Broadband Microstrip-Coupled TiN KIDs: A Scalable Detector Technology for CMB-S4

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Outline

Review of needs for CMB-S4

Why microstrip coupling

Why TiN KIDs

Overview of design

Expected performance

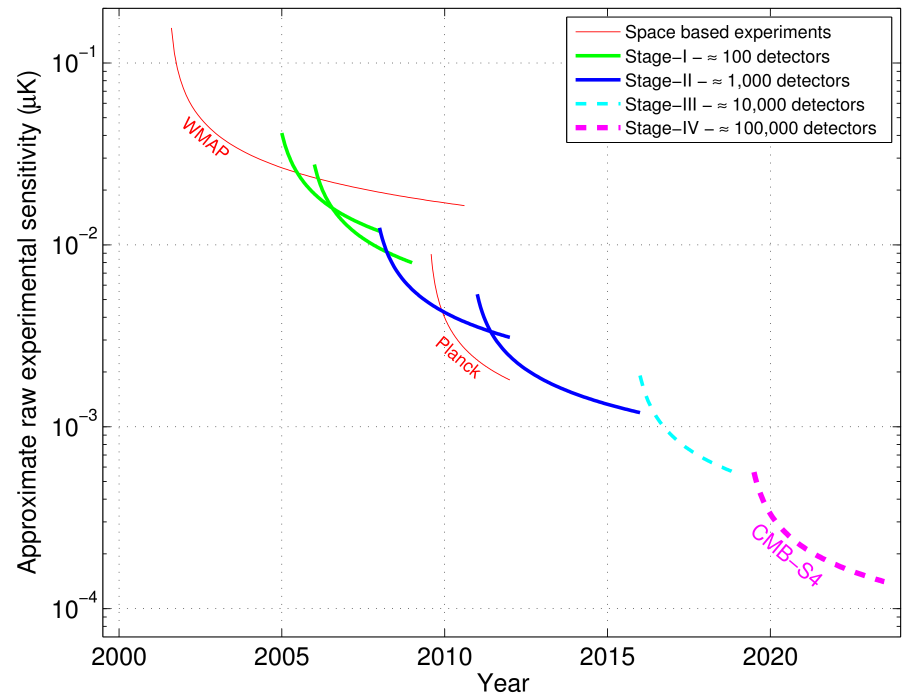
Review of Needs for CMB-S4

Raw Sensitivity:

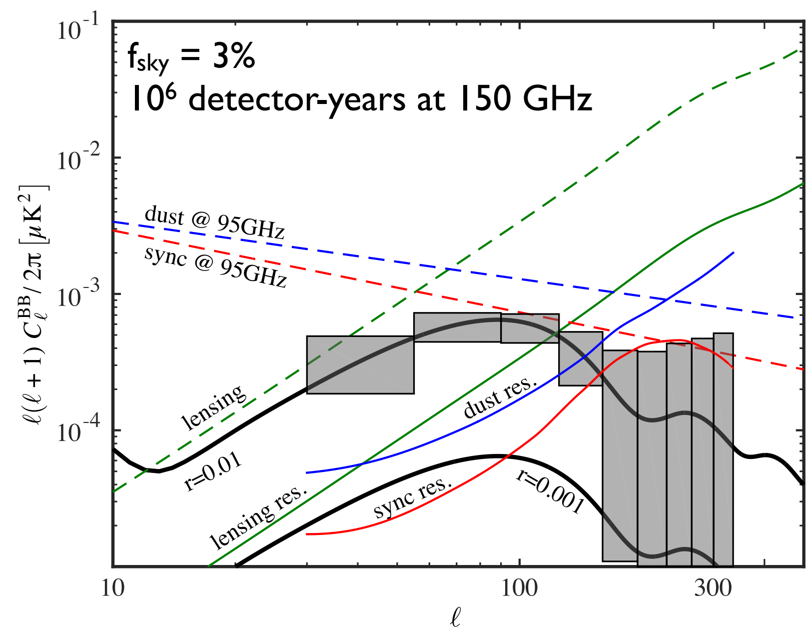
- 10^5-10^6 detectors required to achieve desired sensitivity bec. limited by irreducible photon noise
- Multiplexability is critical!

Systematics Control:

- Now known that foregrounds exceed inflationary signal even in cleanest sky: need multiple spectral bands
- Polarization systematics must be controlled and measured precisely



CMB-S4 science book

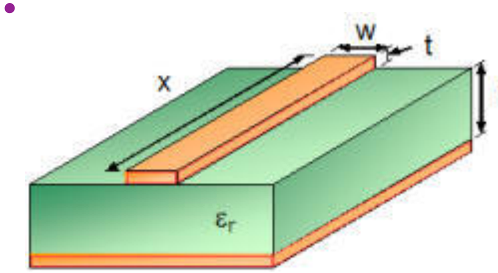


CMB-S4 science book

antenna/bandpass filter systematics requirements from EPIC-IM study
(same sensitivity goal as CMB-S4, σ(r) = 0.0005)
100 GHz, 8.4' FWHM (some relax for finer beams)

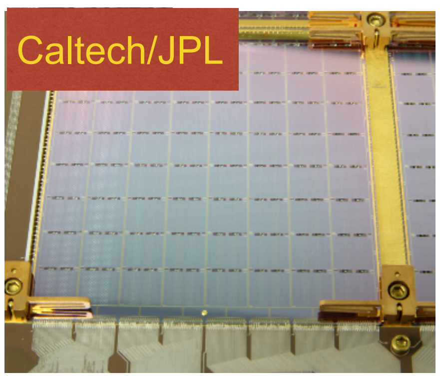
Systematic Error	Description	Knowledge to Meet Requirement
Δ Beam Size	FWHM$_E$ ≠FWHM$_H$, $\lvert\sigma_E - \sigma_H\rvert/\langle\sigma\rangle$	1.8×10^{-3}
Δ Beam Offset	Pointing E ≠ H, $\lvert\theta_E - \theta_H\rvert/\sigma$	3×10^{-3}
Δ Ellipticity	$e_E \neq e_H$, $\psi = 0°$, $\lvert e_E - e_H\rvert$	5×10^{-1}
	$e_E \neq e_H$, $\psi = 45°$, $\lvert e_E - e_H\rvert$	5×10^{-3}
Δ Rotation	E & H not orthogonal, $\lvert\theta_E - \theta_H - 90°\rvert$	13.4′
Pixel Rotation	E ⊥ H but rotated w.r.t. beam major axis	2.9′
Bandpass Mismatch	Variation in filters, $\delta\nu_c/\nu_c$	10^{-3}

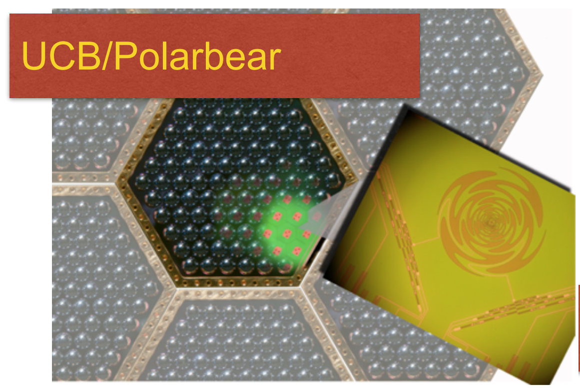
Why Microstrip Coupling?

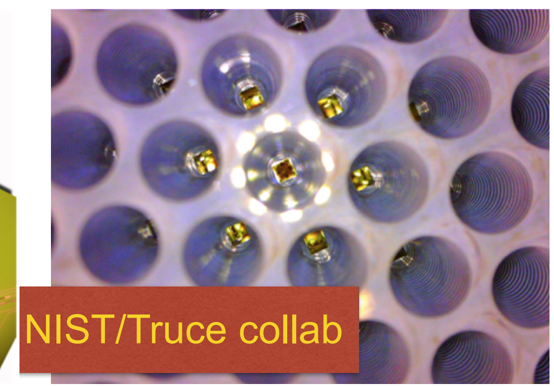


Flexible

- Many optical reception architectures can output onto superconducting microstripline
- Microstrip enables use of bandpass filters, decouples detector size from optical reception element







Excellent systematics control demonstrated in the field for these technologies via BICEP/Keck, Polarbear, SPTpol, ACTpol

Scalable

- Fully photolithographic (phased arrays), photolithographic + mass-hybridized (lens-coupled, feedhorn-coupled)
- All amenable to scaling to 6” wafer fab modulo yield

Why TiN KIDs?

High kinetic inductance fraction due to high normal state resistivity

responsivity in recombination-limited,
mm-wave quasiparticle-limited regime

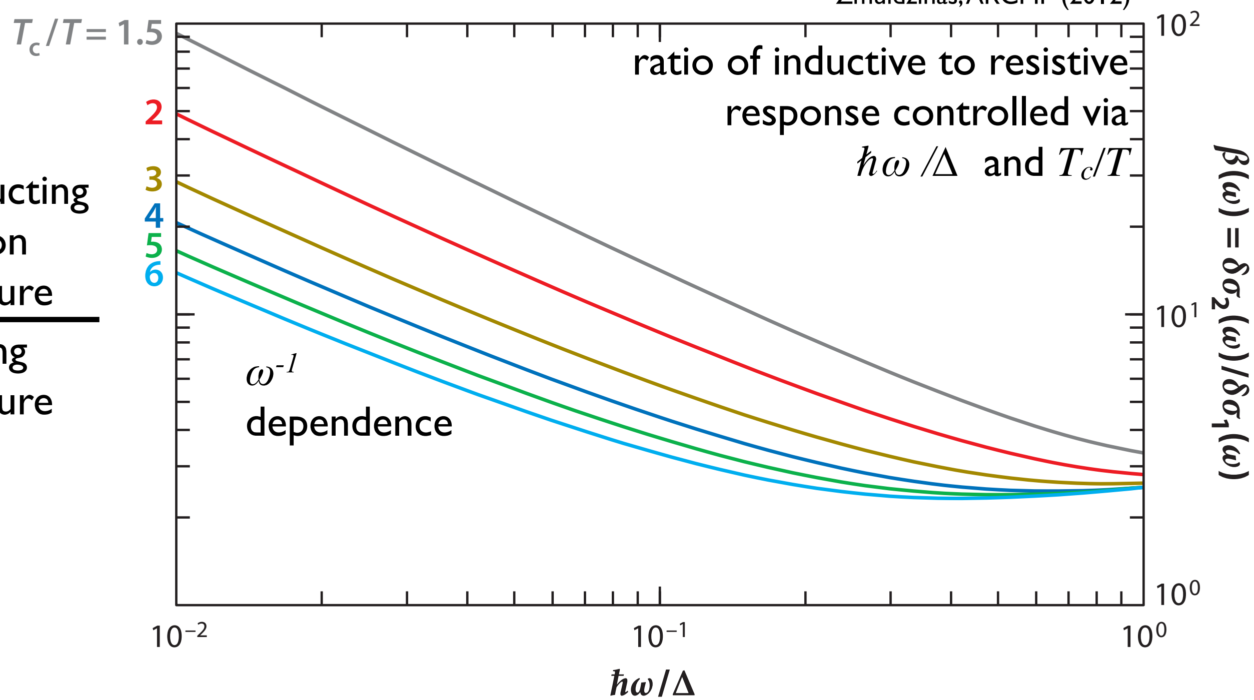
$$\frac{d(\delta f/f)}{dP_{opt}} = -\frac{\beta(f_r, T)}{4\, P_{opt}\, Q_i}$$

$\beta(f_r, T) > 2$
= ratio of imaginary (freq) to real (Q) responsivity to qps

$$\beta \propto f_r^{-1} \propto \text{kinetic inductance} \propto \text{superconducting penetration depth} \propto \rho_n^{1/2}$$

Zmuidzinas, ARCMP (2012)

superconducting transition temperature / operating temperature



TiN: ρ_n ~ 100 μΩ cm
Al: ρ_n ~ 1 μΩ-cm

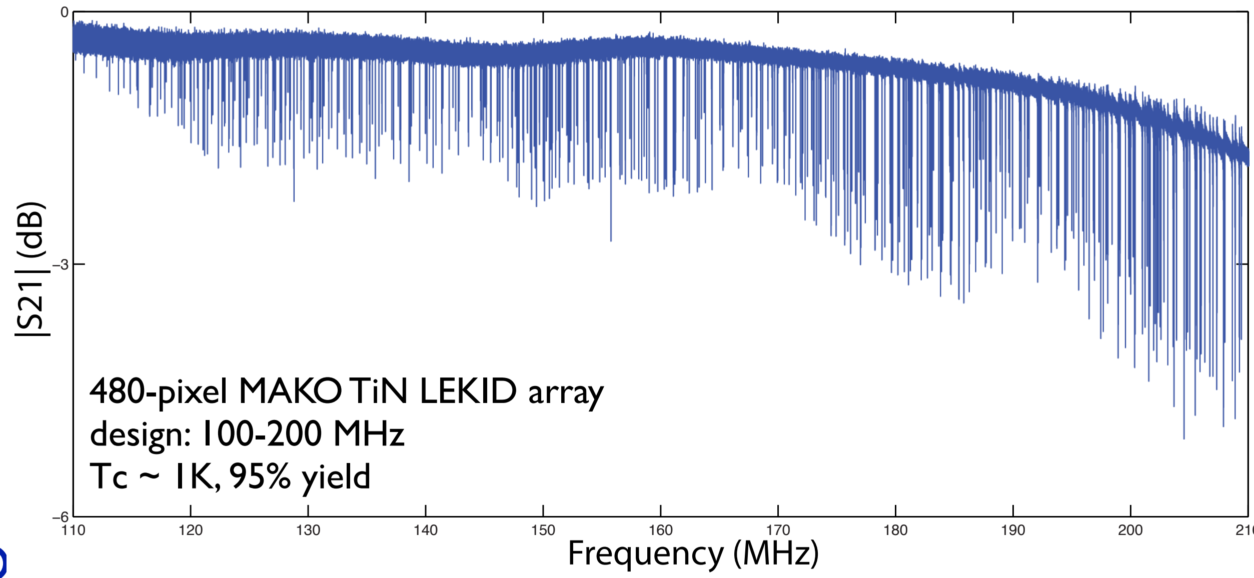
imaginary responsivity / real responsivity

h x resonator frequency / superconducting gap energy

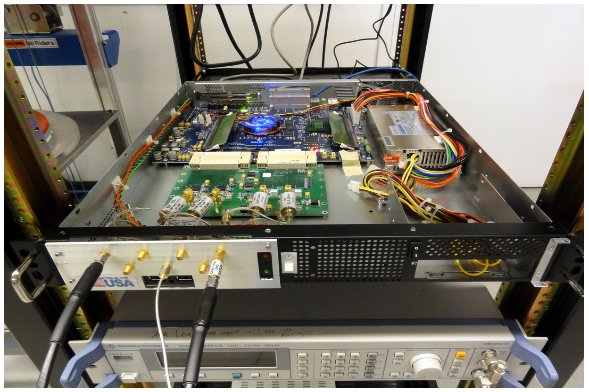
Why TiN KIDs?

High kinetic inductance
→ low operating frequency (10s of MHz)
→ demonstrated N_{mux} ~ 1000 at low cost

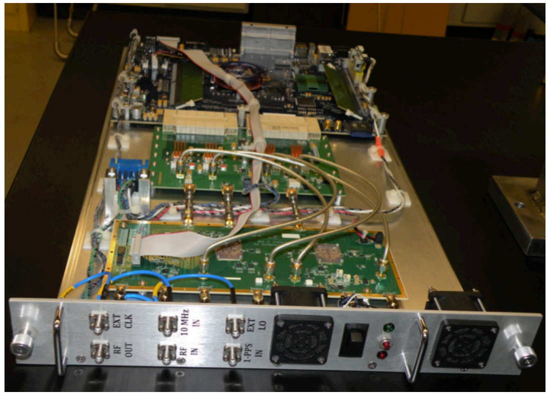
- e.g. ROACH1 + MUSIC/ARCHONS ADC/DAC board + MAKO
  $4/detector → $1/detector if optimized
- e.g. BLAST-TNG ROACH2 + MUSIC/ARCHONS ADC/DAC: 1K detectors also
- e.g. NIKA2, A-MKID readouts



MAKO readout (no IF)



MUSIC thermal-engineered readout module



MUSIC 8-module readout rack

Why TiN KIDs?

High kinetic inductance

→ low operating frequency (10s of MHz) → high β

→ amplifier and two-level-system noise subdominant to fundamental noises (photon + recombination)

$$\mathrm{NEP}^2_{\mathrm{fund}} = \mathrm{NEP}^2_{\mathrm{shot}} + \mathrm{NEP}^2_{\mathrm{Bose}} + \mathrm{NEP}^2_{\mathrm{rec}} = 2\, P_{opt}\, h\nu \left[1 + \frac{P_{opt}}{h\nu\, \Delta\nu} + \frac{2\,\Delta}{\eta_{abs}\, \eta_{ph}\, h\nu}\right]$$

In recombination-dominated, mm-wave quasiparticle-dominated regime:

Amplifier noise:

$$\mathrm{NEP}^2_{\mathrm{amp}} = 2\, P_{opt}\, h\nu\, \frac{32}{[\beta(f_r, T)]^2}\, \frac{P_{opt}}{P_{read}}\, \frac{k_B\, T_N}{h\nu}$$

$P_{opt}/P_{read} < 1$ generally holds

$k_B\, T_N / h\nu \approx 2$ for T_N = 4 K and ν = 45 GHz

$\beta \approx 55$ for our design

Two-Level-System Noise:

$$\mathrm{NEP}^2_{\mathrm{TLS}} = \frac{16\, P^2_{opt}\, Q^2_i}{[\beta(f_r, T)]^2}\, S^{\mathrm{TLS}}_{\delta f/f}(f^0_r, f^0_a, T_0, V_{d,0}, E_0)\, \frac{E_0\, V_{d,0}}{\ell^2_C} \sqrt{\frac{2\,\pi\, f_r\, C}{Q_i\, P_{read}}} \sqrt{\frac{f^0_a}{f_a}} \left(\frac{T_0}{T}\right)^{1.7} g\left(\frac{f_r}{f^0_r}\right)$$

TLS noise level measured for material in specific geometry

scalings to desired geometry and operating parameters

high $\beta \approx 55$ for our design makes this subdominant

Why TiN KIDs?

Fundamental noise level comparable to TESs:

$$\mathrm{NEP}^2_{\mathrm{fund}} = \mathrm{NEP}^2_{\mathrm{shot}} + \mathrm{NEP}^2_{\mathrm{Bose}} + \mathrm{NEP}^2_{\mathrm{rec}} = 2\,P_{opt}\,h\nu\left[1 + \frac{P_{opt}}{h\nu\,\Delta\nu} + \frac{2\,\Delta}{\eta_{abs}\,\eta_{ph}\,h\nu}\right]$$

KIDs suffer recombination noise, TESs suffer phonon noise:
both are noise on coupling to bath needed for optical power to escape

$$\mathrm{NEP}^2_{\mathrm{rec}} = 2\,P_{opt}\,\frac{h\,\nu_{min}}{\eta_{abs}\,\eta_{ph}} \qquad \mathrm{NEP}^2_{\mathrm{G}} = 4\,k_B\,\gamma\,(T_c^{\mathrm{T}})^2\,G_c \approx 2\,P_{opt}\,\left(2\,S\,\gamma\,k_B\,T_c^{\mathrm{T}}\right)\frac{T_c^{\mathrm{T}}}{T_c^{\mathrm{T}} - T}$$

Calculate for

ground-based optical loads

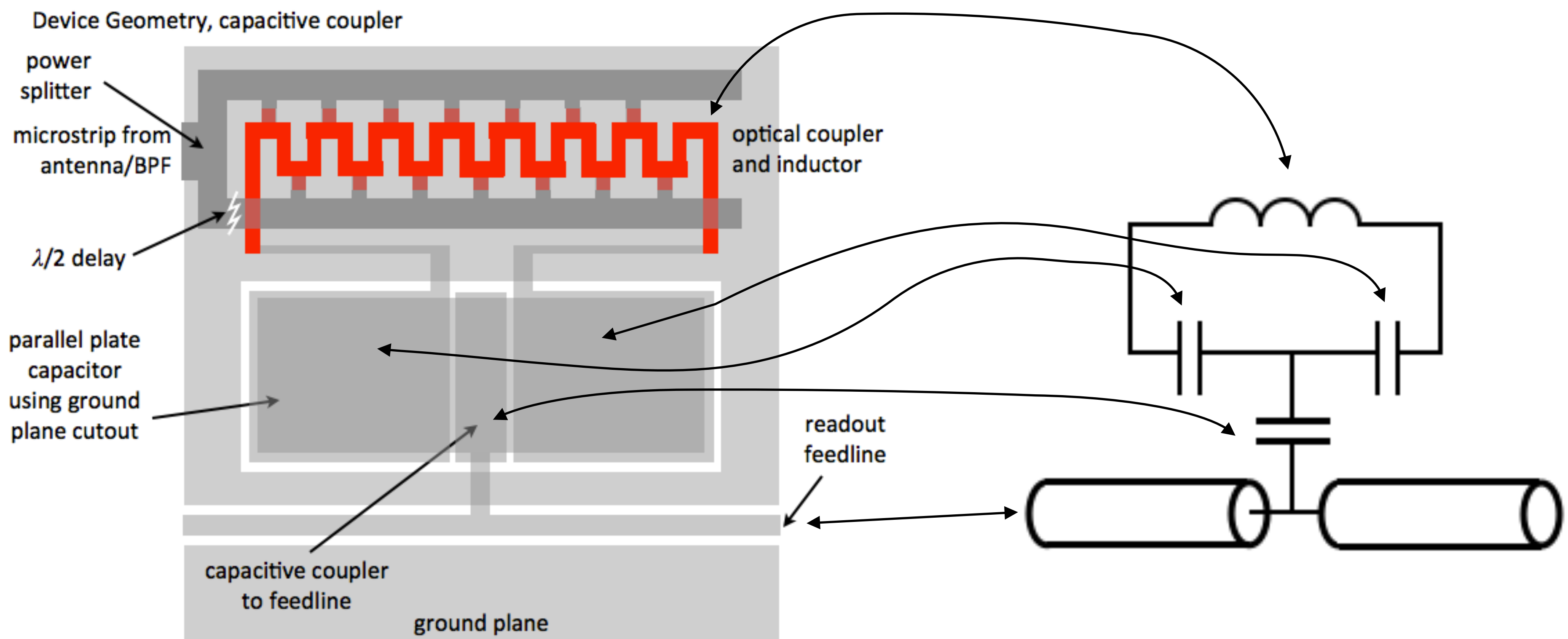
KID: T_C = 0.52 K, T = 0.05 K, η_{abs} near unity, η_{ph} = 1.0 at ν_{min} → 0.57 as ν → ∞

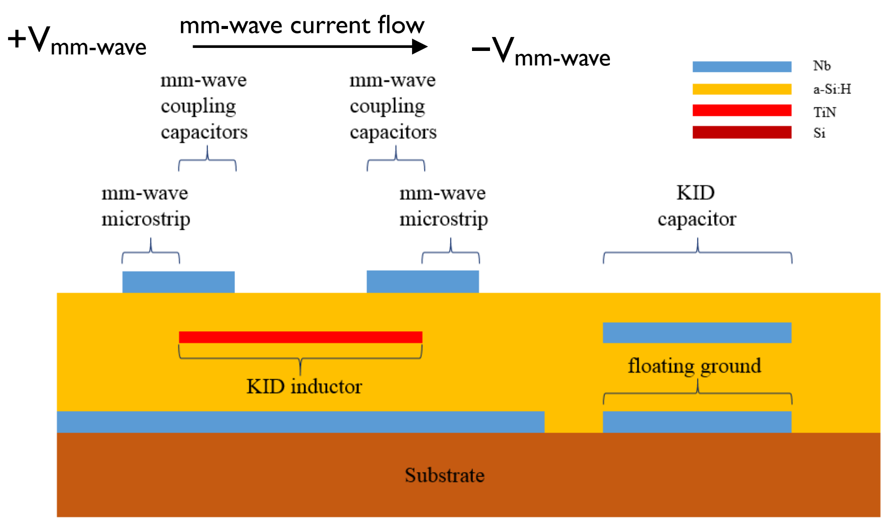
TES: T_C = 0.1 K, T = 0.05 K, γ = 0.5, safety factor S = 3

ν [GHz]	$\Delta\nu$ [GHz]	P_{opt} [pW]	η_{ph}	$\mathrm{NEP}_{\mathrm{shot}}$ [aW/$\sqrt{\mathrm{Hz}}$]	$\mathrm{NEP}_{\mathrm{Bose}}$ [aW/$\sqrt{\mathrm{Hz}}$]	$\mathrm{NEP}_{\mathrm{rec}}$ [aW/$\sqrt{\mathrm{Hz}}$]	$\mathrm{NEP}^{\mathrm{KID}}_{\mathrm{fund}}$ [aW/$\sqrt{\mathrm{Hz}}$]	$\mathrm{NEP}_{\mathrm{G}}$ [aW/$\sqrt{\mathrm{Hz}}$]	$\mathrm{NEP}^{\mathrm{TES}}_{\mathrm{fund}}$ [aW/$\sqrt{\mathrm{Hz}}$]	$\frac{\mathrm{NEP}^{\mathrm{KID}}_{\mathrm{fund}}}{\mathrm{NEP}^{\mathrm{TES}}_{\mathrm{fund}}}$
45	13.5	1.0	0.85	8	12	8	16	6	15	1.05
100	30	1.7	0.57	15	14	12	24	8	22	1.10
150	47	2.5	0.57	22	17	15	32	9	29	1.08

Negligible difference in theory; real-world effects will dominate

Overview of Design

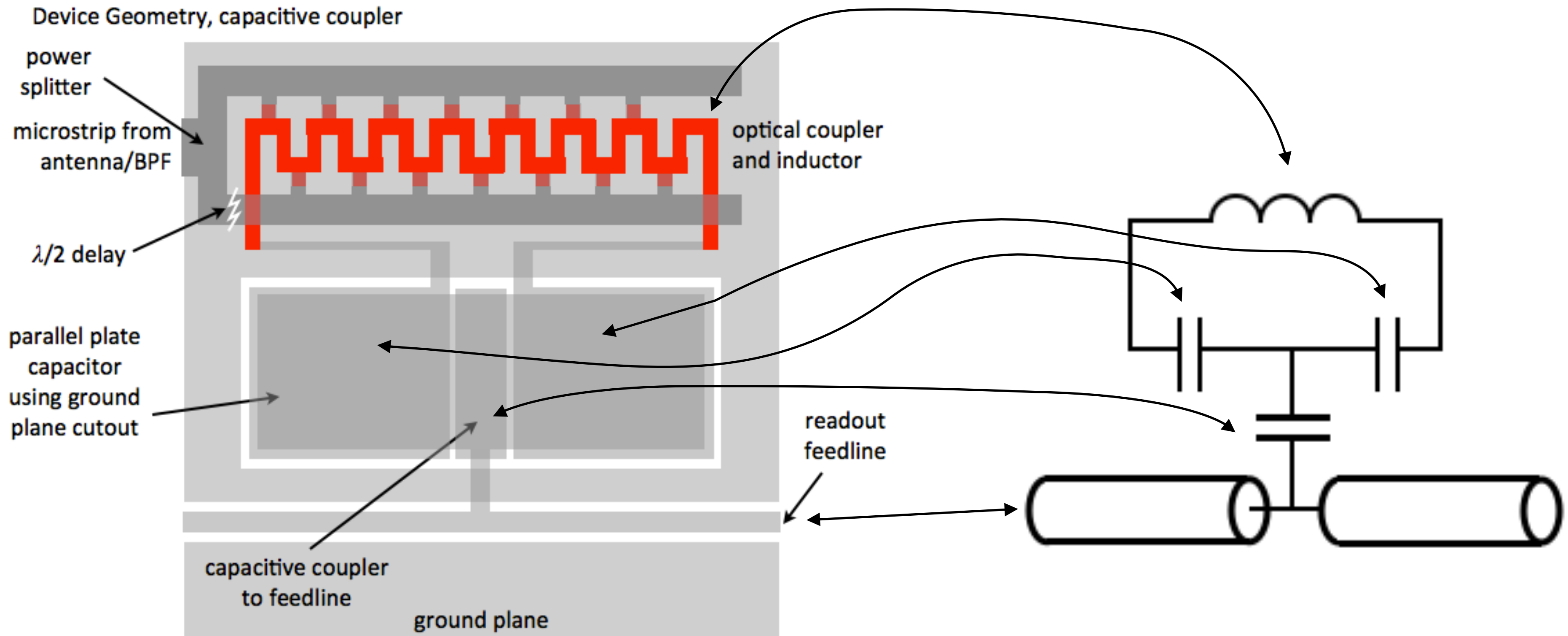


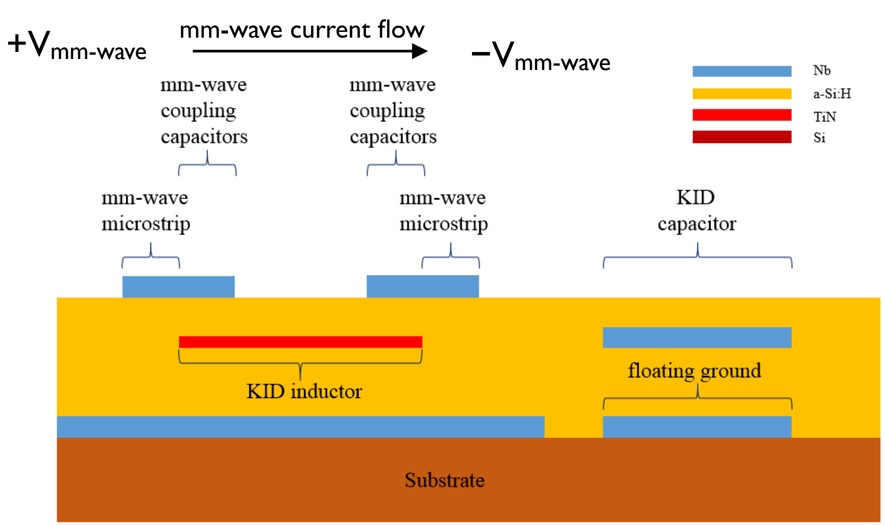


Microstrip coupling

- High sheet resistance of TiN makes it good match to free space ($Z_0 = 377\ \Omega$)
- Poor match to microstrip ($Z_0 = 10\ \Omega$)
- Solution: adiabatic coupler, achieves η_{abs} near unity

Overview of Design

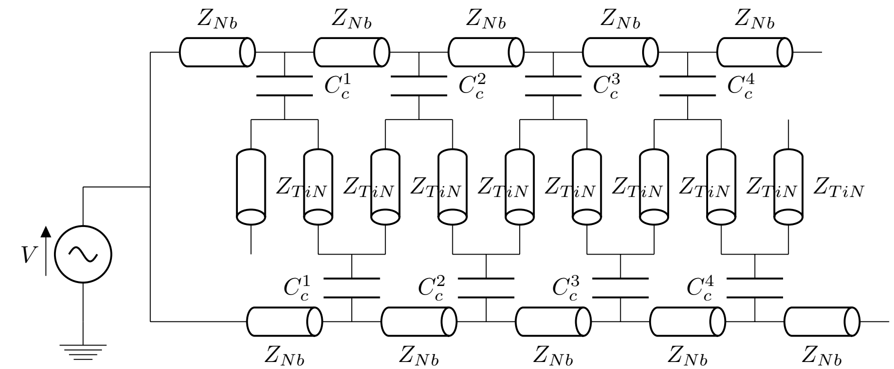




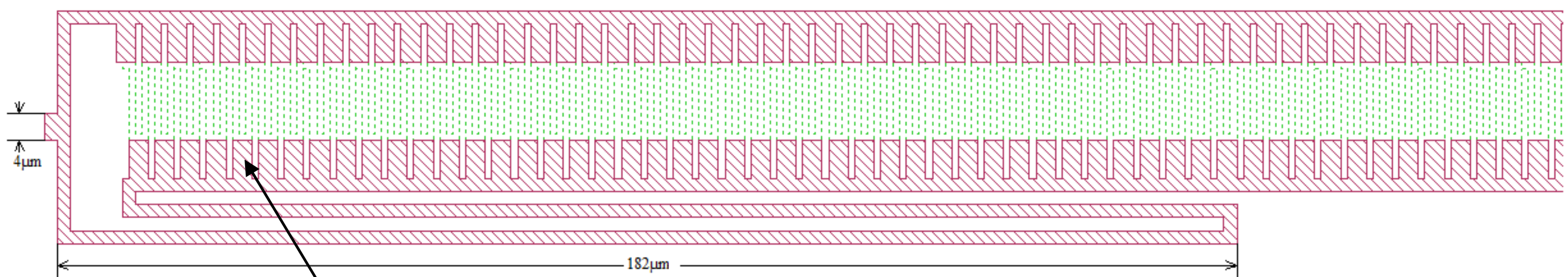
Prevents direct absorption

- Use parallel plate rather than interdigitated capacitor
- TLS noise of a-Si:H (Mazin et al 2010) good enough (v. little from inductor)
- Ground plane shields inductor, capacitor via short-circuit condition

Millimeter-Wave Coupler



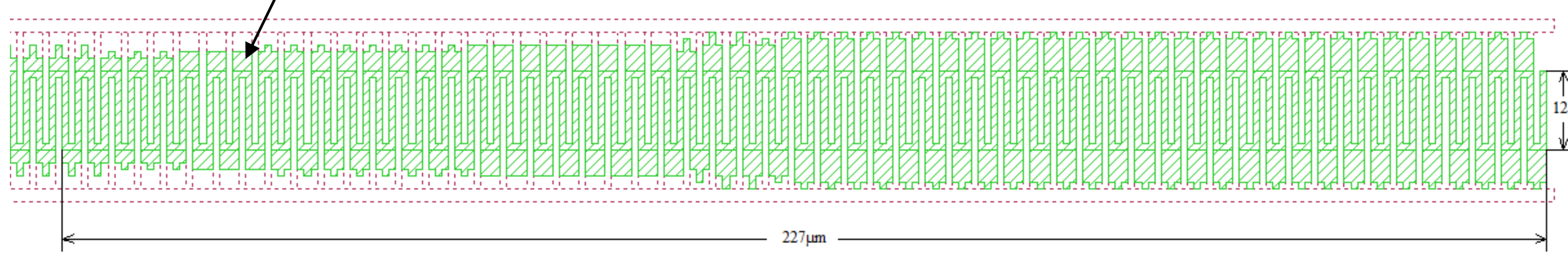
microstrip
from antenna and
bandpass filters



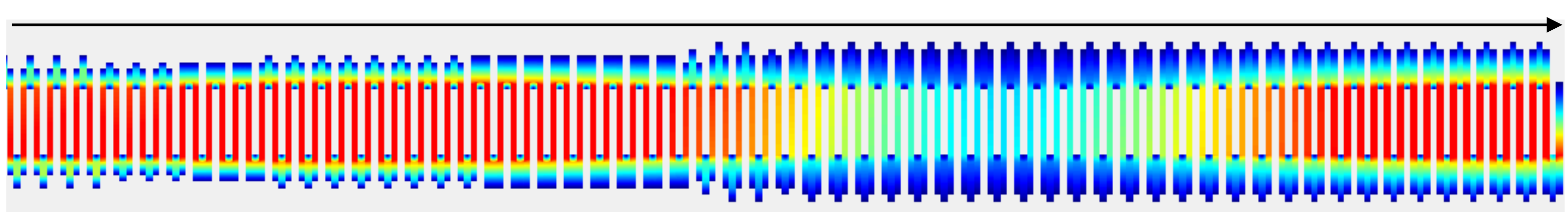
half-wavelength delay

capacitive tabs to apply voltage on microstrip across inductor meanders

weak coupling of individual meanders prevents high sheet resistance of TiN from presenting impedance mismatch to microstrip



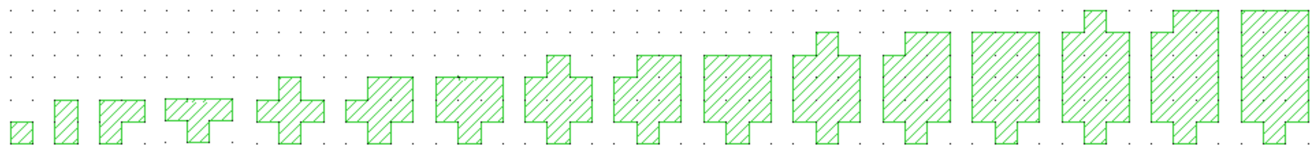
increase coupling left to right by increasing capacitor size: ensure uniform mm-wave power absorption

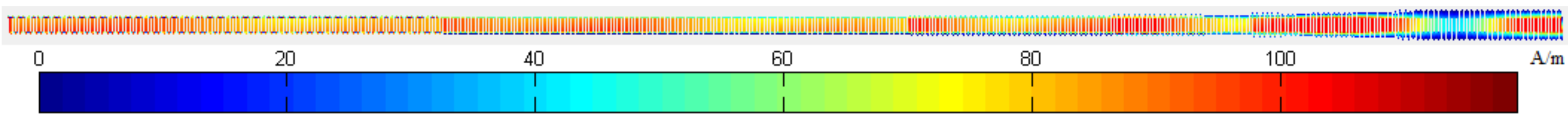


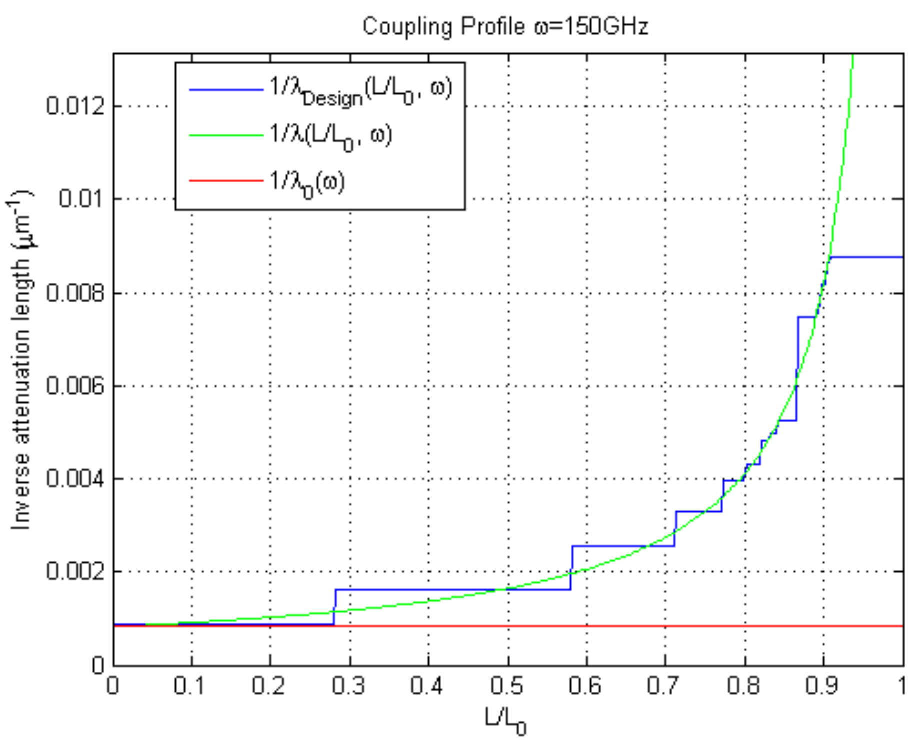
mm-wave current density; modest standing wave due to reflection at open end

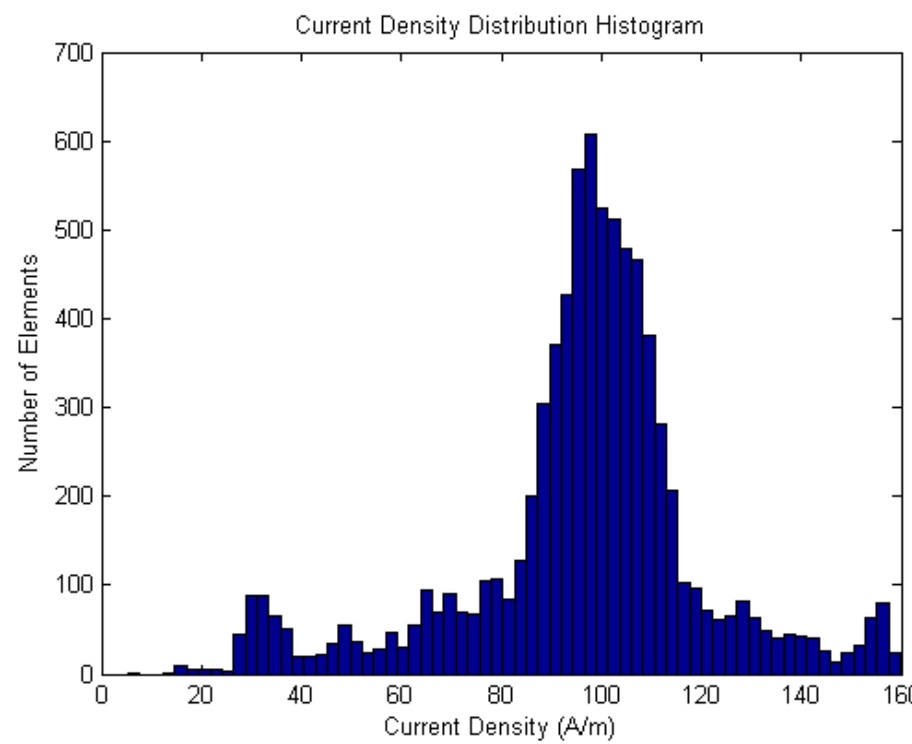
Millimeter-Wave Coupler

Increasing coupling adiabatically yields uniform mm-wave current density, power absorption

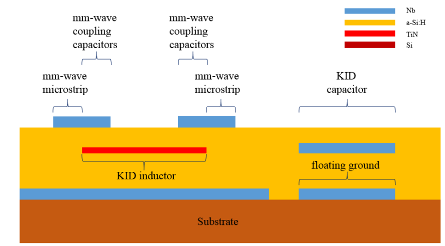








KID Design

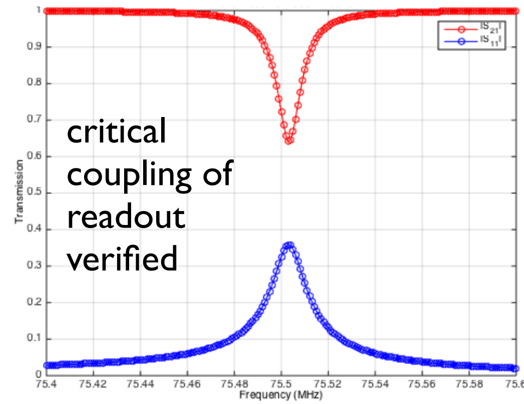


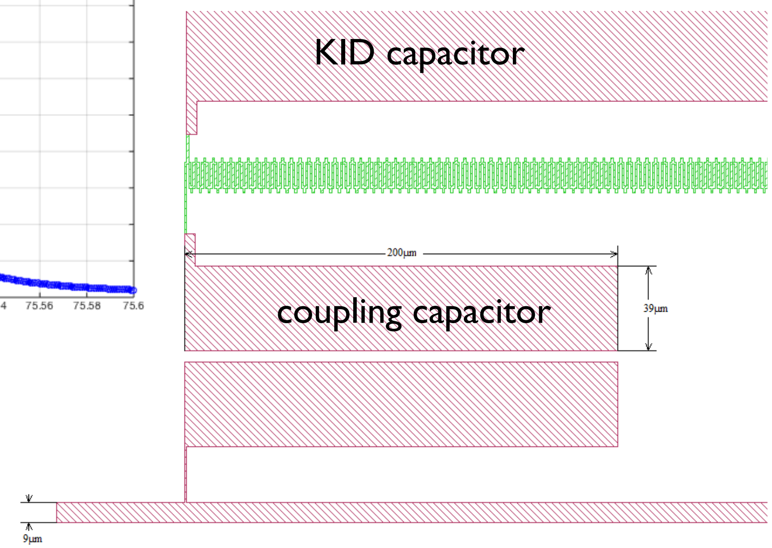
Coupling to feedline

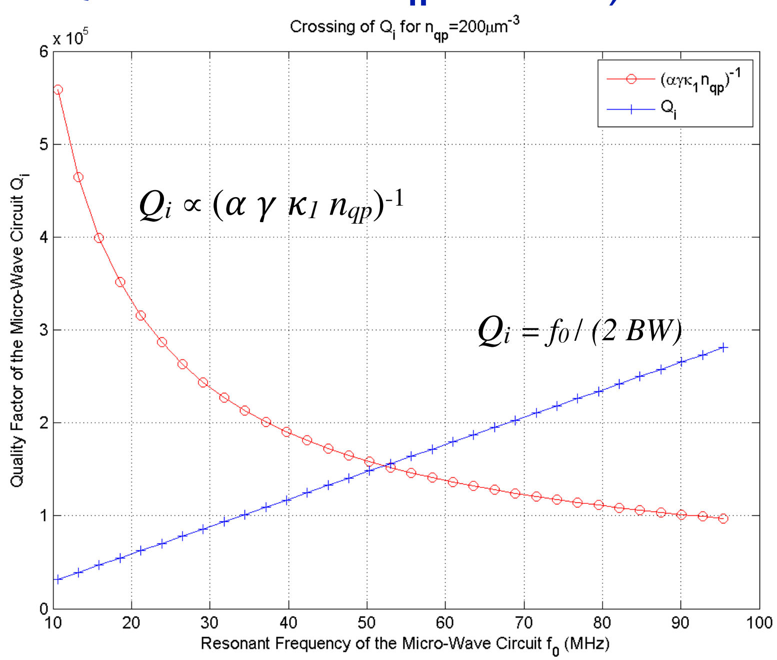
Use parallel plate capacitor like KID capacitor

Readout frequency

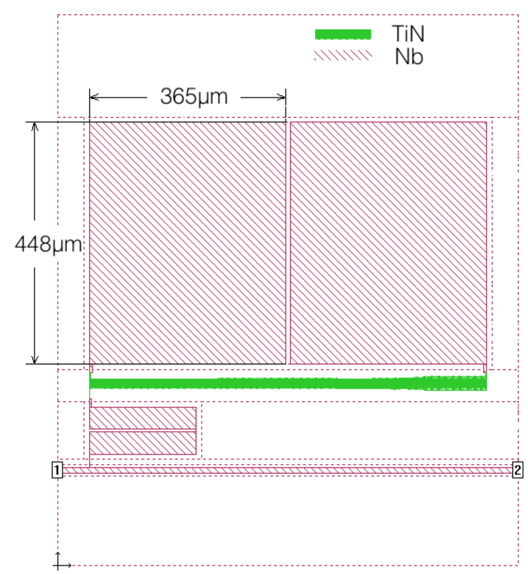
Maximize Q_i subject to constraint that resonator bandwidth $f_0/2Q_i$ > astronomical signal BW (50 Hz for ℓ = 5000 and 1°/s; Qi is mm-wave qp-limited)



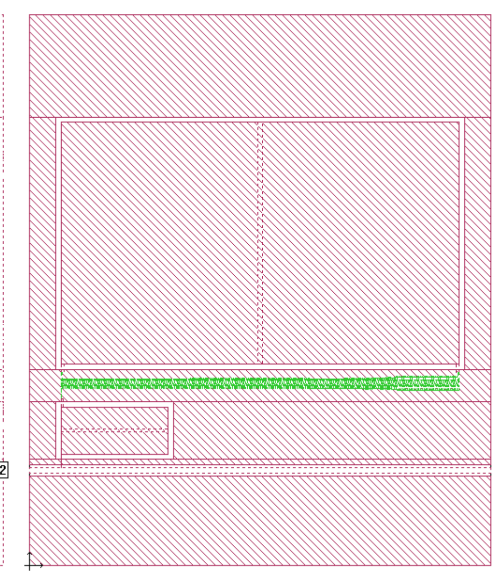




middle Nb, TiN layers



bottom Nb layer



Optimization Pressures

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- TiN thickness and inductor width saturate at min allowed values, 20 nm and 1 μm
  - Limits have been chosen ensure robust fabrication (thinner/narrower possible, but concern about yield)

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  - At fixed capacitor area, increasing thickness reduces the TLS noise ($\delta C/C$ or $\delta f/f$ units) bec. TLS noise $\propto 1/\sqrt{N_{fluctuators}} \propto 1/\sqrt{V_{cap}}$, so choosing the maximum value is sensible

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- f_0 always prefers lowest value allowed by audio bandwidth and multiplex factor because of $1/f_0$ dependence of responsivity
- TLS noise pushes for high P_{read}. Require $J <$ critical current density to avoid nonlinearity

Expected Sensitivity

Quantity	100 GHz	150 GHz
$\mathrm{NEP_{ph}}$ [aW $\mathrm{Hz^{-1/2}}$]	21	38
$\mathrm{NEP_{r}}$ [aW $\mathrm{Hz^{-1/2}}$]	17	30
$\mathrm{NEP_{amp}}$ [aW $\mathrm{Hz^{-1/2}}$]	2	4
$\mathrm{NEP_{TLS}}$ [aW $\mathrm{Hz^{-1/2}}$]	9	20
$\mathrm{NEP_{fund}}$ [aW $\mathrm{Hz^{-1/2}}$]	27	48
$\mathrm{NEP_{tot}}$ [aW $\mathrm{Hz^{-1/2}}$]	28	52
$\mathrm{NEP_{tot}^{eff}}$ [aW $\mathrm{Hz^{-1/2}}$]	29	53
$\mathrm{NEP_{tot}^{eff}/NEP_{ph}}$	1.40	1.41
$\mathrm{NEP_{tot}^{eff}/NEP_{fund}}$	1.07	1.10
$\mathrm{NET_{CMB}^{eff}}$ [$\mu\mathrm{K_{CMB}}$ $\mathrm{s^{1/2}}$]	200	250

T_c = 1 K, T = 0.1K
evaluated at 1 Hz
→ ℓ = 100 at 1°/s
$\Delta\nu/\nu$ = 0.3
T_{load} = 15 K
η_{opt} = 0.26, 0.40
P_{opt} = 1.9, 3.9 pW

Expected Sensitivity

Yields very competitive expected sensitivities

- c.f on-sky sensitivities:
  - BICEP2/Keck Array: 400 $\mu K_{CMB}\, s^{1/2}$
  - SPTpol: 500 $\mu K_{CMB}\, s^{1/2}$
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- Substantial headroom for real-world degradations

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Some other aspects of design:

- capacitor area ~ 2 mm^2 >> A_{feed} = 44 mm^2 assumed
- inductor length ~ 7 mm, inductor volume ~ 150 μm^3
- qp density ~ 2000 μm^{-3} >> "irreducible qp density" ~ 100 μm^{-3}
- $\beta \approx 55$; Q_i ~ 70000, dominated by optical load

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Design is scalable over range 45-420 GHz (T_c = 0.52K for 45 GHz)

Caveats/Modeling To Do

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Assumes TiN obeys Mattis-Bardeen; known to be not true

- But TiN responsivity seems to decrease less quickly with increasing P_{opt} than expected (or even increase!); our calculations are conservative
- Need to add empirical model for TiN responsivity

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- P_{read} generation of qps not included
  - P_{read} = -90 dBm (= 1 pW) assumed; heating effects not usually seen at this low power (e.g., deVissers et al 2010, Hubmayr et al 2015)
  - Need to incorporate in modeling

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Plans

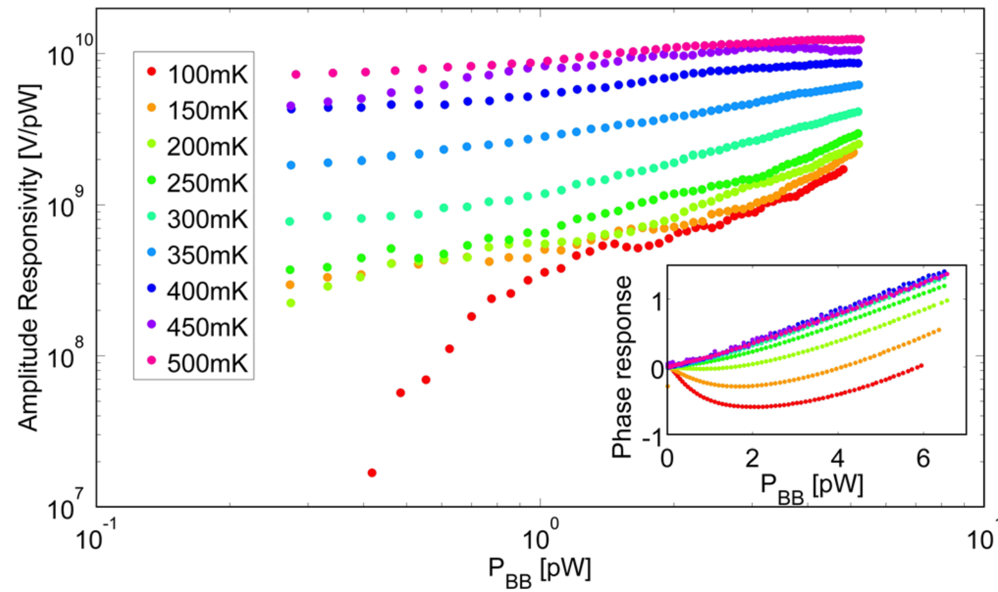
- Mask in hand; will make first pass at fabricating this FY on JPL R&TD (seed) funds
- DOE detector R&D proposal submitted
- Also working on crystalline silicon capacitors (and microstrip) as backup for a-Si:H

Backups

Optical Power Density and Responsivity

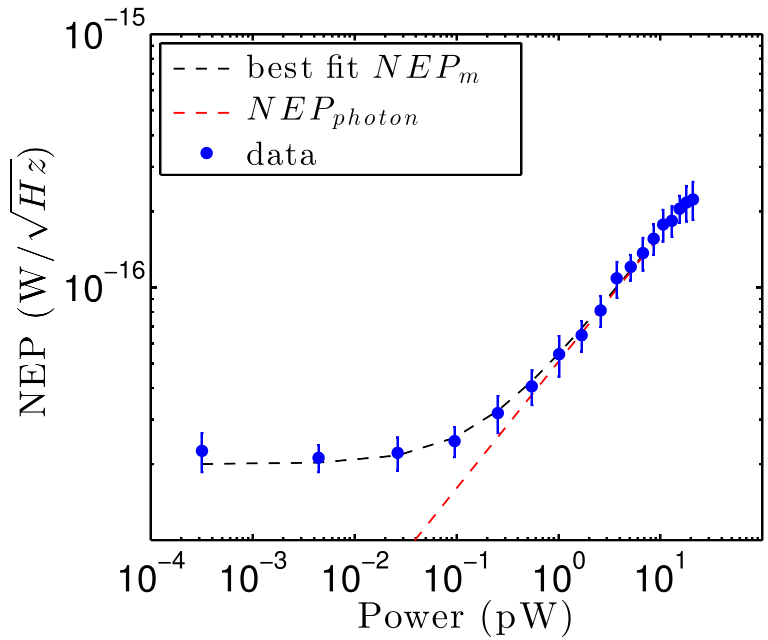
Bueno et al 2014

- Ignore TLS-dominated phase response
- Amplitude response increases with load rather than decreasing as $1/\sqrt{P_{opt}}$ as expected from M-B
- This would improve margin relative to amplifier and TLS noise!
- Strange discrepancy between optical and electrical NEP observed



Hubmayr et al 2015

- −97 dBm < P_{read} < −87 dBm, still linear
  - P_{res} comparable to our design
- $V_{inductor}$ = 86 μm^3, only 2x smaller than ours
- Shows photon noise limited behavior for P_{opt} > 1 pW
  - Measured at 1.2 THz, so NEP_{rec} negligible



Optimization Detail

Table 2: Parameters of KID design.

External (fixed) parameters at left, optimized parameters and parameters derived from them at right. Parameters not defined in the text: A_{feed} is the assumed area of the feed and corresponds to $2.2\, f\,\lambda$ at 150 GHz and $1.3\, f\,\lambda$ at 90 GHz for $f/\# = 1.5$. These numbes are typical of current systems (*e.g.*, Keck Array [24], SPTpol [64, 32]); $A_L = \ell_L\, w$; $V = A_L\, t$; $A_C = \ell_C^2$; $A_{KID} = A_L + A_C$; $L = \mu_0\, \lambda_{pen}\, \ell_L / w$; $C = \epsilon_d\, \epsilon_0\, \ell_c^2 / t_d$ where $\epsilon_d = 12$ is the dielectric constant of a-Si:H; E = electric field in capacitor; $\ell_{coupler}$ = length of inductive coupler to feedline.

Band-Independent External Parameters

Quantity	Value
T_c	1.0 K
2Δ	300 μeV
$2\Delta/h$	73 GHz
N_0	3.5×10^{10} μm^{-3} eV^{-1}
R	100 μm^3 s^{-1}
τ_0	100 μs
T	0.1 K
t_d	400 nm
T_N	4.0 K
P_{read}	1.0 pW
J^*	6.0 mA μm^{-2}
$S^{TLS}_{\delta f/f}$	see text
f_a	1 Hz

Band-Dependent External Parameters

Quantity	90 GHz	150 GHz
$\Delta\nu$ [GHz]	35	47
T_L [K]	15	15
A_{feed} [mm^2]	44.4	44.4
η_{opt}	0.26	0.40
P_{opt}	1.9	3.9
η_{ph}	0.81	0.57

Optimized Parameters

Quantity	90 GHz	150 GHz
Varied Parameters		
ℓ_L [mm]	6.3	7.4
w [μm]	1.01	1.04
t [nm]	20	
Derived Geometrical Parameters		
ℓ_C [mm]	1.42	1.13
A_L [mm^2]	0.006	0.008
V [μm^3]	128	154
A_C [mm^2]	2.00	1.28
$A_{feed}/(A_{feed} + A_{KID})$	0.96	0.97
Derived RF Parameters		
λ_{pen} [μm]	30	
L [μH]	0.24	0.27
C [pF]	133	85
f_r [MHz]	28	33
Q_i [10^4]	8.3	6.8
J_{read} [mA μm^{-2}]	2.2	1.7
E [kV/m]	4.7	4.9
$S^{TLS}_{\delta f/f}$ [10^{-19} Hz^{-1}]	2.1	3.1
$\ell_{coupler}$ [mm]	3.4	3.7
Derived Quasiparticle Parameters		
n_{qp} [μm^{-3}]	1850	2000
τ_{dyn} [μs]	2.6	2.4
Derived Responsivity		
η_{abs}	0.81	0.78
$d(\delta f/f)/dP_{opt}$ [10^6 W^{-1}]	95	50
Derived Sensitivity		
$\mathrm{NEP_{ph}}$ [aW Hz$^{-1/2}$]	21	38
$\mathrm{NEP_{r}}$ [aW Hz$^{-1/2}$]	17	30
$\mathrm{NEP_{amp}}$ [aW Hz$^{-1/2}$]	2	4
$\mathrm{NEP_{TLS}}$ [aW Hz$^{-1/2}$]	9	20
$\mathrm{NEP_{fund}}$ [aW Hz$^{-1/2}$]	27	48
$\mathrm{NEP_{tot}}$ [aW Hz$^{-1/2}$]	28	52
$\mathrm{NEP^{eff}_{tot}}$ [aW Hz$^{-1/2}$]	29	53
$\mathrm{NEP^{eff}_{tot}/NEP_{ph}}$	1.40	1.41
$\mathrm{NEP^{eff}_{tot}/NEP_{fund}}$	1.07	1.10
$\mathrm{NET^{eff}_{CMB}}$ [μK$_{\mathrm{CMB}}$ sec$^{1/2}$]	200	250

Crystalline Si and a-Si:H Loss Tangent Comparisons

Next steps:

- noise measurements to correlate TLS noise w/high-field Q_i
- mm-wave loss measurements to correlate w/low-power Q_i

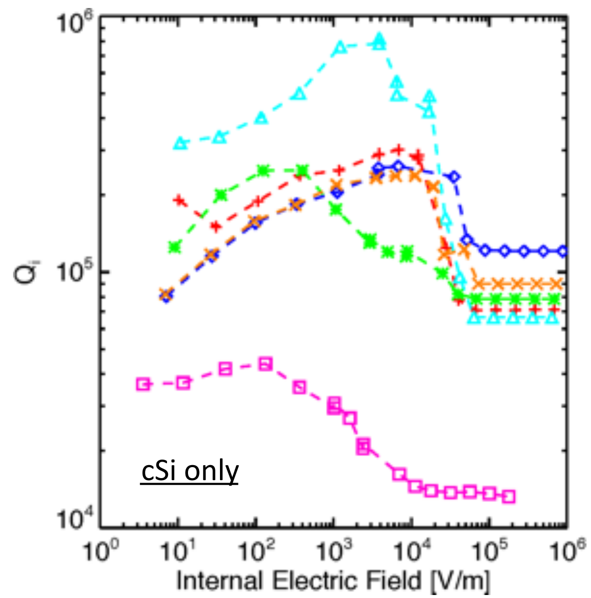
Virgin cSi results comparable w/Siddiqi gp. (though not precisely)

Currently, wafer-bonded cSi shows poorer high-field Q_i than a-Si:H, comparable low-field Q_i

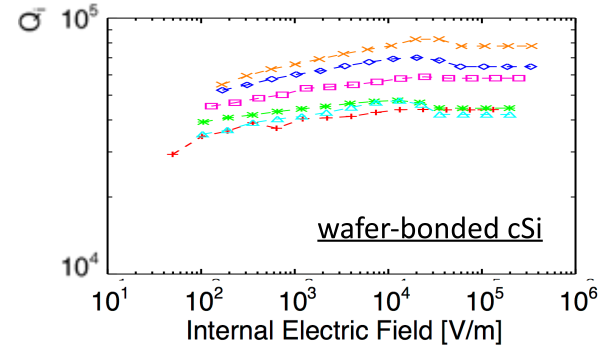
Wafer-bonded cSi comparable to virgin cSi w/native oxide

a-Si:H comparable to virgin cSi at high field, degrades more at low field

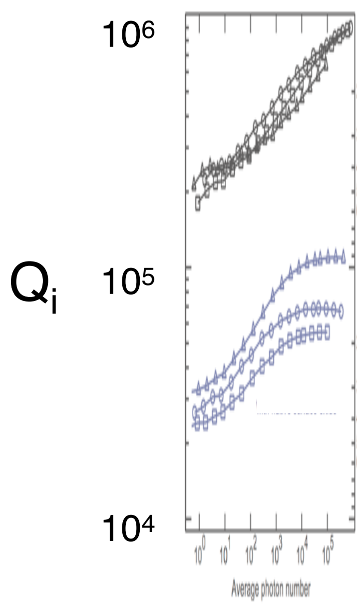
MUSIC a-SiN_x had high-field Q_i ~ 10000 low-field Q_i ~ 1000, all would be vast improvements



Low-power from freq shift vs. T: 30000-70 000



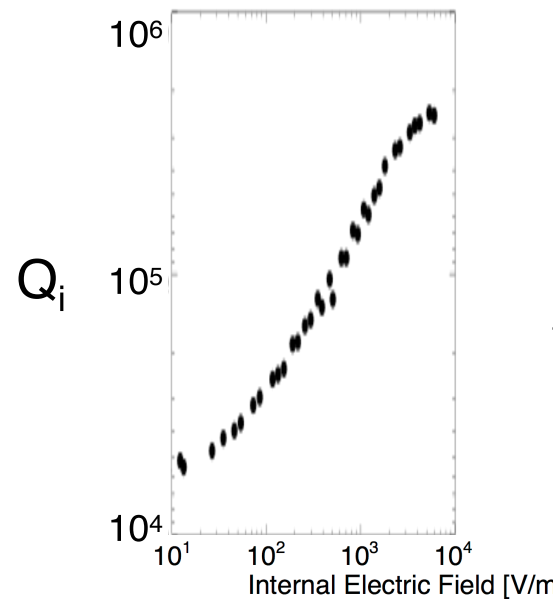
Low-power from freq shift vs. T: 8000-20000



Weber et al 2011 (Siddiqi group) cSi only

surface oxide removed

native surface oxide



Mazin et al 2010 a-Si:H/Al microstrip resonator