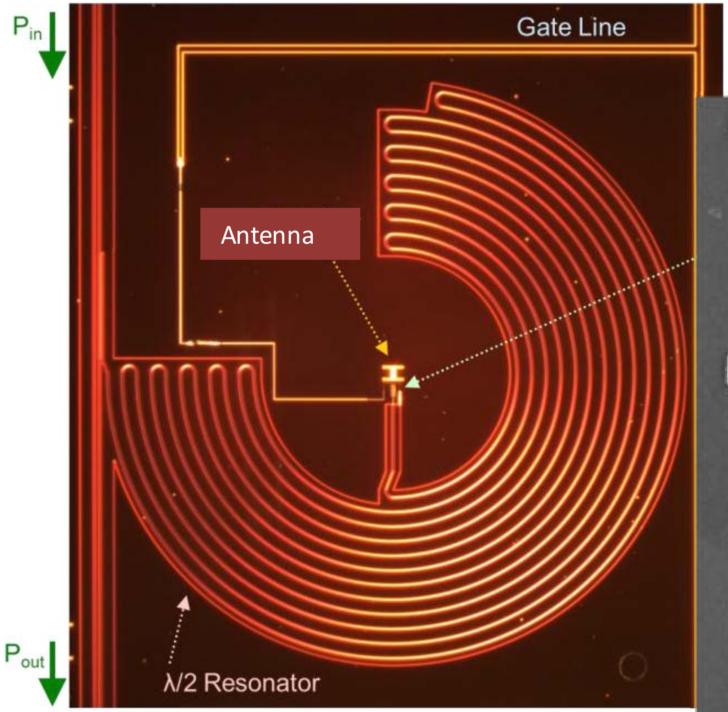
Theoretical Sensitivity vs. Signal Power

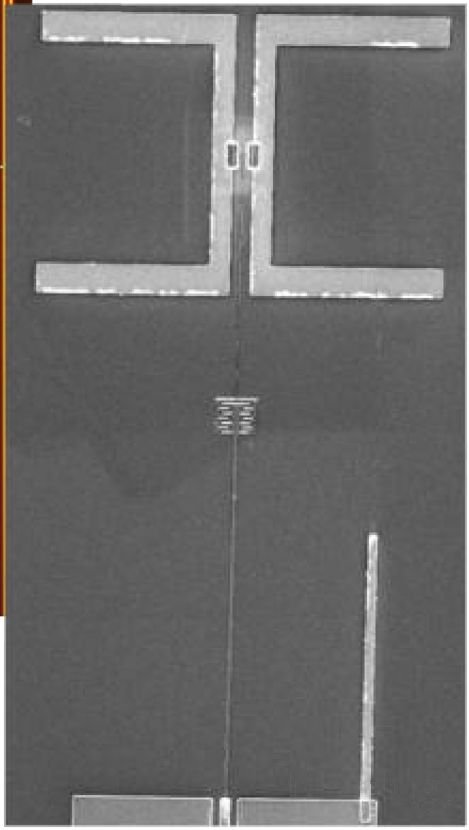


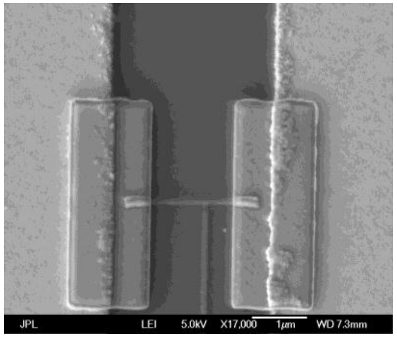
- *Detector is background limited over a wide range of operation*

Quantum Capacitance Detector: 5x5 Array



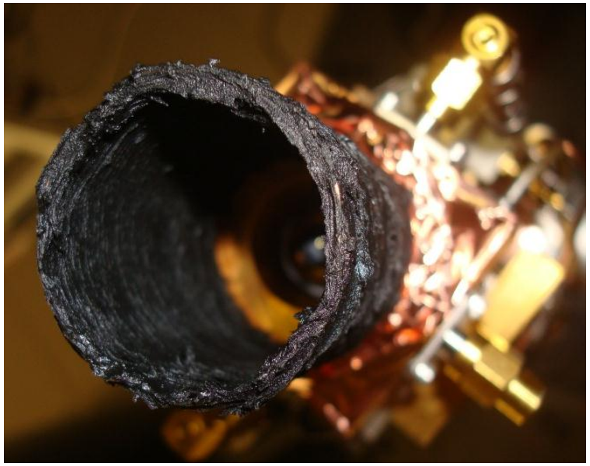


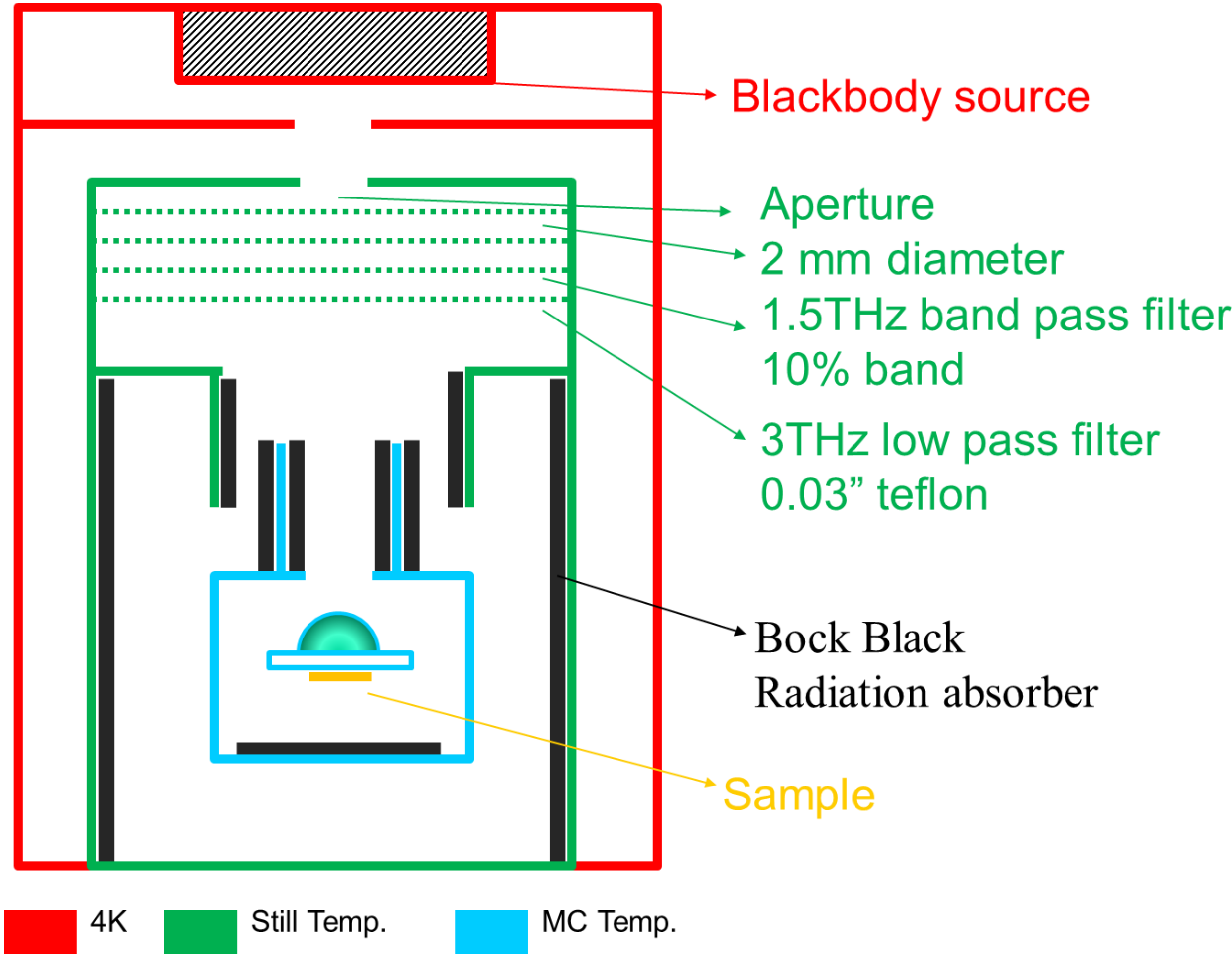




Only center device
Illuminated by lens.
Each device has a slightly
Different resonance frequency.

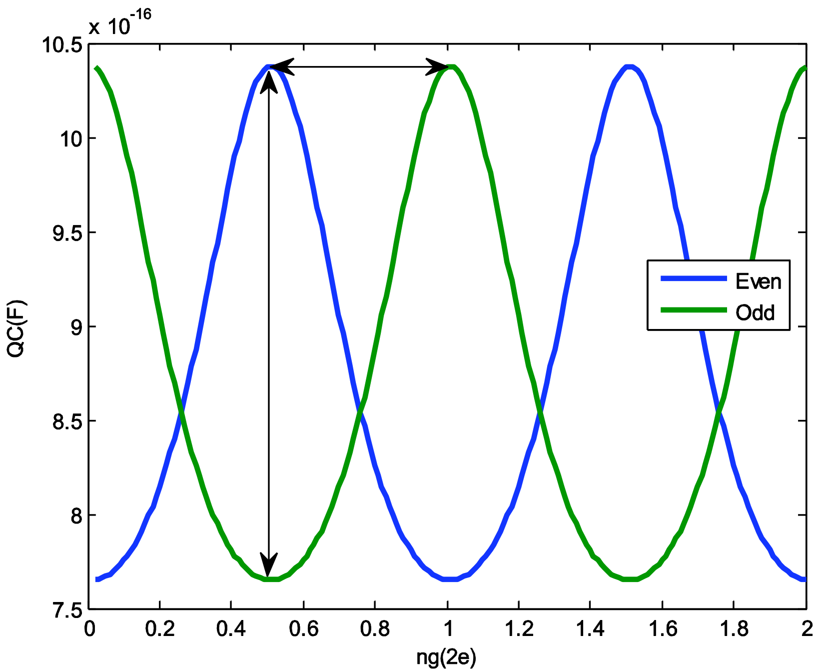
Experimental Setup

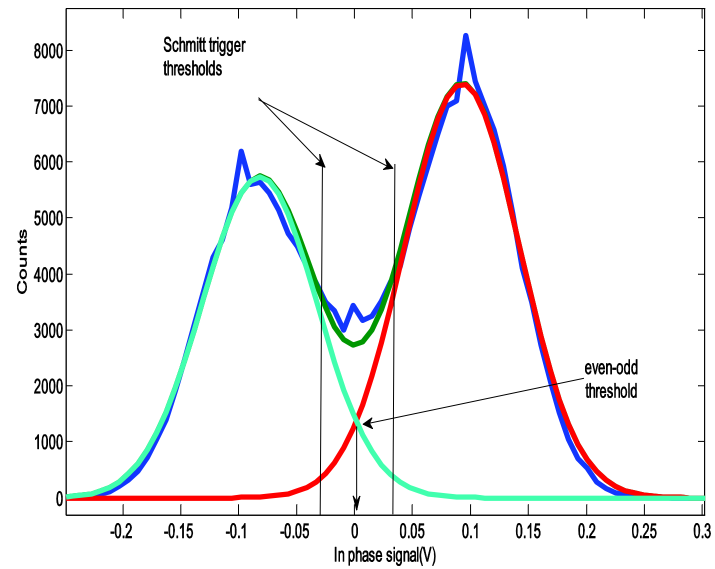


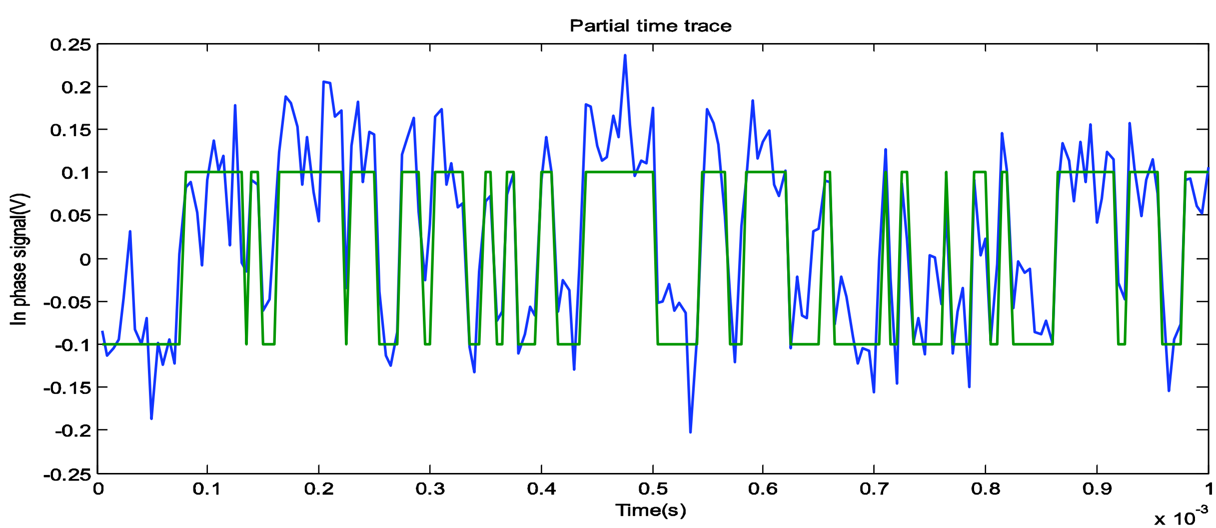


- Black body source and filters provide 1.5THz radiation from 4.2 – 40 K. Bock Black absorbs stray 4K radiation

Real time measurement – telegraph noise

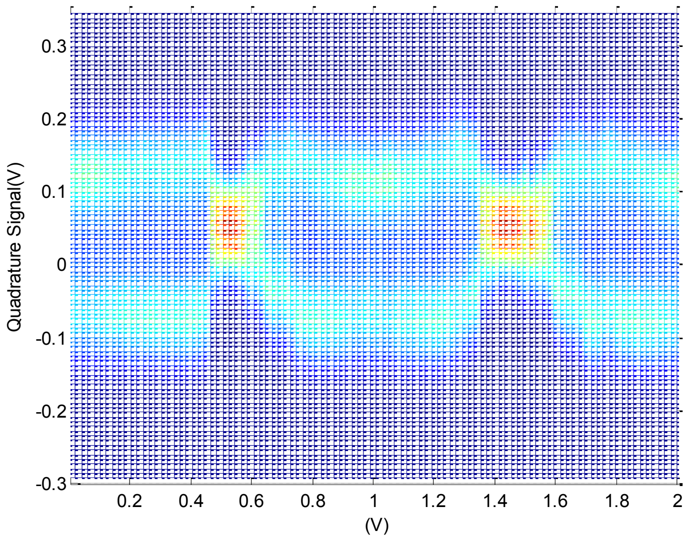




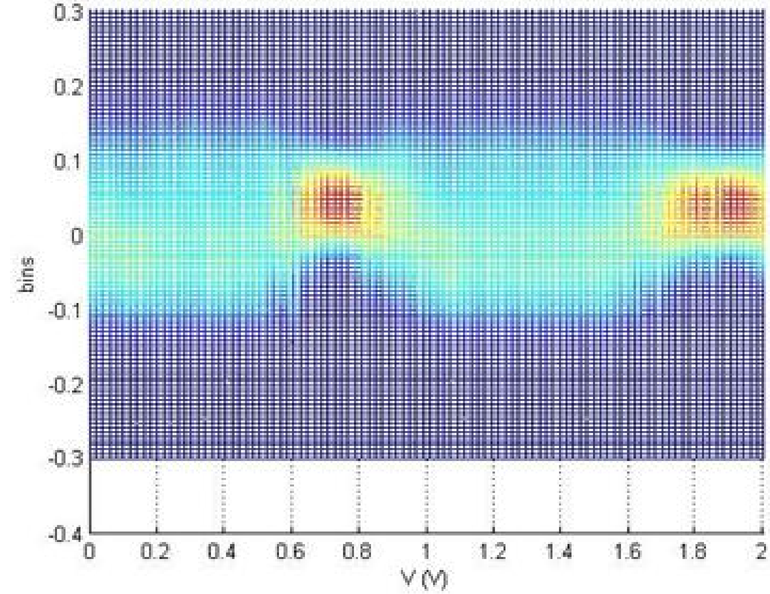


Telegraph noise histograms as a function of gate voltage and optical signal power

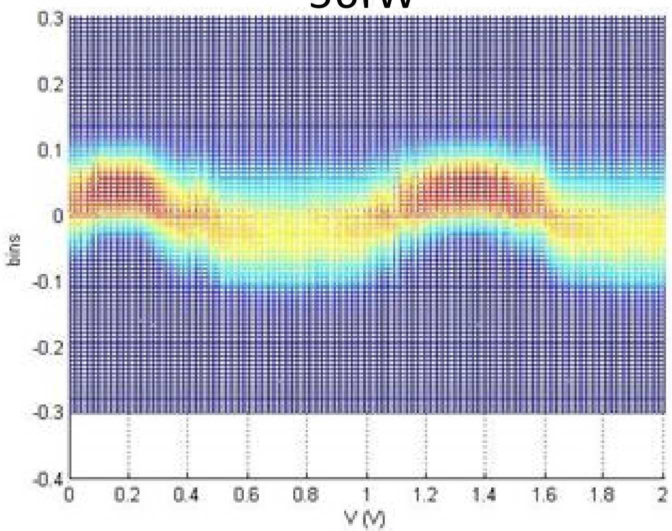
0.9aW



9.7fW

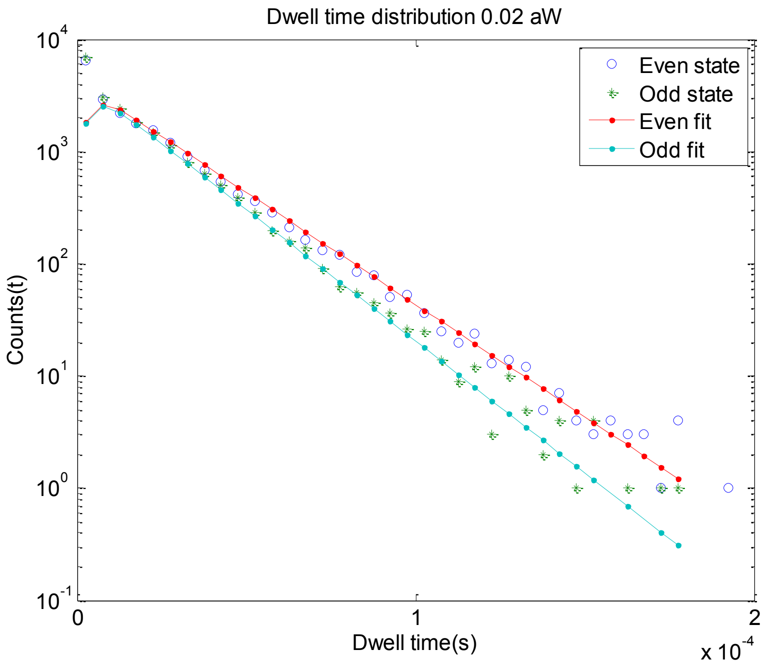


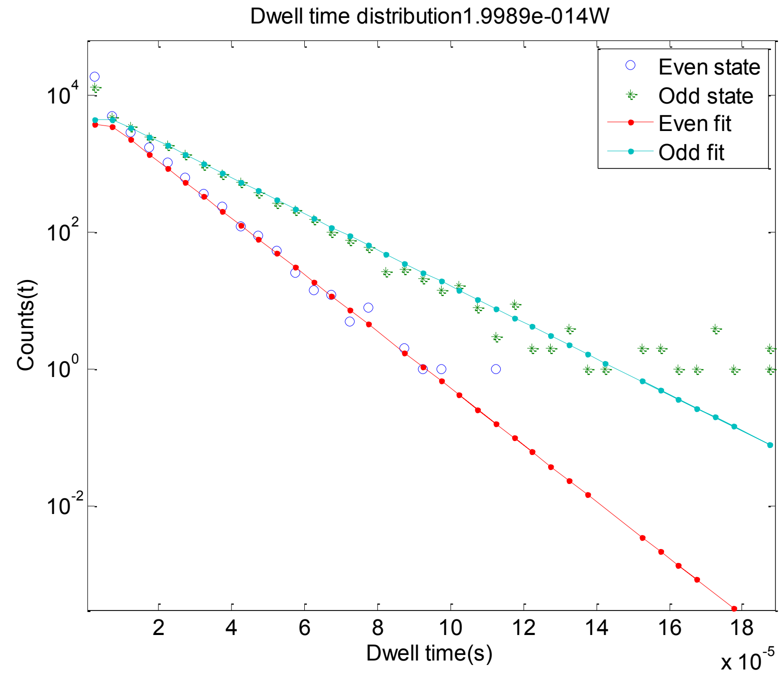
56fW



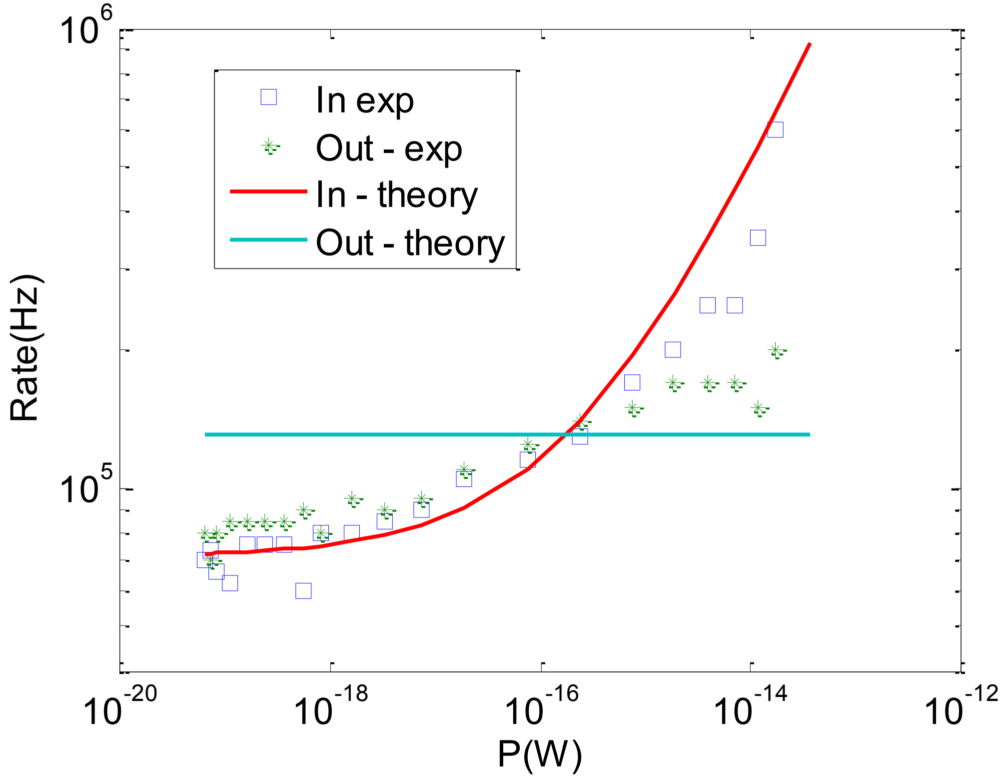
- Histogram peaks trace even and odd states
- As a function of optical power, even peak shrinks and odd peak grows

Dwell time distribution – optical power dependence

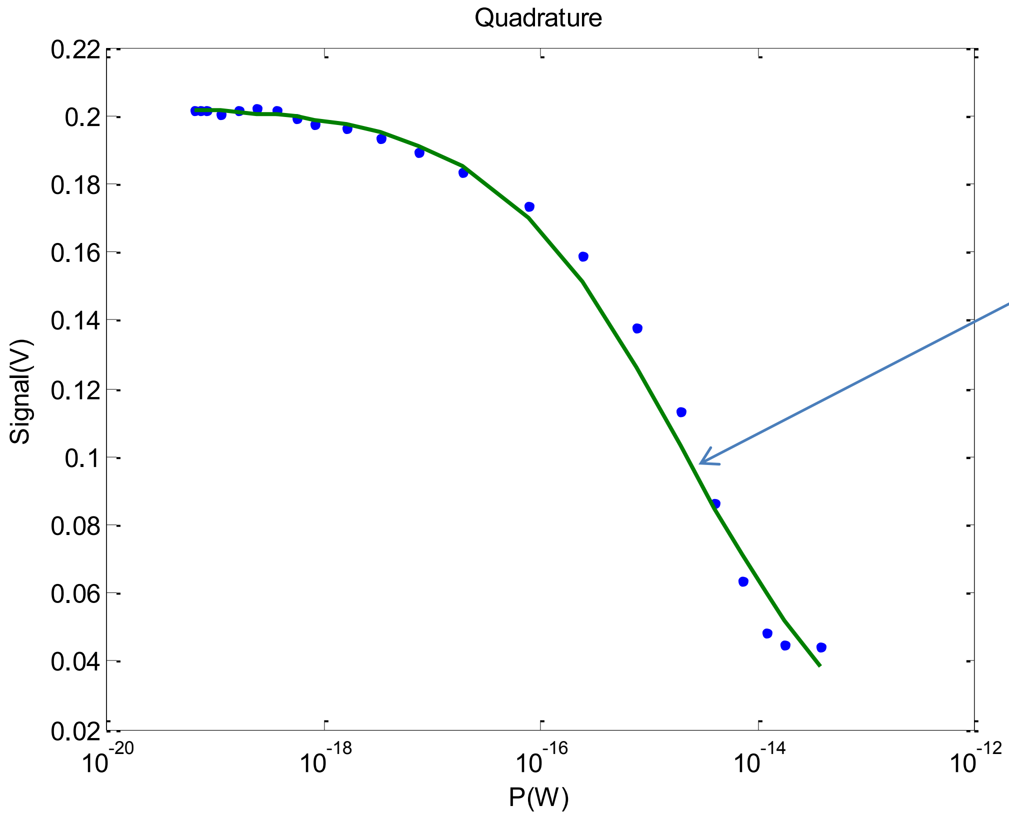




Optical power dependence of tunneling rates



Response fit using tunneling rates

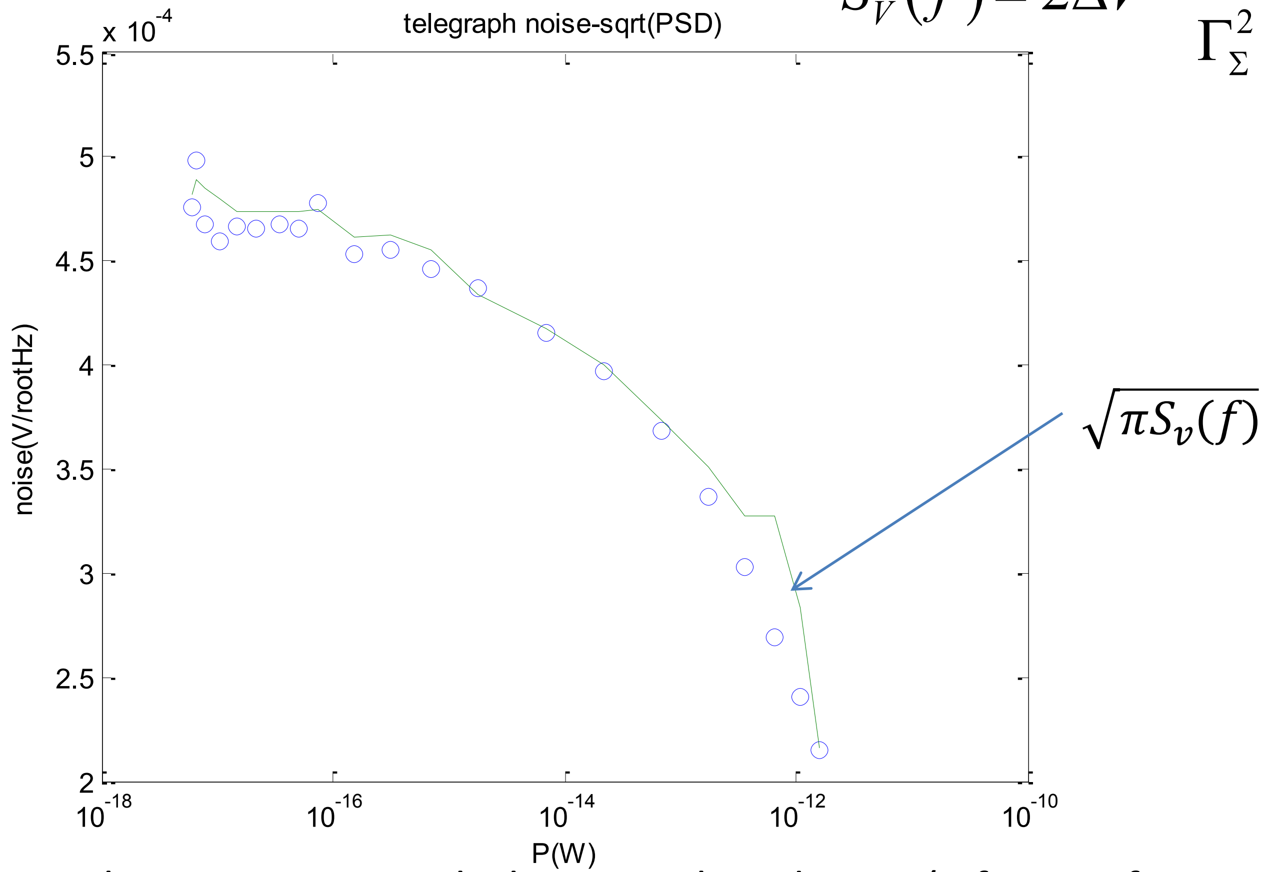


$$R = \frac{\Gamma_{OUT}}{\Gamma_{OUT} + \Gamma_{IN}} A_{EVEN}$$

- Fit is used in NEP calculation

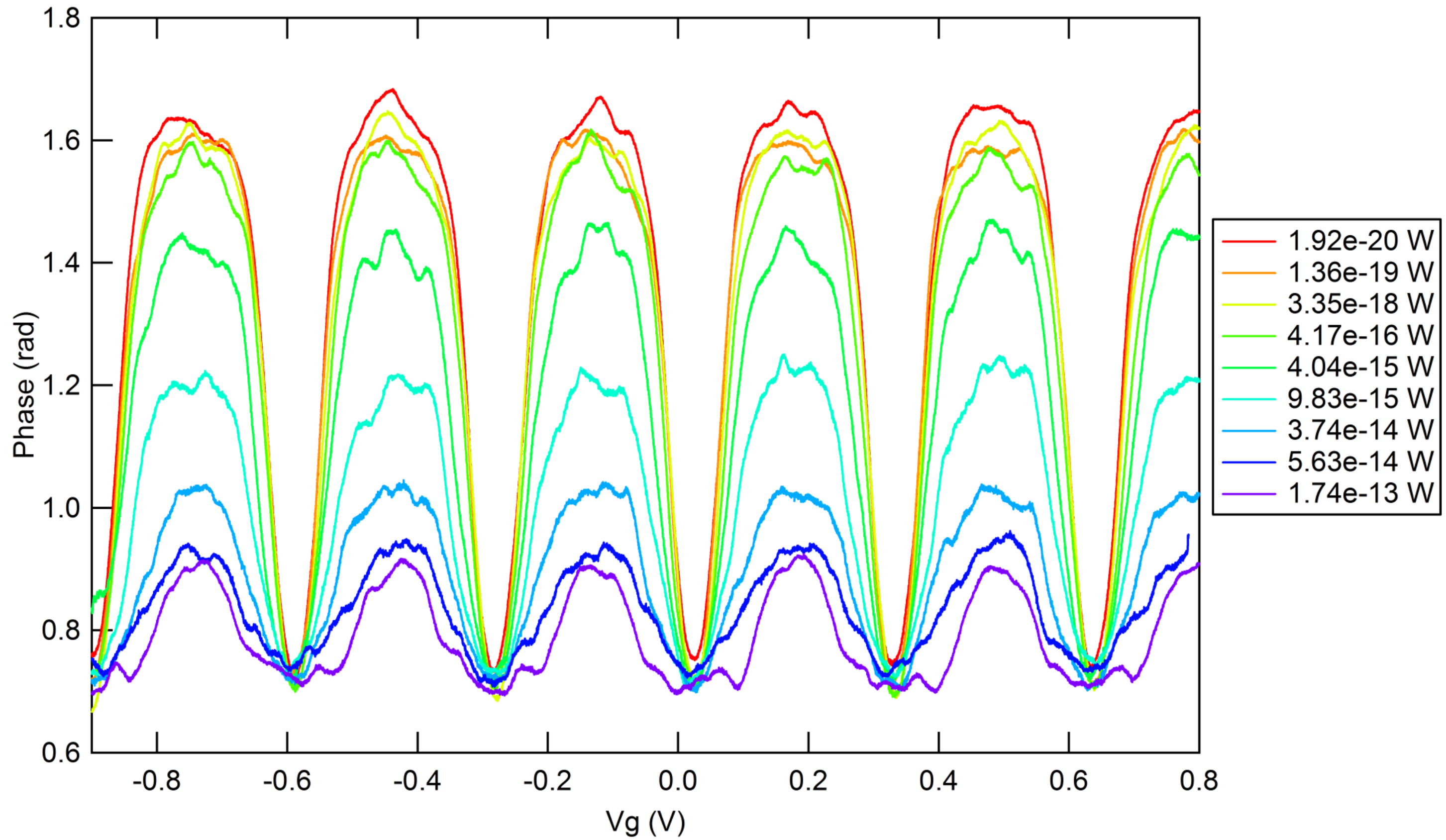
Telegraph noise power spectrum density

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

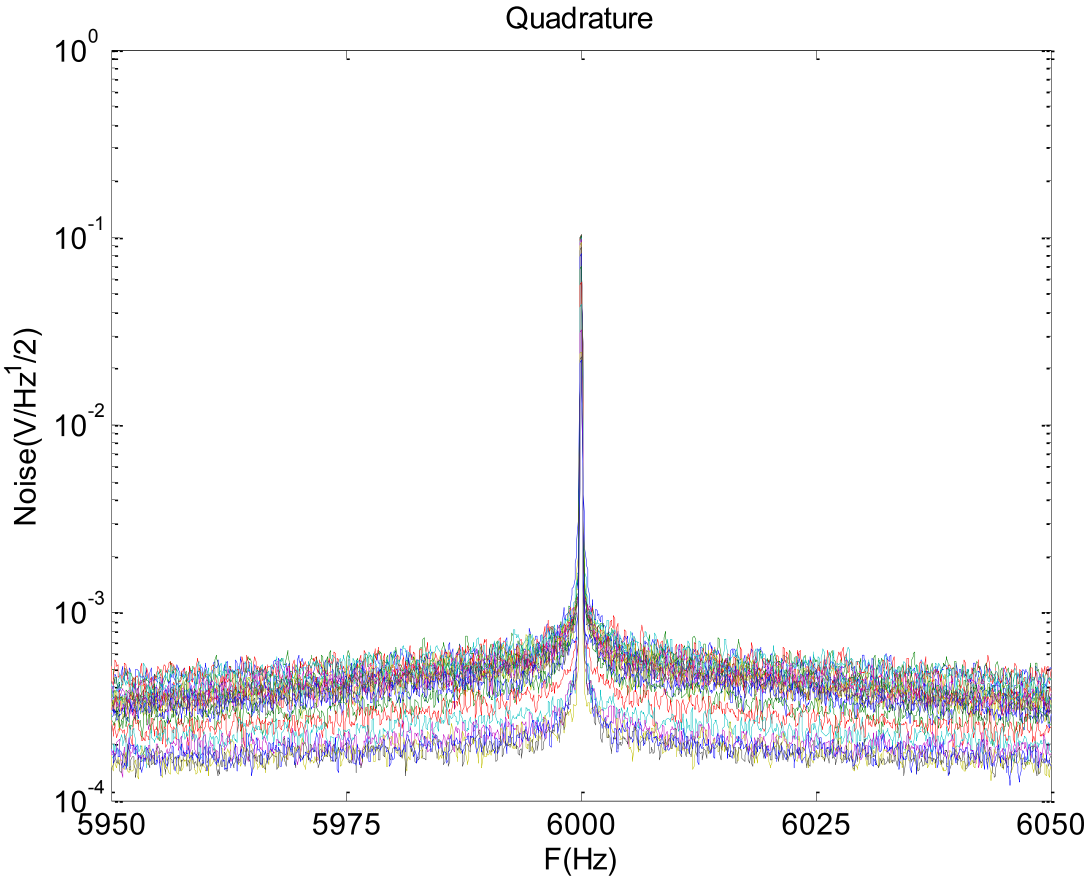


- Telegraph noise agrees with theoretical prediction (a factor of pi too high) using rates obtained from fits
- As predicted is the major noise source (> phase noise due to offset charges, > amplifier noise)

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

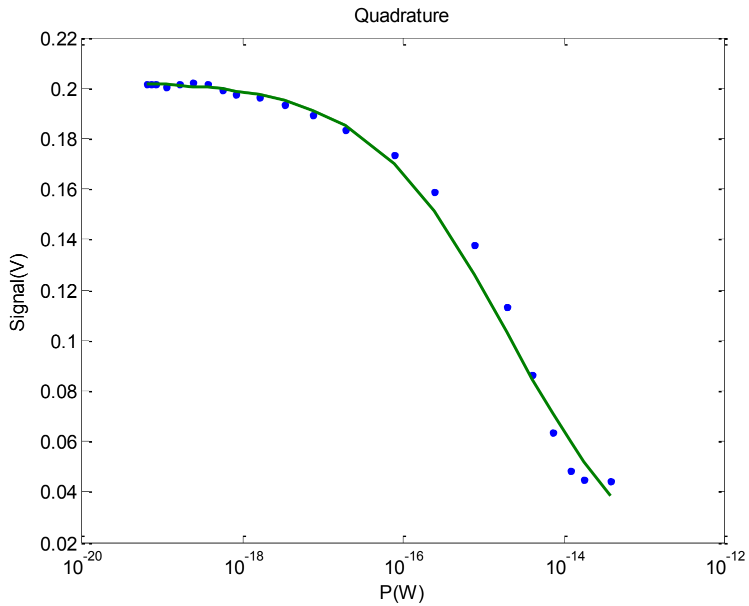


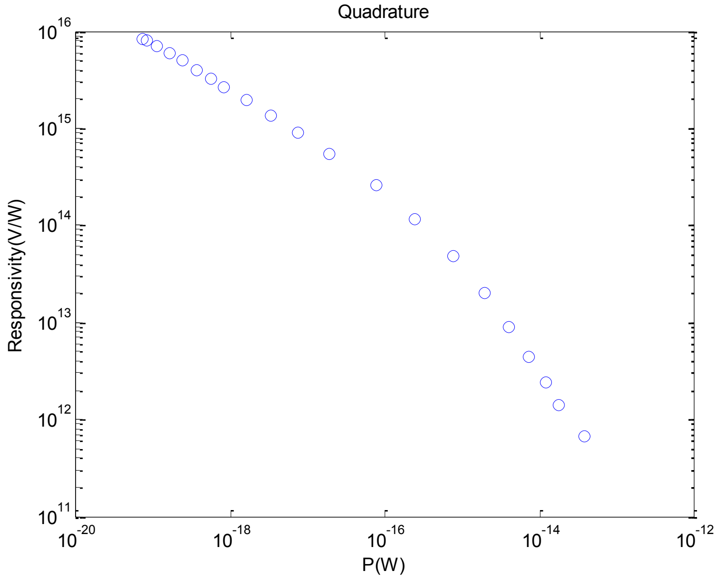
Spectrum analyzer response



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

Response and responsivity

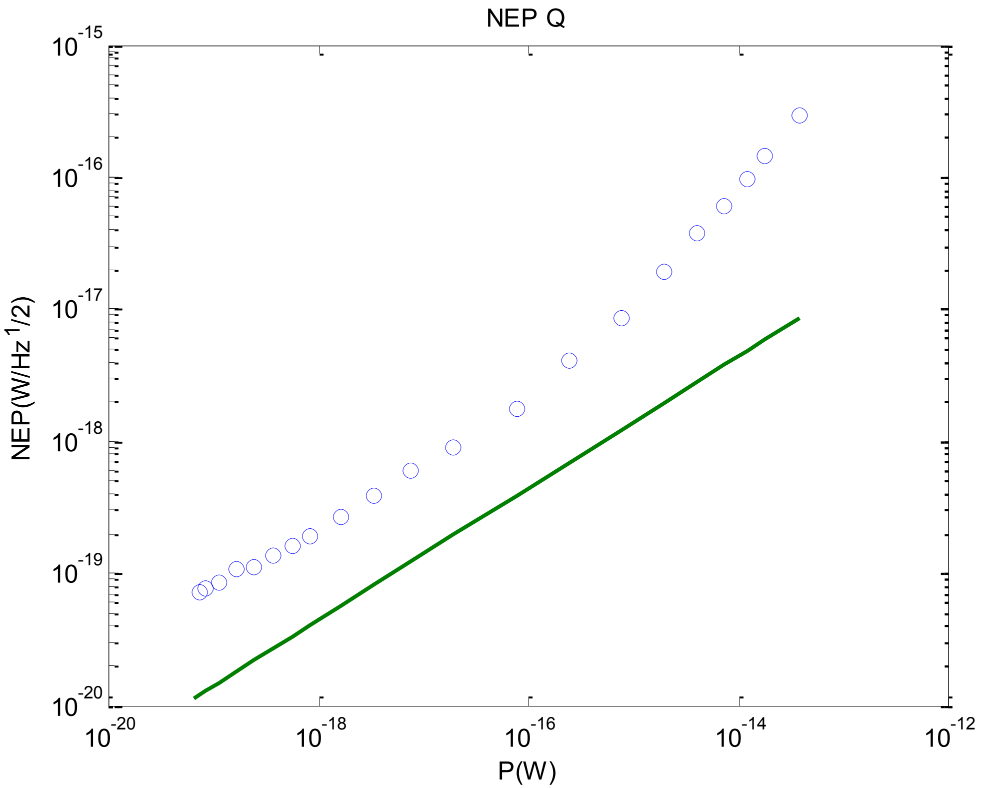




Amplitude of 6KHz peak as a function of optical signal power.
Fit comes from simulation of device based on telegraph noise measurements

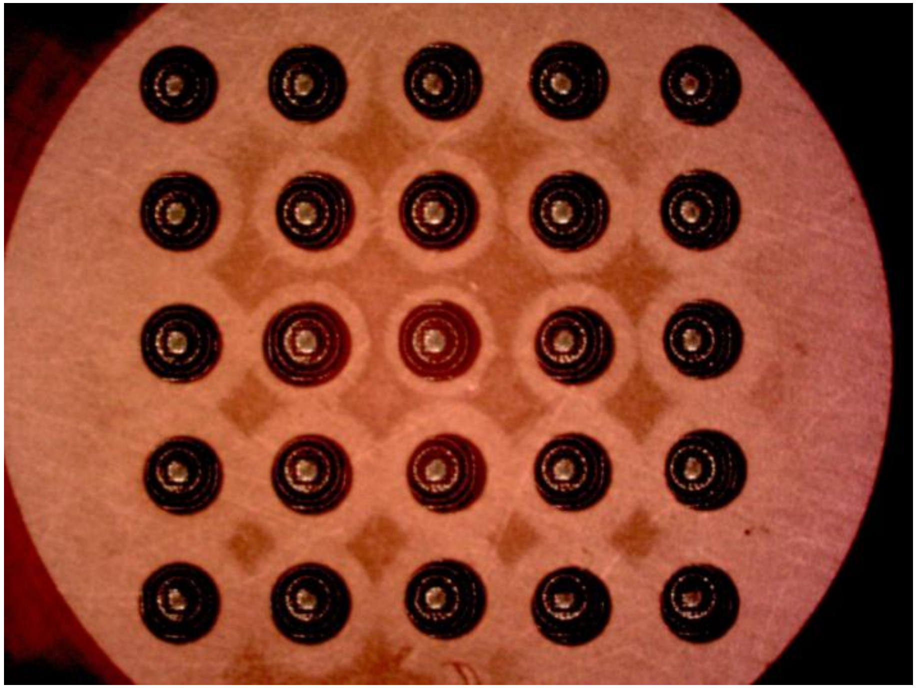
Responsivity dR/dP

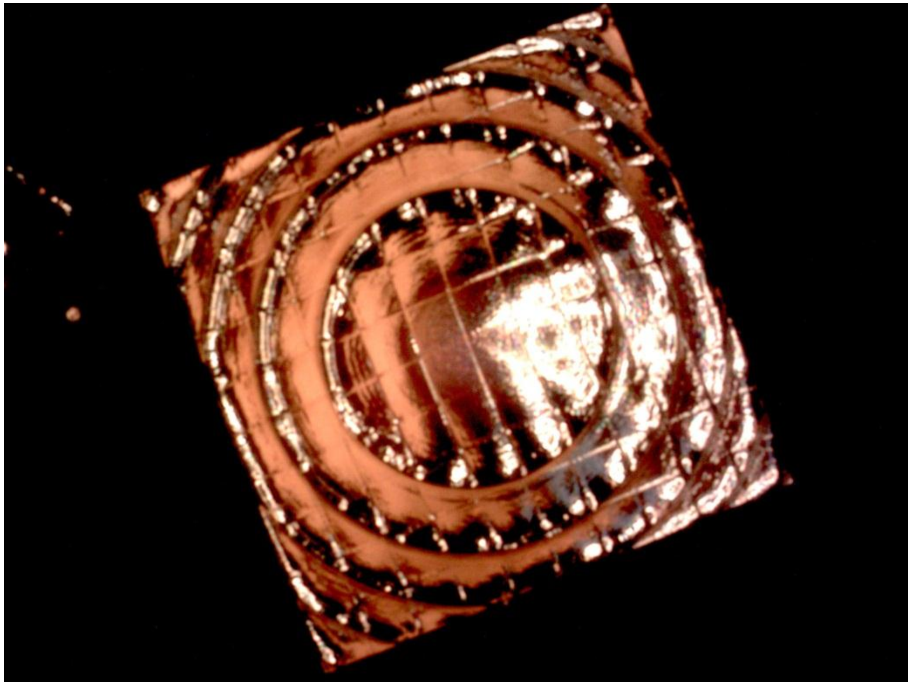
Noise Equivalent Power



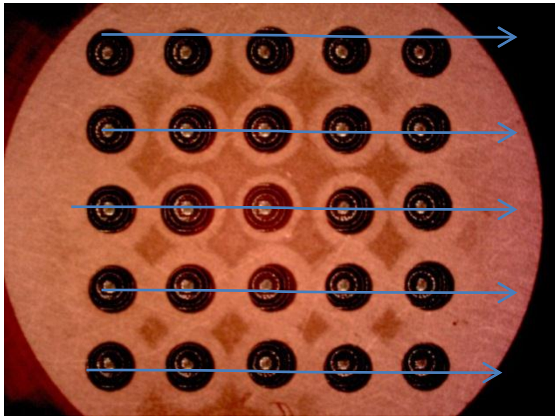
Fresnel lens array

Lens array made by Dan Wilson using an electron beam lithography technique developed by Paul Maker, Dan Wilson and Rich Muller at JPL



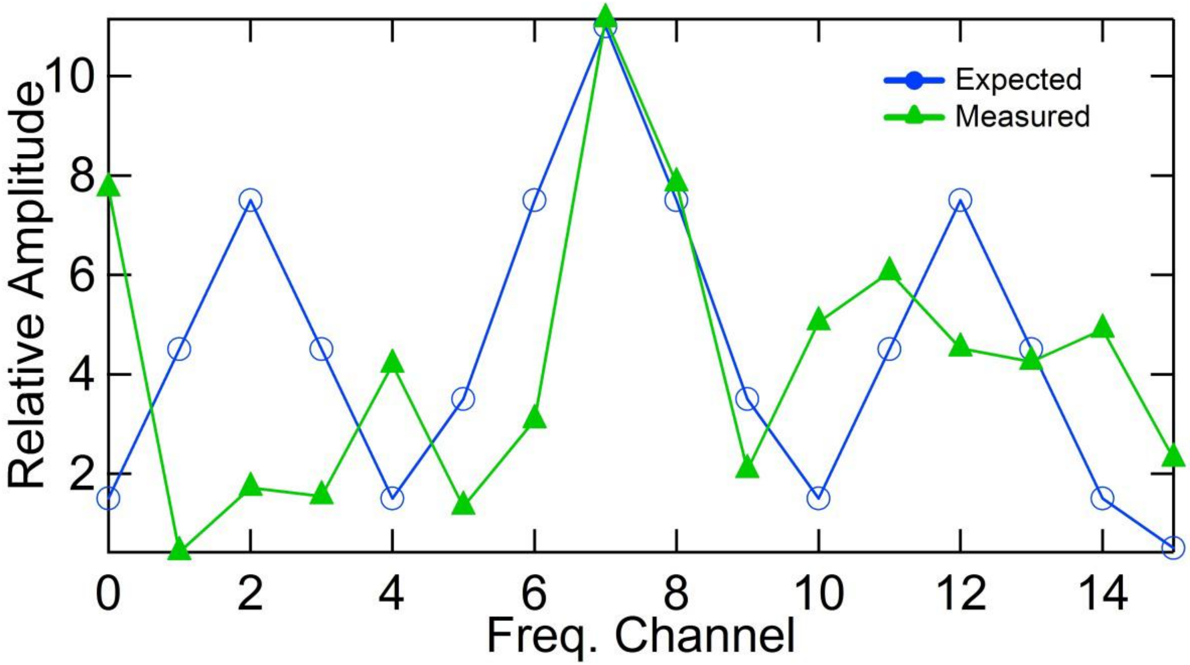


Fresnel lens array



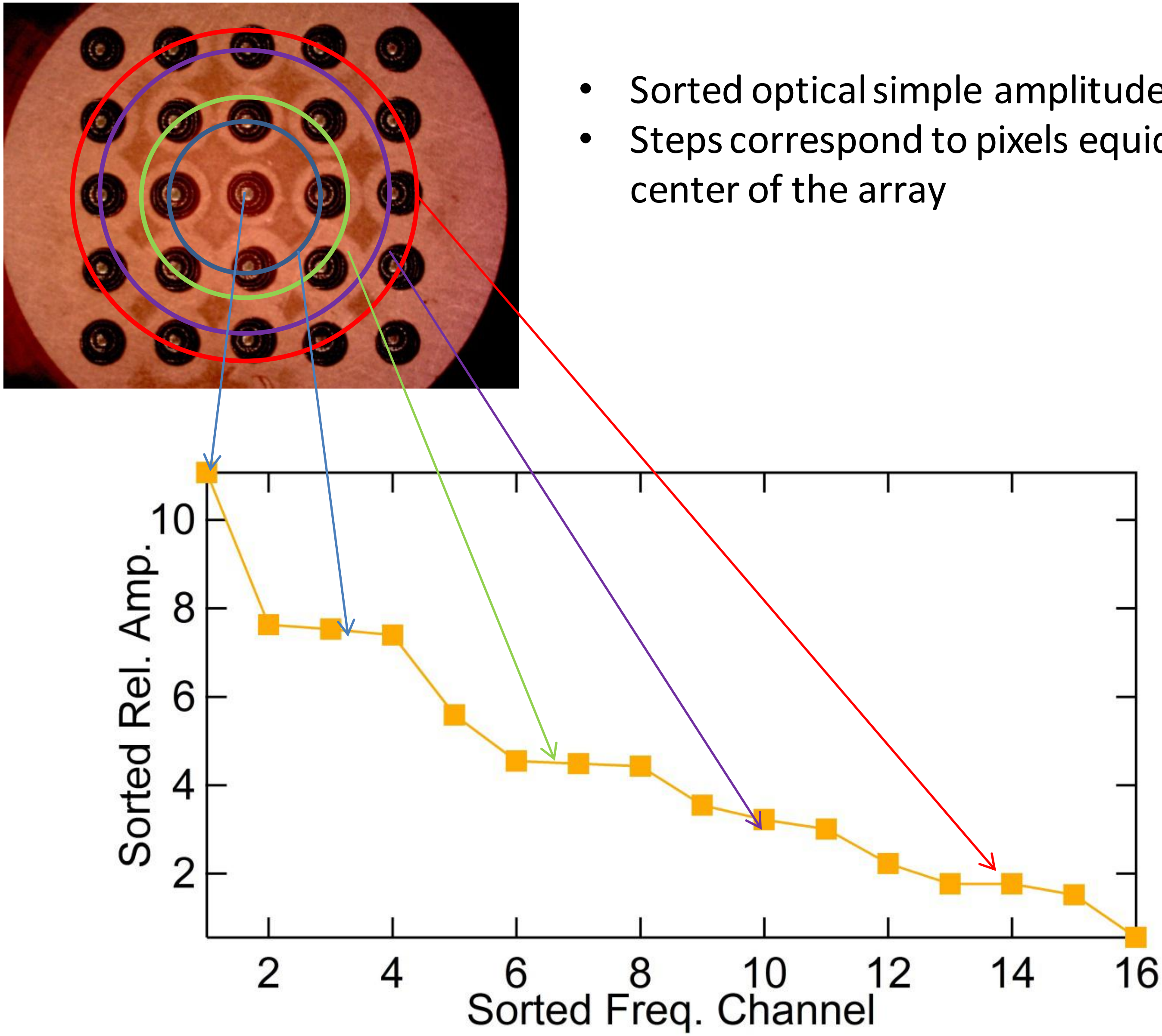
Increasing pixel frequency

- Measured relative optical signal intensity using response of individual QCD pixels
- Using a 4mm aperture aligned to the center of the array
- Some pixels responses are missing (only 16 channels found)

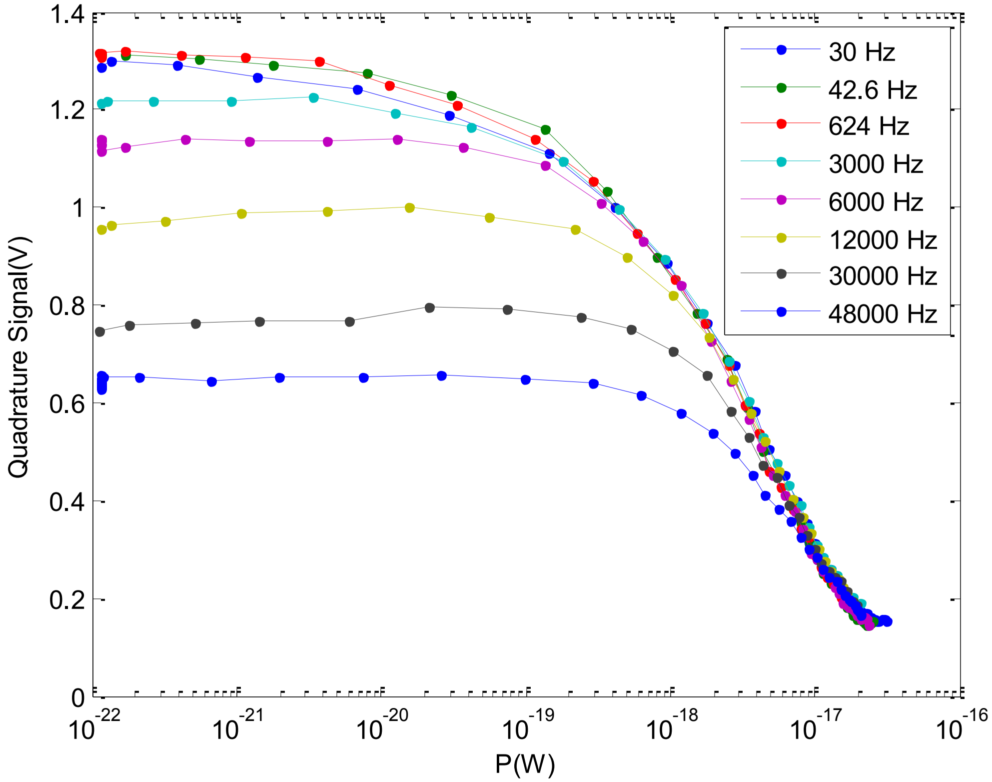


Fresnel lens array

- Sorted optical simple amplitudes
- Steps correspond to pixels equidistant form center of the array

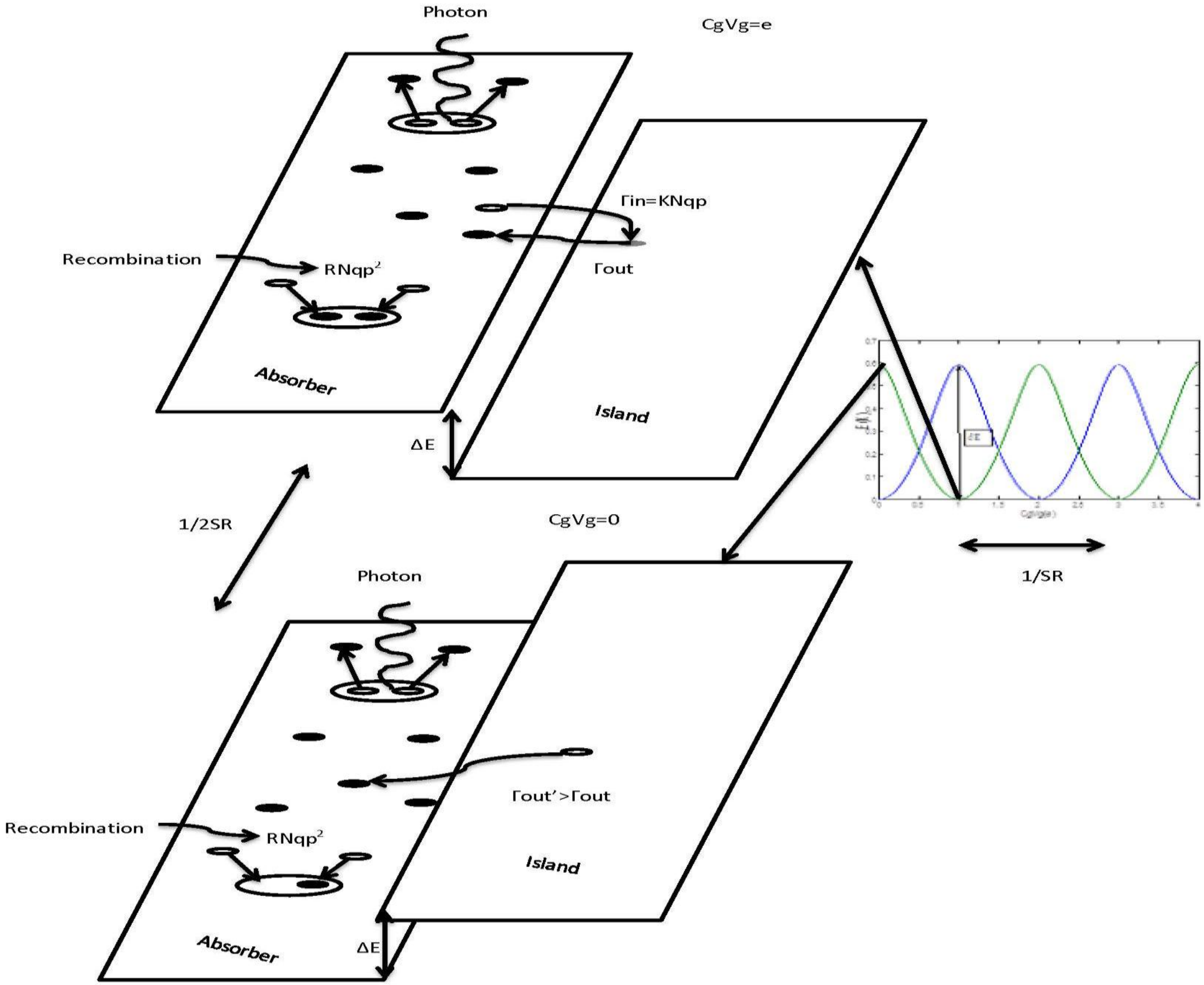


Measurements of Response versus optical power for various gate sweep rates



- Absorber width reduced to 50nm – higher impedance – better match to antenna
- Aperture was changed to 500um
- Diffraction causes illumination to be about the same for all pixels
- Response similar from pixel to pixel
- What causes sweep rate dependence?

Sweep rate dependence model



Sweep rate dependence model

Detailed balance equation

$$\frac{dN_{qp}}{dt} = \eta\frac{P}{\Delta} - RN_{qp}{}^{2} - \Gamma_{in}N_{qp} + \Gamma_{eff} = \eta\frac{P}{\Delta} - (R+K)N_{qp}{}^{2} + \Gamma_{eff}\ .$$

Nqp = number of quasiparticles
P= optical signal power
η = conversion efficiency from photon energy to quasiparticles ~ 0.57
R= recombination rate
Γin= tunneling rate from absorber to island = KNqp
Γeff= effective tunneling rate from island to absorber

Model for Γeff -> $\Gamma_{eff} = \sqrt{\Gamma_{out}^{2} + SR^{2}}$

At the end of each sweep quasiparticles are dumped back into reservoir. If the sweep rate (SR) is faster than the intrinsic tunneling out time Γout, then Γ_{eff}~ SR. If SR is much slower, Γ_{eff}~ Γ_{out}

Sweep rate dependence

Steady state solution

$$N_{qp} = \sqrt{\left(\frac{\eta h\nu}{\Delta} PR + \Gamma_{eff}\right)/(R+K))}$$

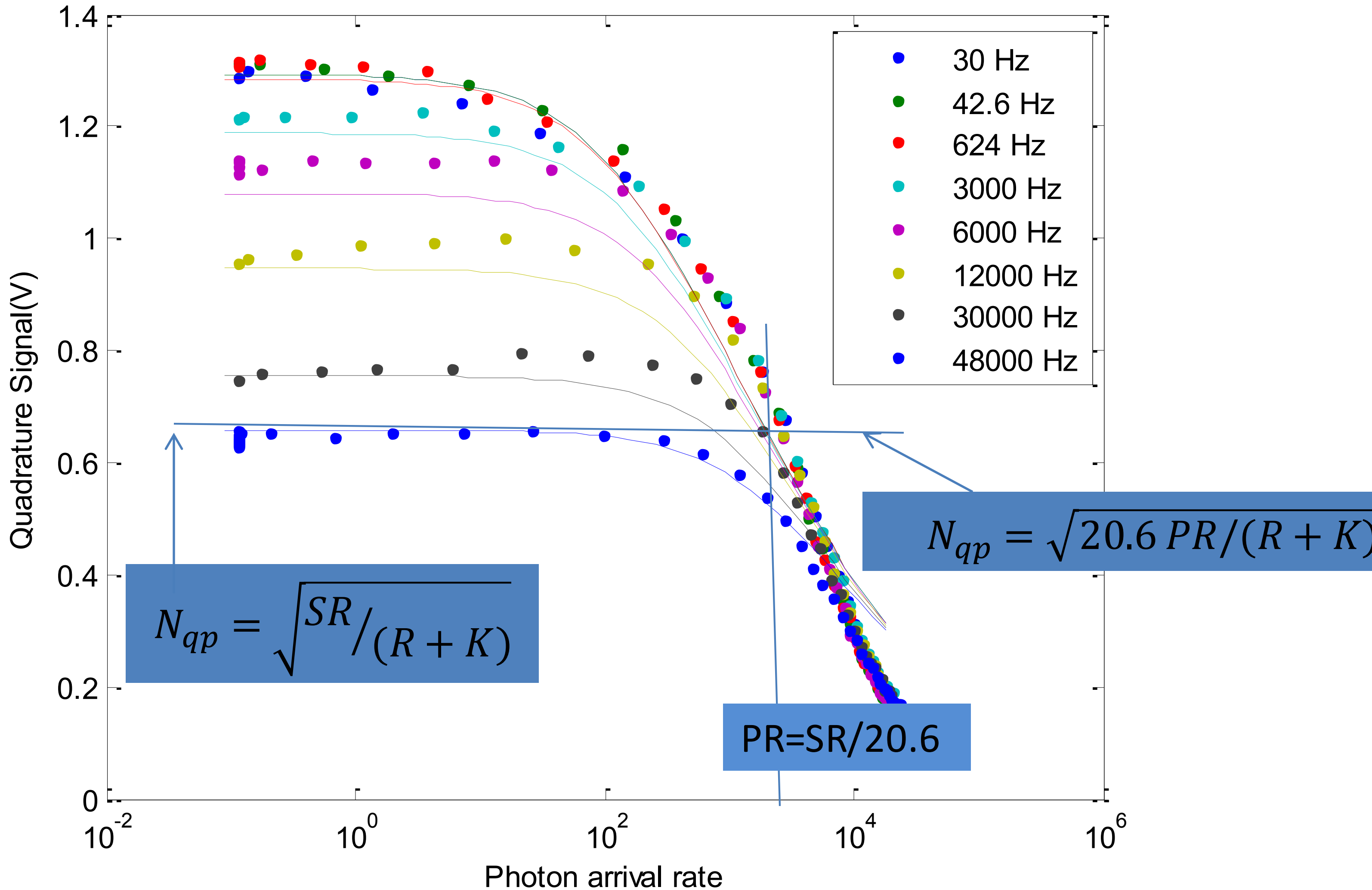
PR is the photon arrival rate, hυ the photon energy, Δ the absorber superconducting gate

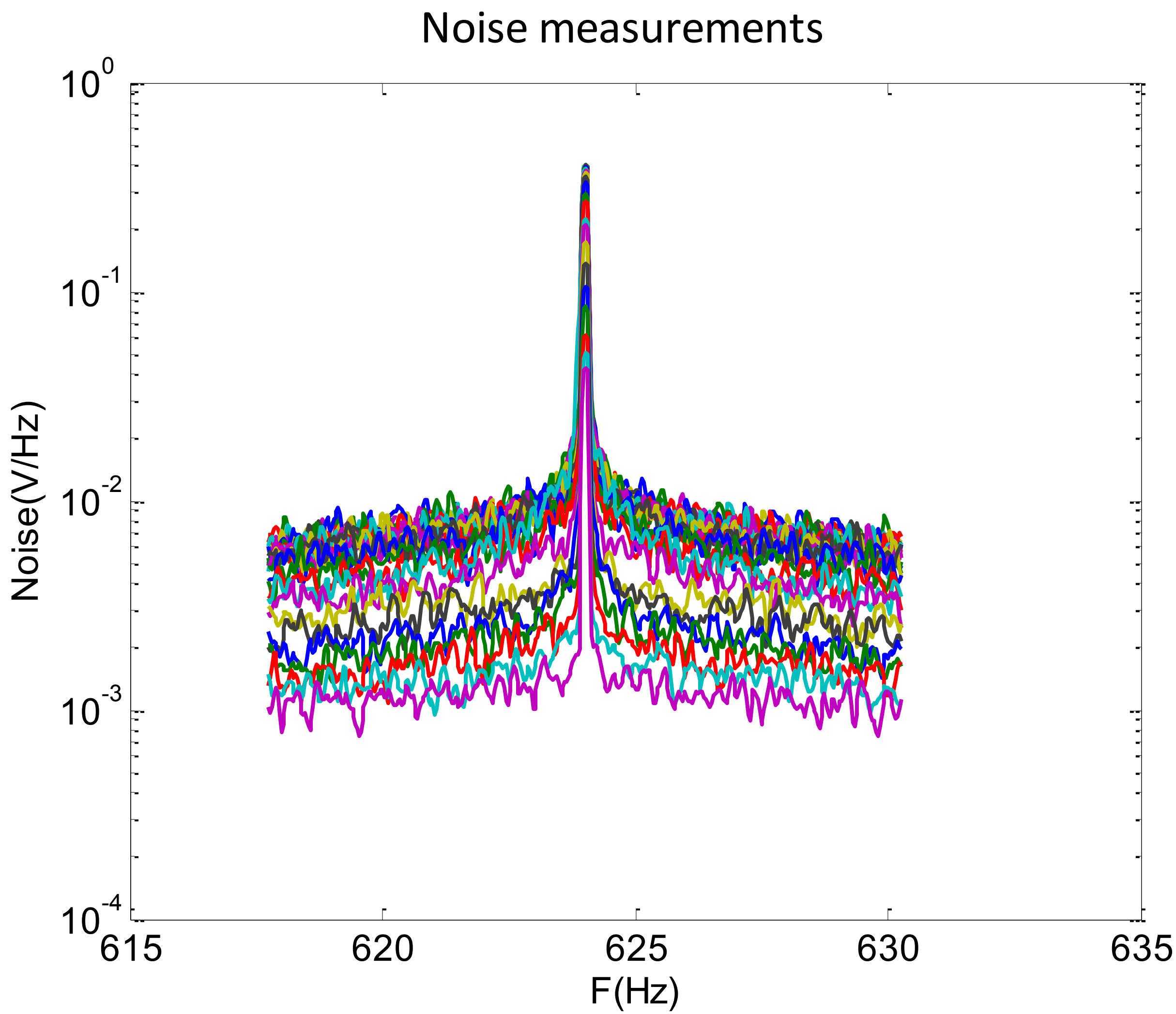
The signal is given by

$$S = A.\frac{\Gamma_{eff}}{\Gamma_{eff} + \Gamma_{in}} = \frac{A}{1 + \frac{KN_{qp}}{\Gamma_{eff}}} = \frac{A}{1 + \frac{K}{\Gamma_{eff}}\sqrt{\frac{20.6\,PR + \Gamma_{eff}}{R+K}}}$$

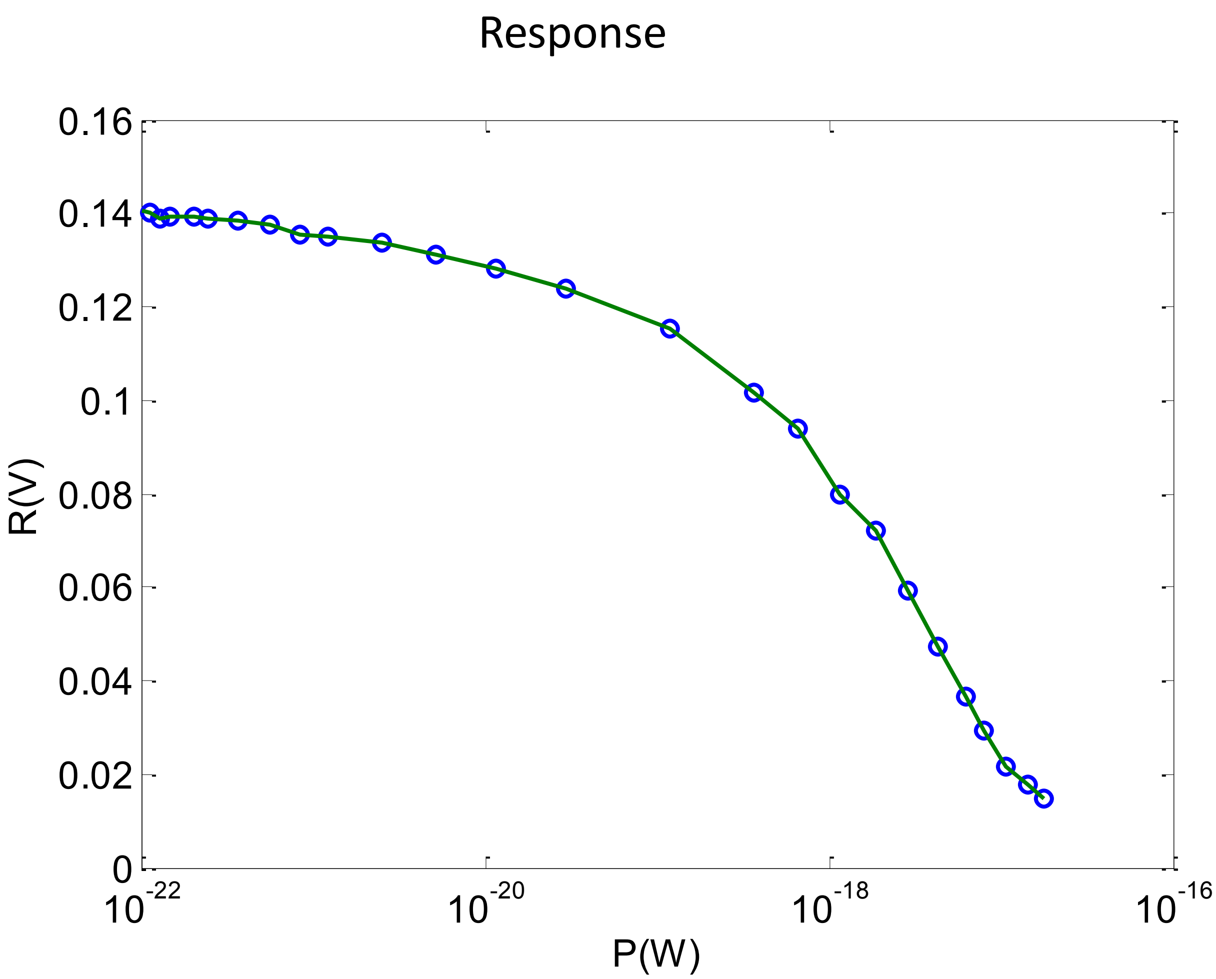
A is a constant (depending on the electronics)
and 20.6 is the average number of quasiparticles generated by a 1.5THz photon
In an Aluminum absorber

Sweep rate dependence = calibration of photon arrival rate!



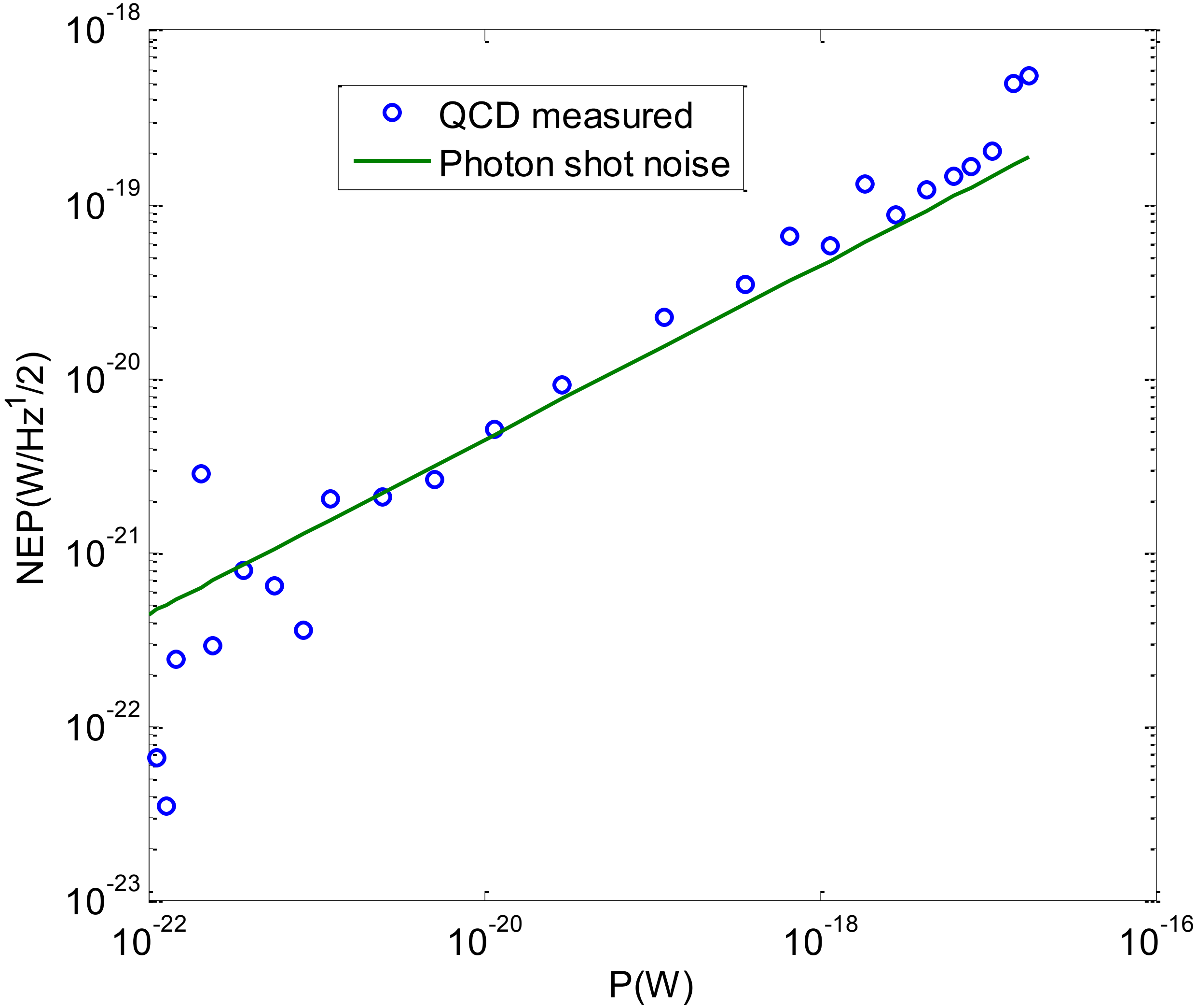


Noise measurements
Noise(V/Hz)
F(Hz)
10^0
10^-1
10^-2
10^-3
10^-4
615
620
625
630
635


Response
R(V)
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
10^{-22}
10^{-20}
10^{-18}
10^{-16}
P(W)

NEP measured with power calibration

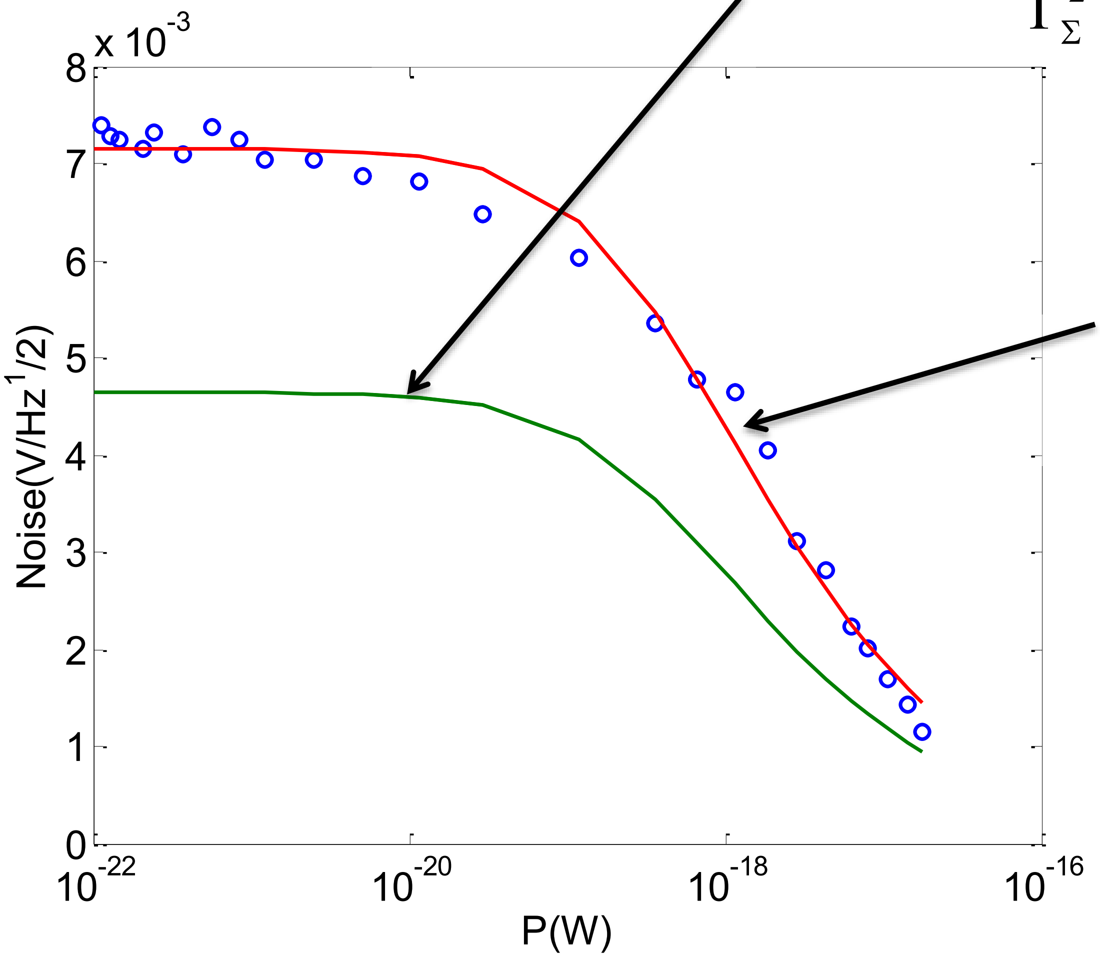
Photon shot noise limited!



Noise agrees with telegraph noise

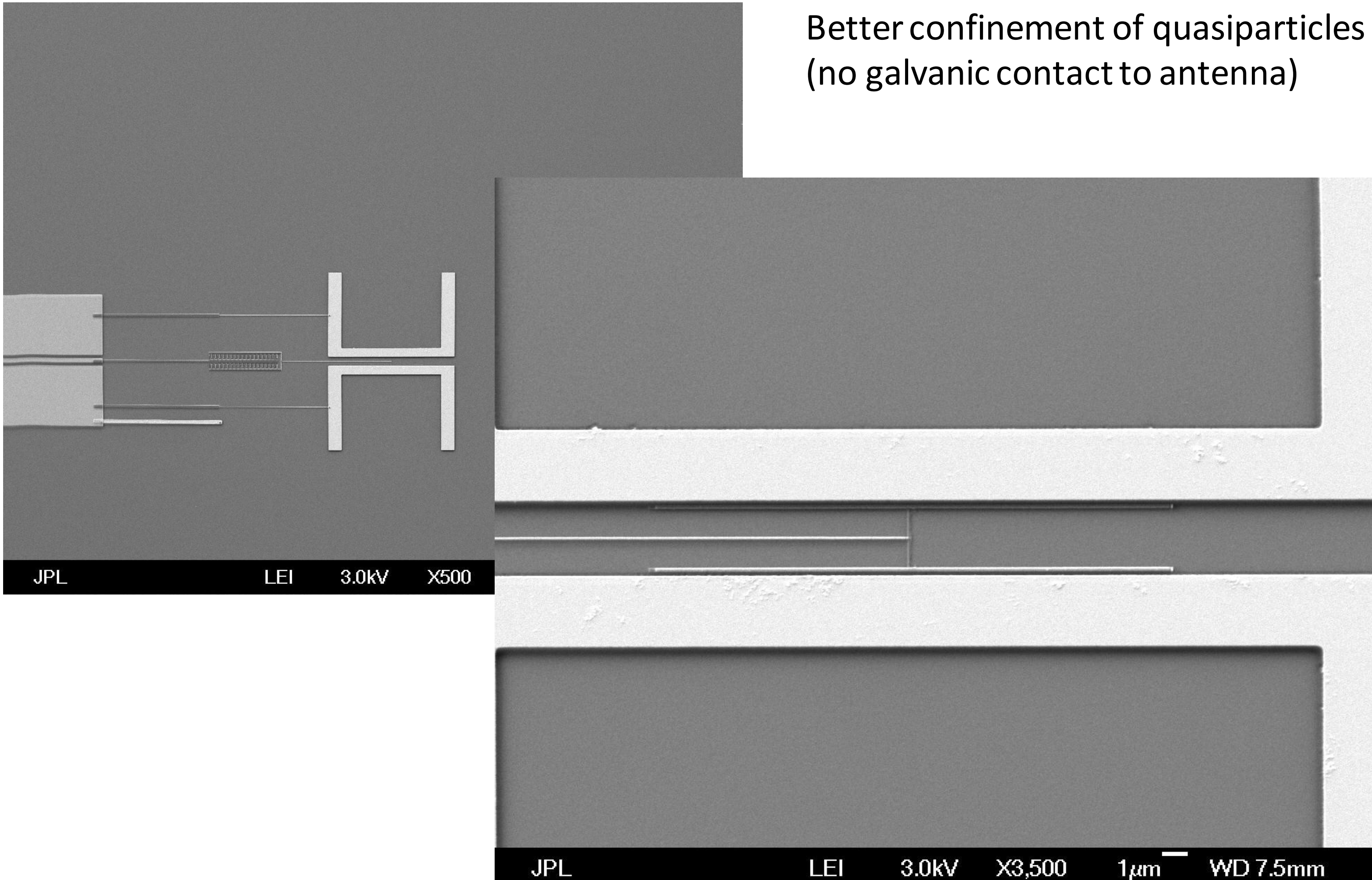
$$S_V(f) = 2\Delta V^2 \frac{\Gamma_{IN}\Gamma_{OUT}/\Gamma_\Sigma}{\Gamma_\Sigma^2 + (2\pi f)^2}$$

$$\sqrt{2.4 S_v(f)}$$

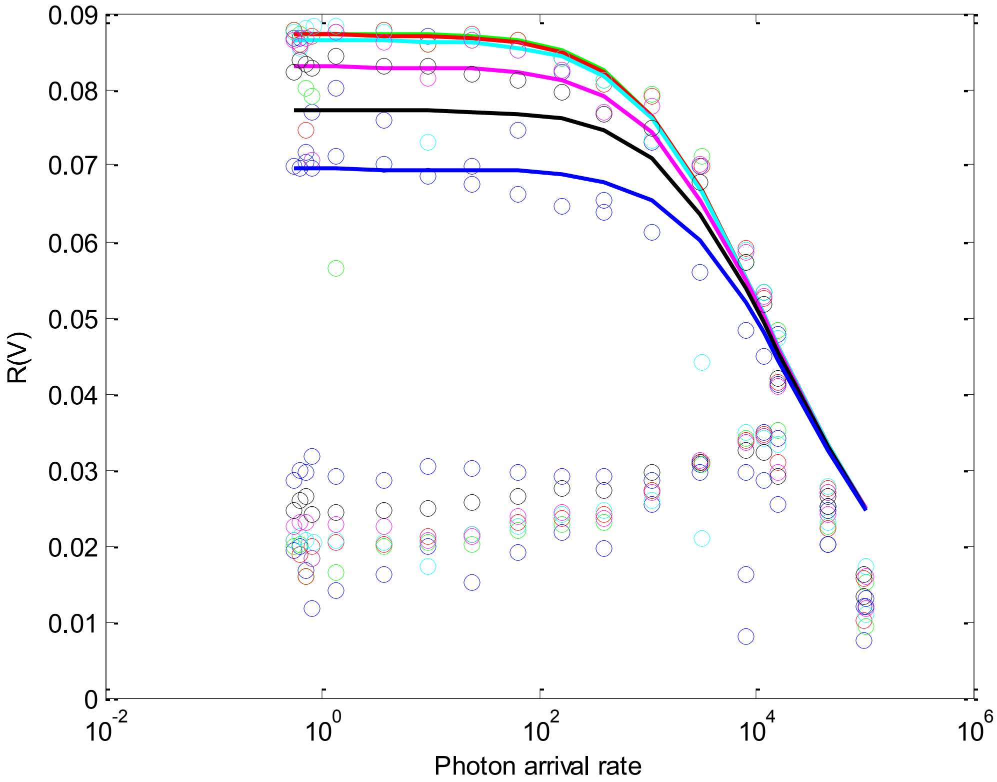


One attempt - Capacitively Coupled QCD

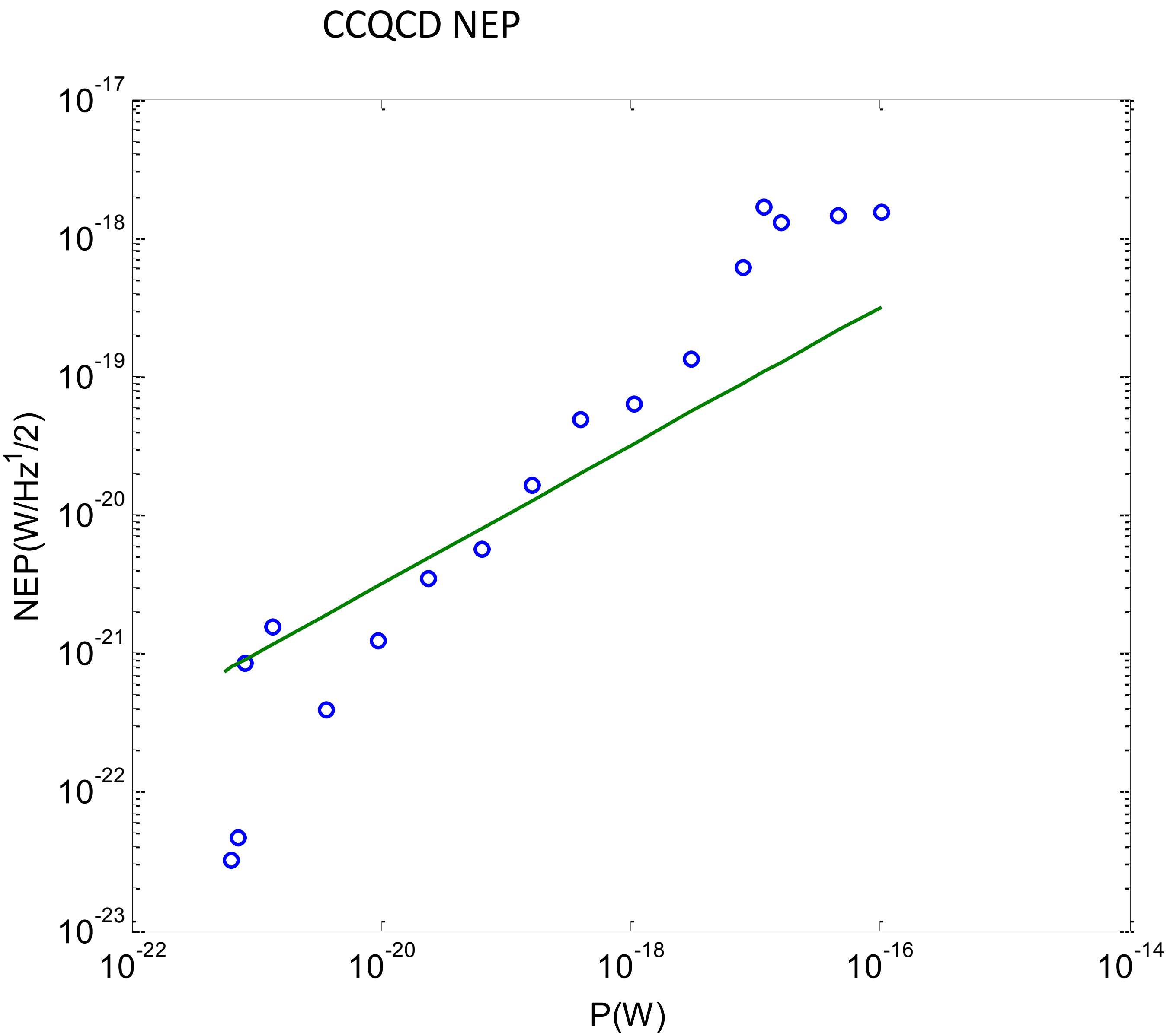
Better confinement of quasiparticles
(no galvanic contact to antenna)



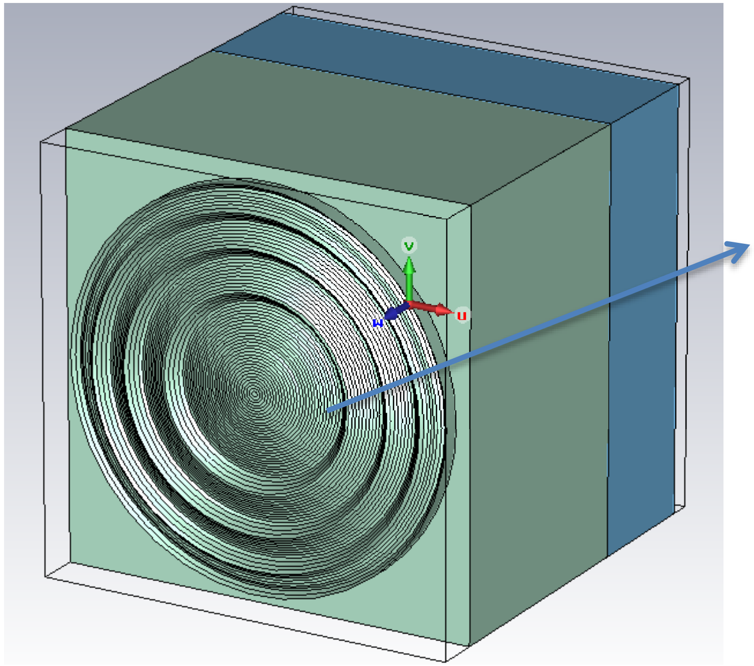
Sweep rate dependence of CCQCD



- Increased Γout- consistent with smaller difference between absorber and island gap – detrimental to performance
- Decreased recombination rate (larger island area) – good for performance
- Optical coupling seems to be better from calibrated photon arrival rate (probably better matching)
- Overall performance about the same, slightly worse


CCQCD NEP
NEP(W/Hz^1/2)
P(W)
10^-17
10^-18
10^-19
10^-20
10^-21
10^-22
10^-23
10^-22
10^-20
10^-18
10^-16
10^-14

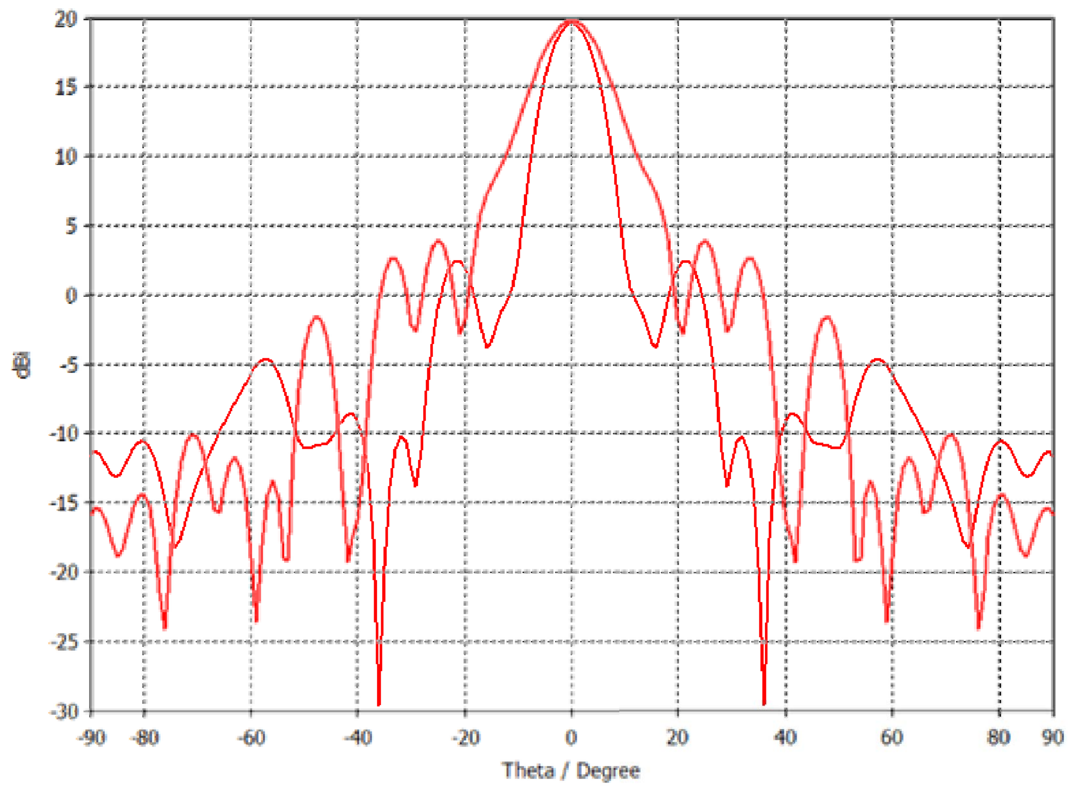
Better antenna design?

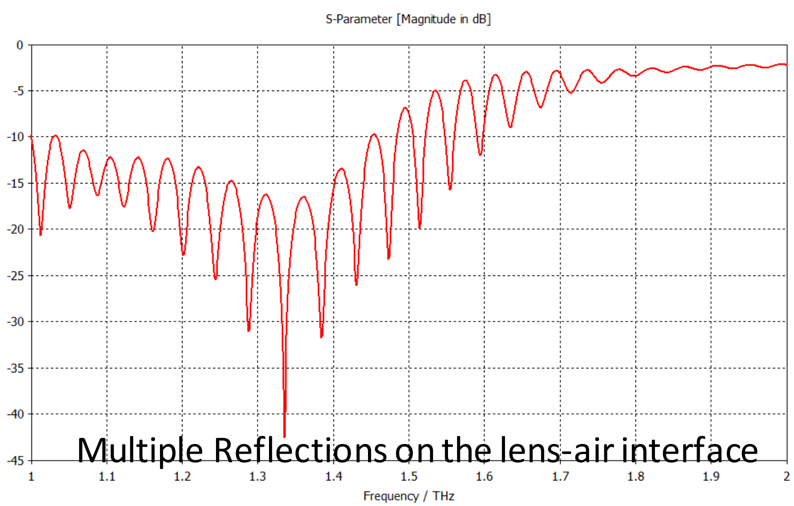


Simulations on the antenna plus Fresnel lens

Far Field:
Low aperture efficiency: 20%
Lens geometry or double slot antenna illumination?
Center frequency off from 1.5THz (discrepancy between HFSS and CST?)

Far Fields
Low aperture efficiency: 20%
Lens geometry or double dipole antenna illumination?

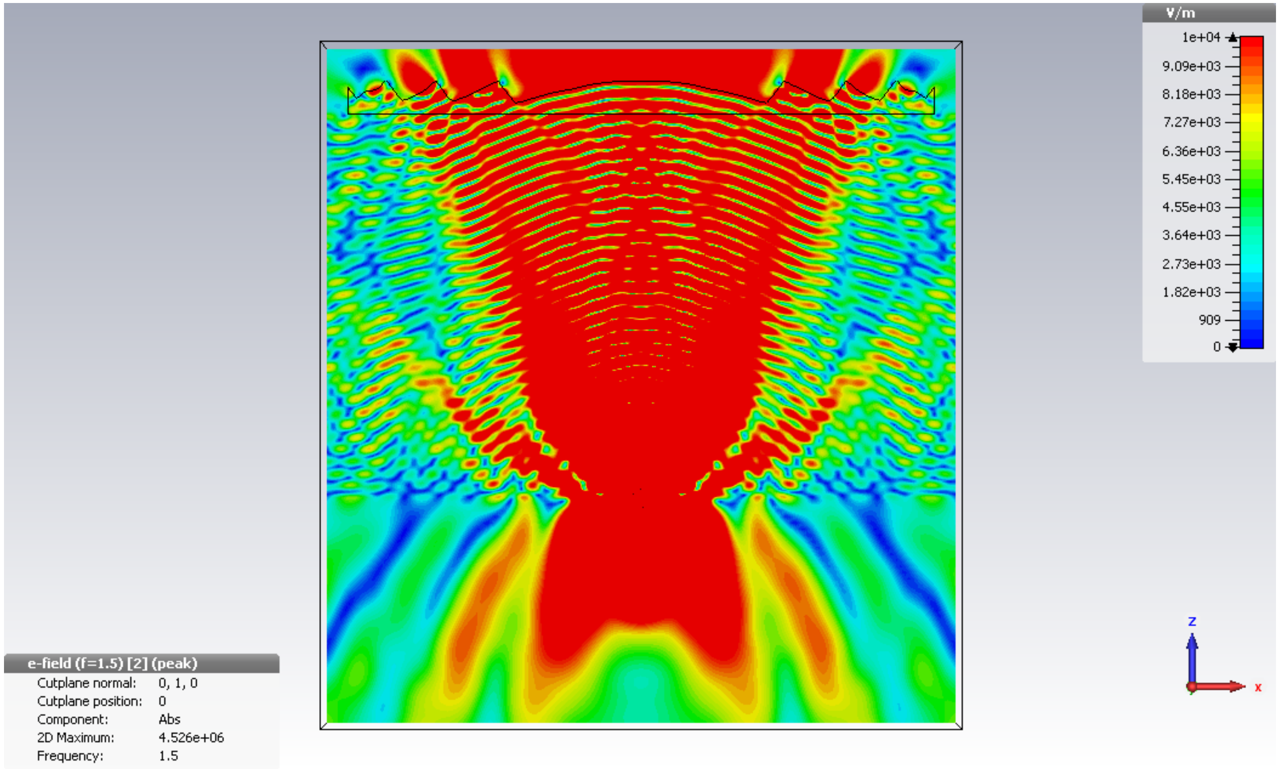




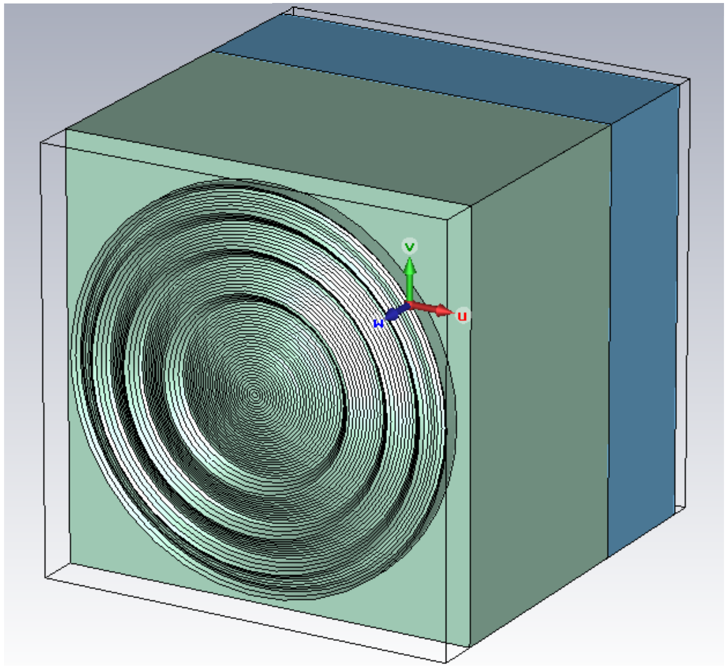
Multiple Reflections on the lens-air interface

Simulations on the antenna plus Fresnel lens

- It seems that the antenna is not illuminating the side of the lens.
- Antenna optimum operating frequency is around 1.2THz. Need to scale its dimensions down to work properly at 1.5THz

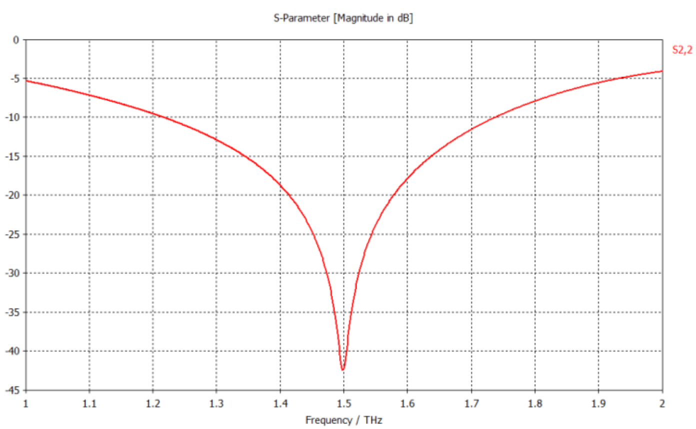


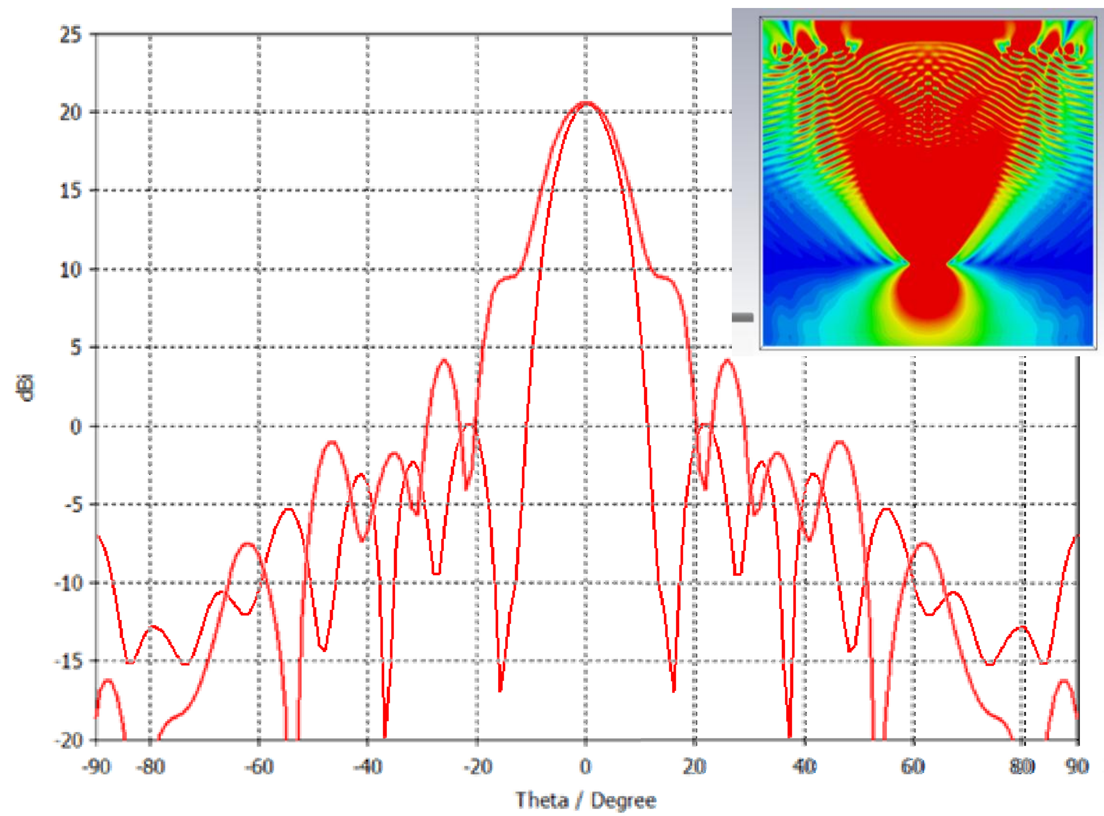
Simulations of new design antenna plus Fresnel lens and QR coating



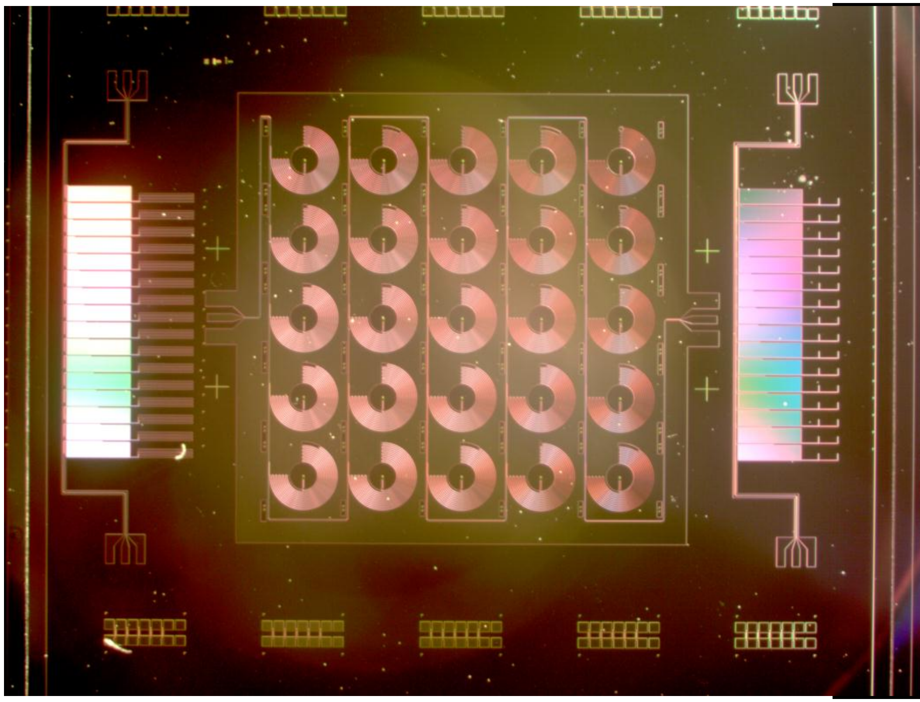
- Less reflection on the lens – air interface
- Use parylene as anti-refection coating
- Antenna dimensions modified to center at 1.5THz

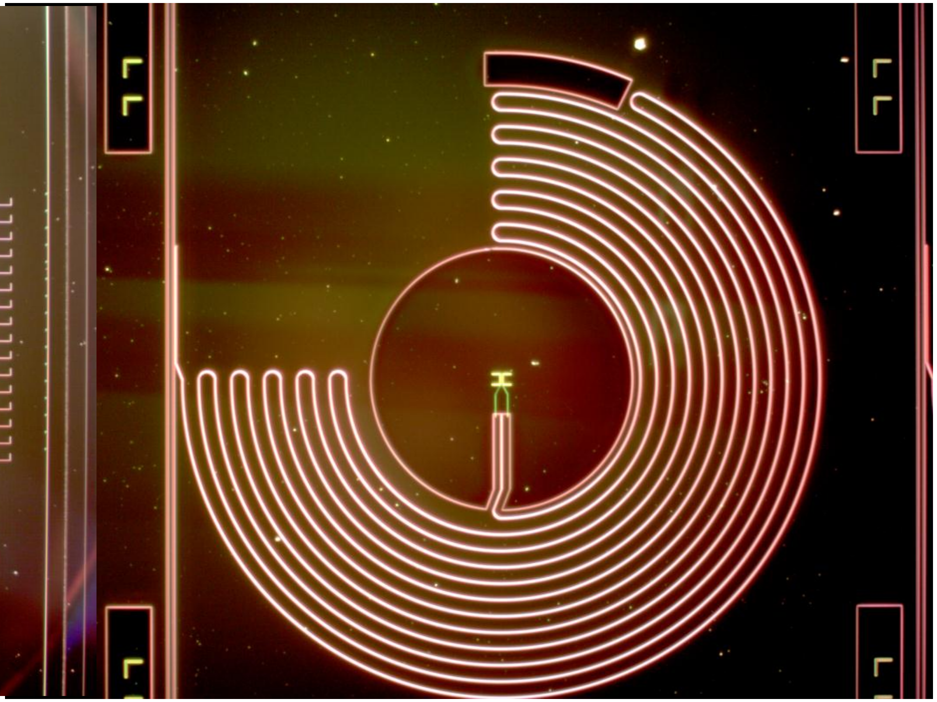
Better antenna illumination, but sill low aperture efficiency (24%)

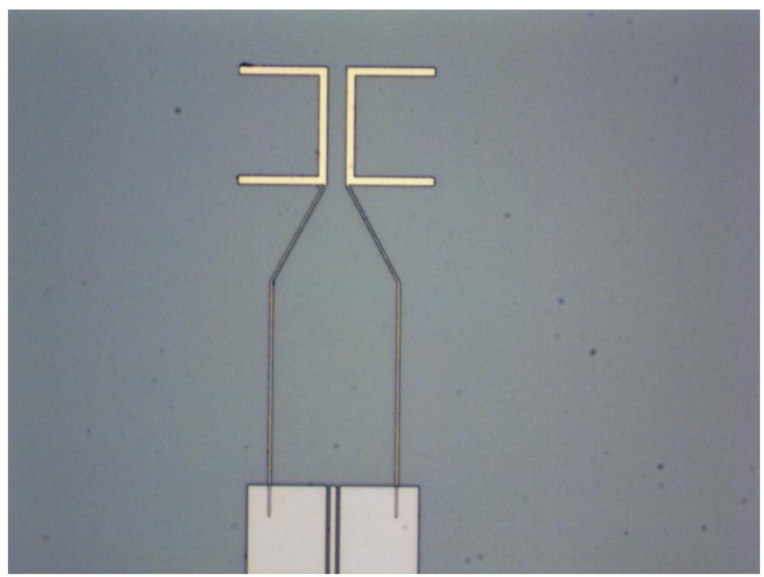




New design in fab







Conclusion

- Achieved photon shot noise limited NEP at 200µm wavelength in a 5x5 array
- Novel way of calibrating absorbed optical power
- Fresnel lenses working
- Introduced special filters to cut down noise through coaxes
- Capacitively coupled QCD results show quasiparticle trapping seems to work well in regular QCDs
- Next
  - Redesign antenna for better efficiency
  - Tweak Fresnel lens fabrication for better lens profile