Quantum Limited Detectors for Astronomical Receivers

Ghassan Yassin
Astrophysics, University of Oxford, UK

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Quantum (Heterodyne) Detectors

- SIS Mixers at Millimere Wave lengths
  - On Chip Arrays
  - Harmonics Multipliers
- THz Mixers
  - ALMA Band 10, band 11 SIS mixers
  - Understanding the physics of SIS mixers above the gap

- Superconducting Parametric Amplifiers
  - Investigation of operating temperature and losses
  - IF amplifiers for SIS mixers
  - Wide band millimeter amplifiers.

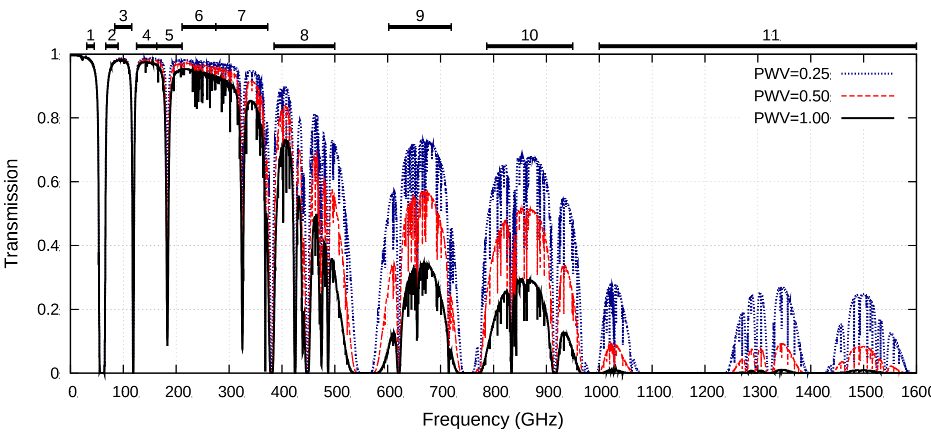
Oxford Quantum Detectors

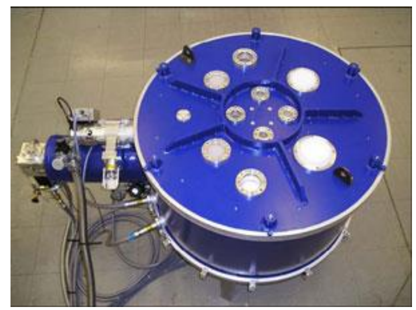
- Group
  - Ghassan, Boon Kok Tan, John Garret, Rik Elliott, Alessandro Traini, Kitti Ratter.
  - Two PhD students.
- Funding
  - STFC Consortium grant (with Cambridge and RAL)
  - Horizon 2020 (RadioNet)
  - ERC Grant+ MERAC fund (SPA)
- Collaboration
  - RAL (LO sources, Mechanical Engineering, Measurements,…)
  - Cambridge (superconducting devices)
  - Paris Observatory (SIS devices Faouzi Boussaha)
  - Harvard-Smithsonian CfA (dual polarization receiver for SMA).

ALMA

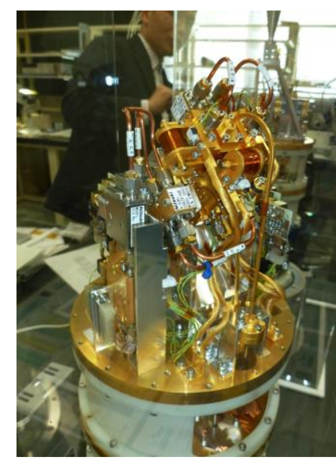
Credit: Dr. Faouzi Boussaha, Paris Observatory

ALMA Receiver Cabin

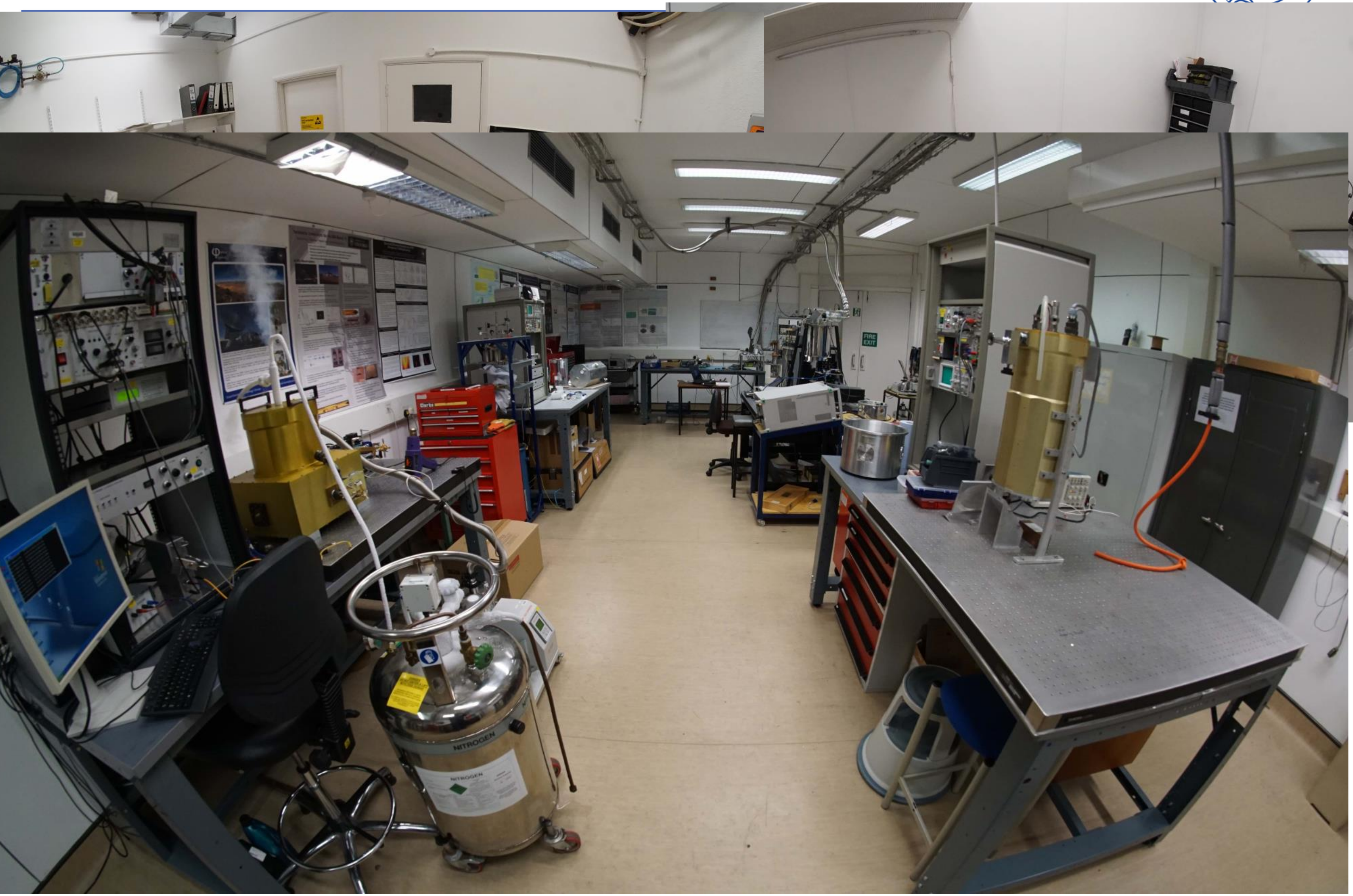




Band	Frequency range (GHz)	Target Receiver Noise Temperature (K)		Detector technology
		80% RF band	At any RF frequency	
1	31–45	17	26	HEMT[a]
2	67–90	30	47	HEMT
3*	84–116	37	60	SIS
4	125–163	51	82	SIS
5	162–211	65	105	SIS
6*	211–275	83	136	SIS
7*	275–373	147	219	SIS
8	385–500	196	292	SIS
9*	602–720	175	261	SIS
10	787–950	230	344	SIS



Lab Photo



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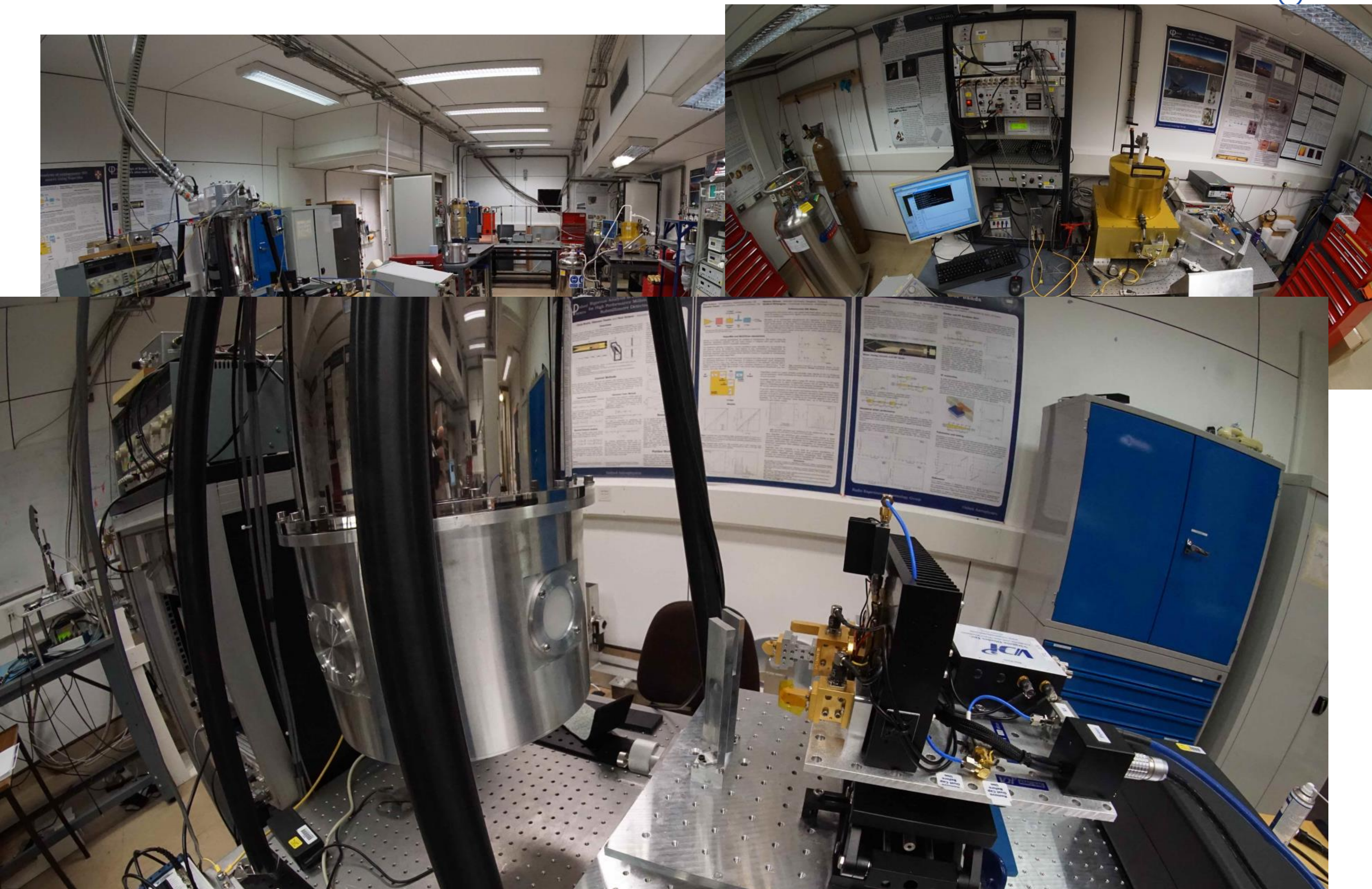
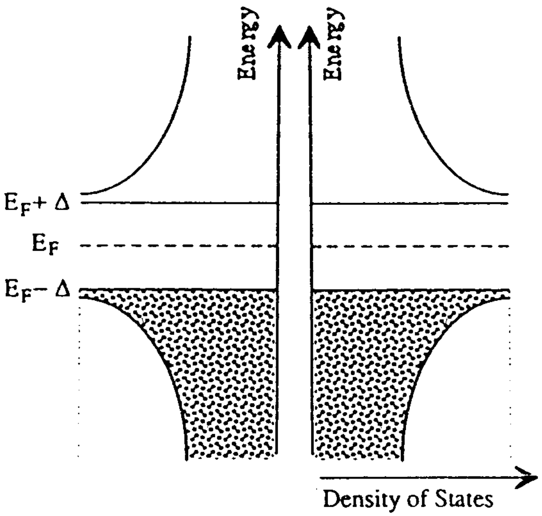
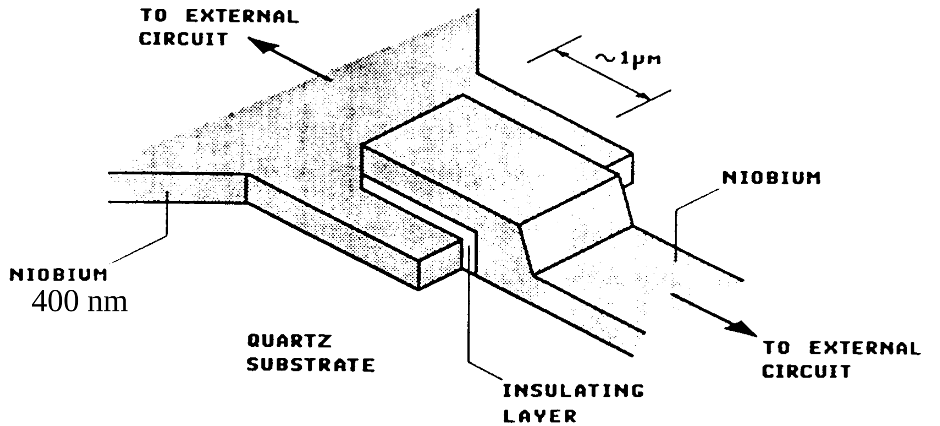


The SIS Tunnel Junction

The SIS (superconductor-insulator-superconductor) is ~ 1μm^2 sandwich of two superconductors separated by a thin (20 A^0)insulator



The semiconductor picture



The SIS Nb tunnel junction

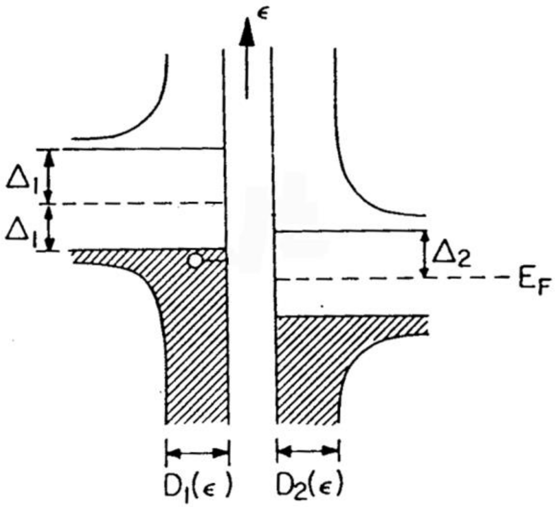
quasiparticles are normal electrons with energy and density of states:

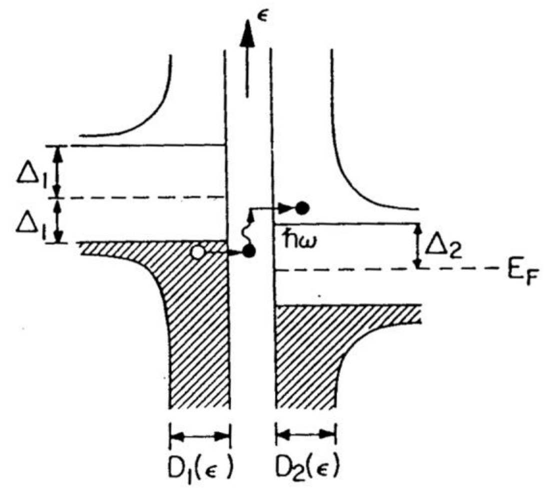
$$E_k = (\varepsilon_k^2 + \Delta^2)^{\frac{1}{2}}$$

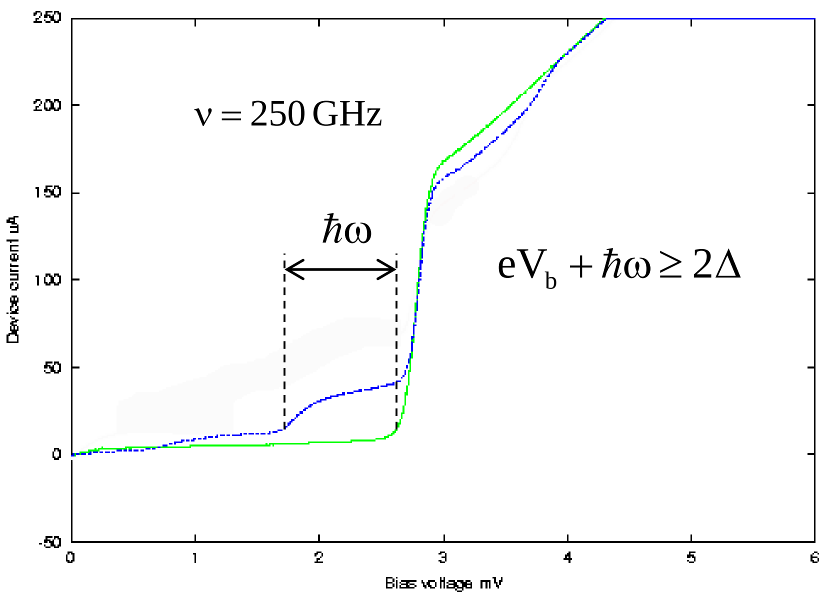
$$\rho(E) = \begin{cases} N(0)\dfrac{|E|}{(E^2 - \Delta^2)^{\frac{1}{2}}} & \text{for } |\mathrm{E}| > \Delta \\ 0 & \text{Otherwise} \end{cases}$$

SIS Tunnel Junctions

Credit: Dr. Faou



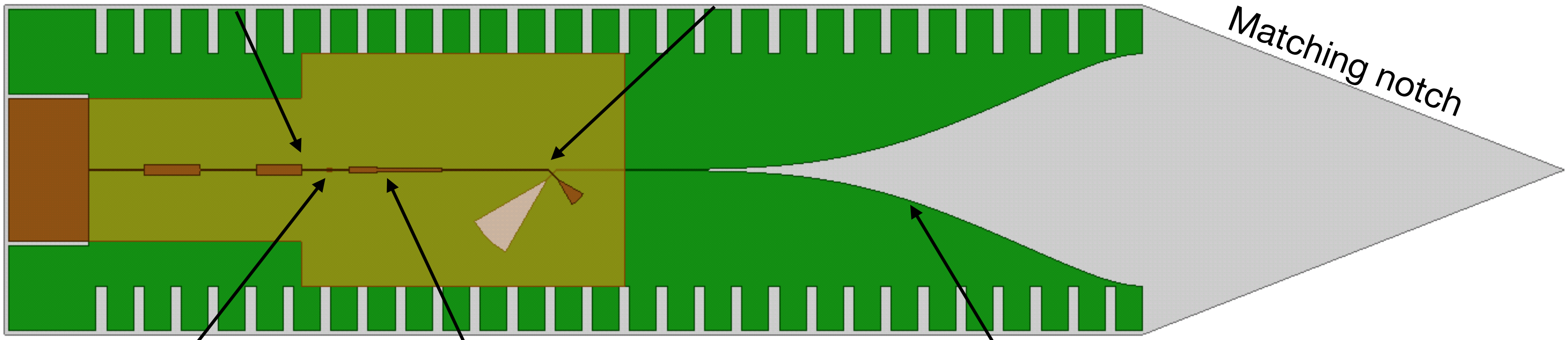


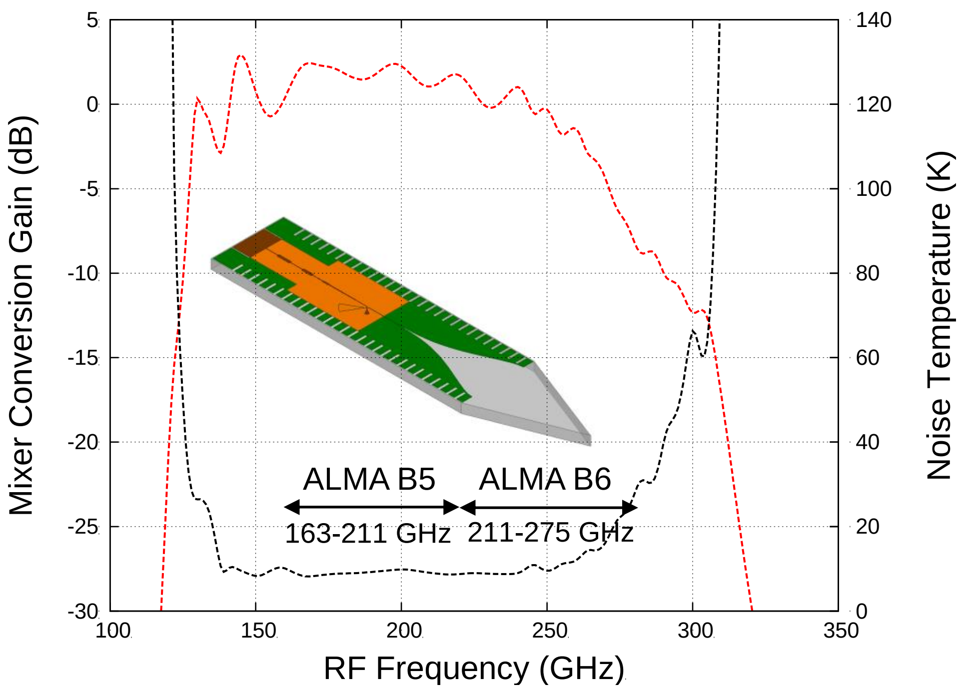


$$E_k = (\varepsilon_k^2 + \Delta^2)^{\frac{1}{2}}$$

$$\rho(E) = \begin{cases} N(0)\dfrac{|E|}{(E^2 - \Delta^2)^{\frac{1}{2}}} & \text{for } |\mathrm{E}| > \Delta \\ 0 & \text{Otherwise} \end{cases}$$

Full RF Mixer Chip



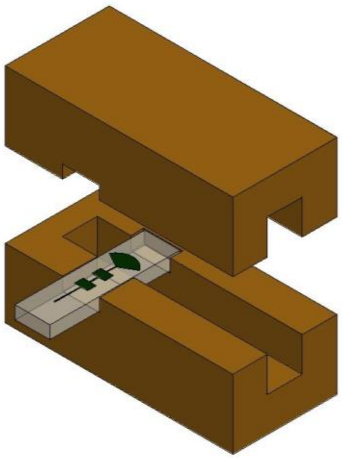


Mixer designs based on:

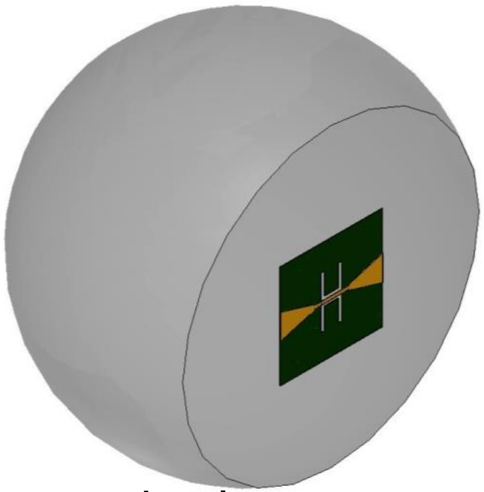
- 15 ohm, 120 fF, 1.5 um^2 junction
- 350 nm Nb / 490 nm SiO / 200 nm Nb
- 100 um Quartz substrate
- Smallest feature 2.5 um

Optimised using HFSS to include **3D electromagnetic effects** and **superconductivity**

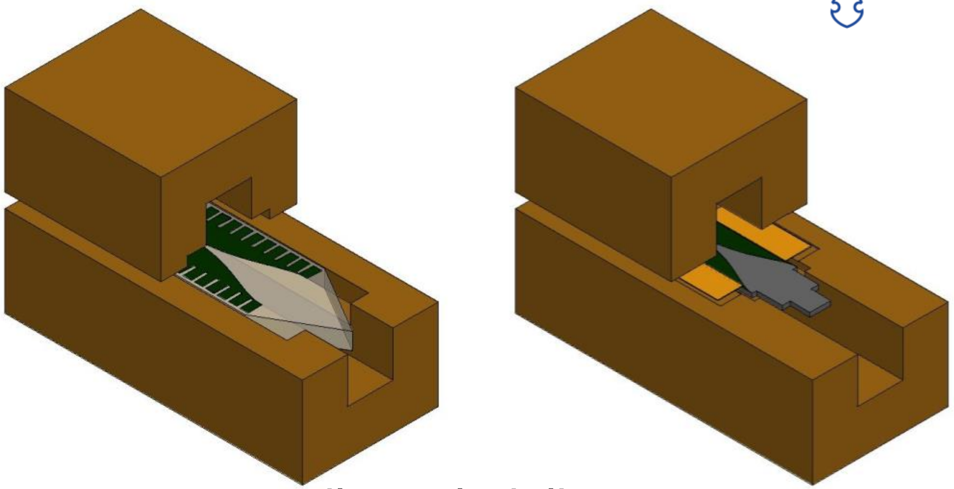
Waveguide to Planar Circuit Transitions



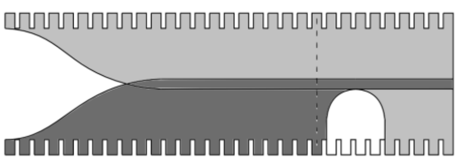
1. Radial Probe

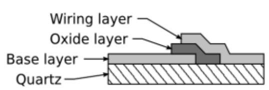


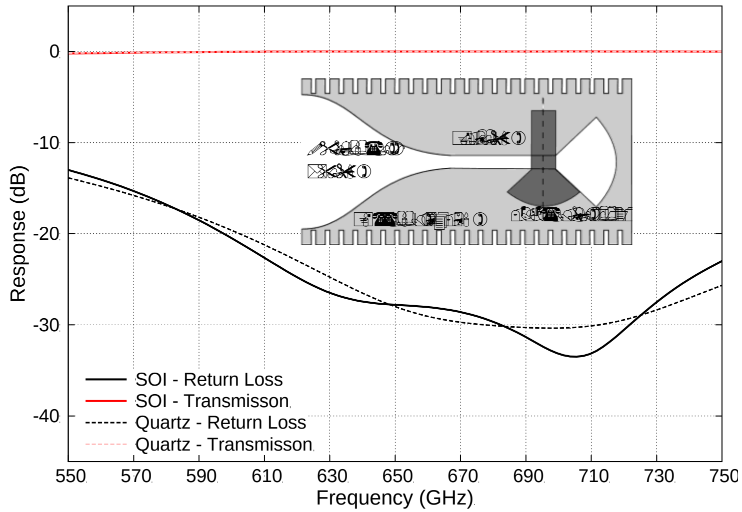
2. Twin-slot Antenna



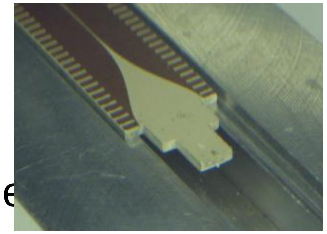
3. Unilateral Finline Taper







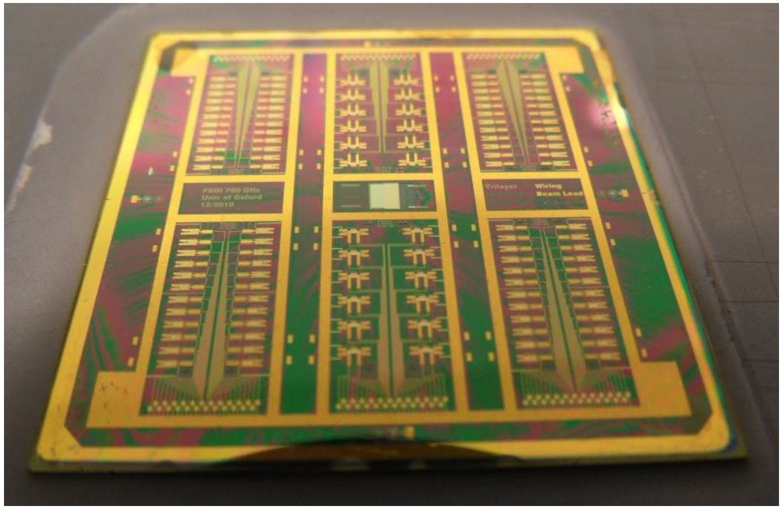
Unilateral Finline Taper

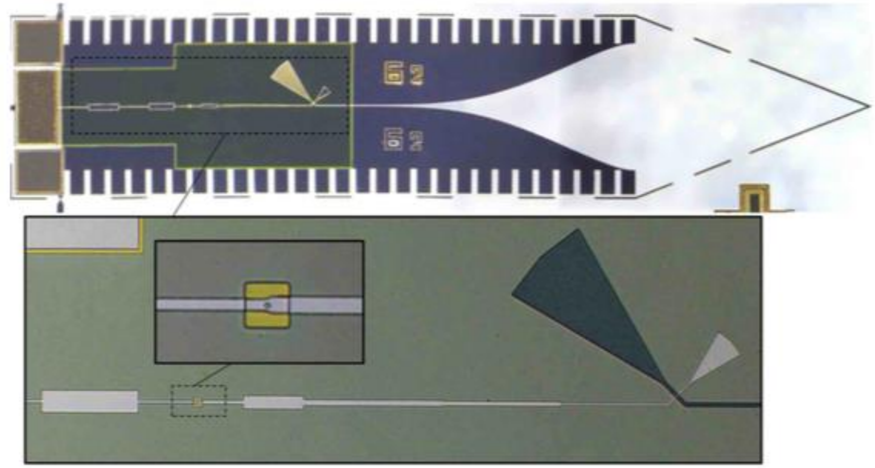


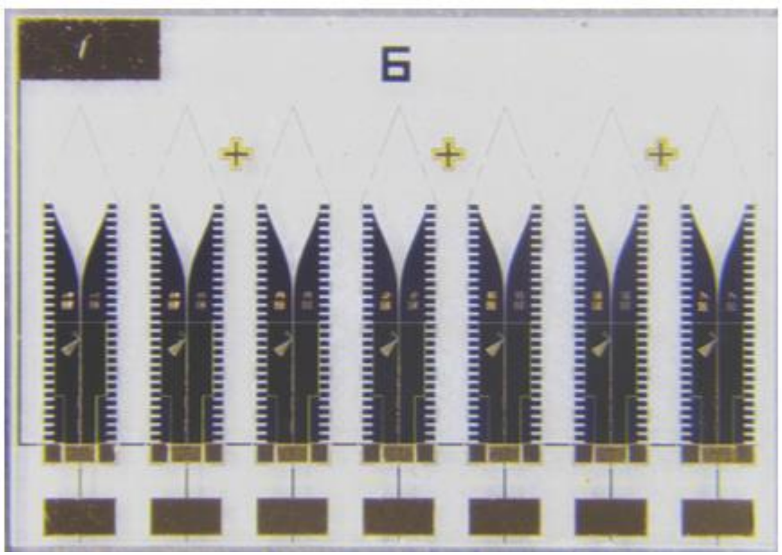
- Oriented along waveguide axis
- No backshort, minimal alignment issue
- Natural bandpass filter, prevent IF signal leakage
- Simple mixer block
- Wide bandwidth, smooth tapering of waveguide impedance to slotline
- Large substrate area for circuit integration
- Fully on-chip fabrication, high frequency

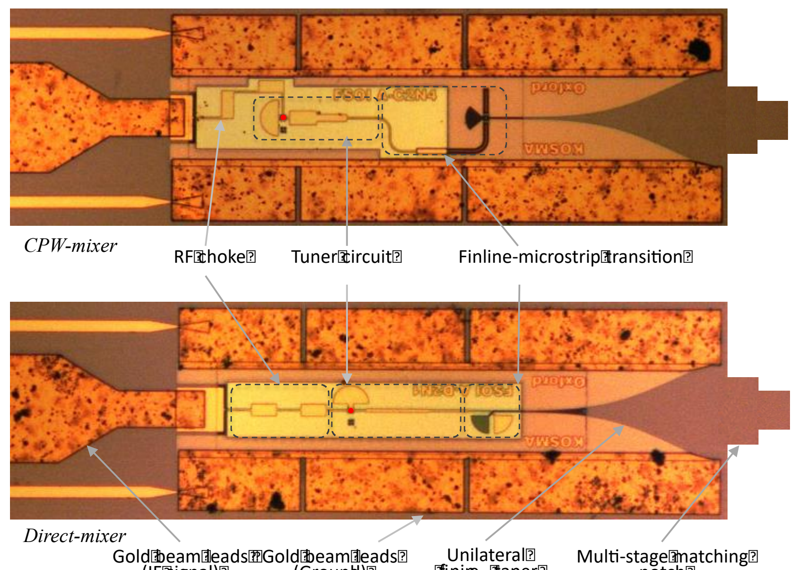
Band 5/6 & Band 9 Mixers

Credit: Dr. John Garrett (Oxford University) & Cologne University



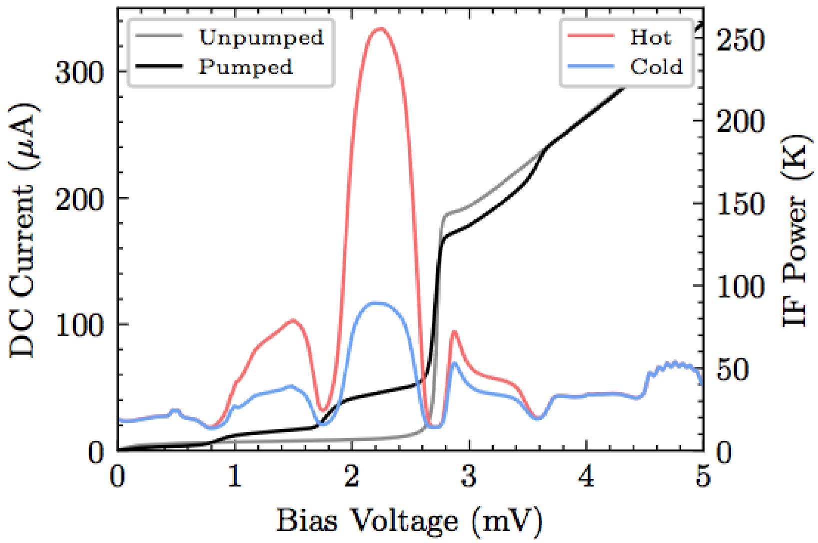


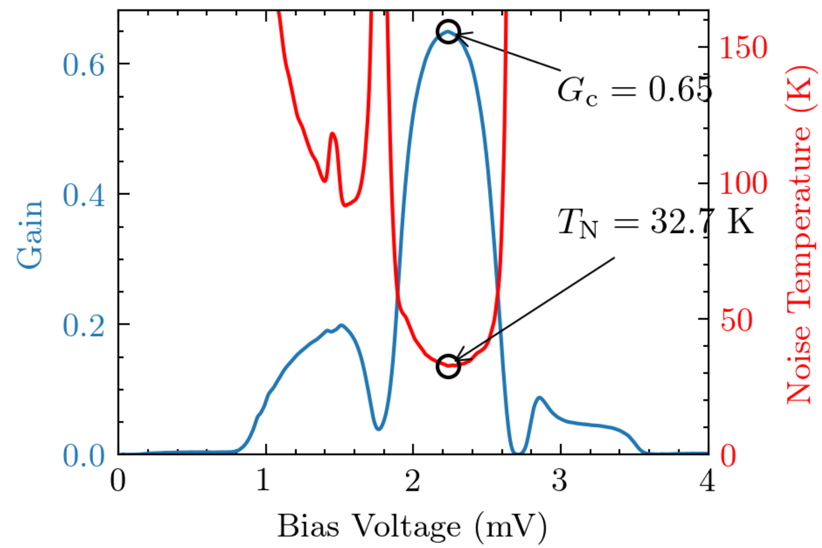


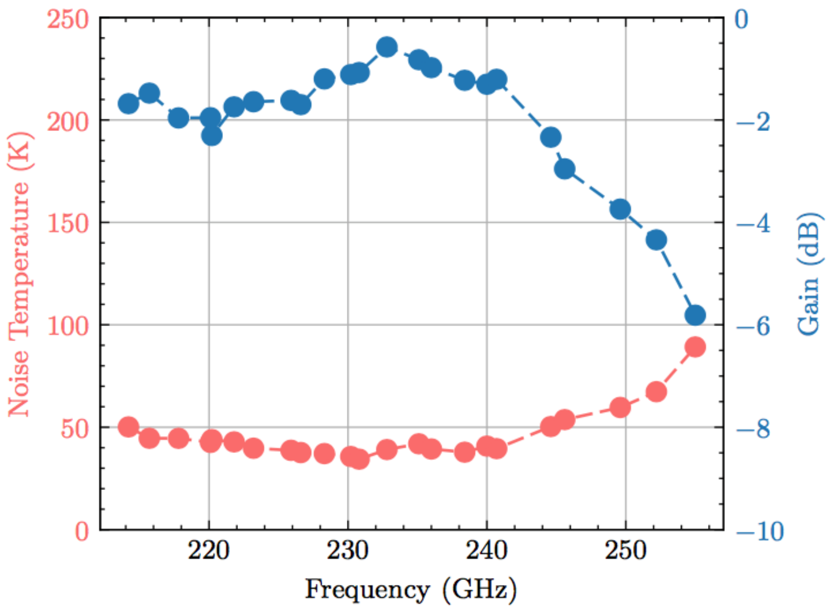


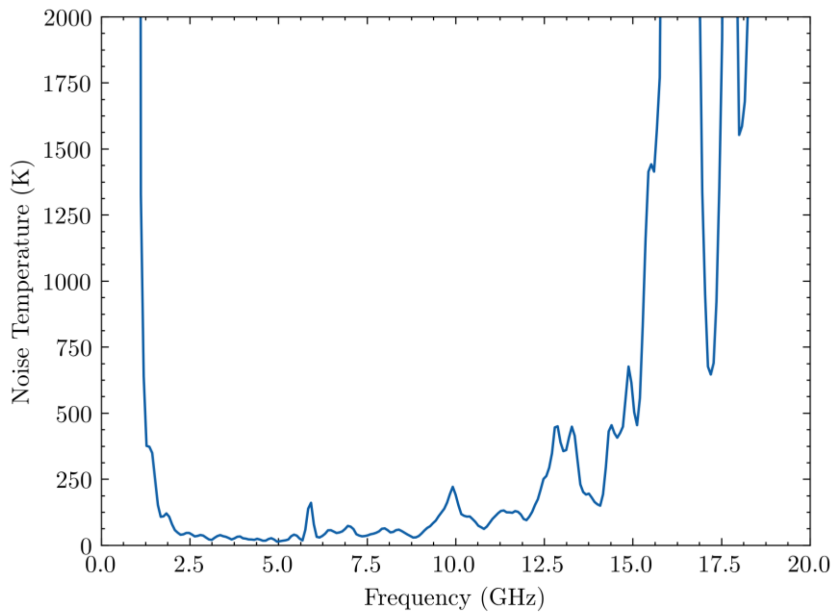
Measured Characteristics

Credit: Dr. John Garrett (Oxford University)

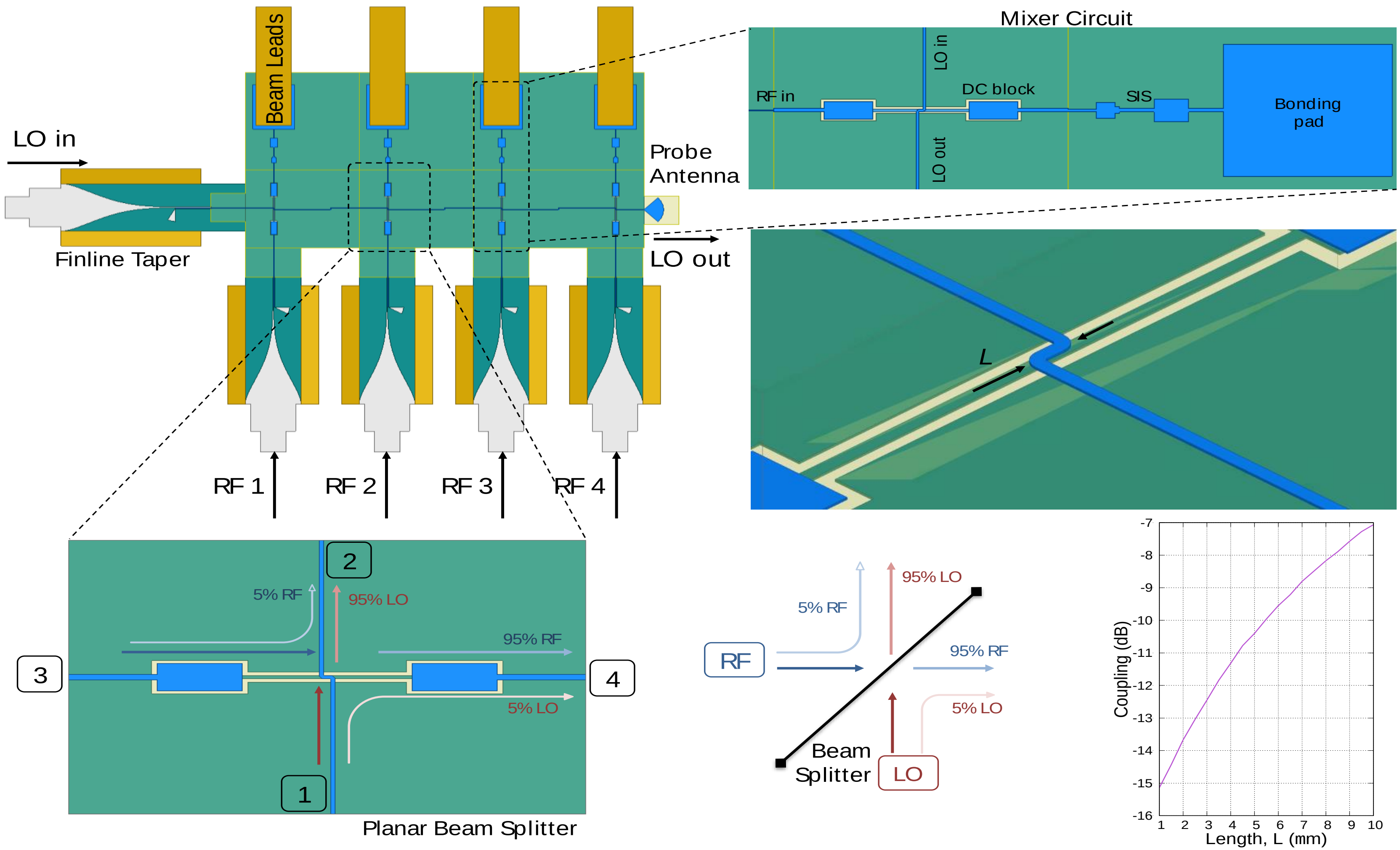




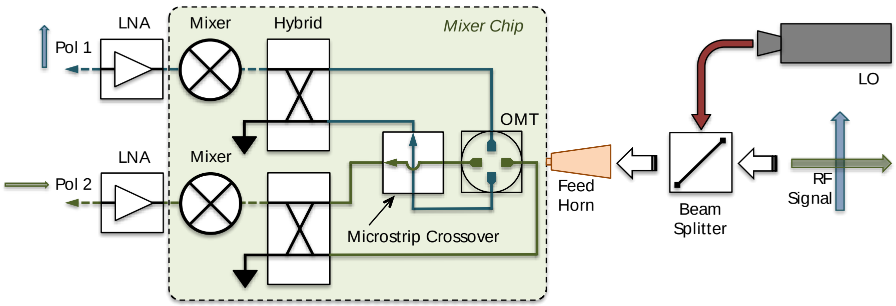


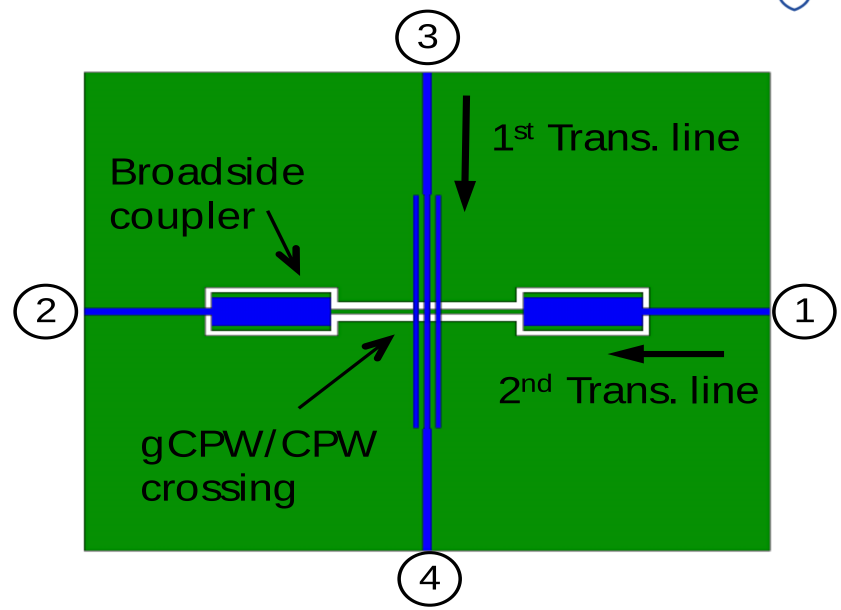


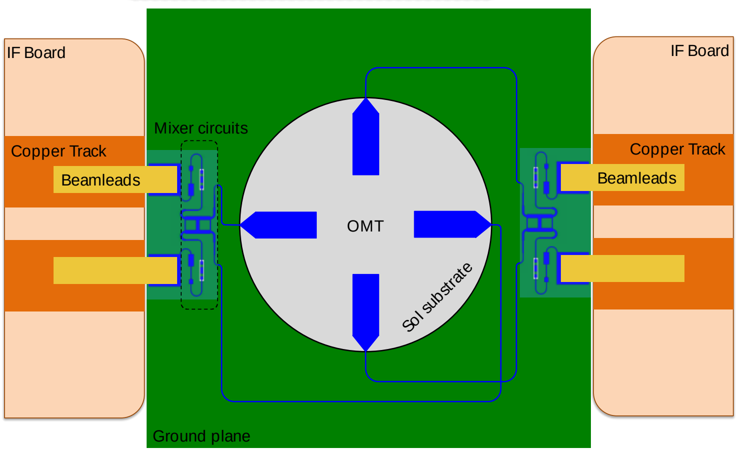
Planar beam splitter

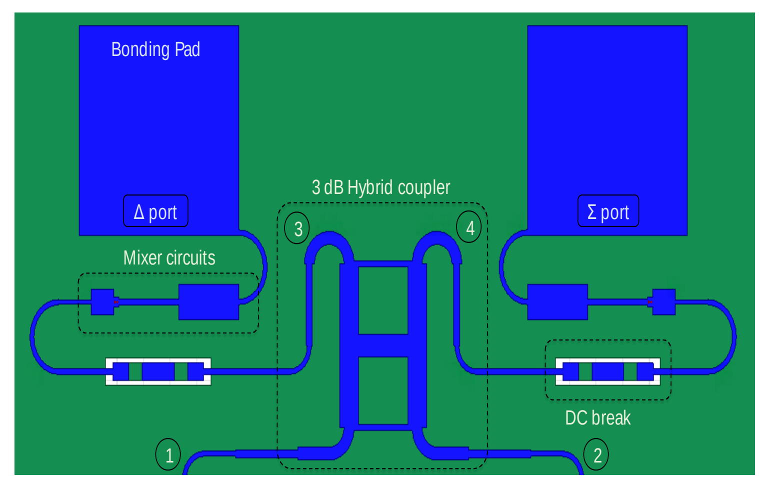


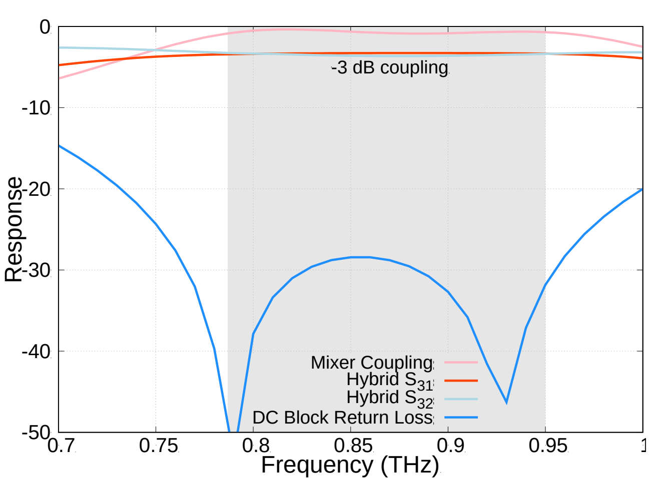
On Chip dual polarization mixer



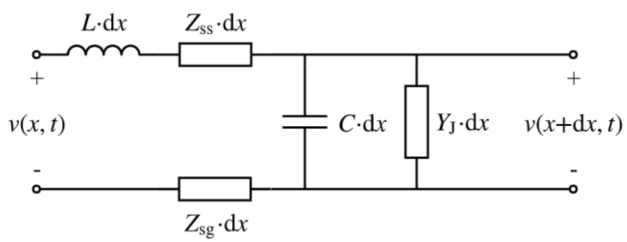


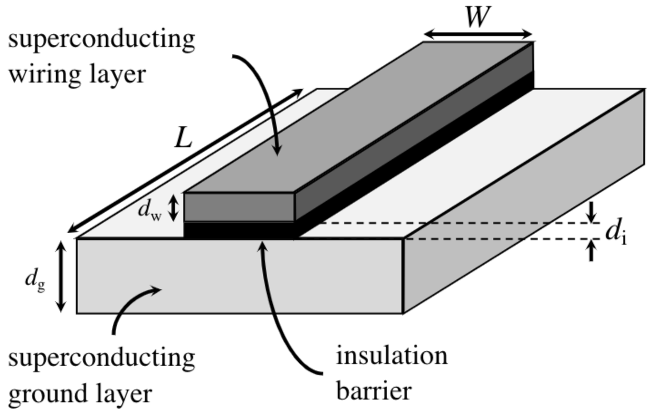






The Distributed SIS Junction





$$Z = W^{-1}\left(j\omega L_s + Z_{sw} + Z_{sg}\right)$$

$$Y = W\left(j\omega C_s + Y_j\right)$$

$$Y_J = \frac{I_\omega}{V_\omega \cdot A}$$

$$\alpha = \frac{V_\omega}{V_{ph}}$$

$$\text{Re}\,\{I_\omega\} = \sum_{-\infty}^{\infty} J_n(\alpha)[J_{n-1}(\alpha) + J_{n+1}(\alpha)]\cdot I_{dc}(V_b + nV_{ph})$$

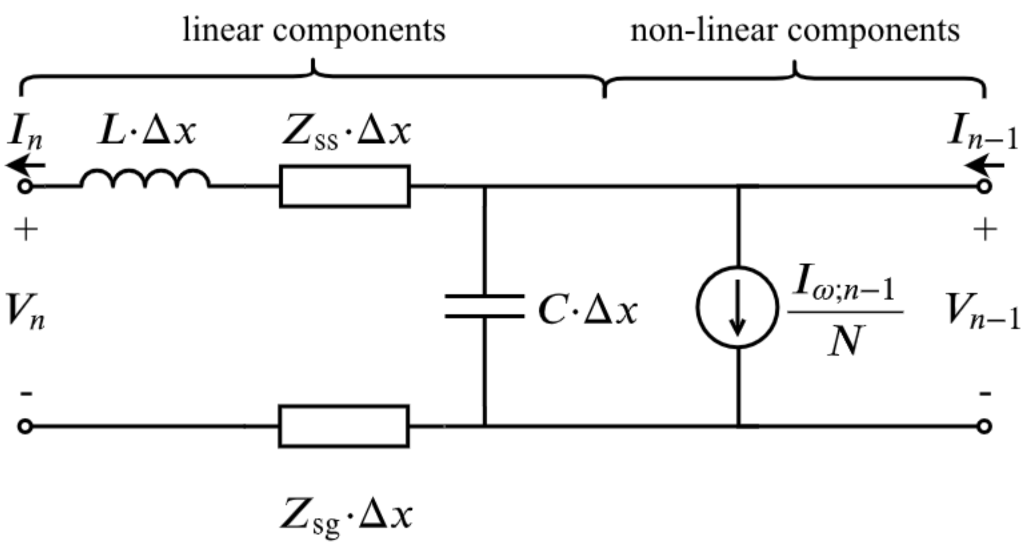
$$\text{Im}\,\{I_\omega\} = \sum_{-\infty}^{\infty} J_n(\alpha)[J_{n-1}(\alpha) - J_{n+1}(\alpha)]\cdot I_{KK}(V_b + nV_{ph})$$

$$\gamma = \sqrt{Z \cdot Y}$$

$$Z_0 = \sqrt{Z/Y}$$

$$Z_{in} = Z_0 \coth \gamma L$$

The nonlinear Model



$$\begin{bmatrix} V_n \\ I_n \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix}^{-1} \begin{bmatrix} V_{n-1} \\ I_{n-1} \end{bmatrix} - \begin{bmatrix} 0 \\ I_\omega / N \end{bmatrix}$$

$$\mathbf{V}^{k+1} = \mathbf{V}^k + [\boldsymbol{J}(\mathbf{V}^k)]^{-1} \cdot \Delta(\mathbf{V}^k)$$

Newton Raphson method

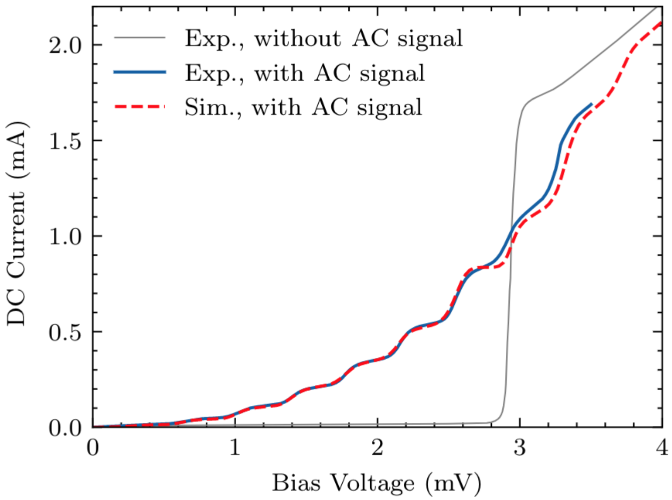
$$\Delta = INZemb - V_{\mathrm{N}} - V_{\mathrm{emb}}$$

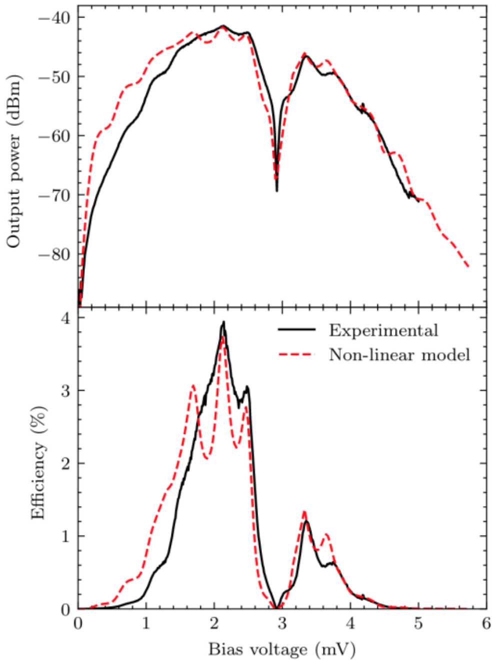
$$\Delta' = I_N' \cdot Z_L' - V_N'$$

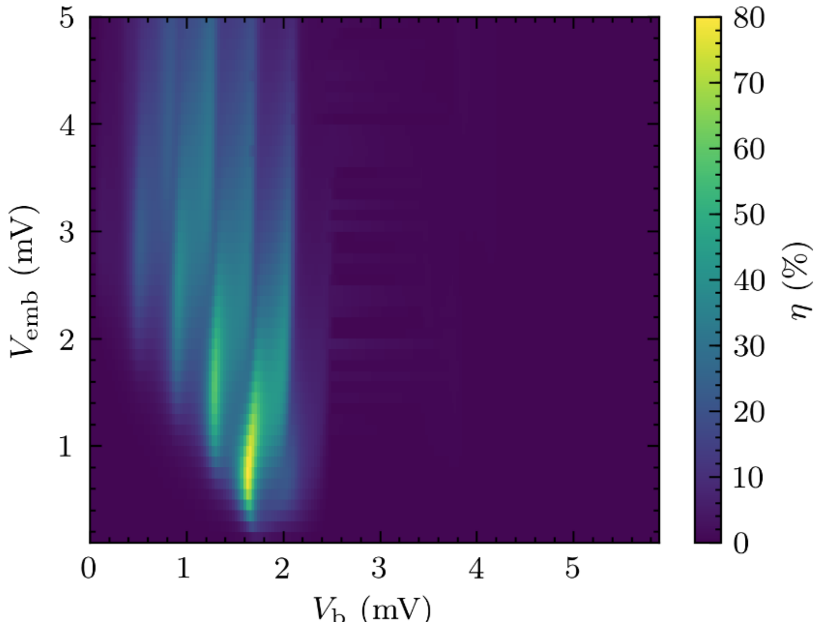
$$P_L' = \frac{|VN'|^2}{2\mathrm{Re}\{Z_L'\}}$$

$$\eta = \frac{P_L'}{P_{emb}}$$

Results from the nonlinear model

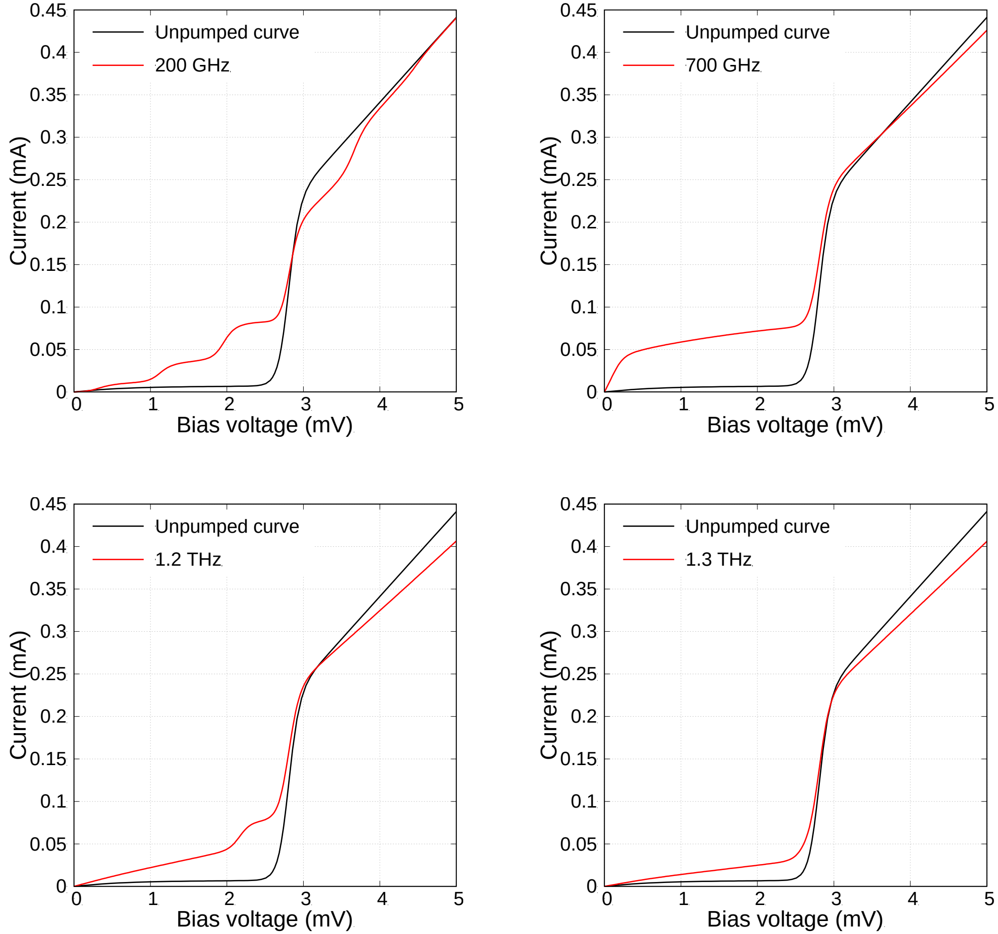


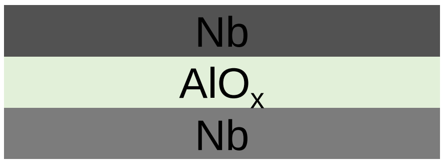




Efficiency of 80% at
(V_b, V_{emb})= (1.62, 0.7) mV
Output power -38 dbm at
(1.24, 5.0) mV

THz Tunnel Junction





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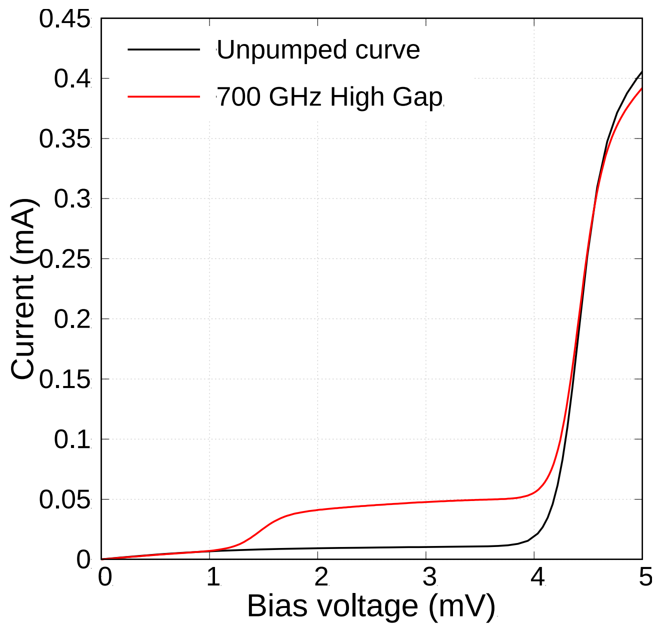
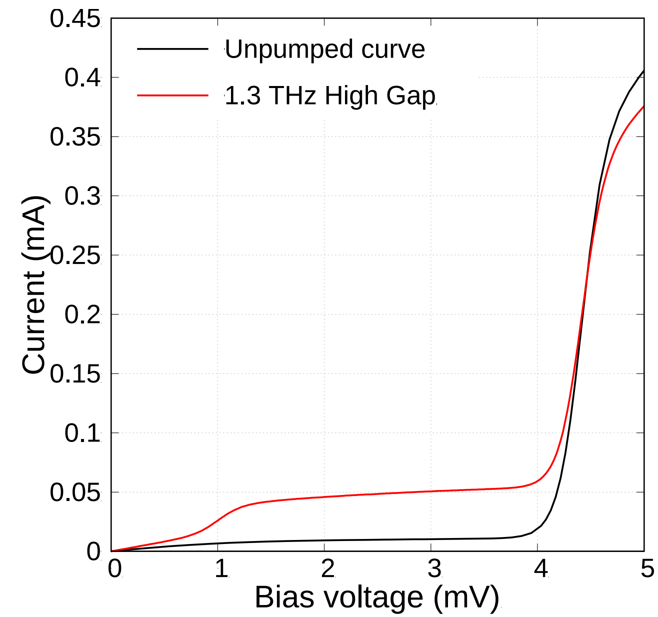
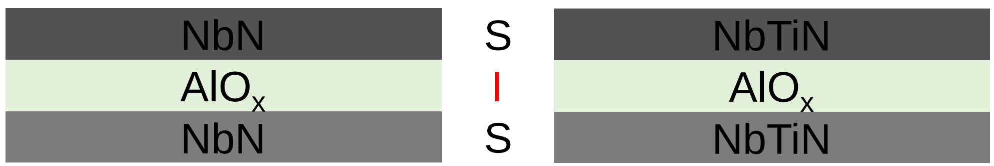


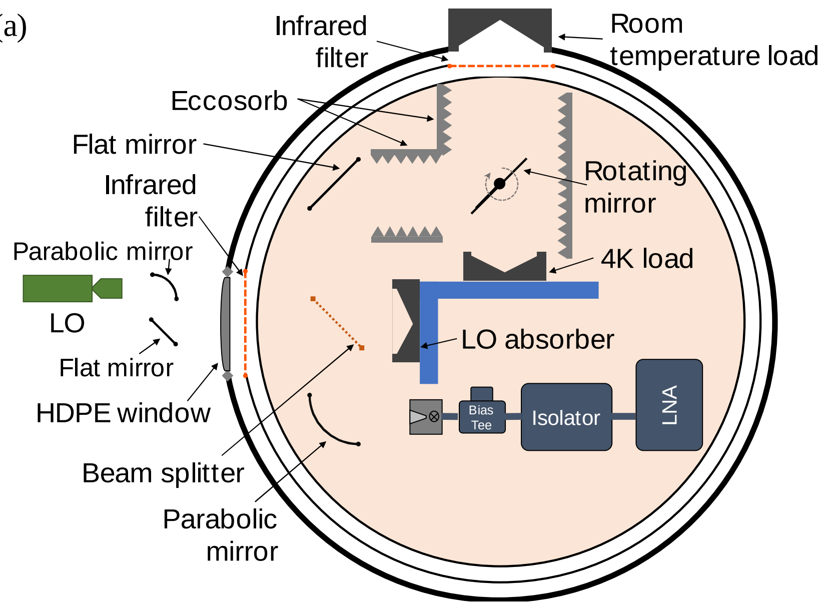


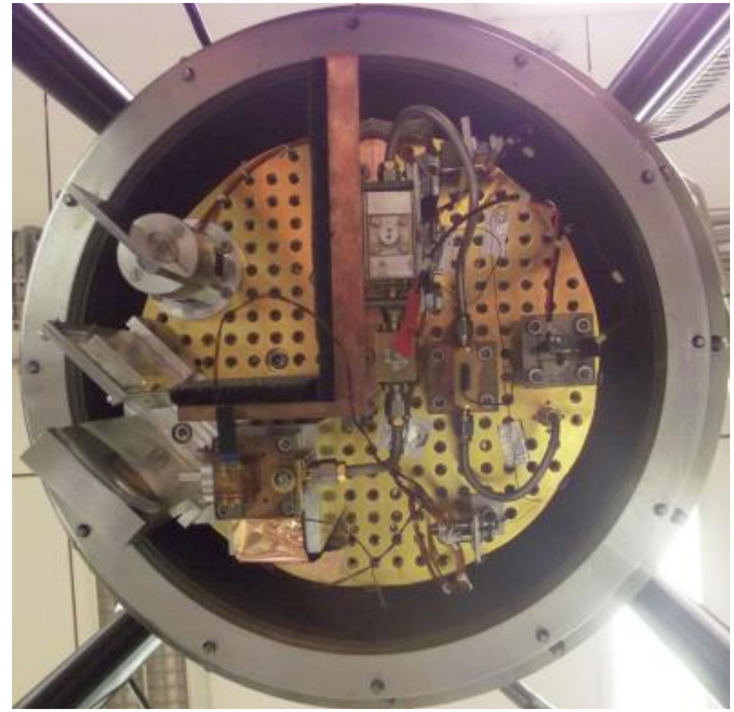


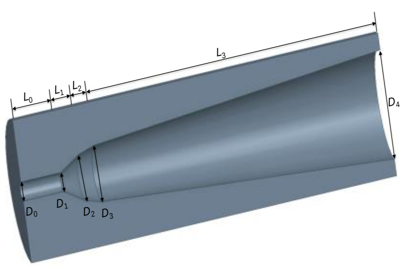
High gap superconductors

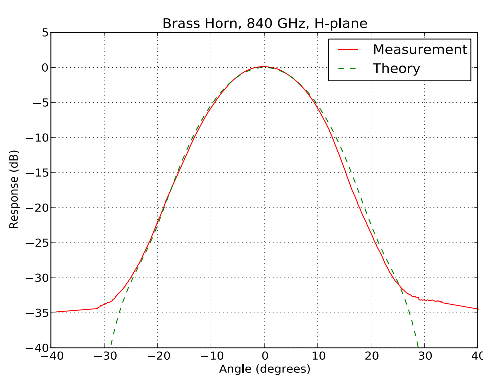
THz Test System

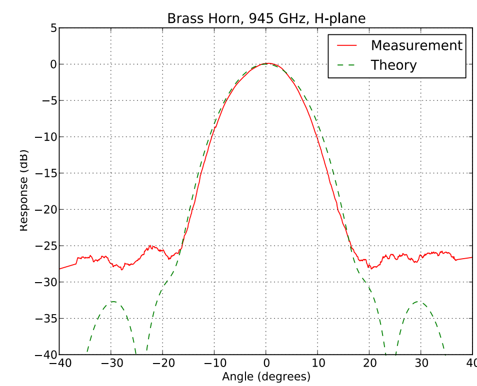
(a)





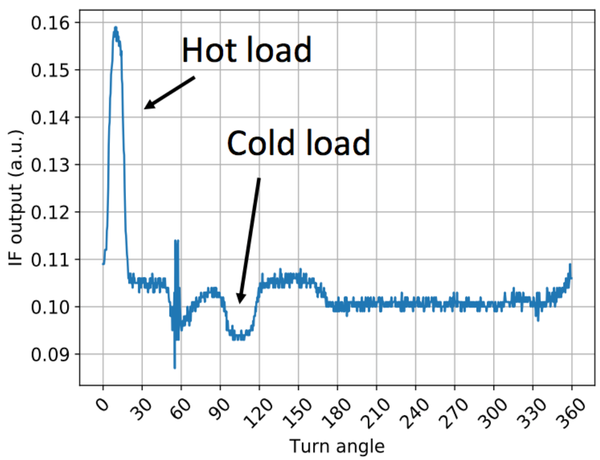


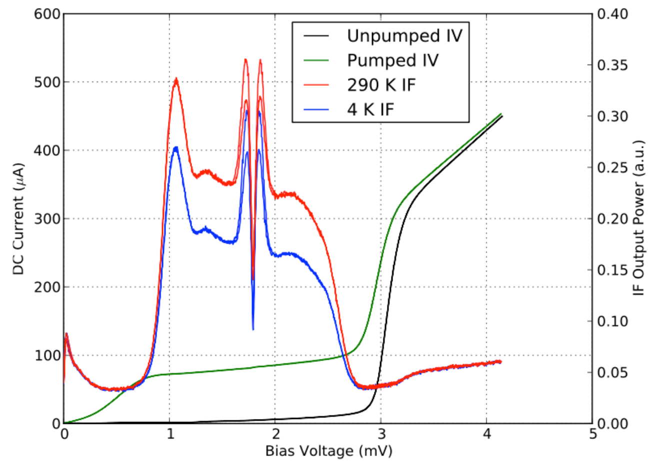


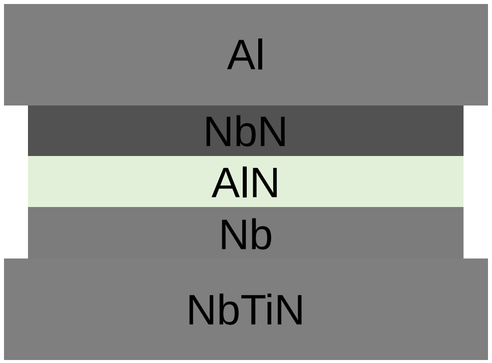


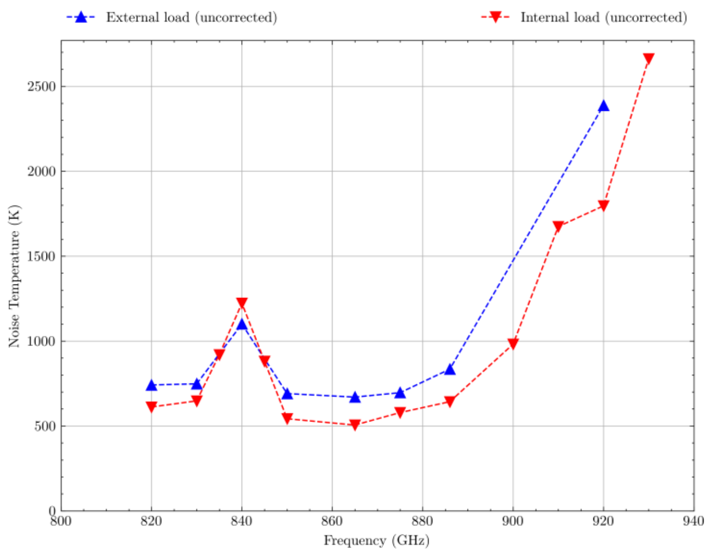
Supra-THz Mixer

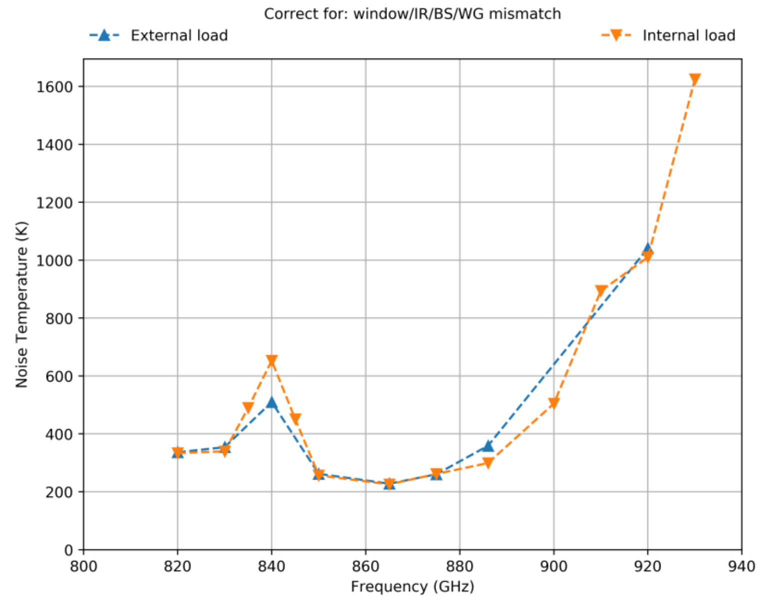
Collaboration project with University of Groningen



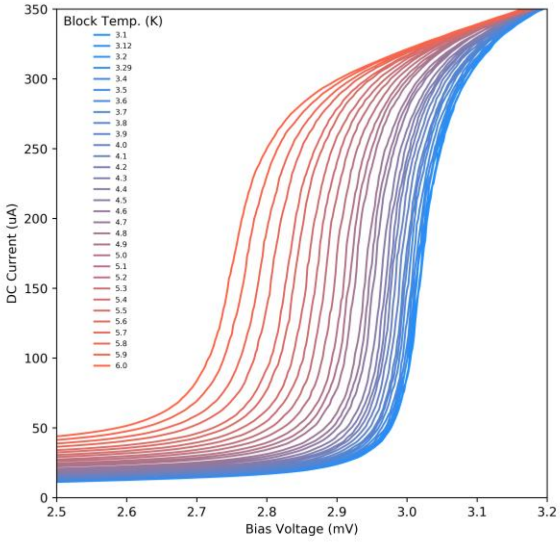


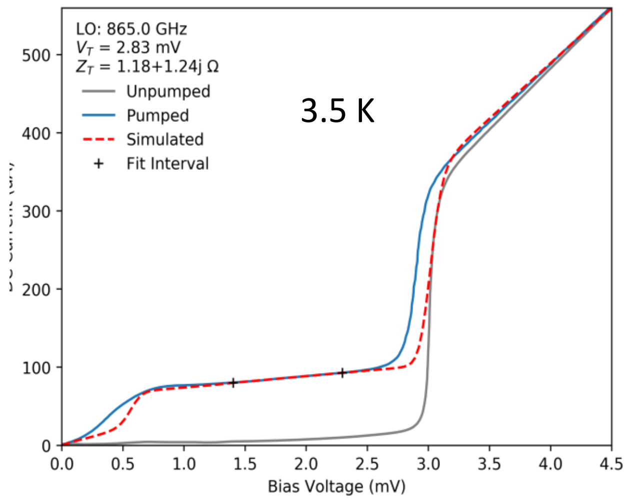


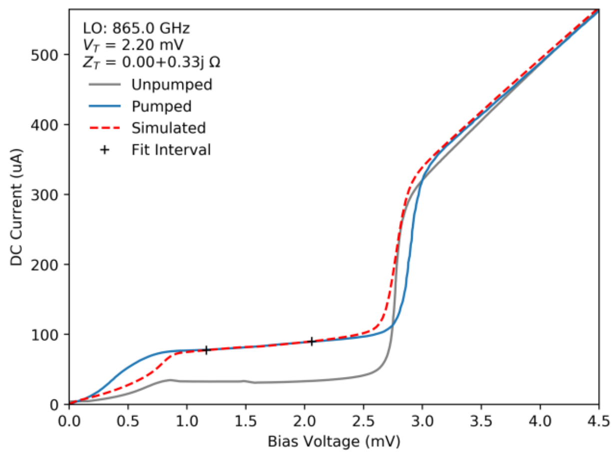


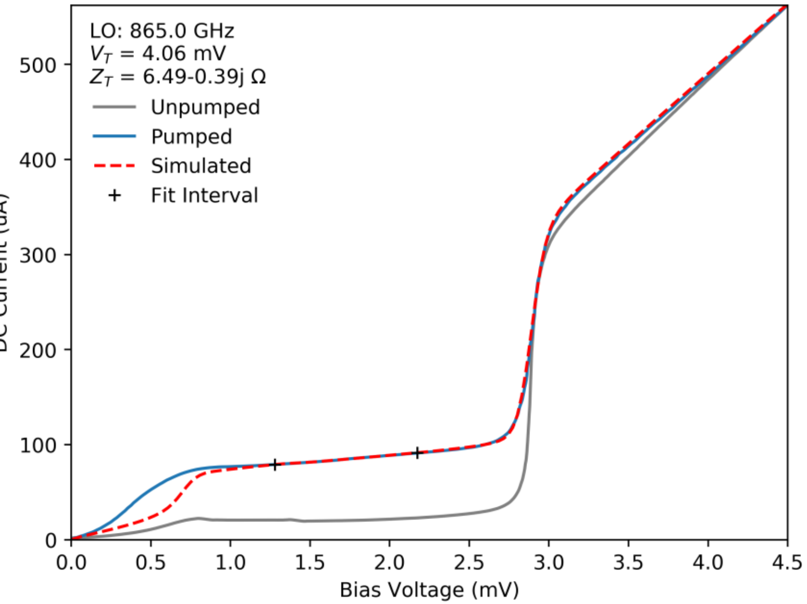


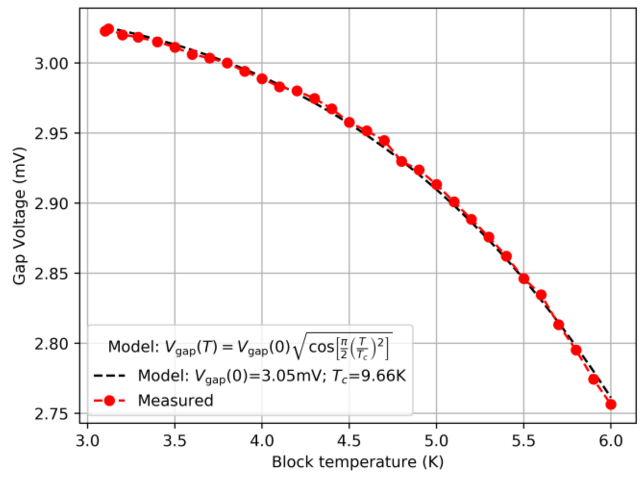
Supra-THz Mixer



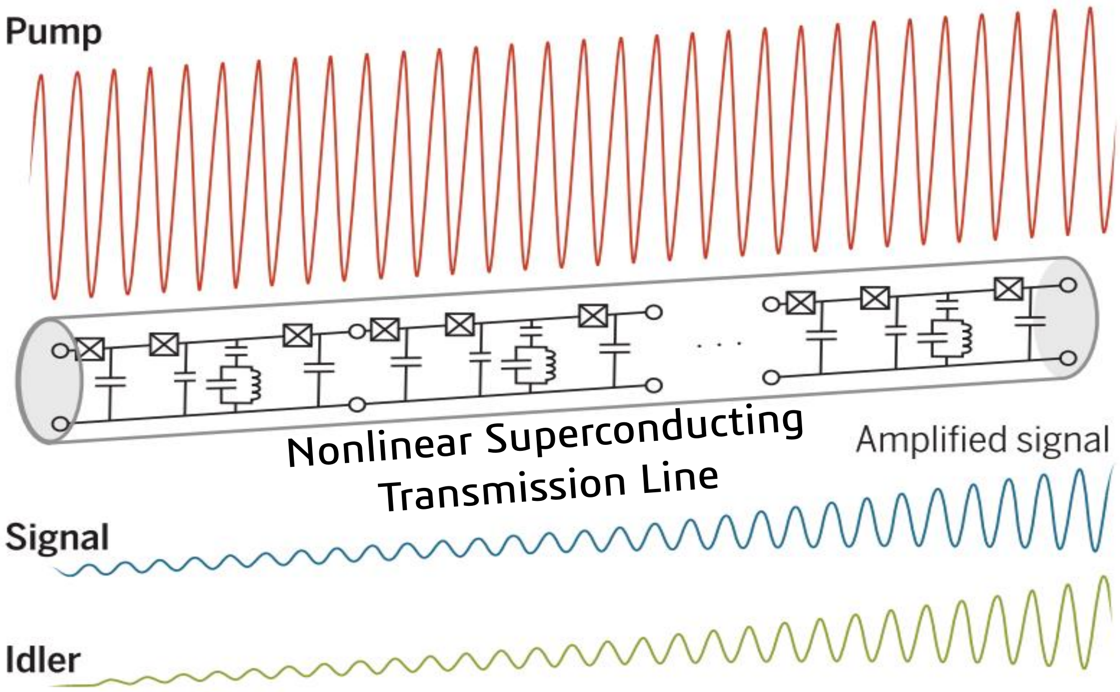




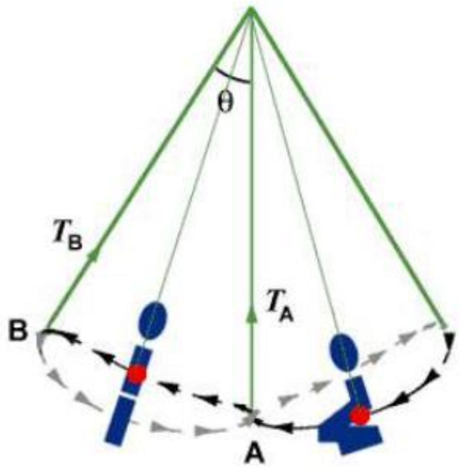




Superconducting Quantum Amplifiers

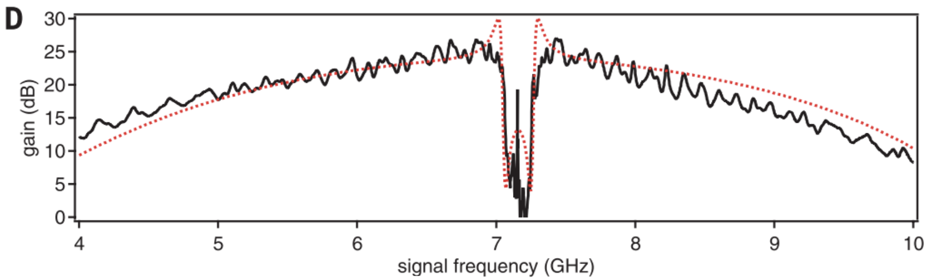


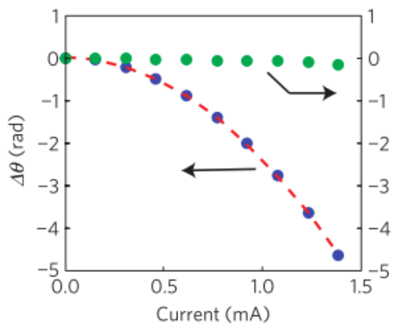
Berkeley, CA 94720,
Andrew N. Cleland Science 2015;350:280

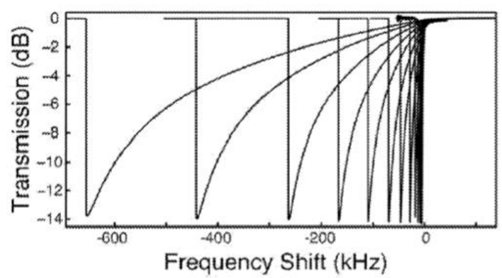


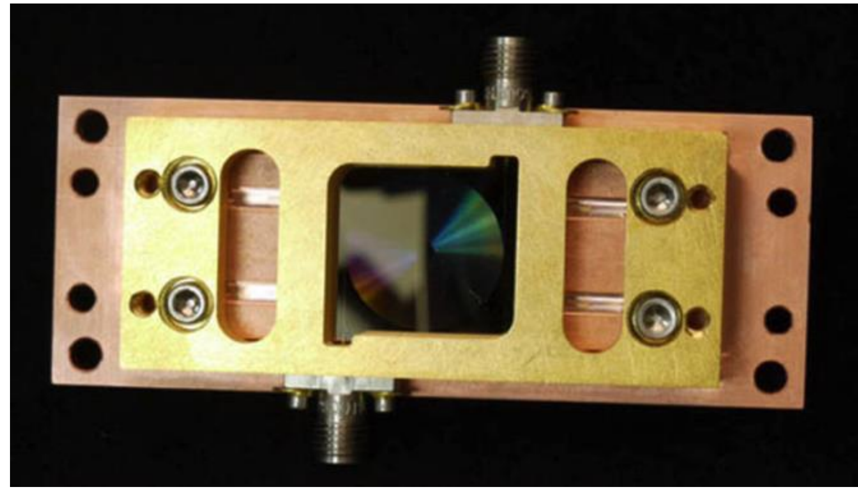
Superconducting devices = quantum limited
Large interaction time between waves

Travelling Wave Paramp – JJ & KI



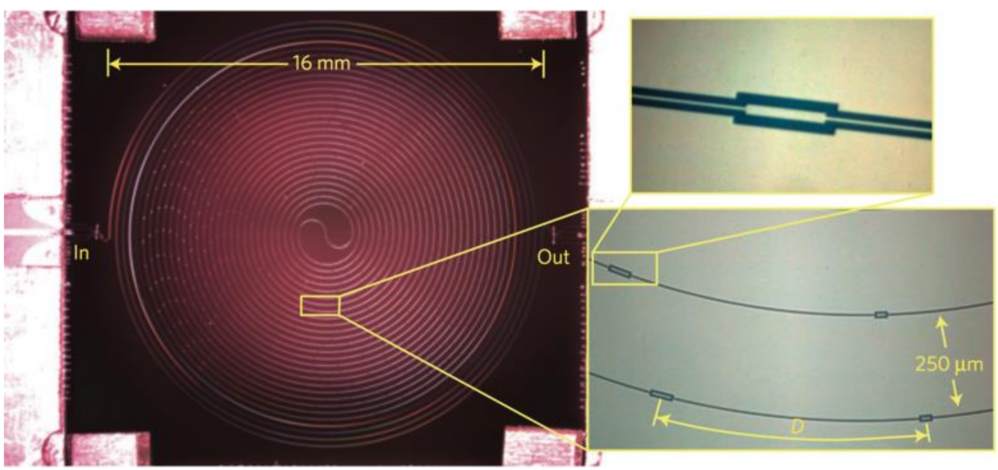






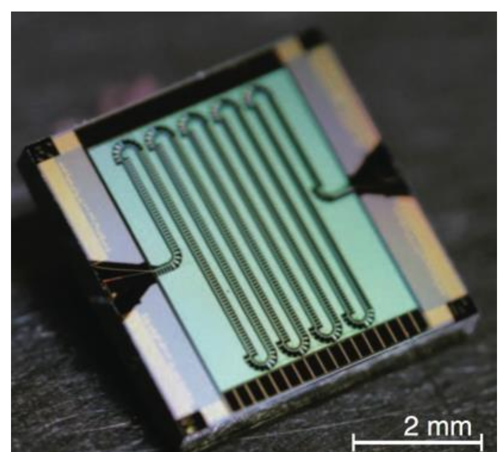
Bockstiegel et. al. J Low Temp Phys (2014) 176:476–482

Kinetic Inductance TWPA



B. Eom Nature Physics 8, 623-627 (2012)

Josephson Junctions TWPA



C. Macklin, Science, 350 (6258), p. 307, 2015

- **High gain, broadband** profile
- **Low heat** dissipation
- **Quantum limited noise**
- Compact
- Compatible with detector circuits

Phase Matching – Exp. Gain

Kevin O'Brien, Chris Macklin, Irfan Siddiqi, and Xiang Zhang. Resonant phase matching of josephson junction traveling wave parametric amplifiers. Physical review letters, 113(15):157001, 2014.
C. Macklin, Science, 350 (6258), p. 307, 2015