Superconducting Micro-resonator Arrays for Far-infrared Detection

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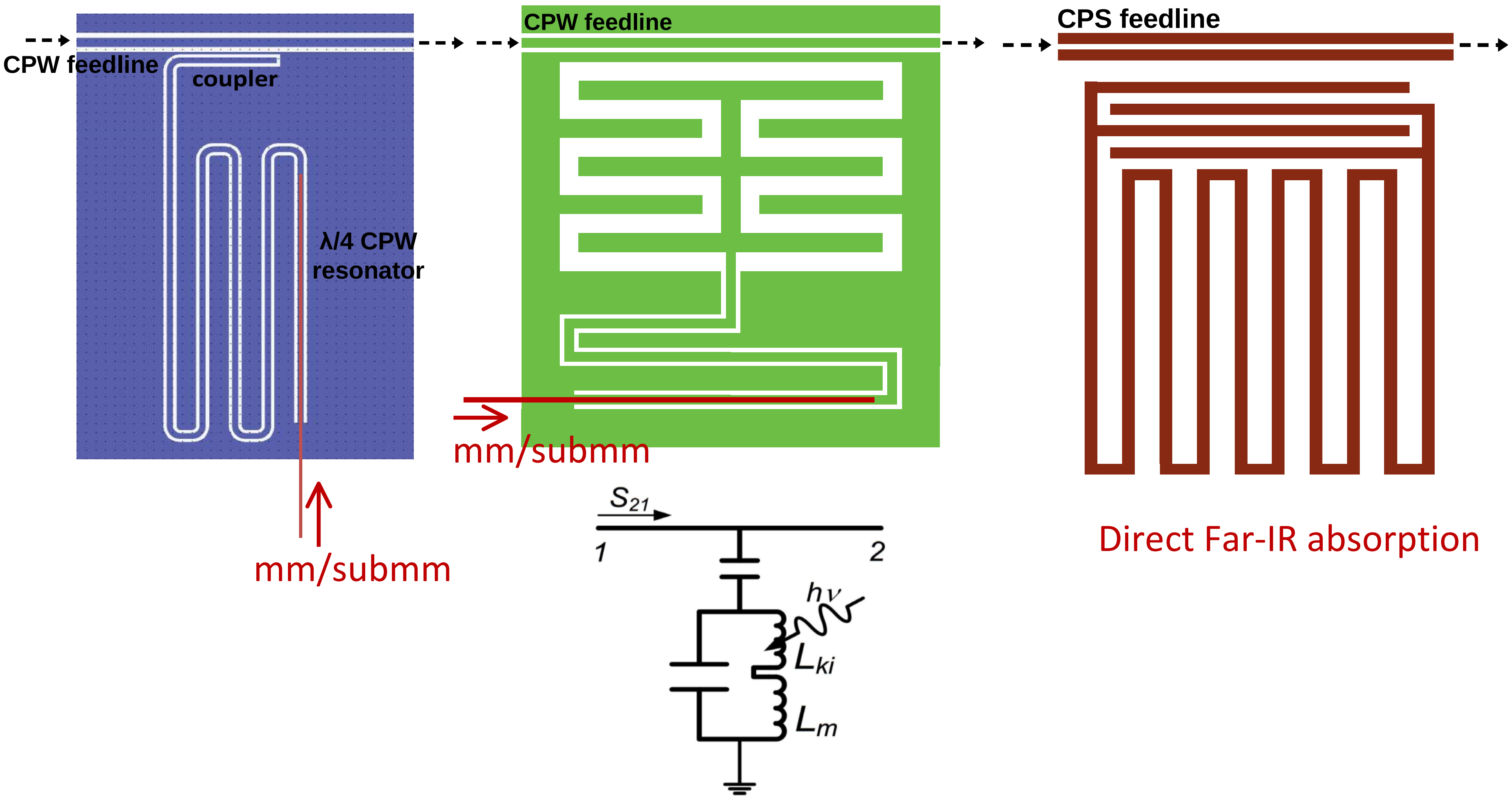
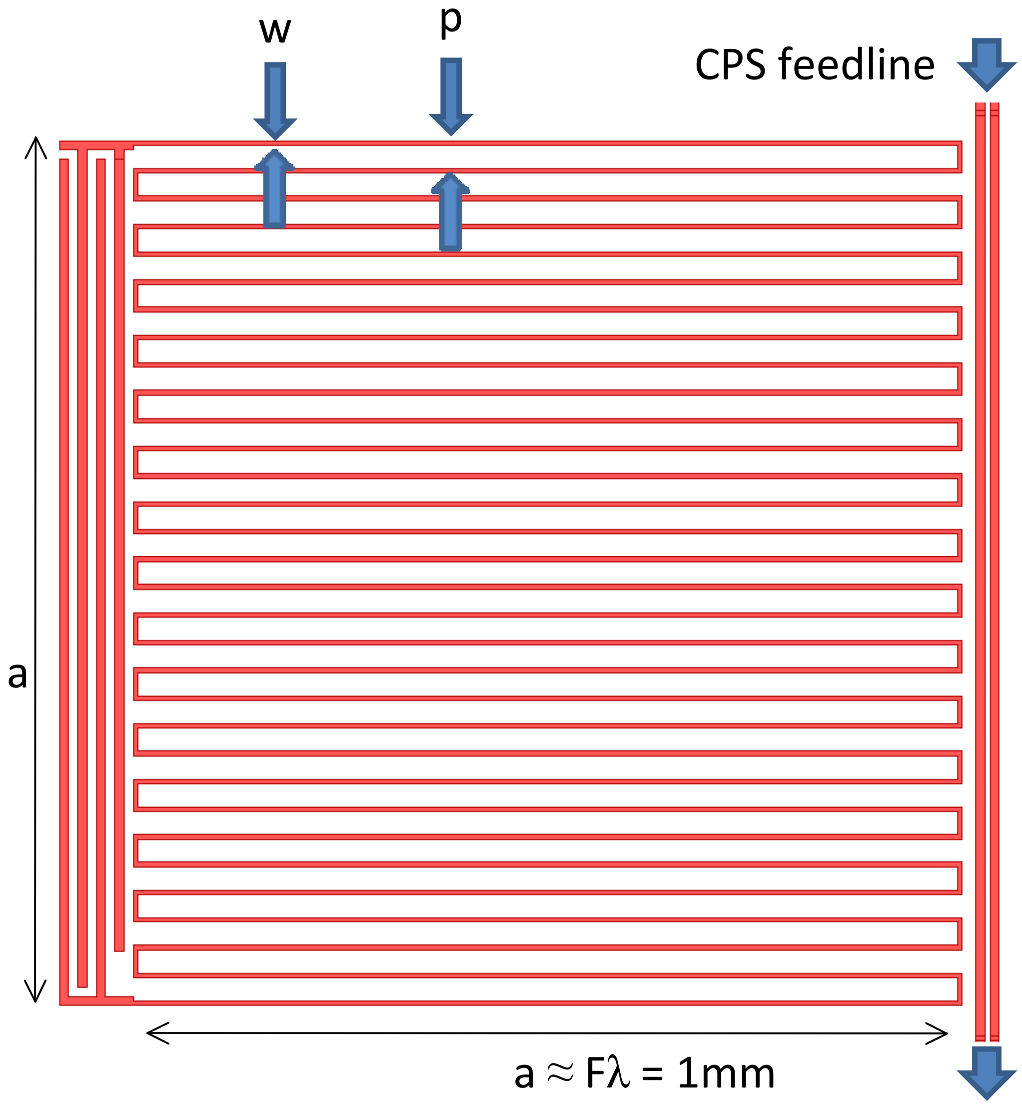
Resonator designs for MKIDs

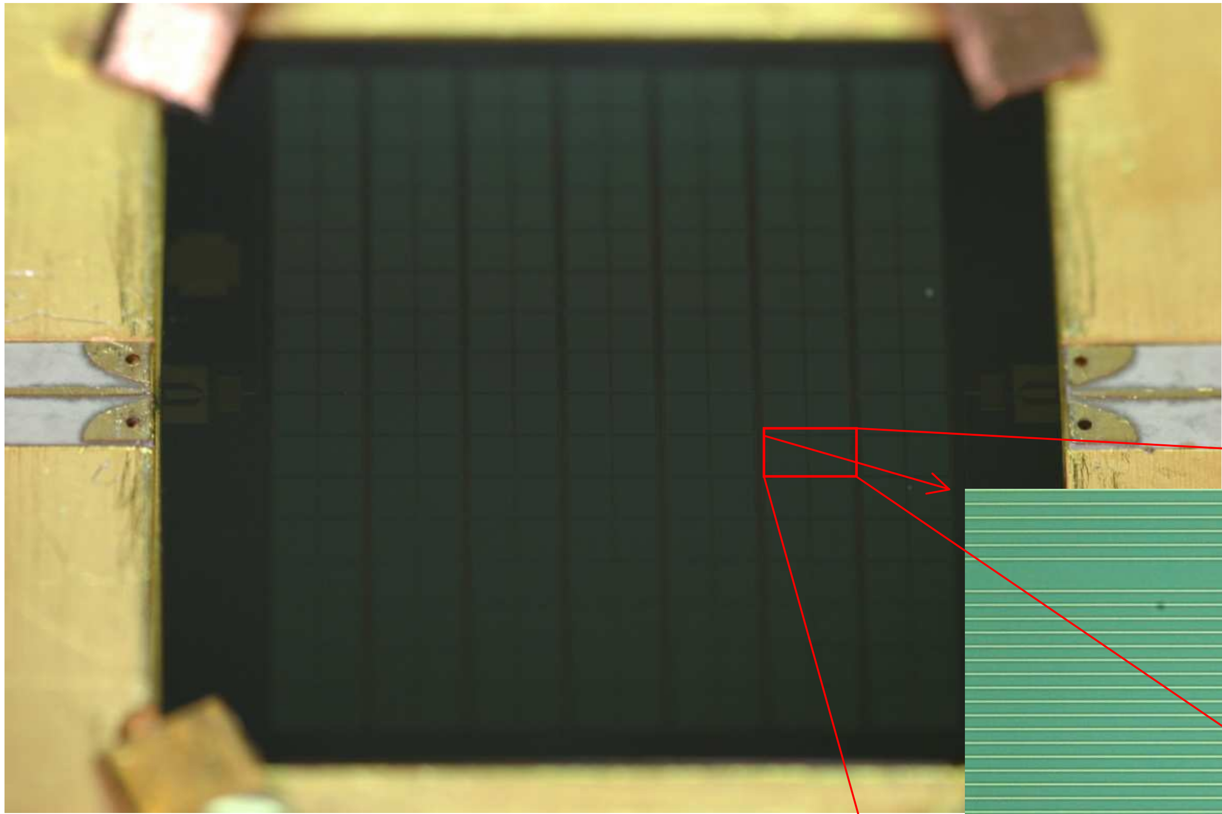


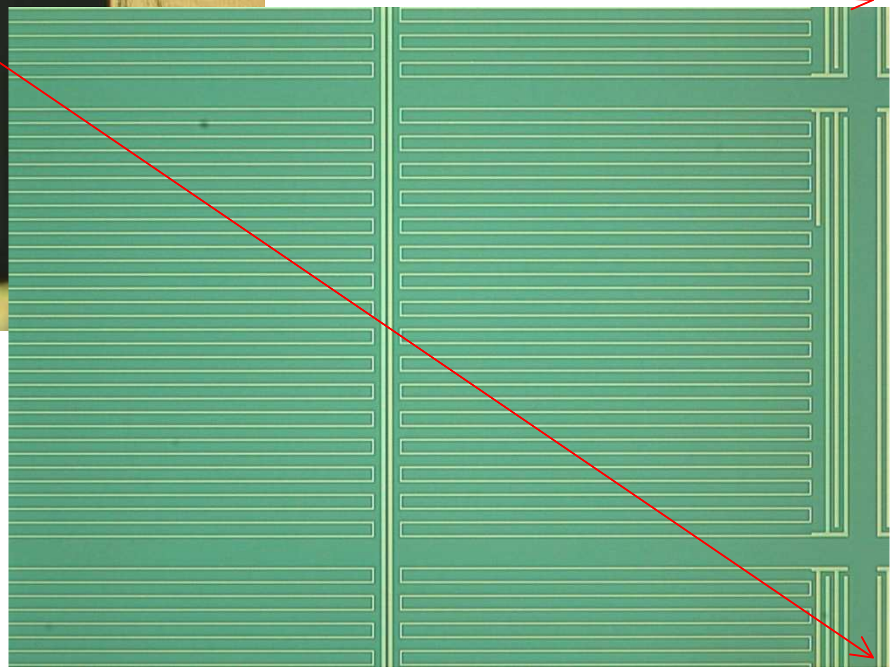
Our first far-IR pixel design (A)



- Cardiff style lumped element resonator
  Doyle et al, J. Low Temp. Phys. 151, 2008
- TiN film on Silicon substrate
  t = 40 nm, Rs ~ 20 Ω/sq, Tc=4.5 K
  LeDuc et al, APL 97, 2010 (JPL, Caltech)
- 90% inductor area, 10% capacitor area
- High impedance CPS feedline
- Inductive or capacitive coupling,
  Qc ~500,000
- Impedance match for direct optical absorption: $R_s = \frac{377\Omega}{1+\sqrt{\epsilon_{Si}}} \times \frac{w}{p}$
  λ(optical) ~ 350 microns

First far-IR array: design (A)



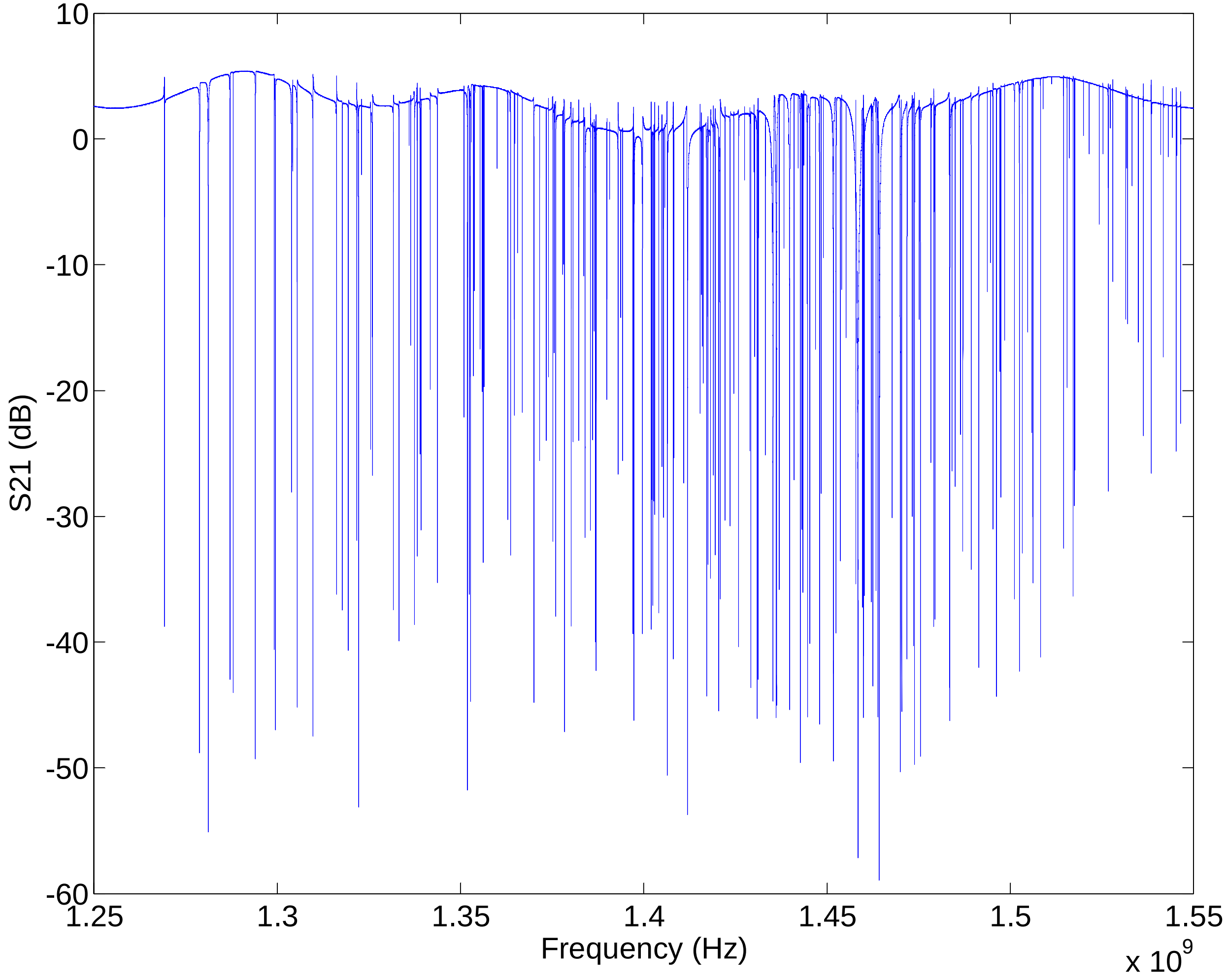


- 16 x 14 = 224 resonators

- Resonators tightly packed in space (for efficiency) and in frequency (for multiplexing):

  Spacing = 60 um, Δf = 1 MHz,
  Coupling Q ~ 500,000.

Measurements: array design (A)



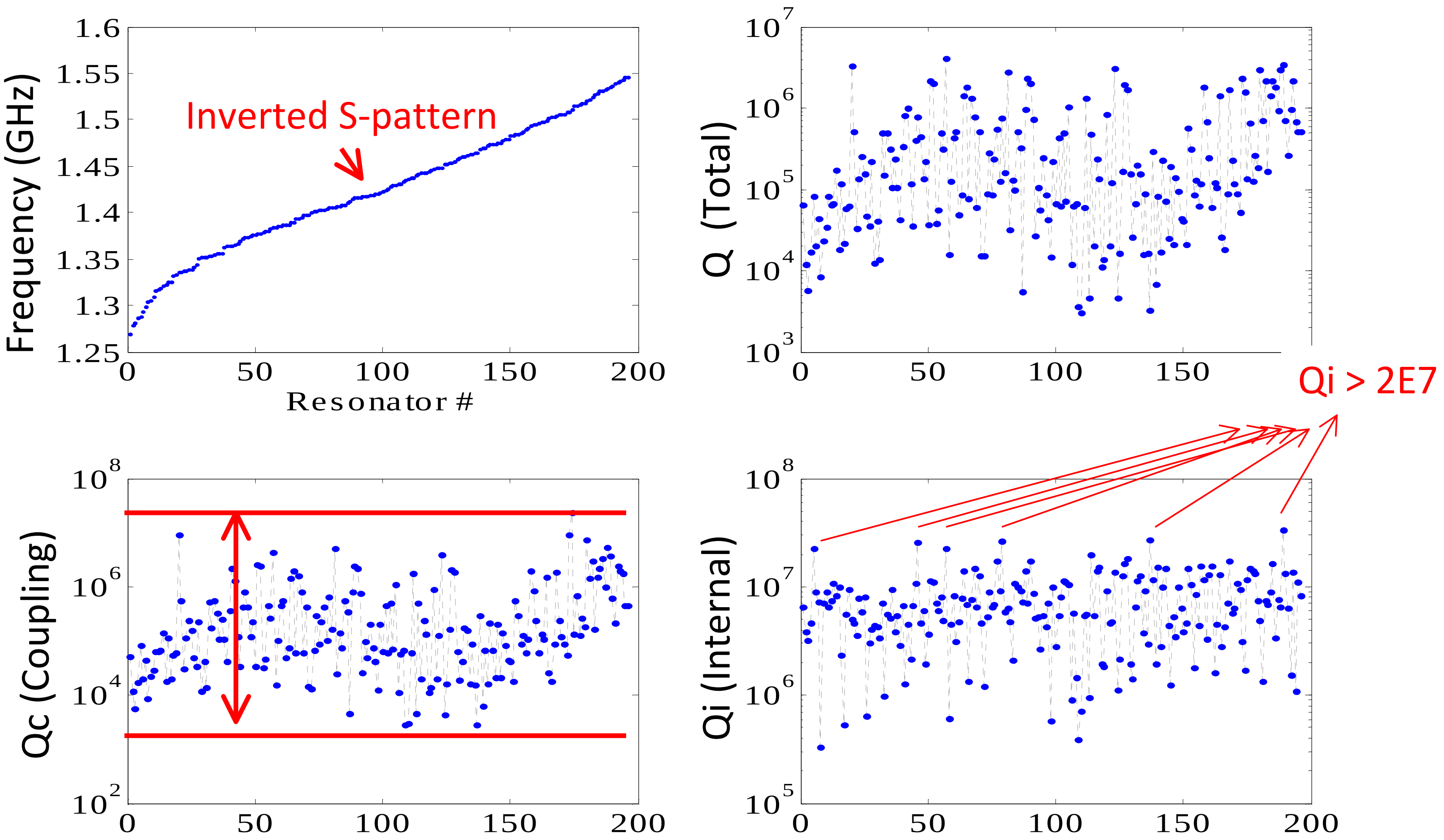
- 210 resonators showed up (out of 224)
- Feedline power = -90 dBm
- Temp = 100 mK
- Range ~ 1.25-1.55 GHz
- Tc = 4.1 K

Measurements: array design (A)

- S-shape pattern in frequency vs. number plot.
- ~3 orders of magnitude variation in coupling quality factor (Qc).

cross-coupling??

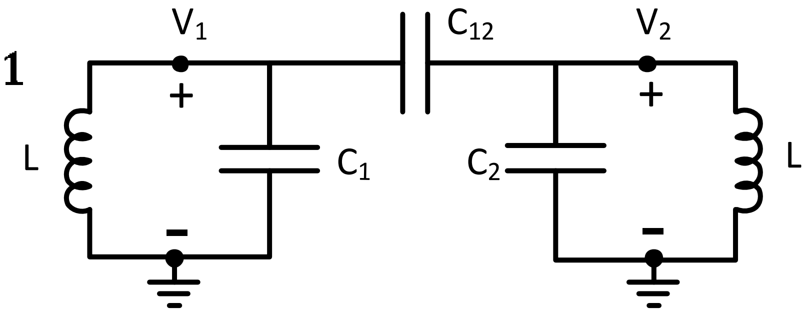
- Extremely high internal Q (Qi $\leq 3.1 \times 10^7$).



Resonator Crosstalk

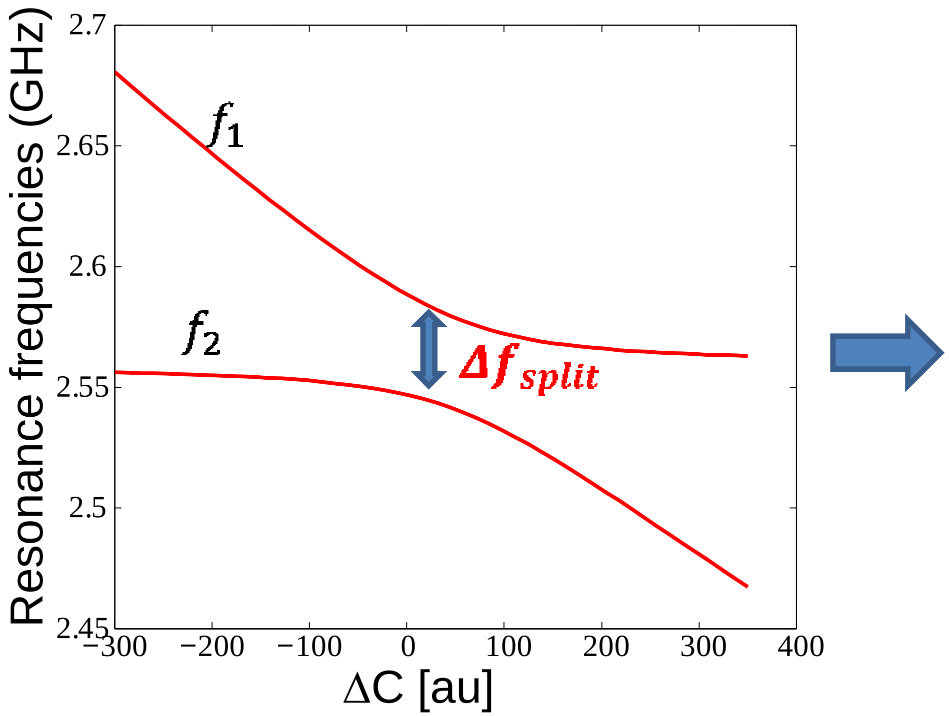
Crosstalk: simple model

Uncoupled: $C_{12} = 0 \;\rightarrow\; f_{0n} = 1/2\pi\sqrt{LC_n} \quad , n = 0{,}1$



Coupled: $f_n = 1/2\pi\sqrt{L\lambda_n}$

$\lambda_n = \overline{C} + C_{12} \mp \sqrt{{C_{12}}^2 + (\Delta C)^2/4}\;, \quad \rightarrow$ Frequency eigenvalues: f_1, f_2



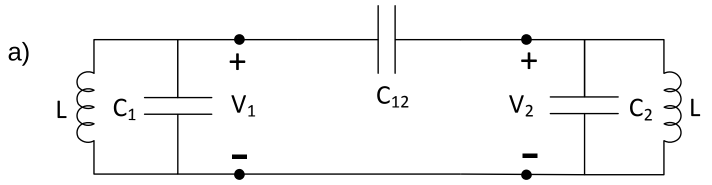
A measure for cross-coupling:

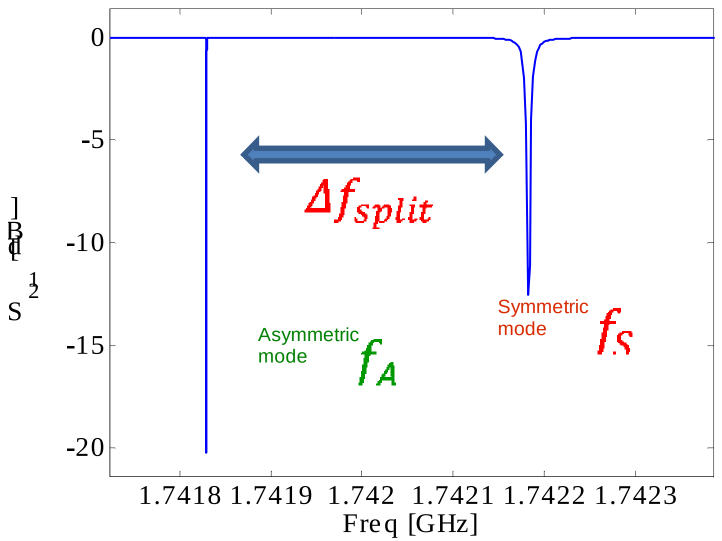
Coupling "energy": Δf_{split}

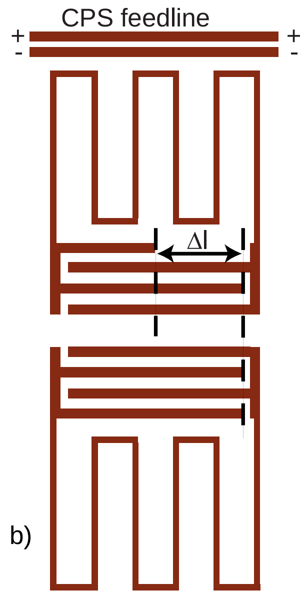
Crosstalk: simple model

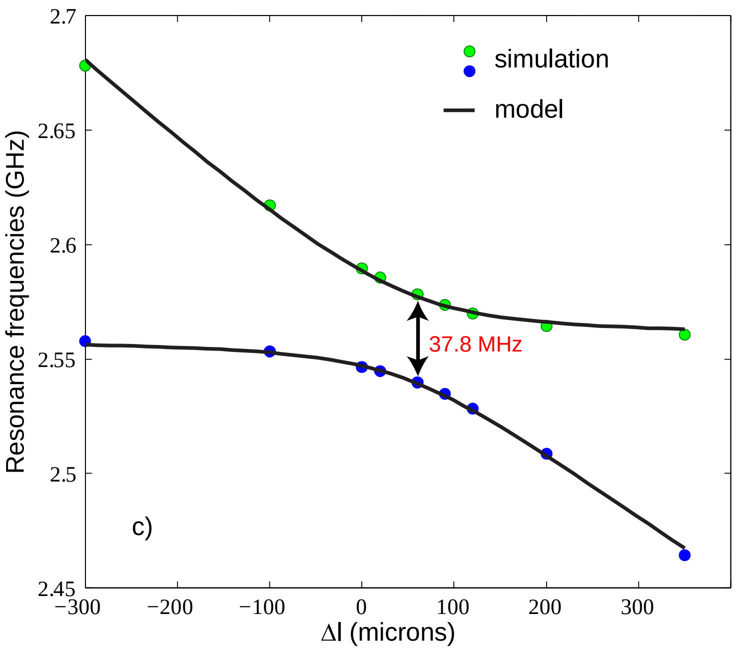
If: $C_1 = C_2 \rightarrow \begin{cases} \lambda_1 = C_1 \rightarrow f_S & \text{(Symmetric)} \\ \lambda_2 = C_1 + 2C_{12} \rightarrow f_A & \text{(A-symmetric)} \end{cases}$

$$\Delta f_{split} = |f_S - f_A| \cong \frac{C_{12}}{C_1} \times f_{01} \quad \rightarrow C_{12}$$



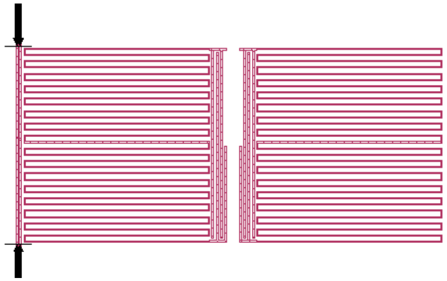




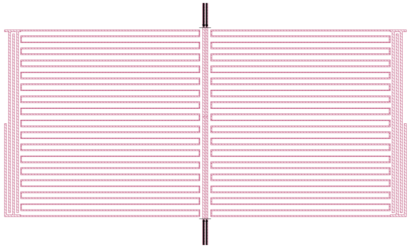


Array simulation for design (A)

Δf =36.2 MHz

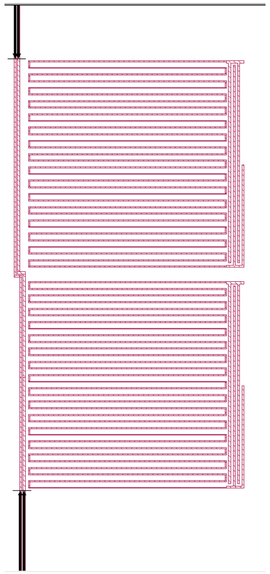


Δf =28.2 MHz

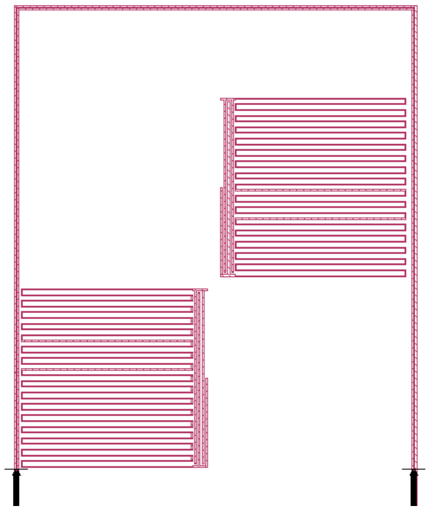


$$\frac{1}{L\omega^2}\begin{pmatrix}V_1\\ \vdots \\ V_N\end{pmatrix} = \begin{pmatrix} C_1+\sum_{j\neq 1}C_{1j} & -C_{12} & \cdots & -C_{1N}\\ -C_{21} & C_2+\sum_{j\neq 2}C_{2j} & & \vdots \\ \vdots & & \ddots & \\ -C_{N1} & \cdots & & C_N+\sum_{j\neq N}C_{Nj}\end{pmatrix}\begin{pmatrix}V_1\\ \vdots\\ V_N\end{pmatrix}$$

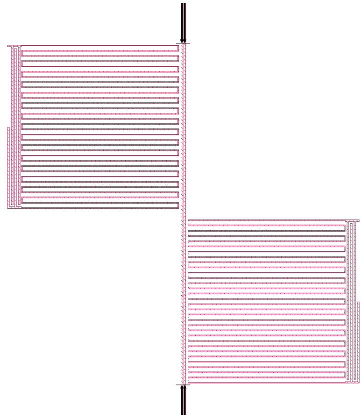
Δf =60.4 MHz



Δf =8.6 MHz



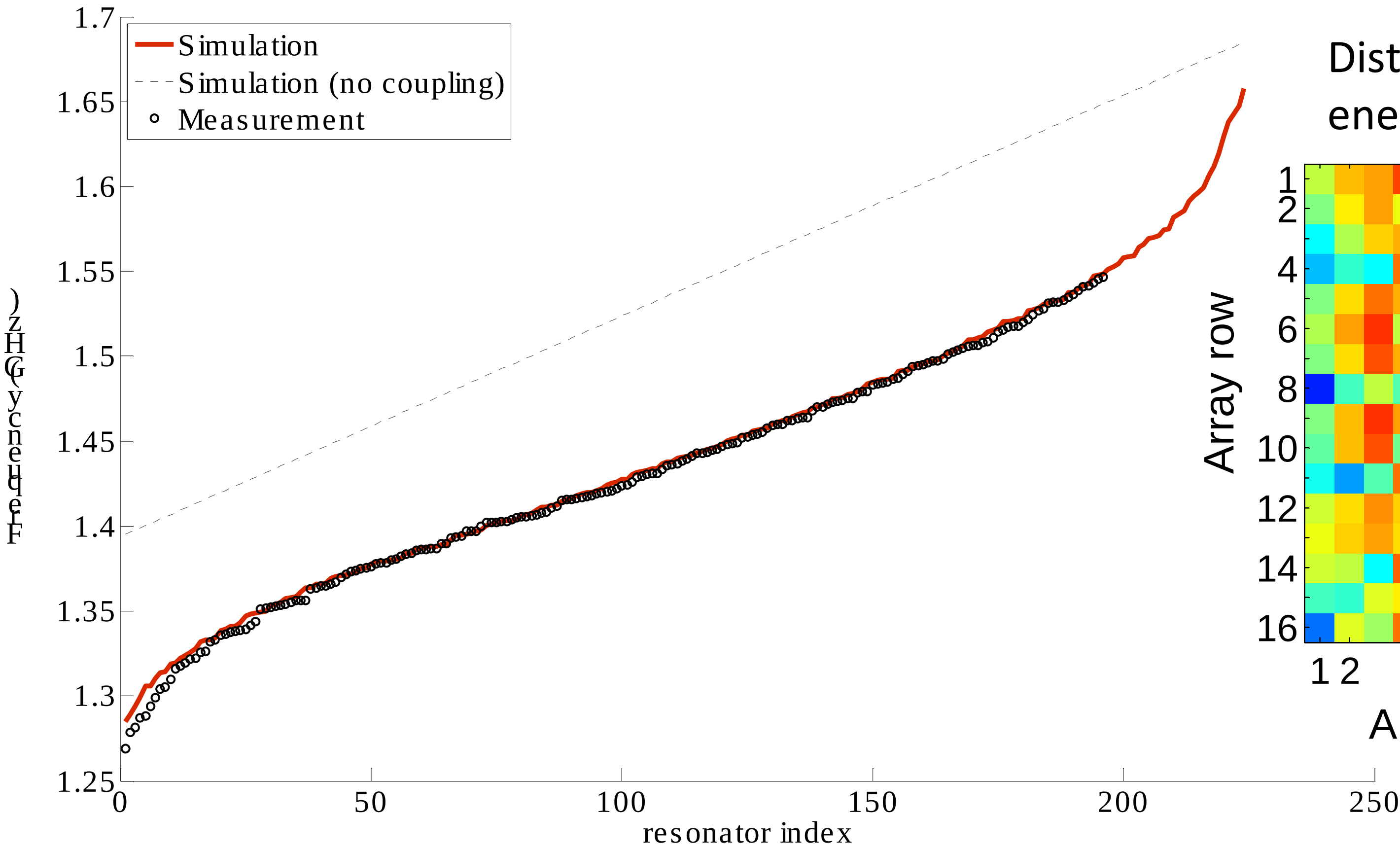
Δf =6.9 MHz

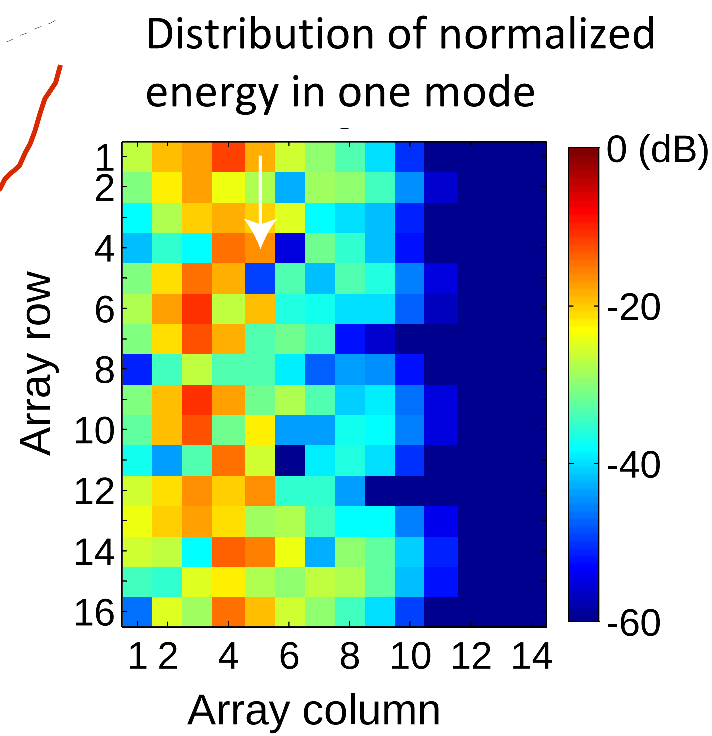


Eigen-frequencies of array

Eigen-frequencies and energy distribution for design (A)

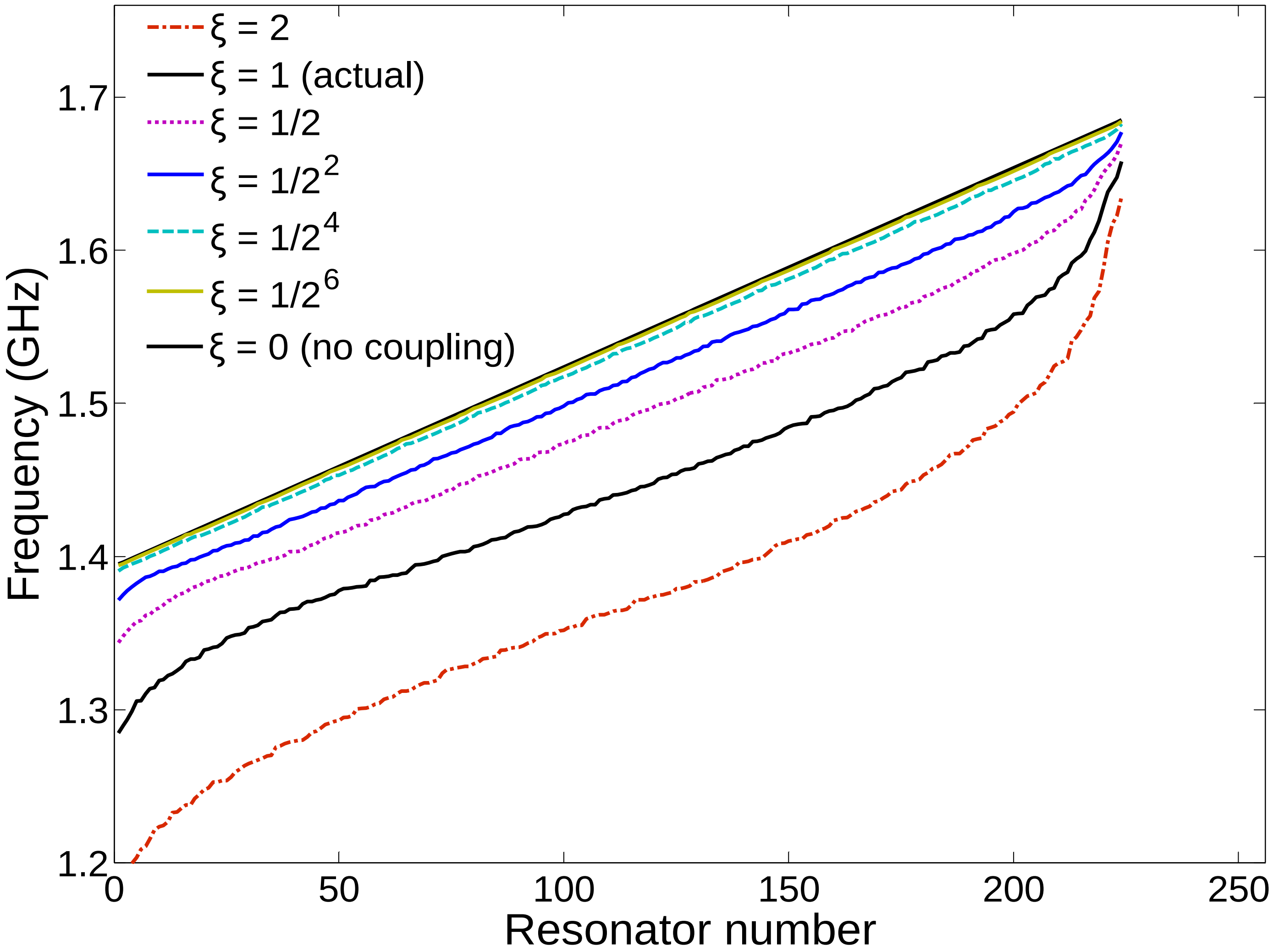
- Simulated circuit model with 16x14 = 224 resonators.
- Using simulated coupling energies, model predicts S-shape pattern in eigen-frequencies!
- Excellent agreement with measurement! (no fitting used).
- Each frequency mode is highly distributed across array → Large cross-coupling



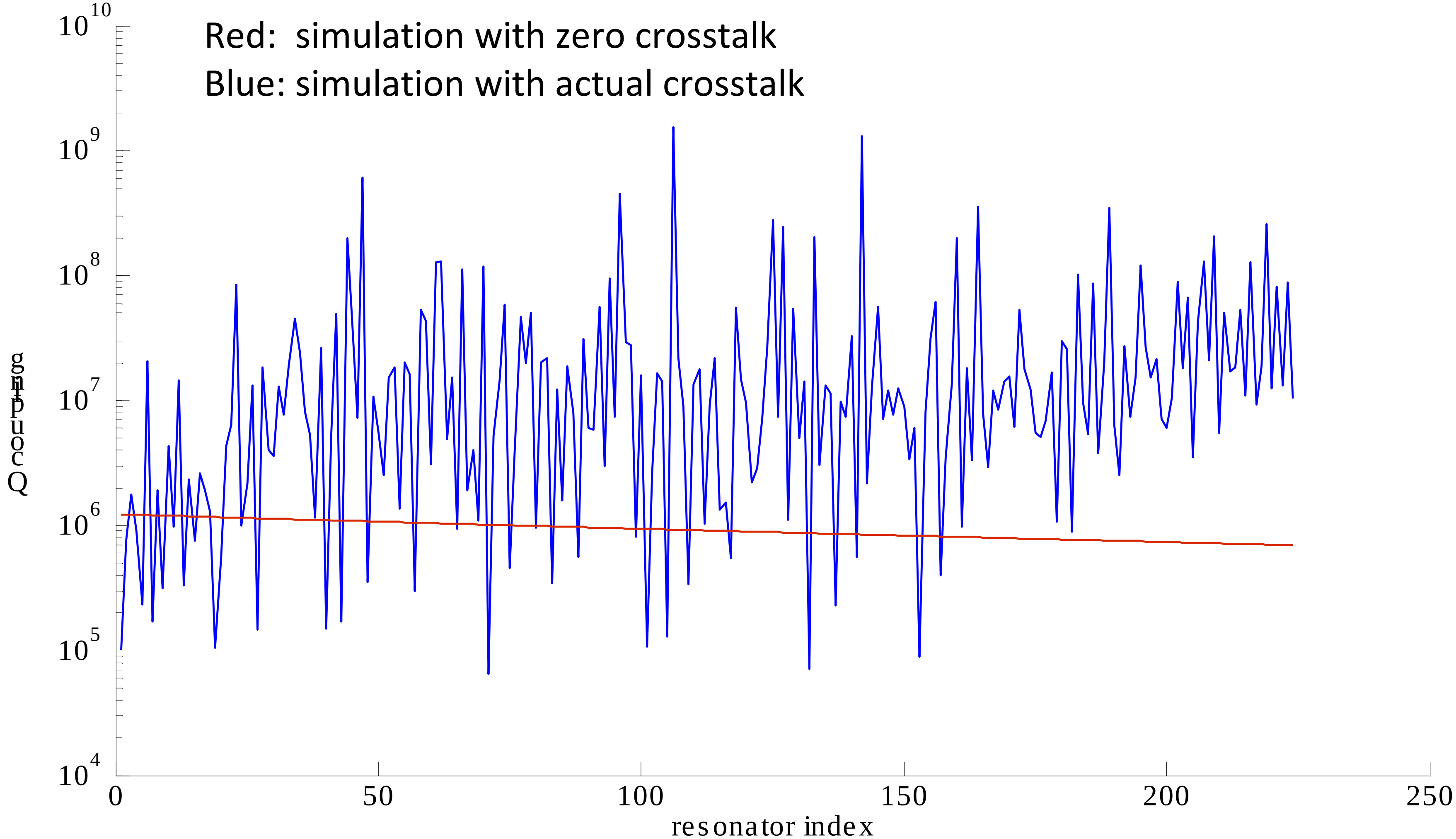


S-pattern in coupled arrays

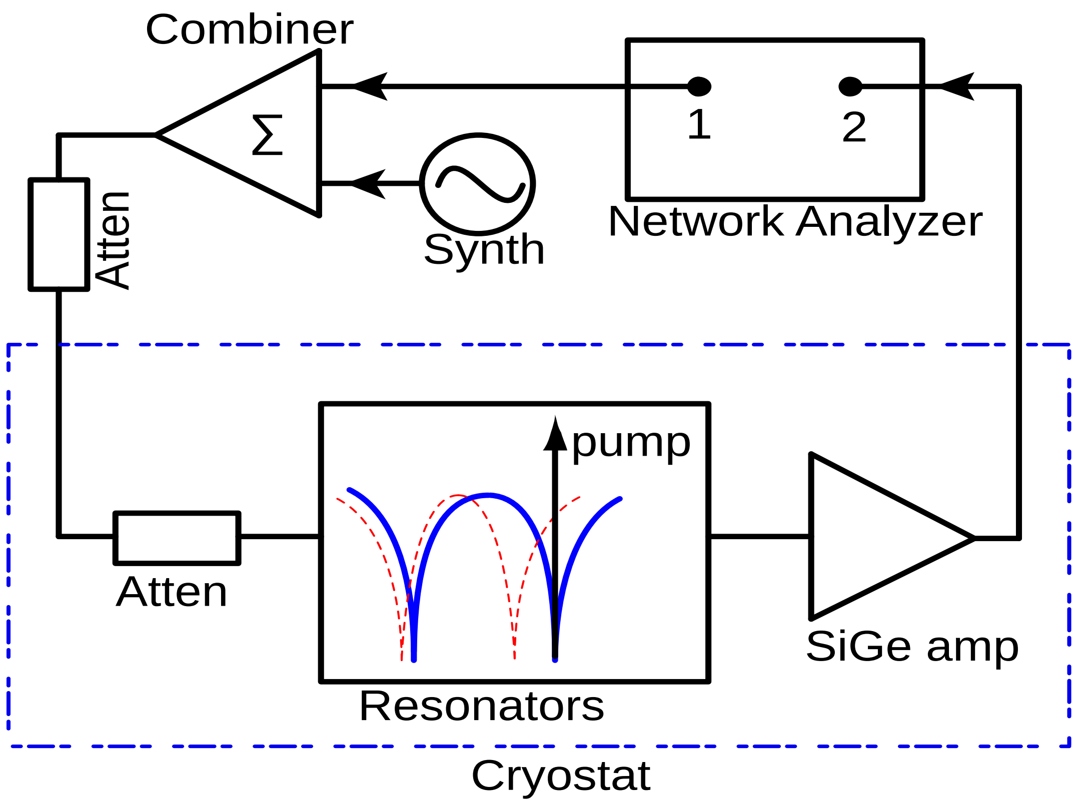
ξ = coupling strength scaling factor



Simulation: effect of crosstalk on Qc for design (A)



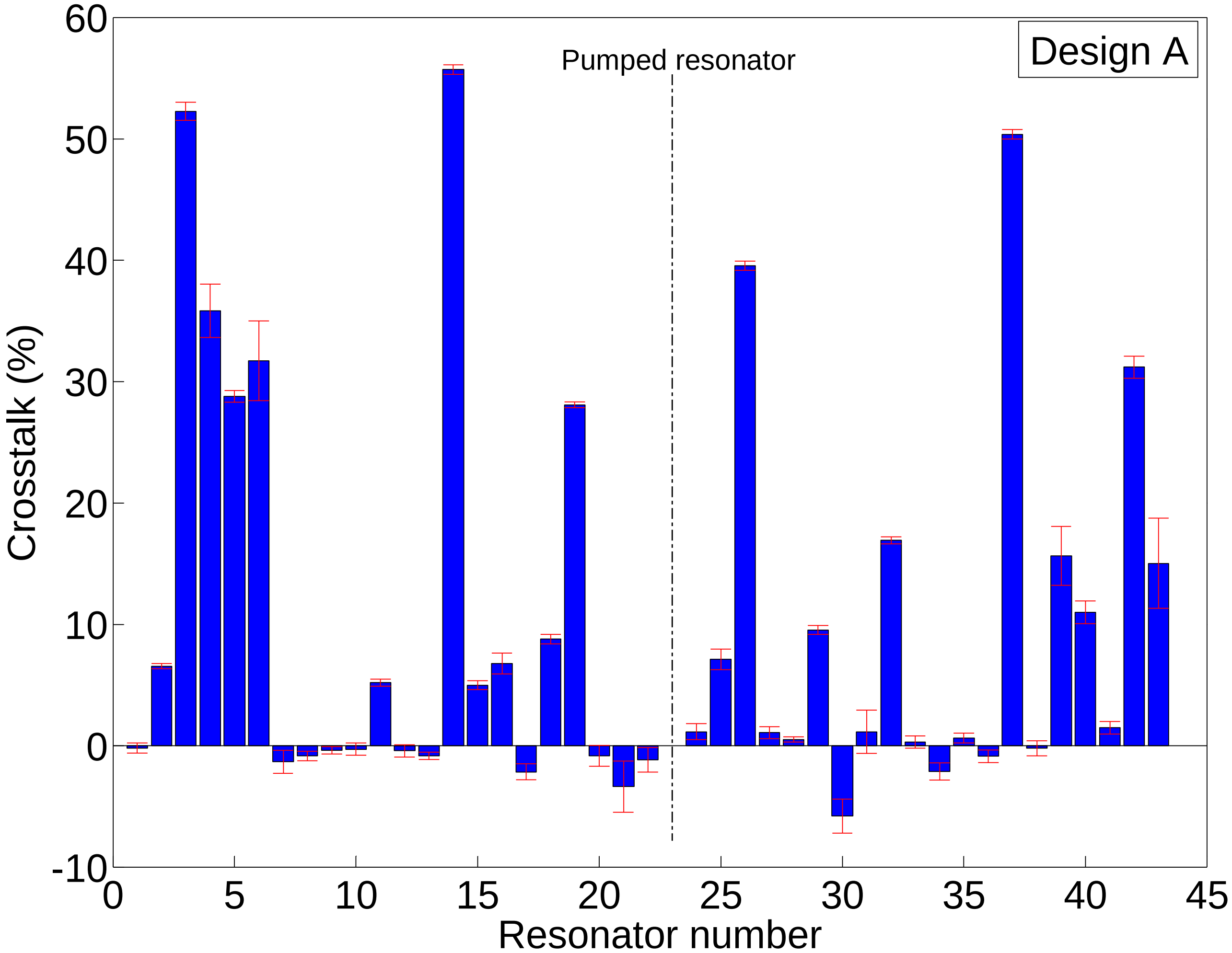
Measuring crosstalk: “pump-probe” experiment



$$Crosstalk \equiv \frac{\Delta f_2}{\Delta f_1} = \frac{\Delta f_{probe}}{\Delta f_{pump}}$$

Crosstalk measurement for design (A)

- Resonances highly coupled together.
- Crosstalk $\leq$ 60% !

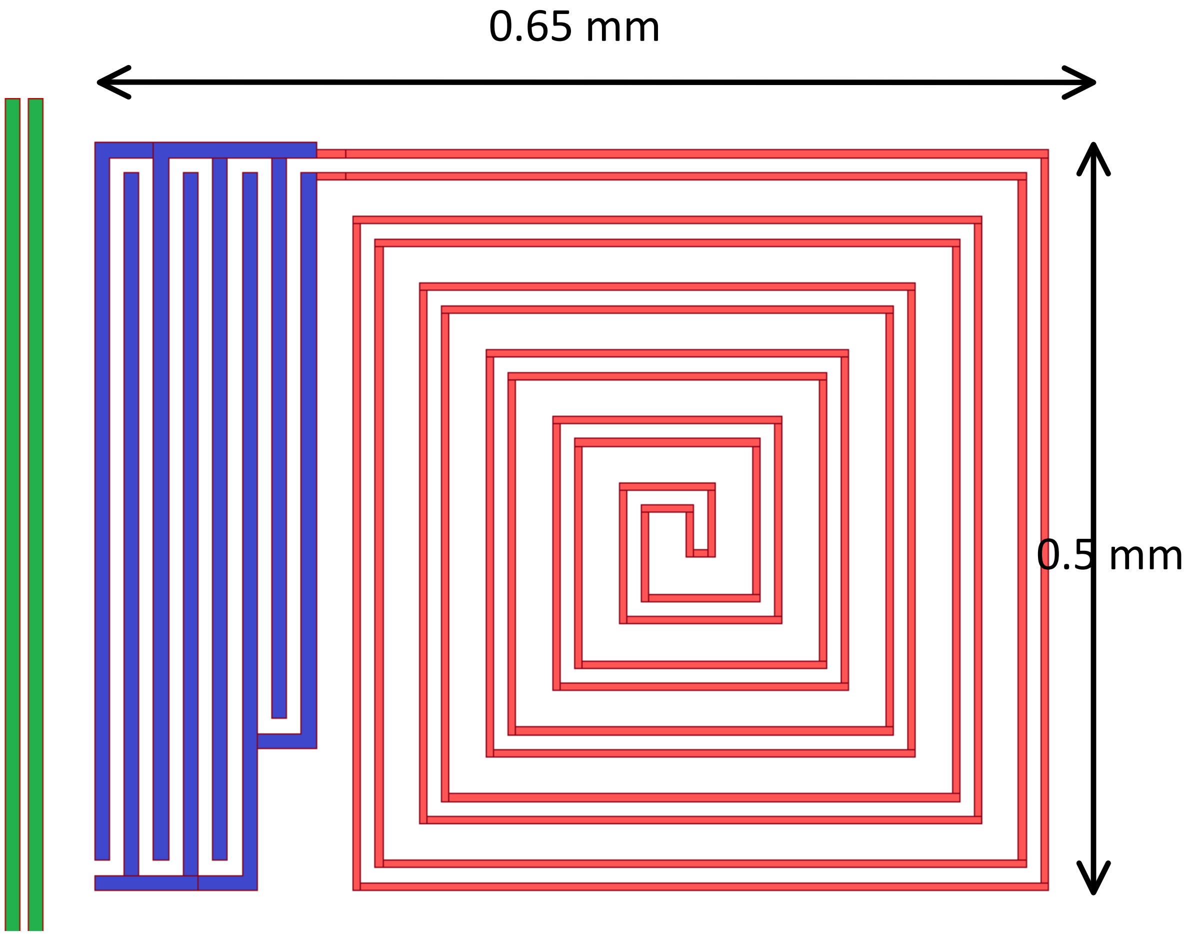


New resonator for reduced crosstalk (design B)

- Close proximity of opposite polarity conductors and charges avoids large electric dipole moments, and results in confined fields.

Reduced cross-coupling

- Spiral design for dual polarization absorption



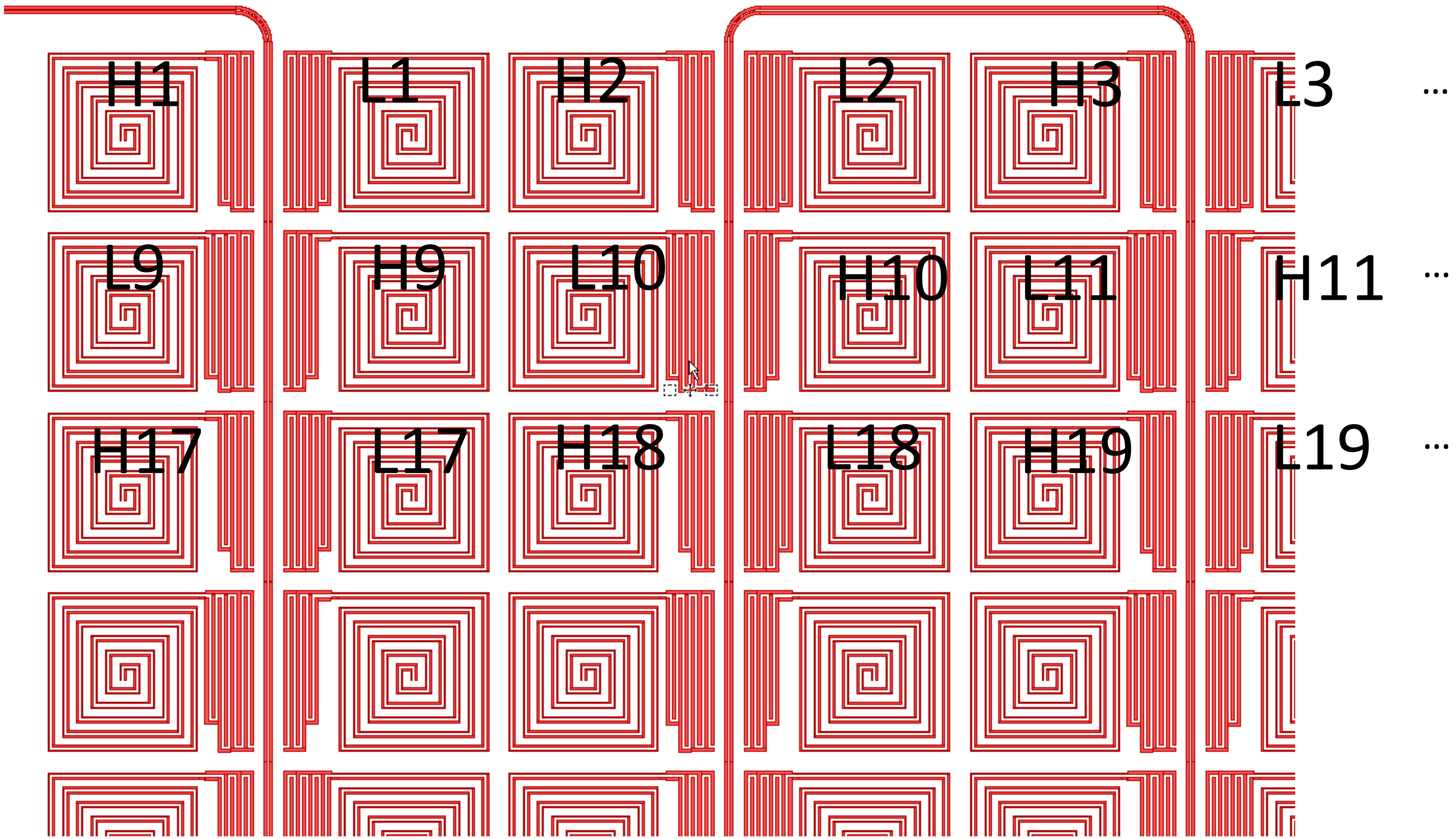
Comparison of coupling strengths in design (A) and (B)

COUPLING SPLITTING FREQUENCIES

Design A		Design B	
Configuration	[illegible] (MHz)	Configuration	[illegible] (MHz)
	36.2		0.20
	60.4		1.75
	8.6		0.25
	28.2		1.18
	6.9		0.35

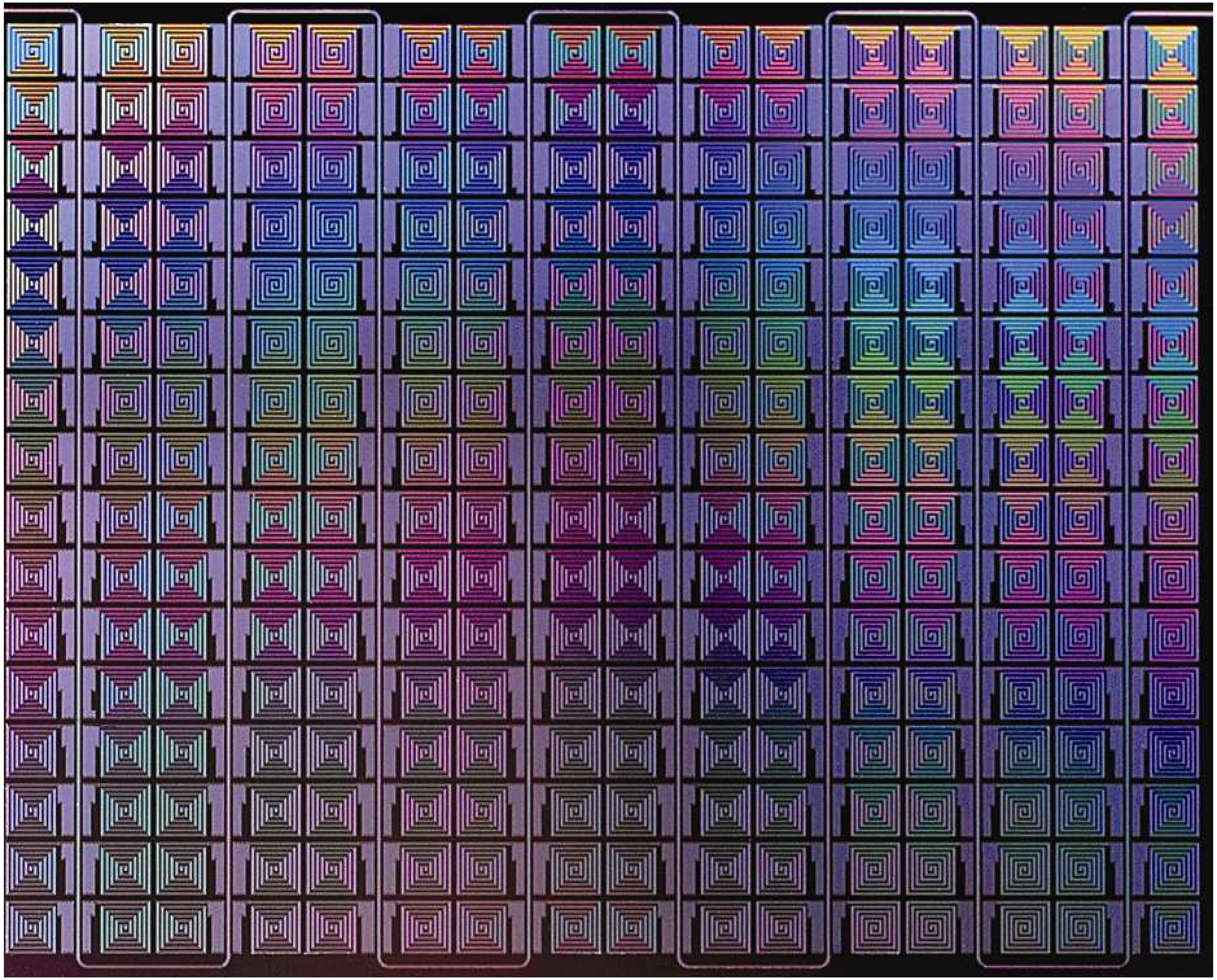
New array design (B)

- High fill-factor array of dual-pol resonators
- Checker-board frequency coding to reduce crosstalk



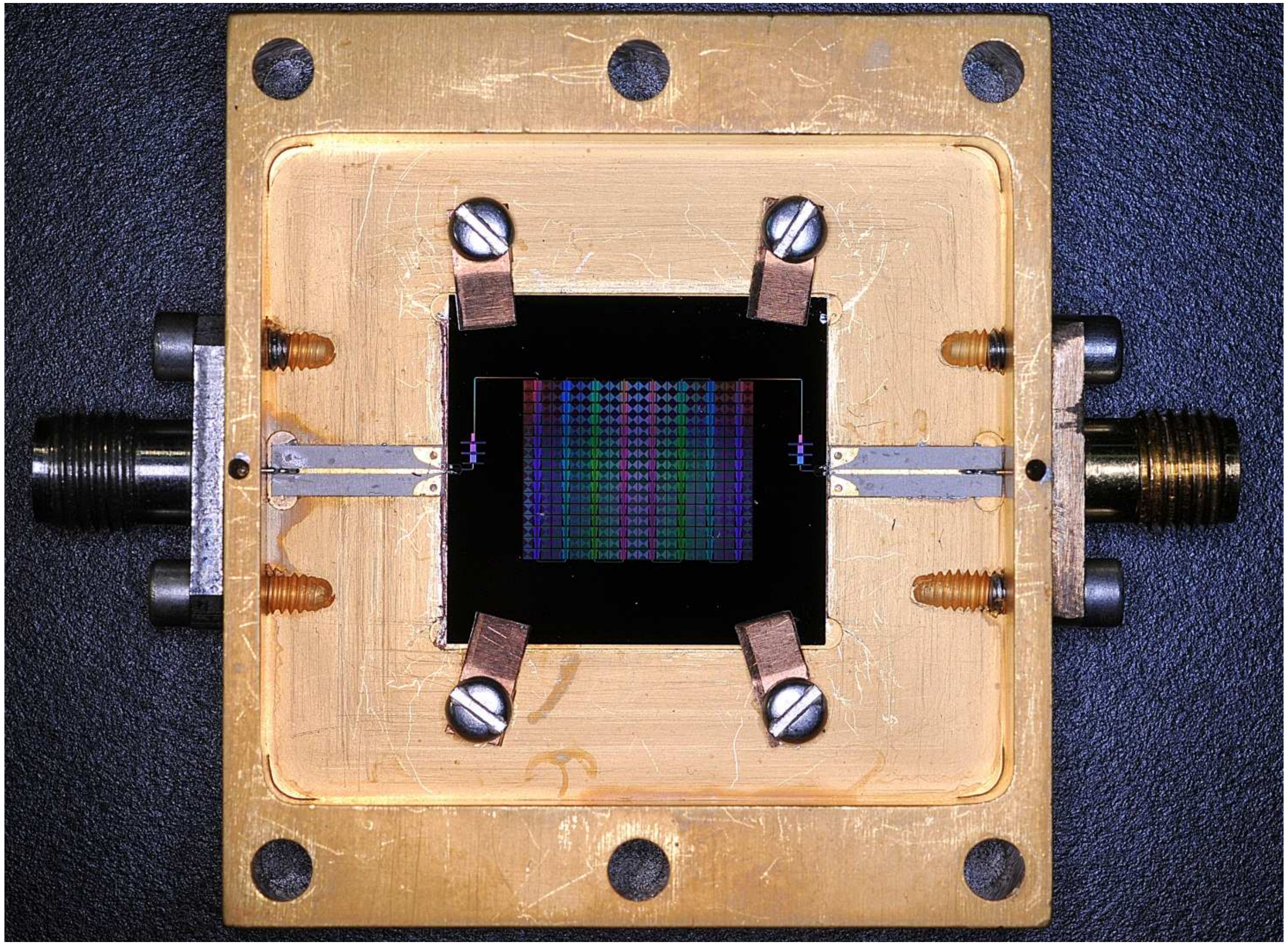
Hn = nth frequency in high frequency band
Ln = nth frequency in Low frequency band

Initial array with resonator design B (16x16)

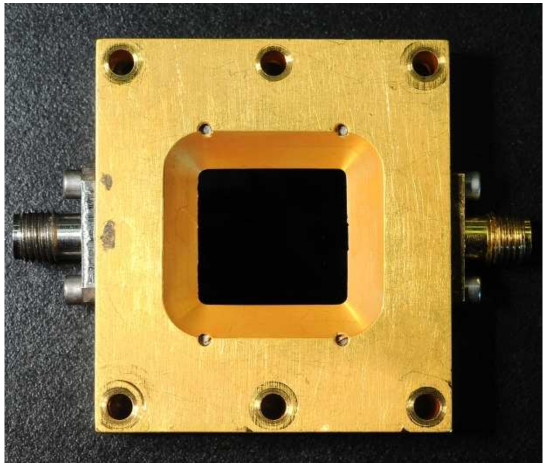


Mounting box

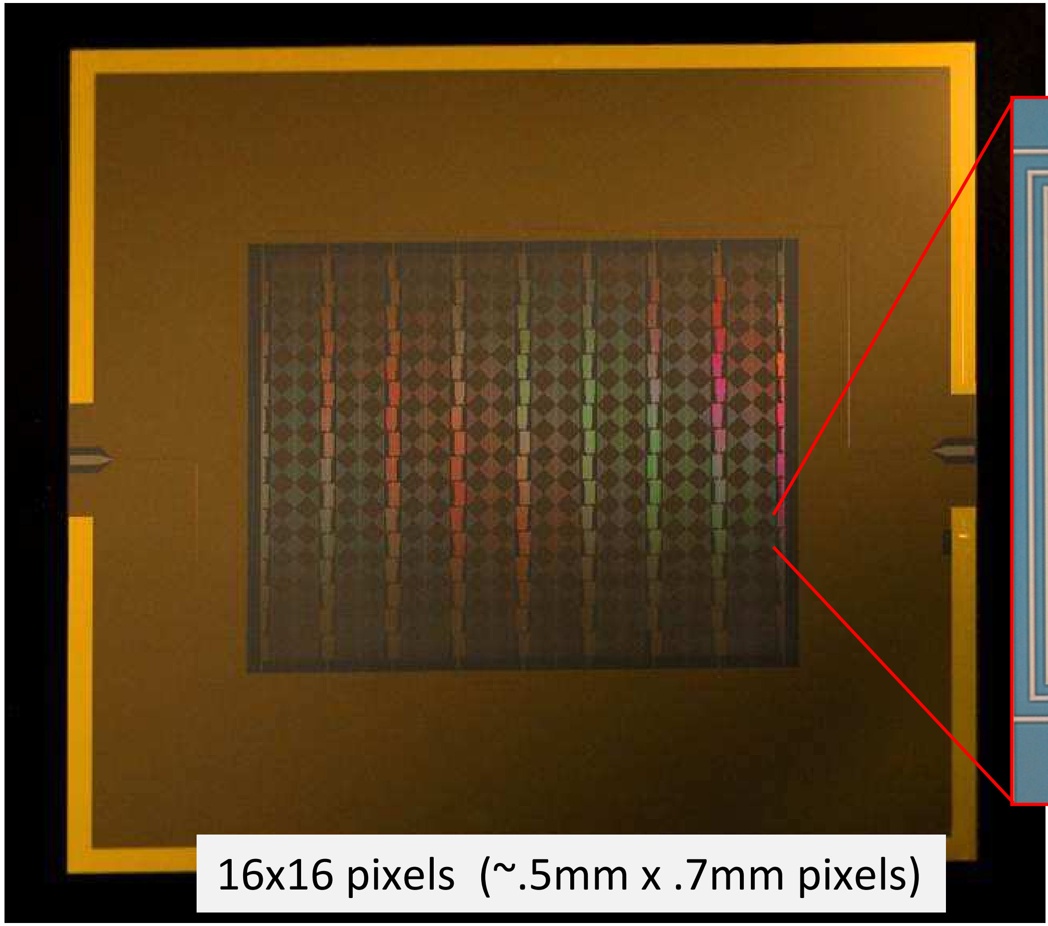
Front side

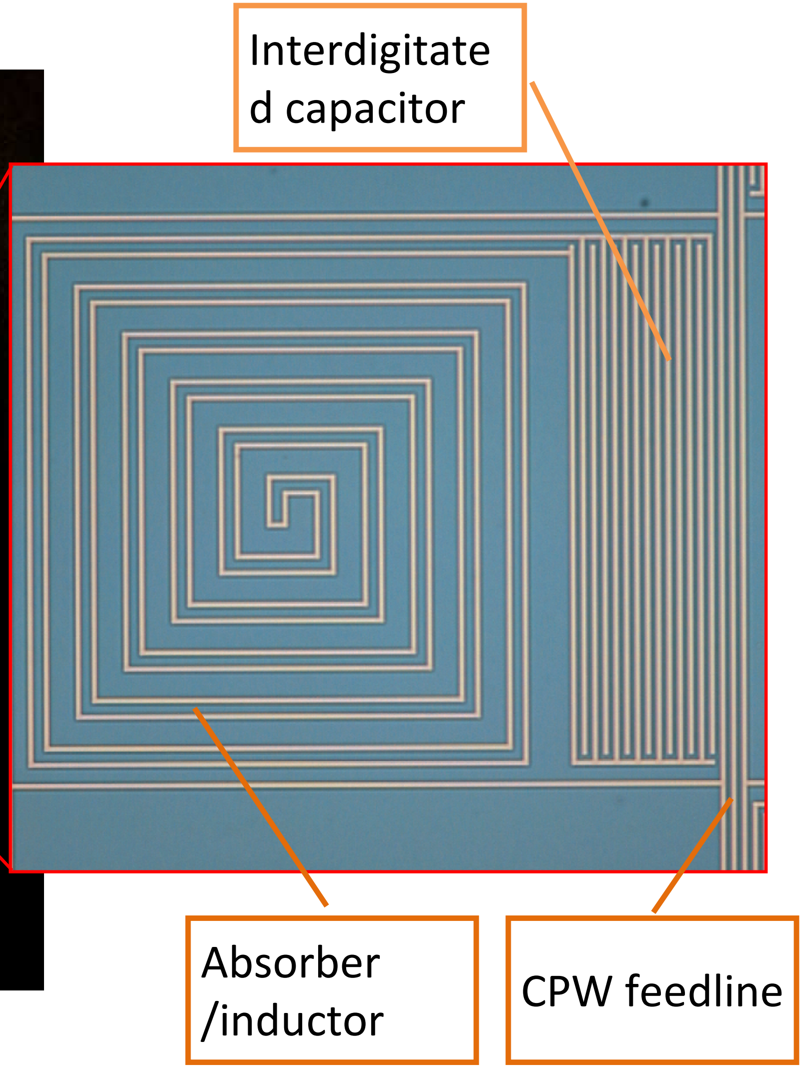


Back side (illumination side)



Latest array with resonator design B (16x16)

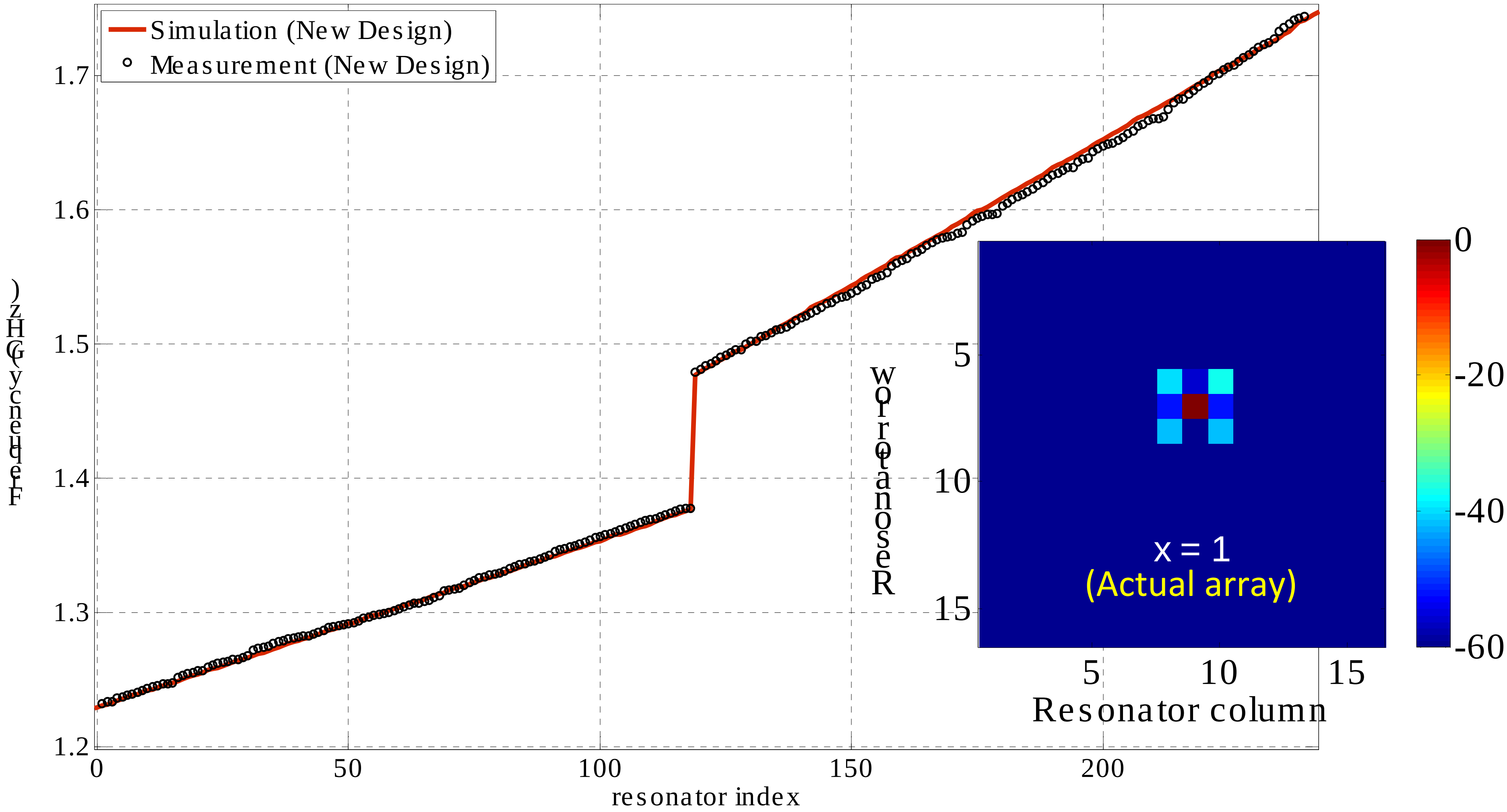




Modifications:
- CPW + ground straps
- Nb feedline (only centerline)
- Gold edge + gold wirebonds

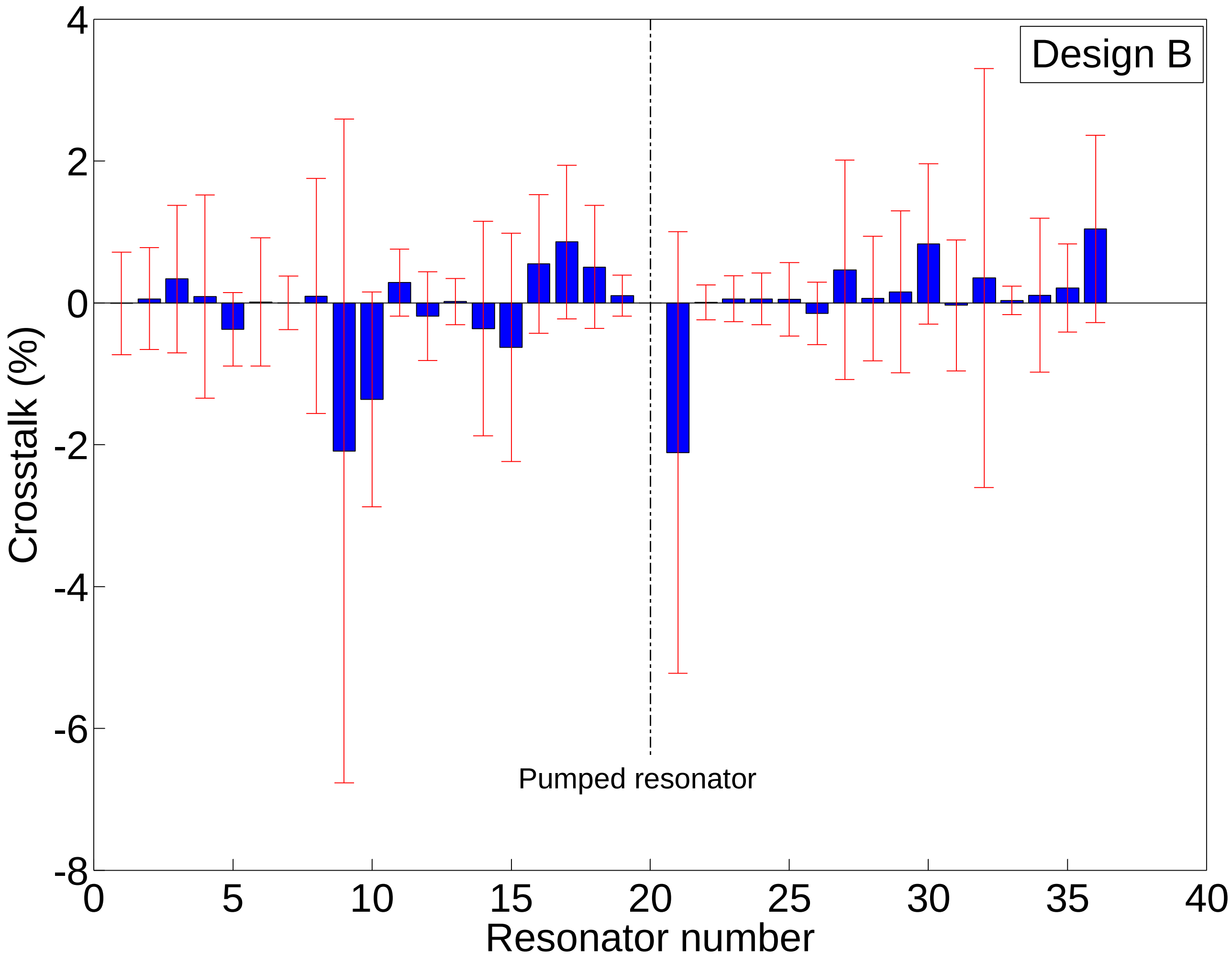
Eigen-frequencies and energy distribution for design (B)

- Much more uniform frequency spacing between 256 resonators.
- Inverted S-shape almost disappeared.
- Nearest neighbor pixels have at least ~40 dB lower energy. → No cross-coupling.

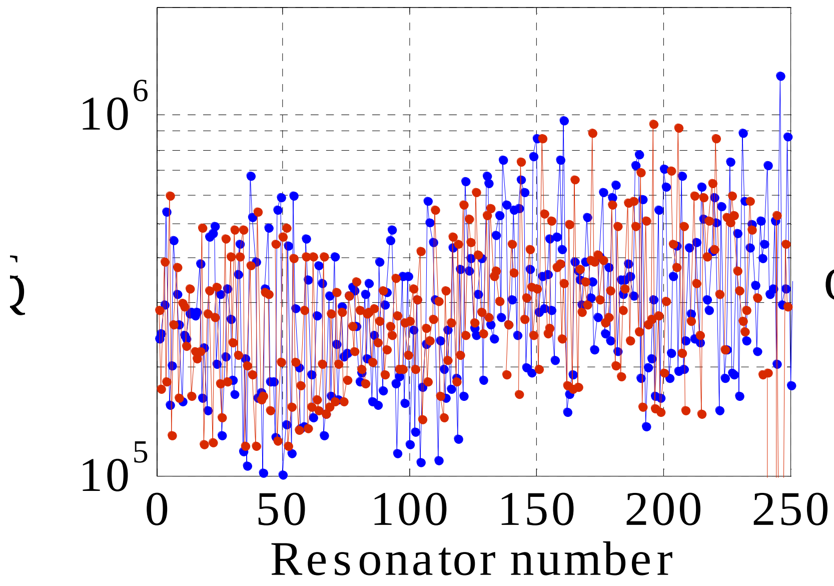


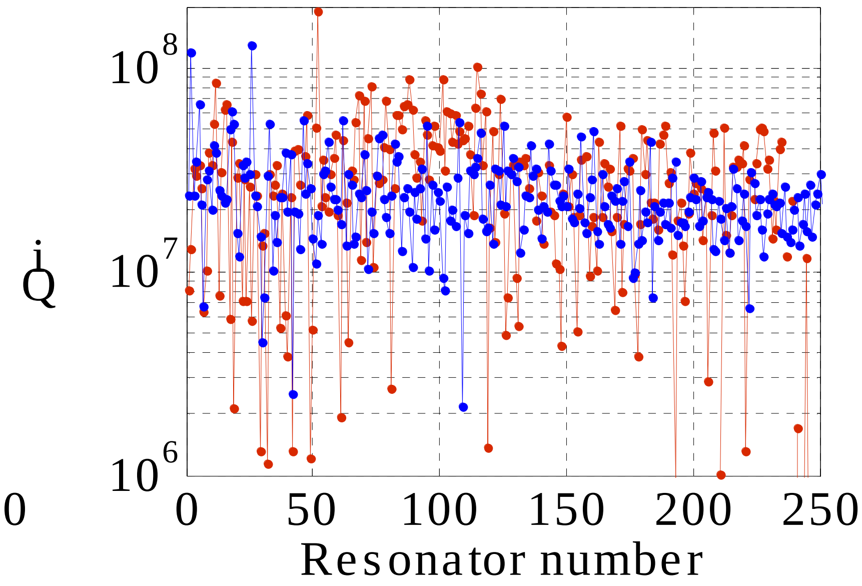
Crosstalk measurement for design (B)

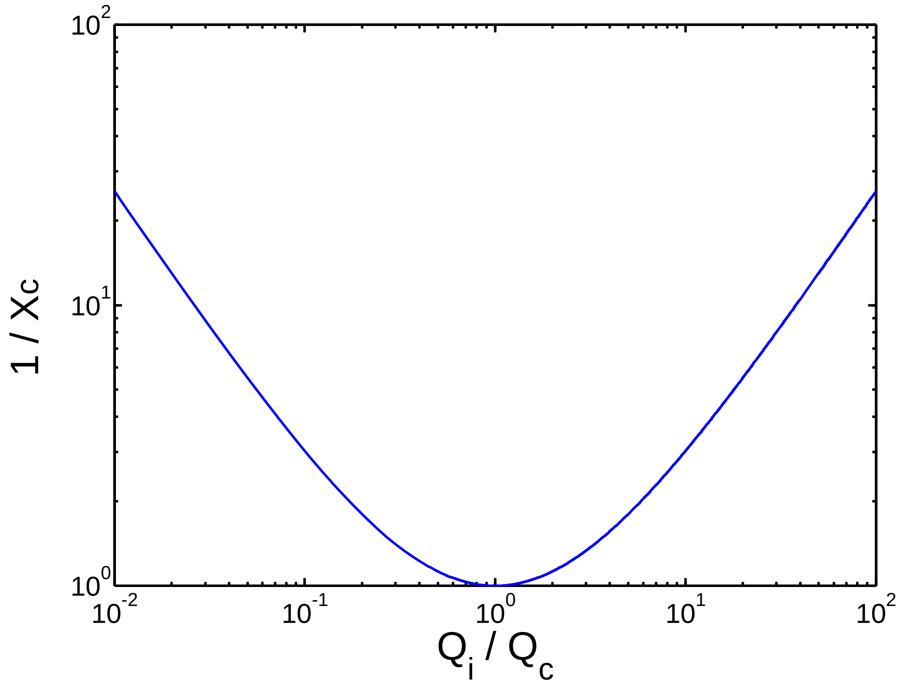
- High fill-factor array
- **Crosstalk ≤ 2% !** → Indeed, crosstalk effectively gone.



Remaining Qc variation and effect on NEP





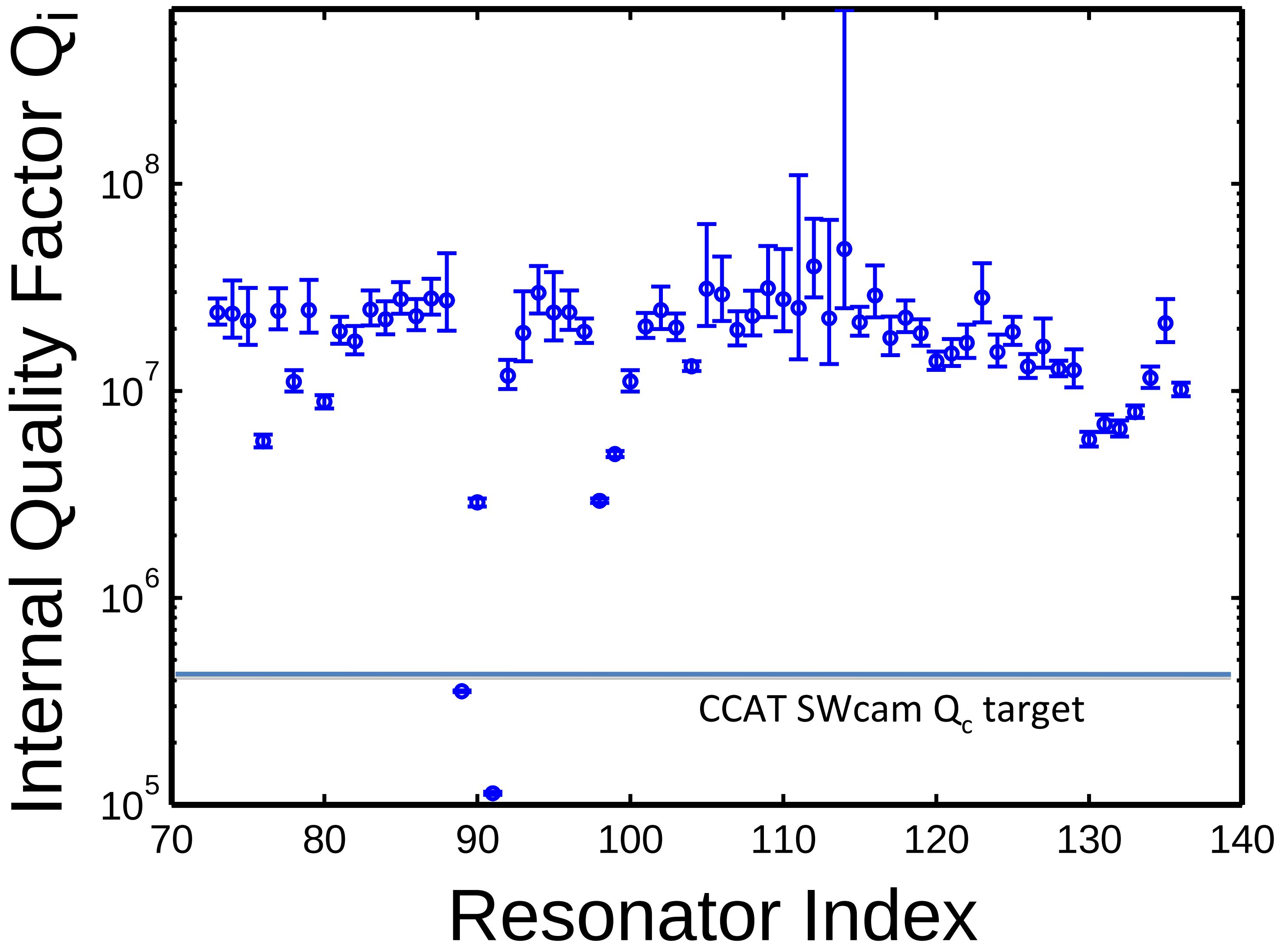


- Qc variation less than one order of magnitude achieved with new array design.
- NEP is a slow function of Qc variation:

$$NEP_{amp} = 2\frac{N_{qp}\Delta}{\eta_{opt}\tau_{qp}\chi_c\chi_{qp}}\sqrt{\frac{2k_B T_{amp}}{P_{gen}}}$$

$$\chi_c = \frac{4Q^2}{Q_c Q_i}$$

Record high Q with TiN (with high pixel yield and uniformity)



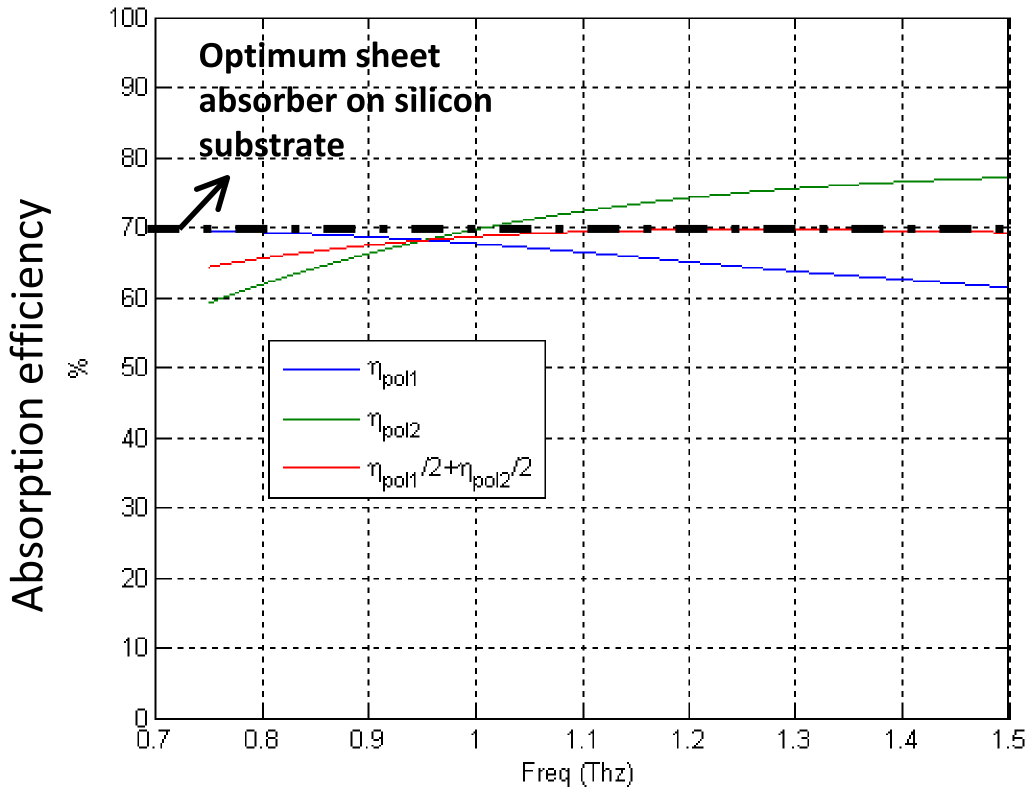
$Q_i \geq 3x10^7$

This means:

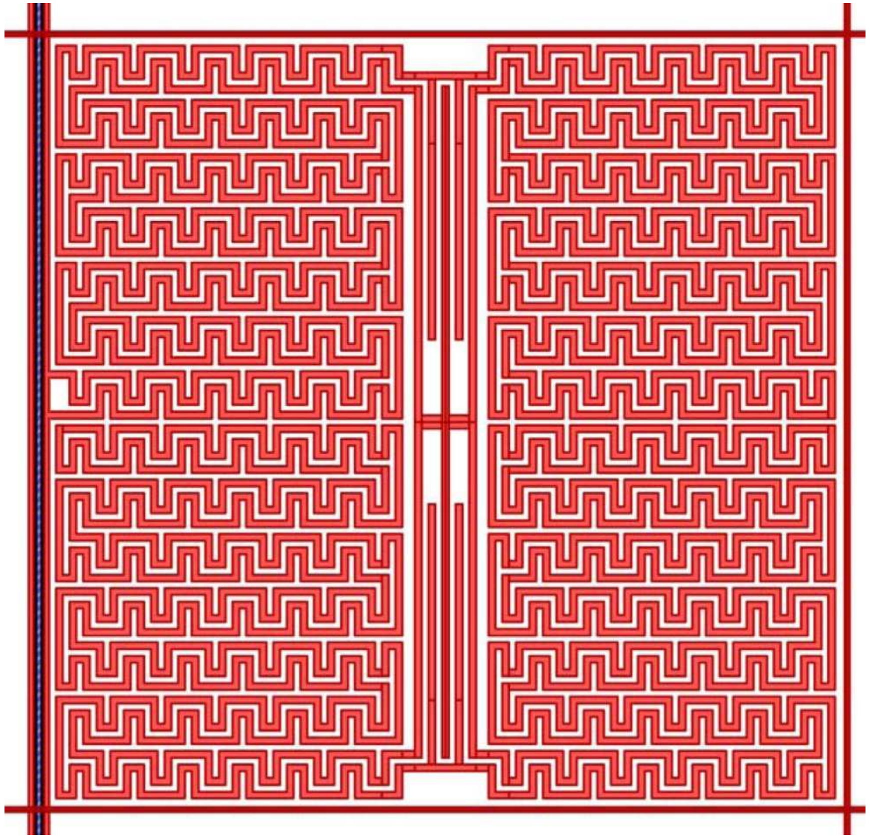
- Very low microwave loss material.
- Very low radiation loss resonator design.

Improved dual-polarization design

Meander simulation with R_s = 20 Ω/sq using HFSS - *N. Llombart*



Resonator design



Low crosstalk properties maintained while improving dual-pol absorption:

Coupling Splitting Frequency				
Horizontal	Vertical	Diagonal	Horz-cross	Diag-cross
1.2 MHz	2.9 MHz	0.2 MHz	2.4 MHz	0.5 MHz

Summary

- Direct absorption far-IR MKIDs using TiN have very simple design and fabrication.
- 256 pixel array developed and demonstrated with good optical absorption, high pixel yield, and very high Qi.
- Crosstalk was major problem in initial design (60%), but was solved:
  - Simple cross-coupling model developed and confirmed.
  - Very low crosstalk (< 2%) resonator and array designed and measured.
  - Simple “pump-probe” technique developed for crosstalk measurement.
- Qc variation more under control (one order of magnitude), but still an issue since it affects NEP.
- Better dual-polarization pixel designed. Measurements under way.
- Effort opens path to very large arrays on CCAT and others.

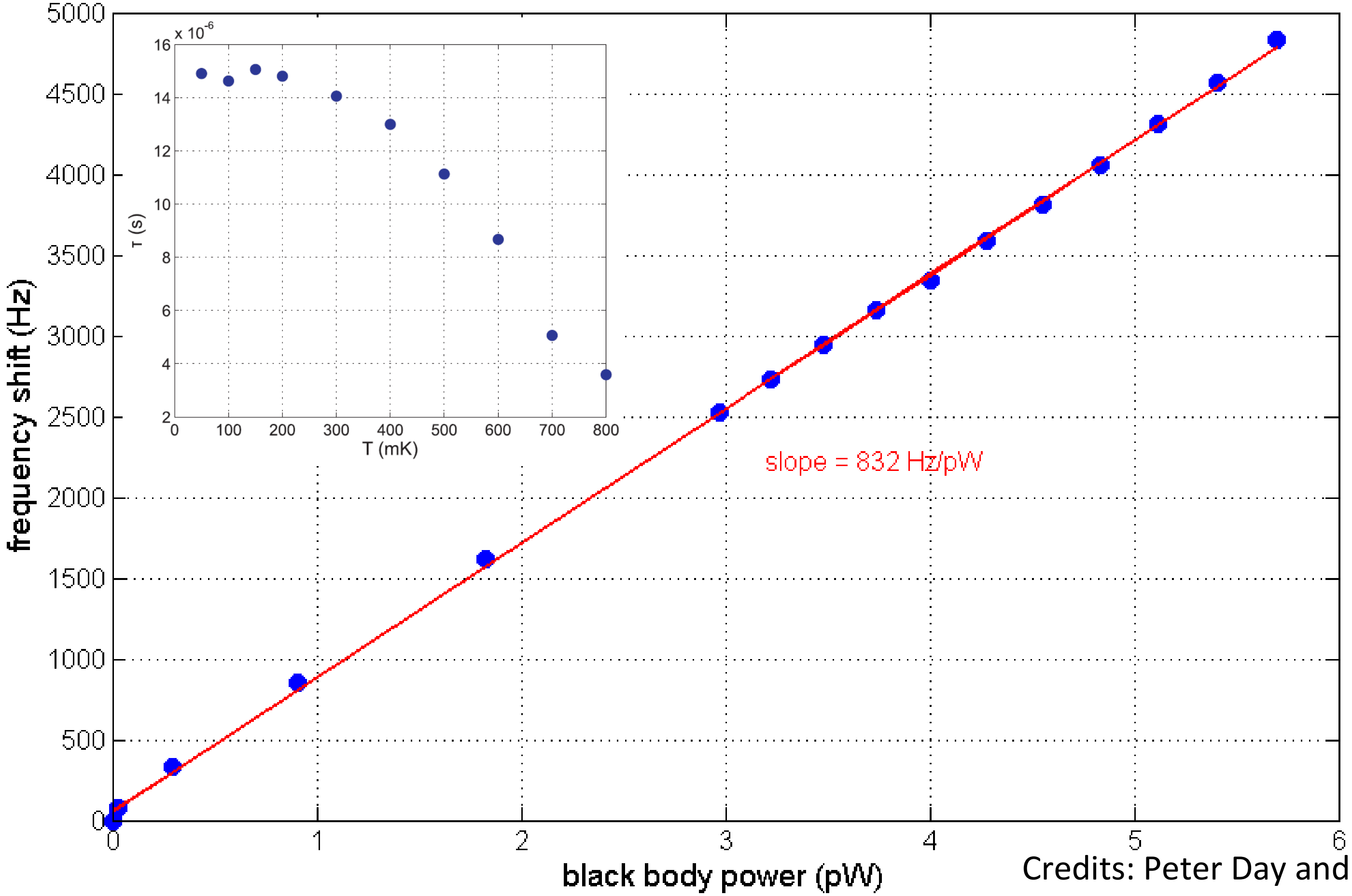
Thank you for
your time!

Extra Slides

Response to black body (design A)

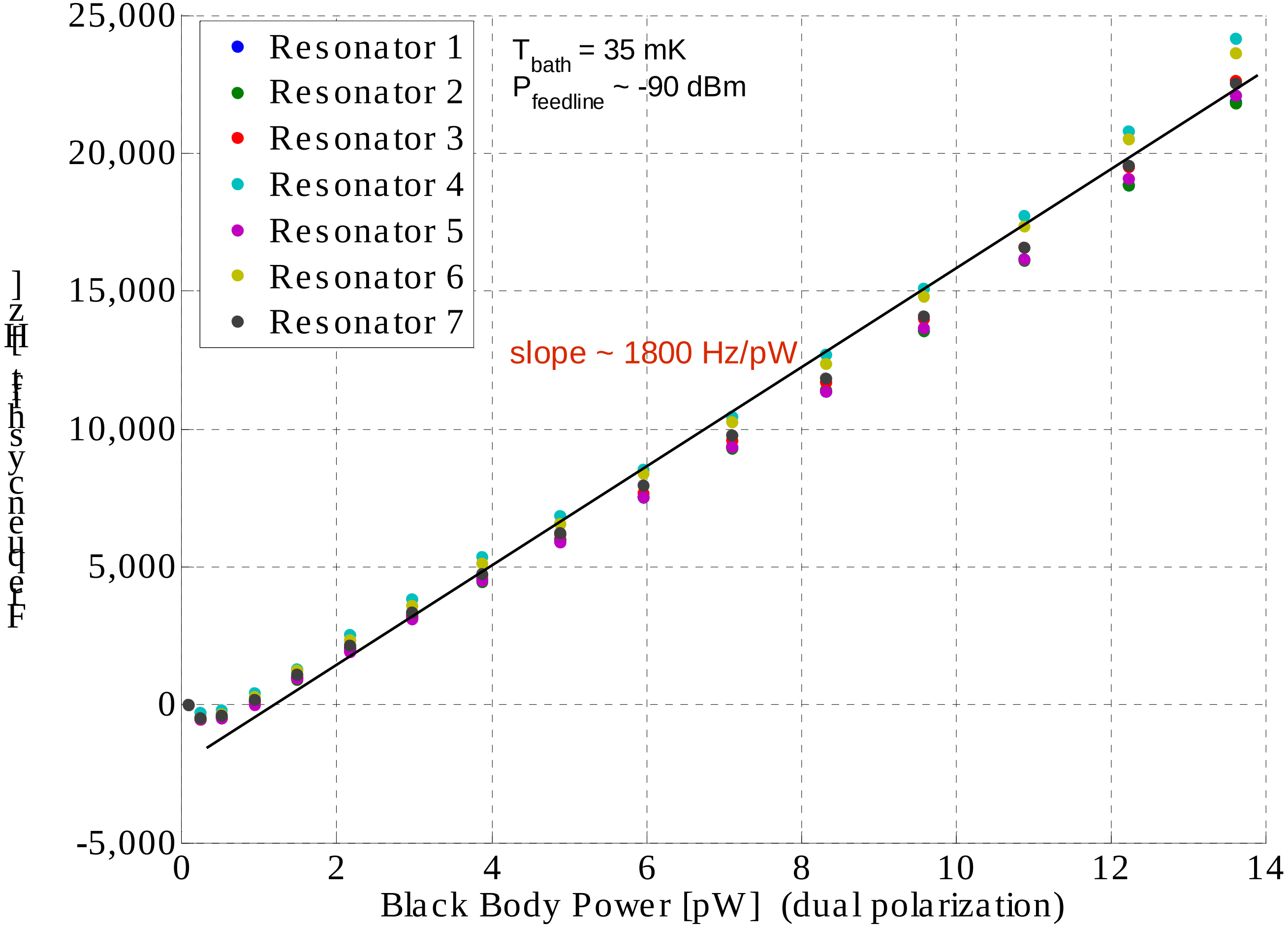
- 215 um band pass filter (metal mesh).
- Response corresponds to ~70% absorption efficiency. (given measured lifetime and temperature response)

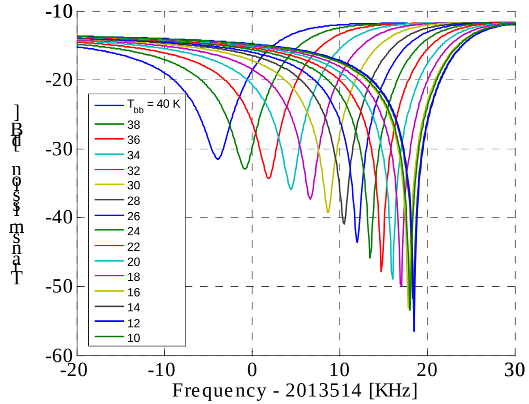
•Efficiency agrees well with CST simulation (credits: Nuria Llombart).



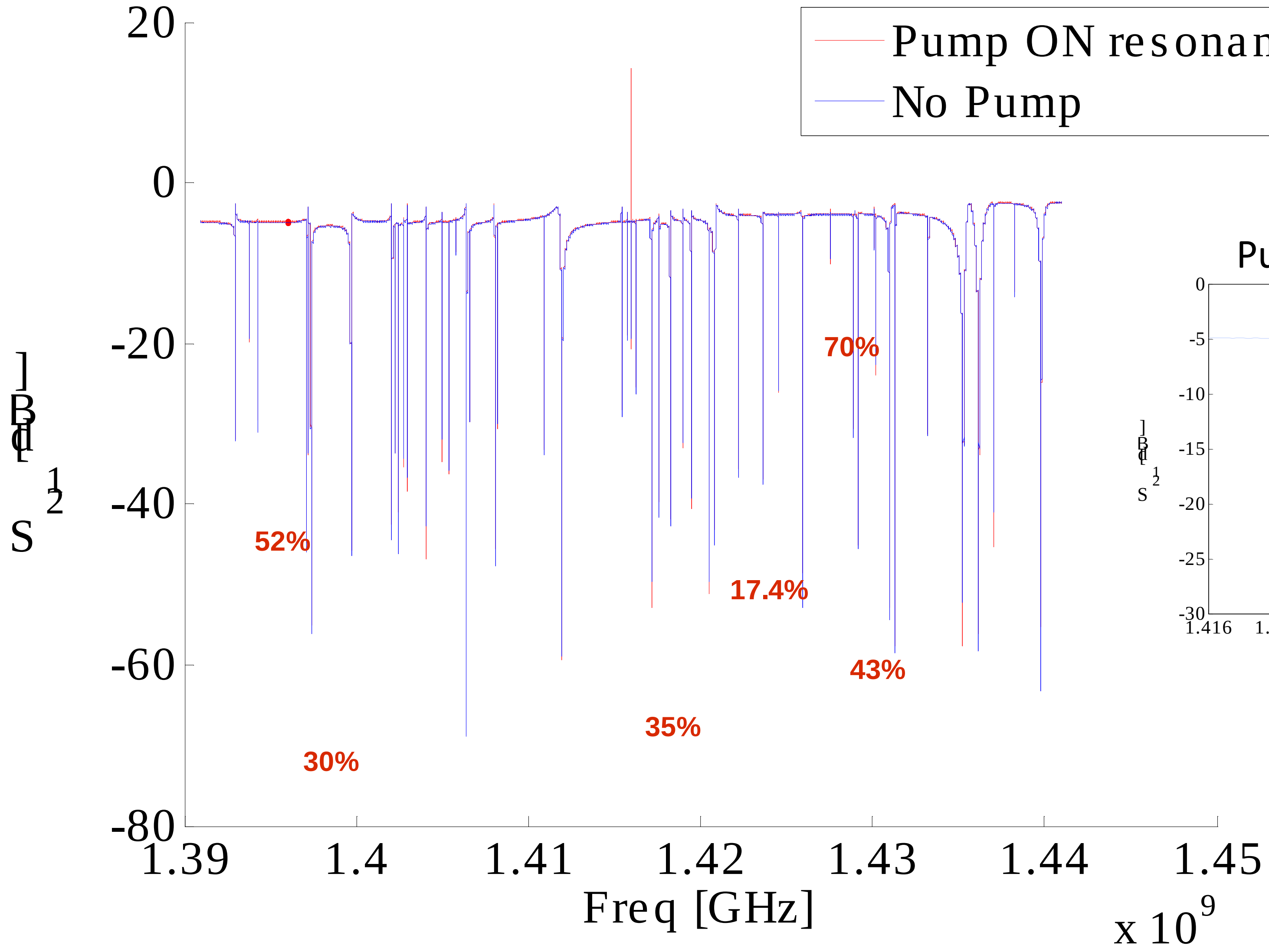
Credits: Peter Day and Byeong Eom

Response to 200 μm Black Body (Design B)

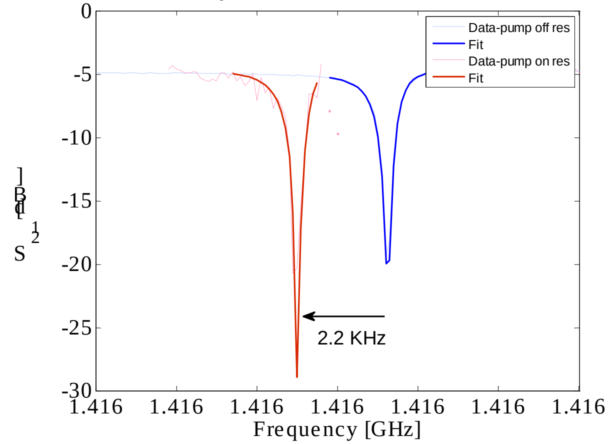




Crosstalk measurement: First FIR array (design A)

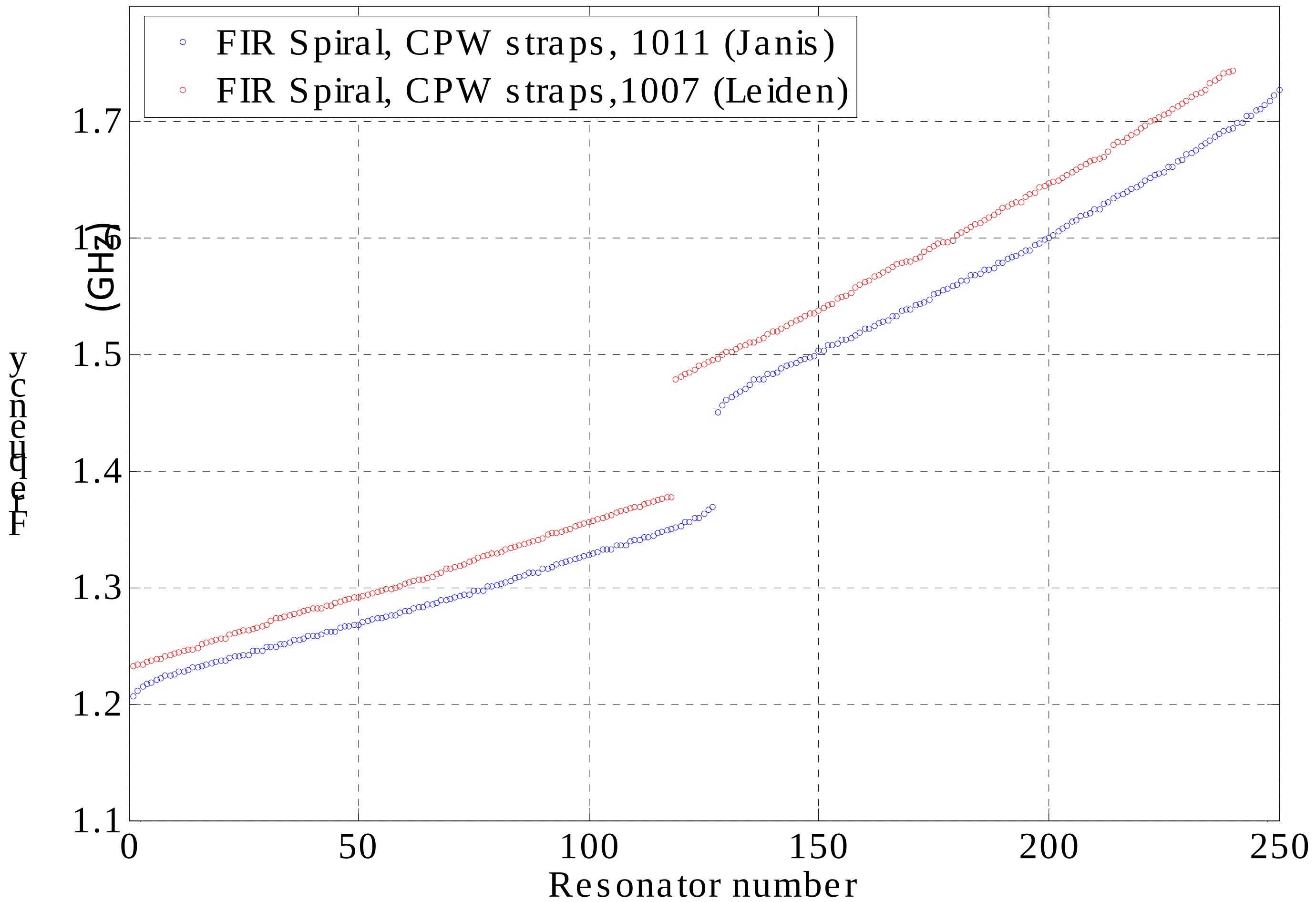


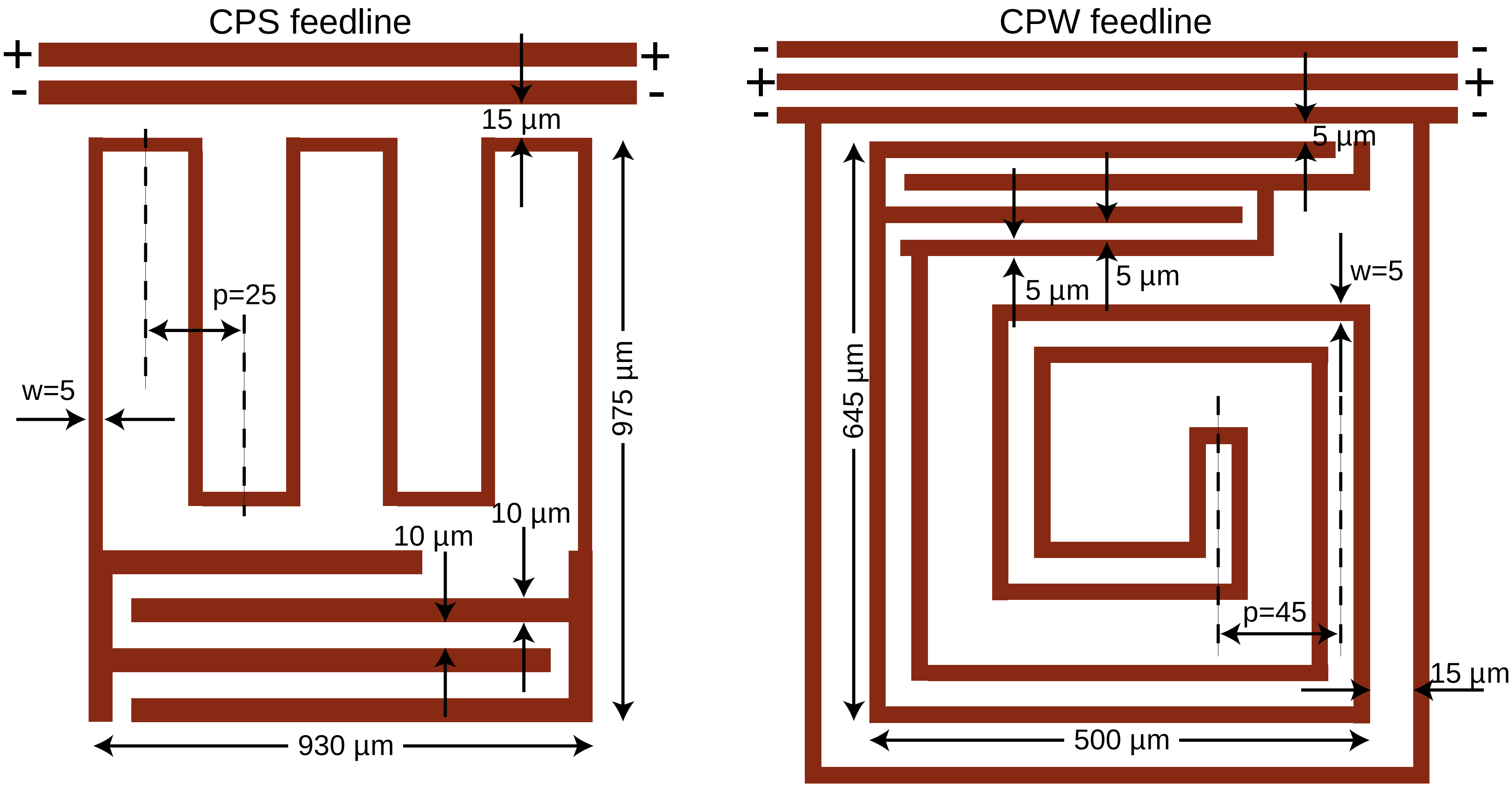
Pumped resonator



Measurement results (latest two array B's)

- Much more uniform frequency spacing between 256 resonators
- Inverted S-shape almost disappeared (Cross-coupling)





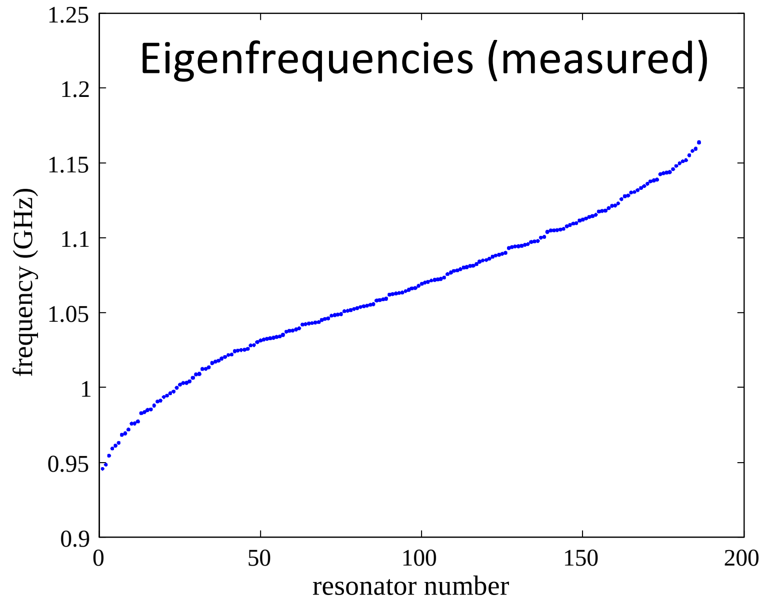
Resonator A

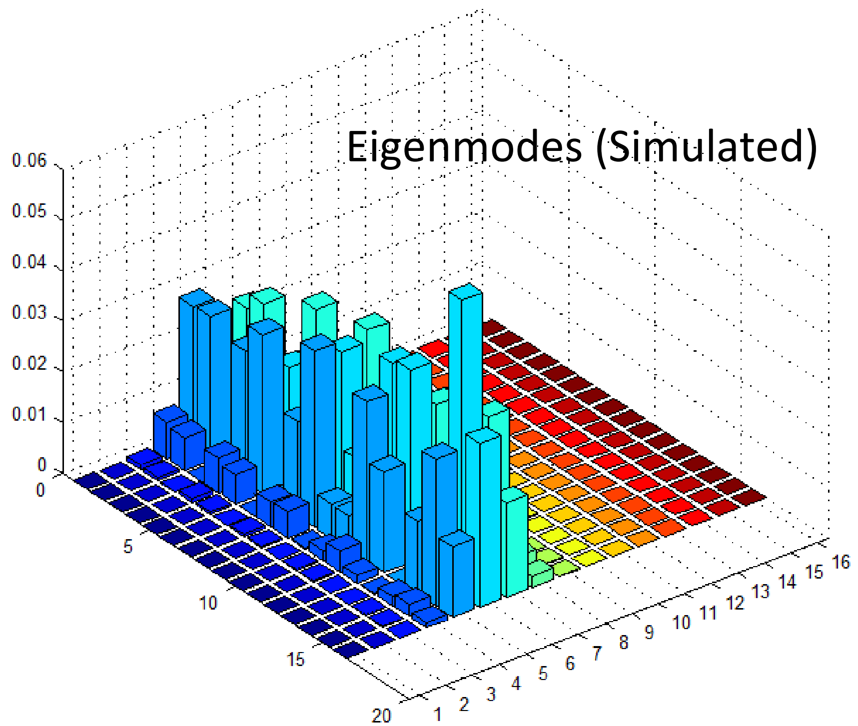
Resonator B

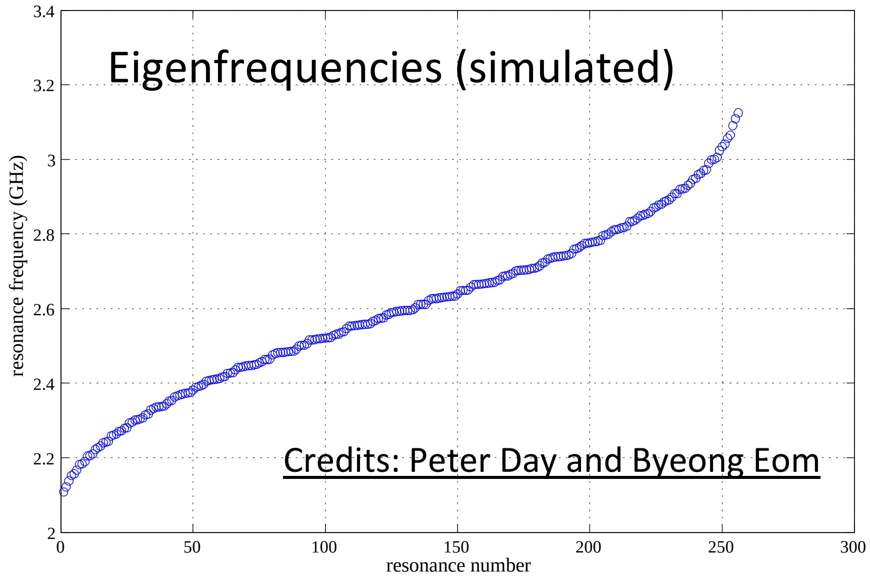
Eigenfrequencies and Eigenmodes for 256 pixel array

- Using coupling energies, circuit model predicts S-shape pattern in eigenfrequencies.

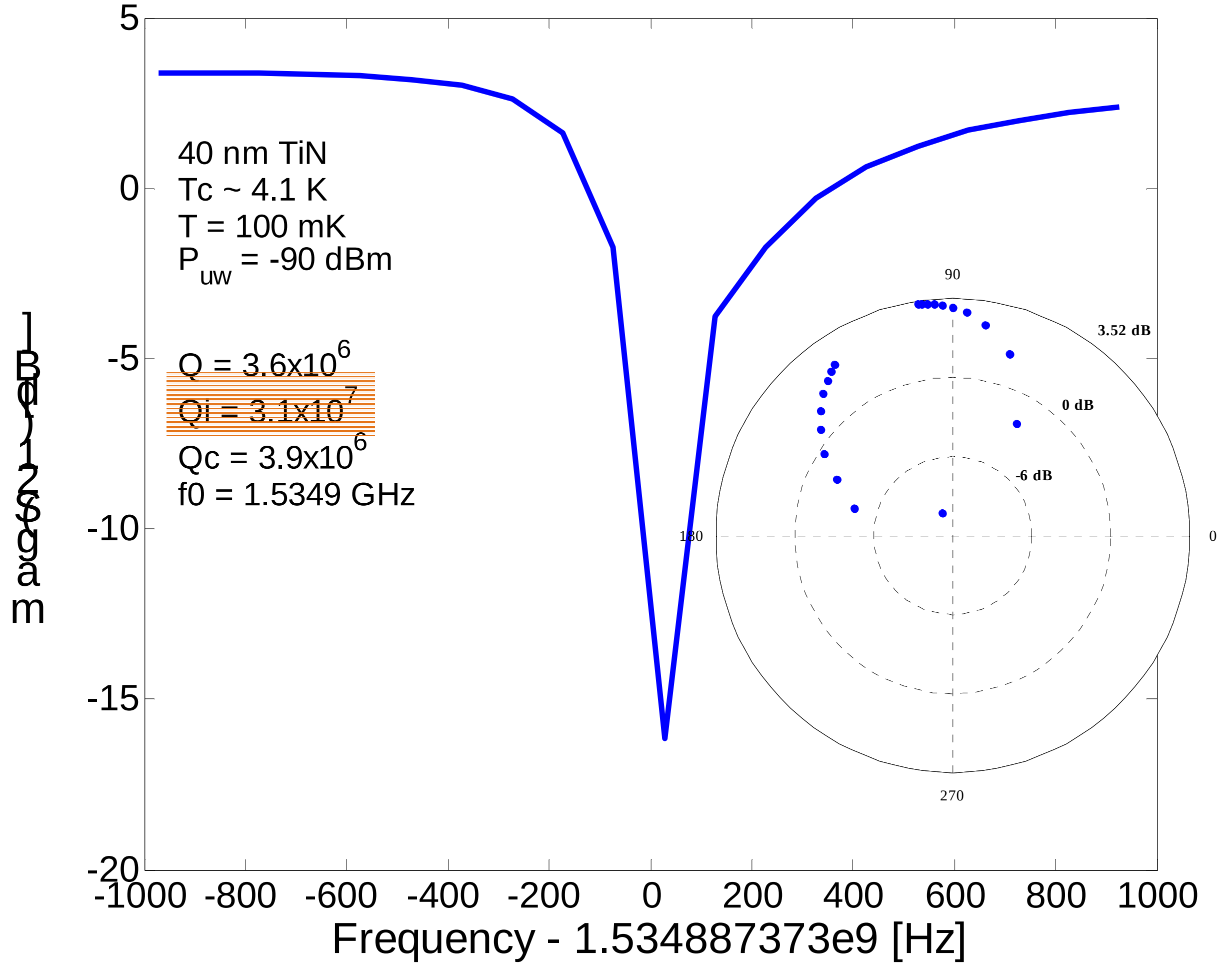
•Eigenmodes distributed over space → crosstalk!



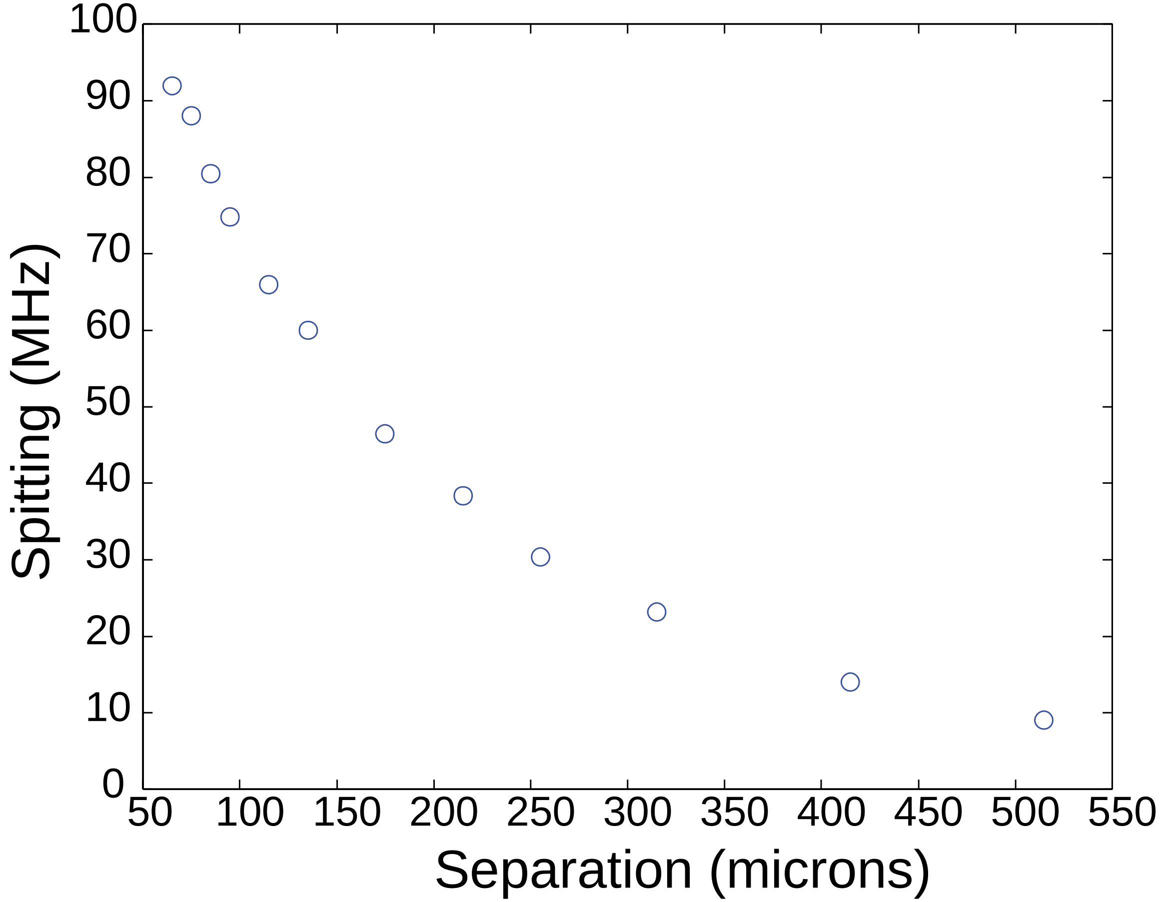




Very high Qi resonator



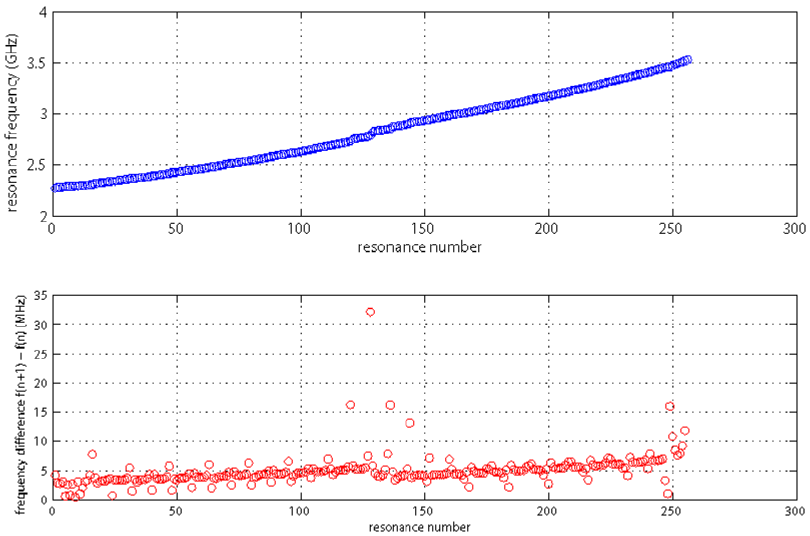
Crosstalk v.s. separation



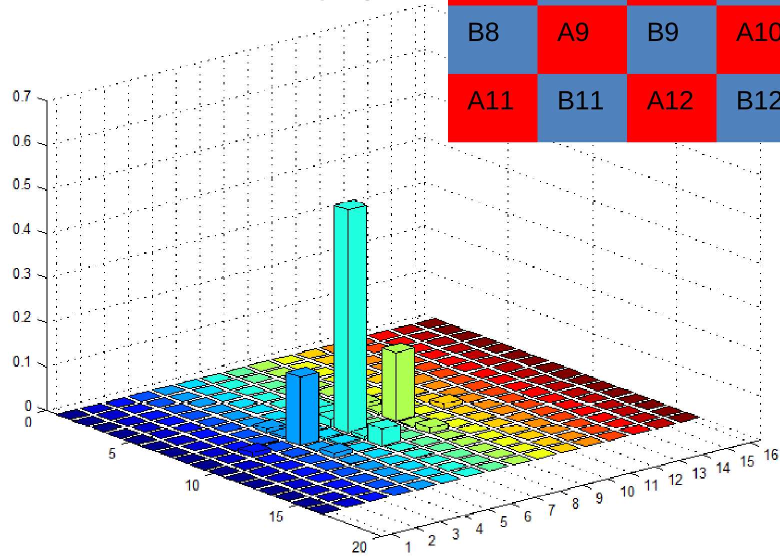
Checkerboard pattern

A1	B1	A2	B2	A3
B3	A4	B4	A5	B5
A6	B6	A7	B7	A8
B8	A9	B9	A10	B10
A11	B11	A12	B12	A13

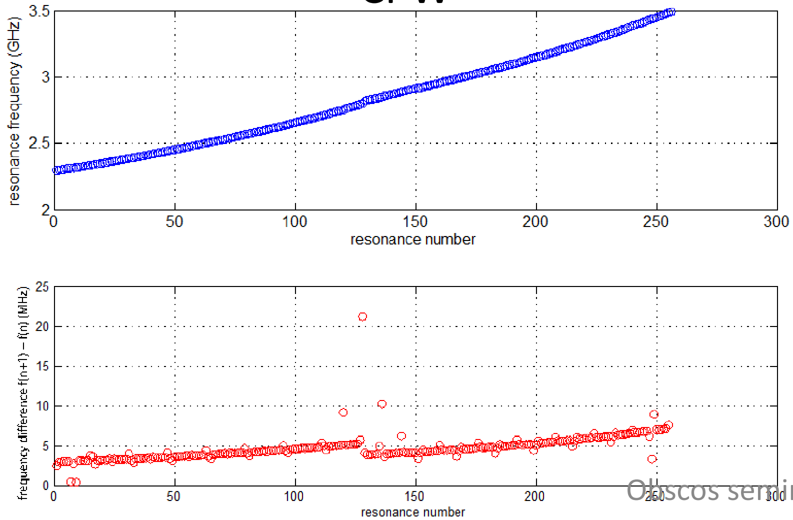
CPS



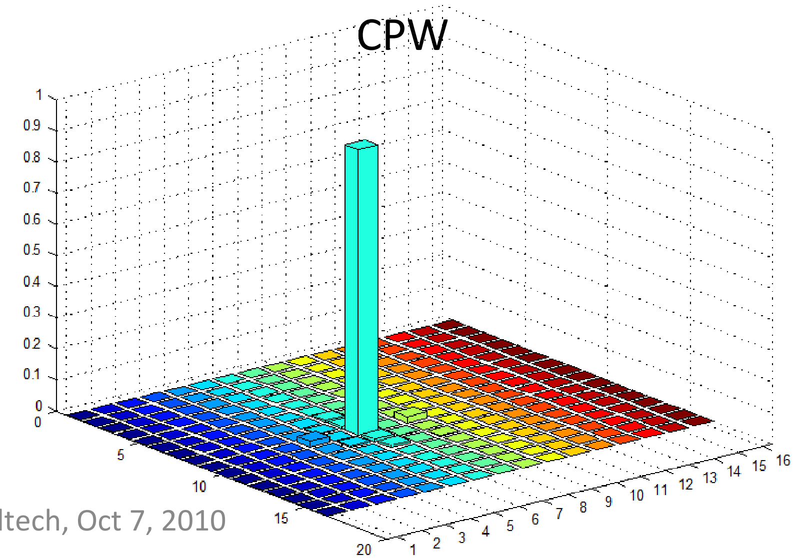
CPS



CPW



CPW



Summary

- Far-IR lumped-element MKID arrays (~250 pixels) using single layer TiN have been designed and measured in the lab and show very promising results.
- Pixel-pixel crosstalk was initially $\leq$ 70% but reduced to $\leq$ 2% in new design!
- Simple circuit model predicts and explains crosstalk.
- Optical absorption with black body demonstrated with ~70% absorption efficiency (single pol) for first pixel design. New design still to be calibrated (expect efficiency of ~35% per polarization)
- Better dual polarization design is underway.
- Variation in coupling Q's reduced from ~3 to ~1 order of magnitude, but still major issue.
- Consistently measured very high internal Q resonators (31 x 10^6, highest up to date in MKIDs).