Superconducting Quantum Arrays for Wideband Antennas and Low Noise Amplifiers

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Outline

- Motivation
- Superconducting Magnetic Sensor
  - SQUID
  - SQUID Arrays
  - Experimental Data
  - Fabrication Aspects
  - Cryogenic Aspects
- Comparison to conventional technologies
- Conclusion

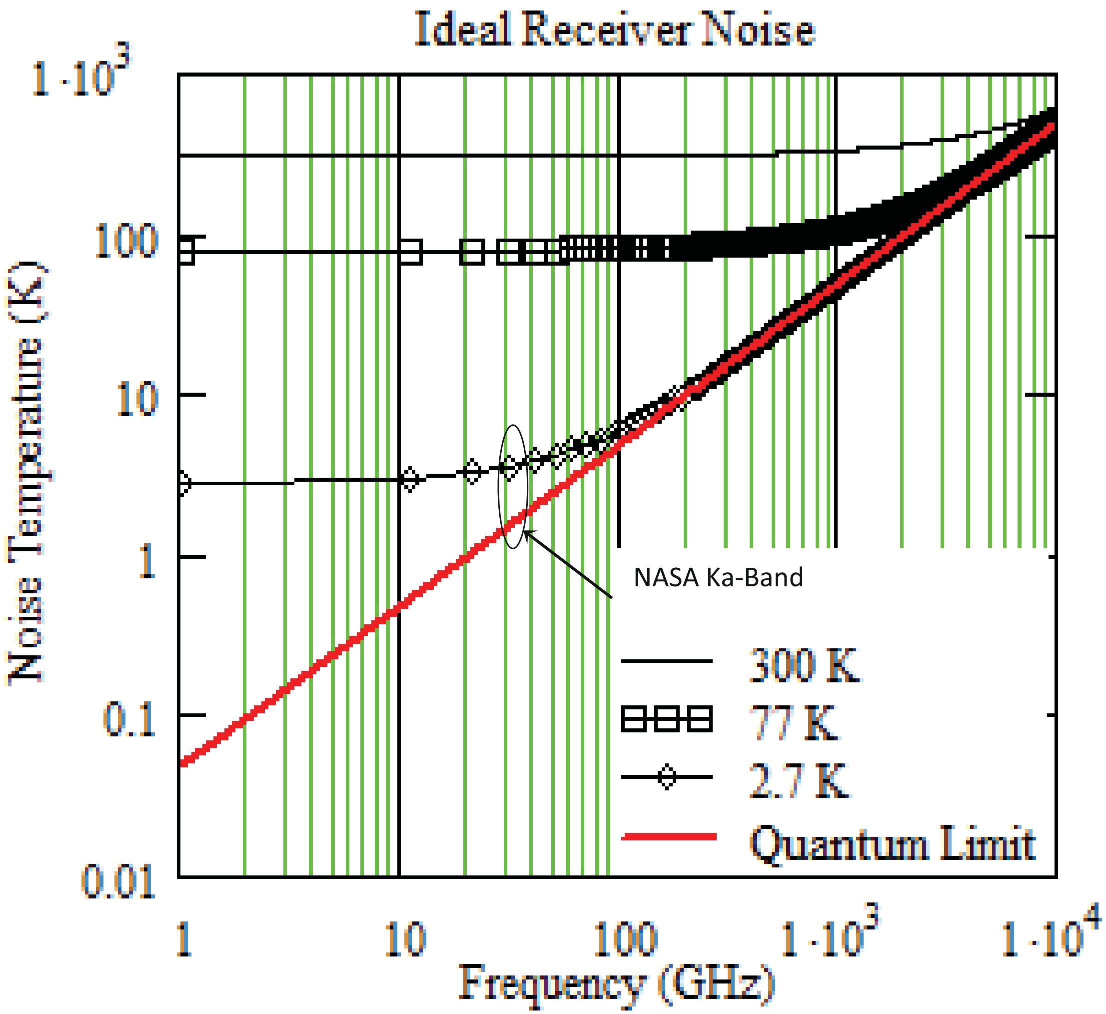
Motivation: Sensitivity, Size, Bandwidth

- Conventional semiconductor electric field detection limited at about $kT \approx 10^{-22}$ J
- Existing communication and direction finding techniques require multiple antennas with sizes that are a significant fraction of the incident wavelength, and that are separated by a distance comparable to the incident wavelength. For frequencies of 3 MHz and 300 MHz the wavelengths are 100 and 1 meter respectively.

- Goals:
  - Decreasing antenna size
  - Increasing bandwidth
  - Increasing sensitivity

Use Magnetic Antenna

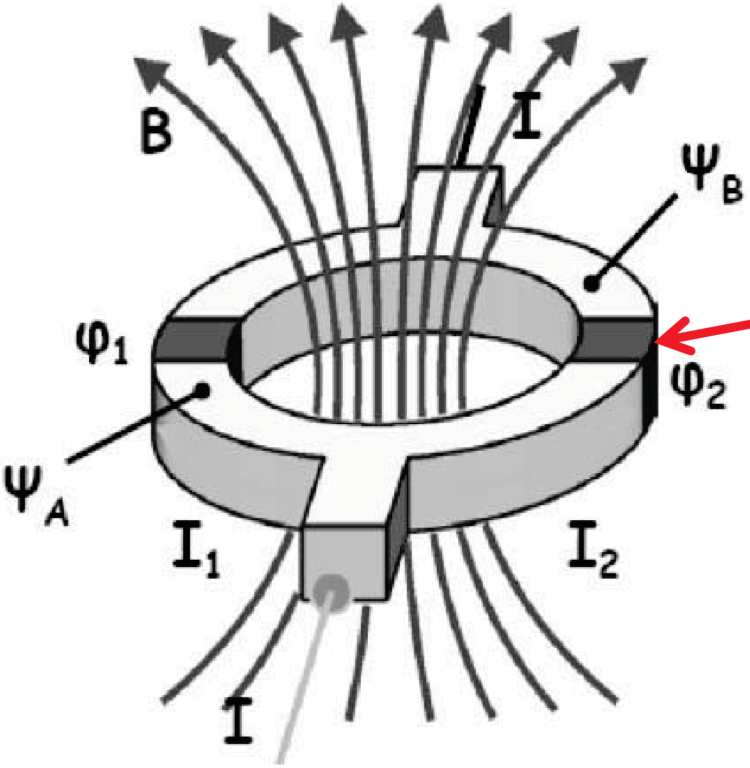
- Use magnetic instead of electric field detection to take advantage of highly sensitive Superconducting Quantum Interference Device (SQUID) arrays.
  - Proven and being used in medical and physics research, geology, etc.
- SQUIDs have a typical energy sensitivity per unit bandwidth of about 10^6 h or $\approx 10^{-28}$ J.
- Conventional semiconductor electric field detection threshold of ~ kT$\approx 10^{-22}$ J.



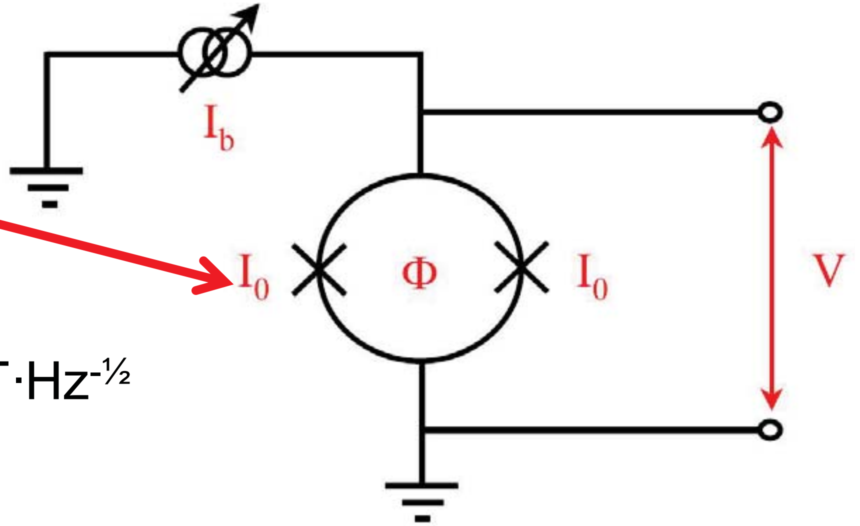
SQUID – magnetic field sensor

Superconducting Quantum Interference Device (SQUID)

invented in 1964 (50 years ago), R.Jaklevic, J.Lambe, J.Mercereau, A.Silver (US)

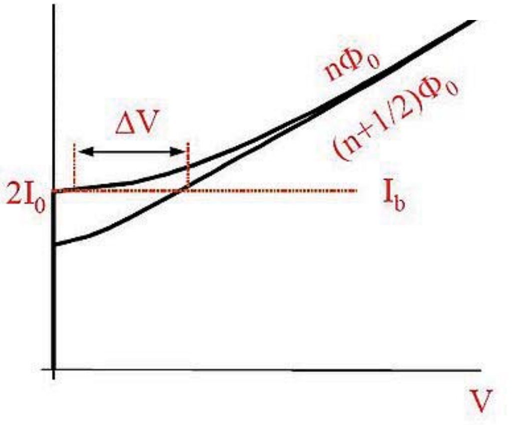


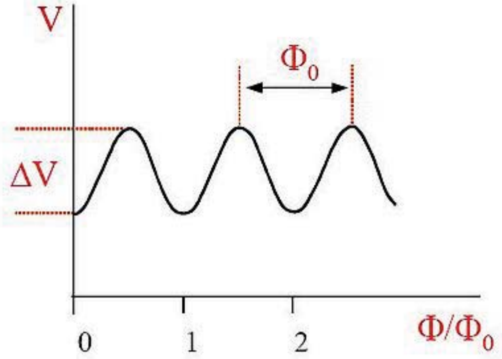
Josephson junction



S_B= 3 fT·Hz$^{-½}$

Can measure fields as low as 5 aT (5×10^{-18} T) (a few days of averaged measurements)

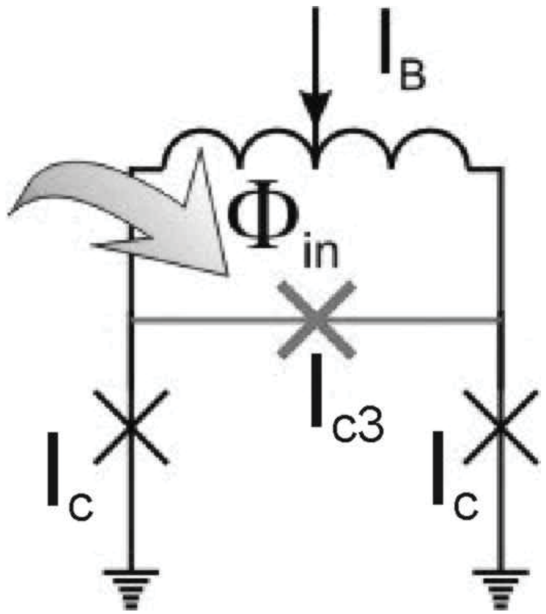


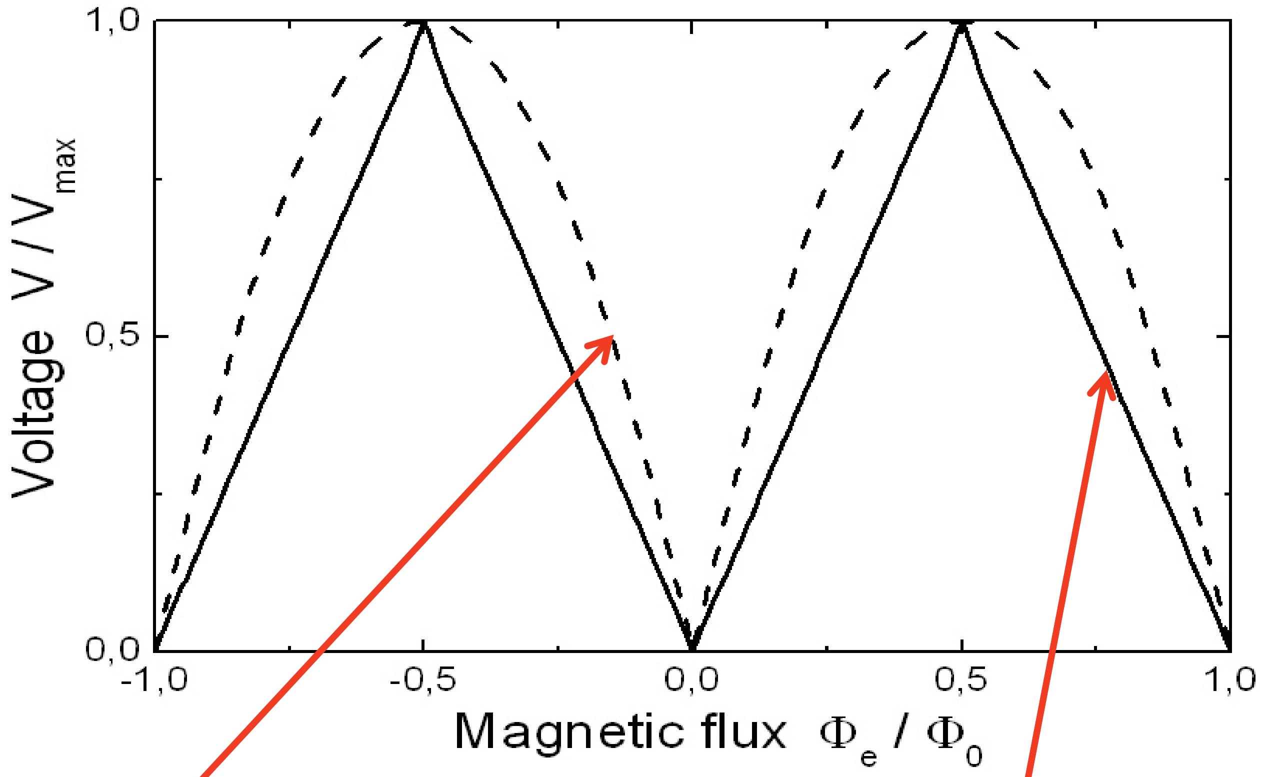


$\Phi_0 = h/2e = 2.07*10^{-15}$ mV ps (Wb)

Bi-SQUID – linearized SQUID

bi-SQUID – a 3-junction dc SQUID





dc SQUID response **bi-SQUID response**

- Non-linear inductance of additional junction (I_{c3}) linearizes the SQUID response

Array of SQUIDs

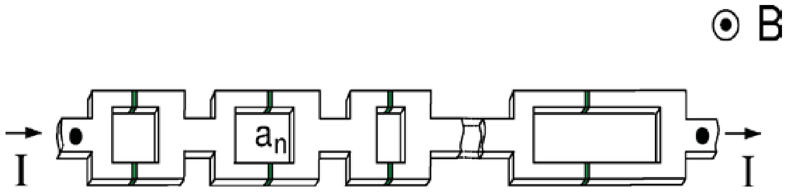
- in a current-biased series array the voltage signal increases with the number of connected SQUIDs in the array (N), but the noise only increases as $N^{1/2}$. Therefore as N becomes larger the signal-to-noise ratio increases as $N^{1/2}$

- In series-parallel SQIFs,
  - (i) increase output voltage and dynamic range;
  - (ii) control response linearity and output impedance;
  - (iii) improve sensitivity to weak signals;
  - (iv) make response robust to variation in junction critical currents.

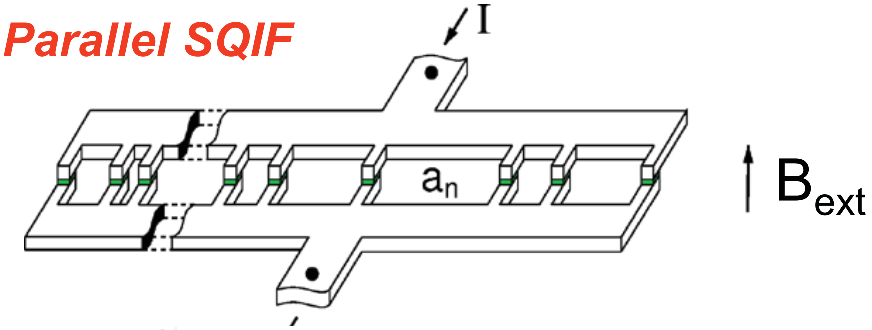
Non-uniform SQUID Array - SQIF

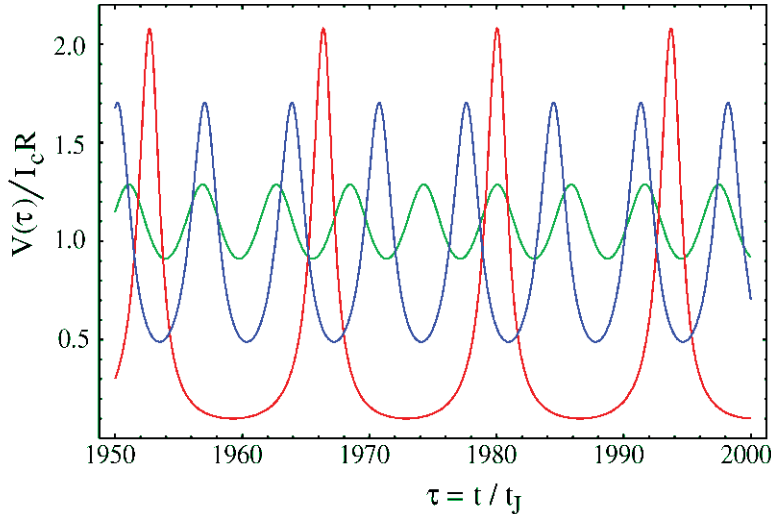
SQIF : **S**uperconducting **Q**uantum **I**nterference **F**ilter - quantum interferometer with non-equal loop geometry

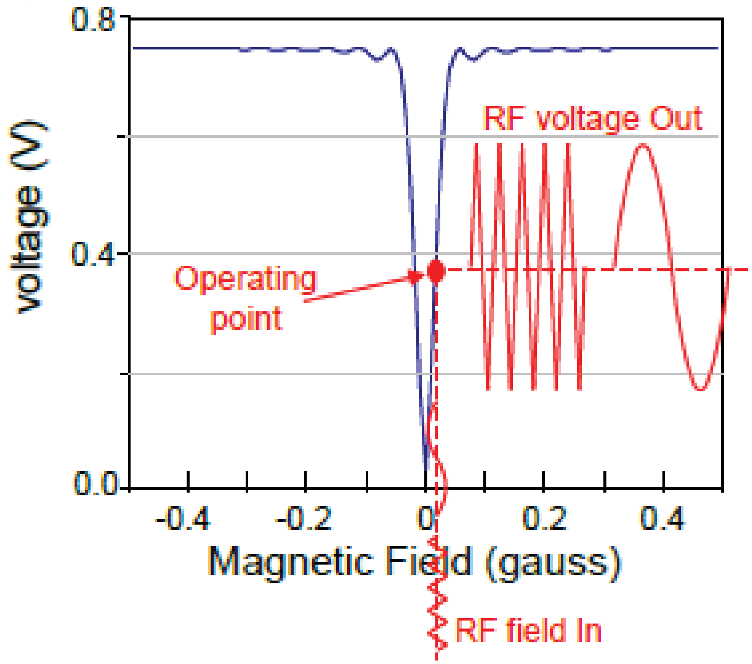
Series SQIF



Parallel SQIF

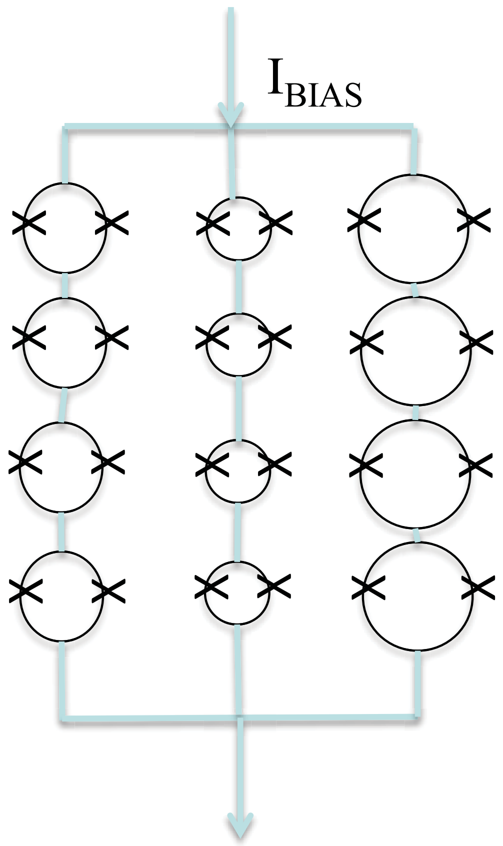






SQIF was invented in 2001 by N. Schopohl, et al. (Germany)

Why SQUID Array

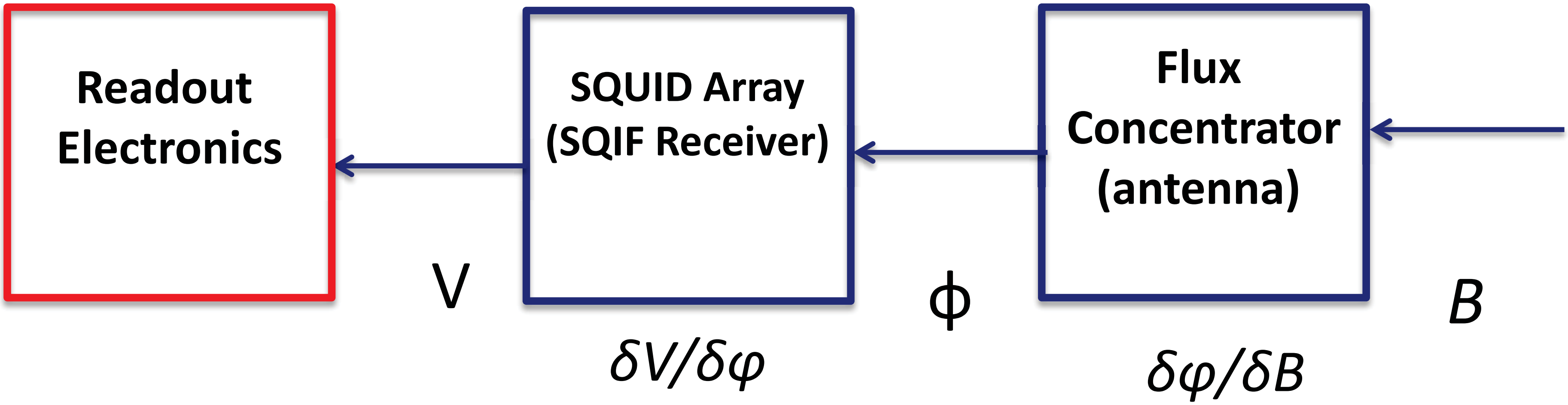


An analogy to explain SQIF operation (in terms of sensitivity):

The SNR output of a discrete Fourier transform, which basically integrates a time *series*, scales as the square root of N, where N is the number of points processed in the FFT, i.e., the signal magnitude scales as N but the noise standard deviation scales as the square root of N, hence SNR is proportional to the square root of N) - processing gain.

The SQIF processes N signals in parallel via N SQUID loops. For an ergodic process (statistics averaged over time are equivalent to statistics averaged over space), the result is the same: SNR scales as the square root of N. This leads to the SQIF's ability to theoretically achieve a noise floor that approaches zero.

SQIF-based Receive Antenna



Readout Electronics

V

SQUID Array (SQIF Receiver)

$\delta V/\delta \varphi$

ϕ

Flux Concentrator (antenna)

$\delta \varphi/\delta B$

B

Can be cryogenic superconducting circuits or room-temperature conventional electronics or both (hybrid)

Cryogenic superconducting circuits

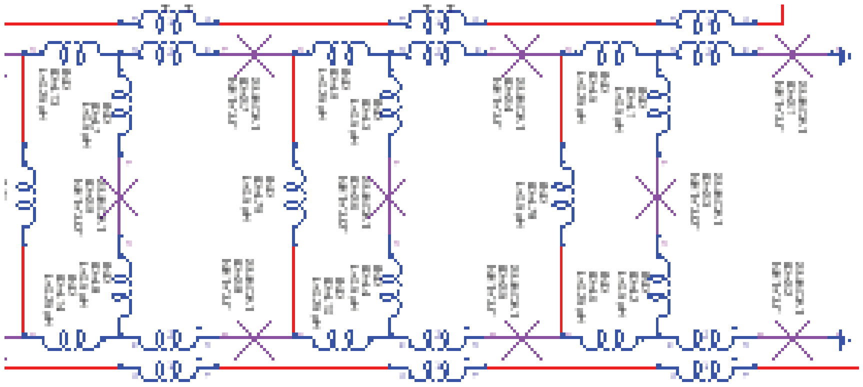
Cryogenic or room-temperature depending on applications

SQUID Serial Array

control line

L3b
J2
L1
J3
L2
L3a
J1

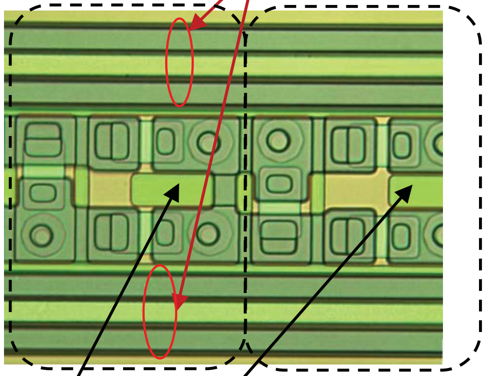
(a)



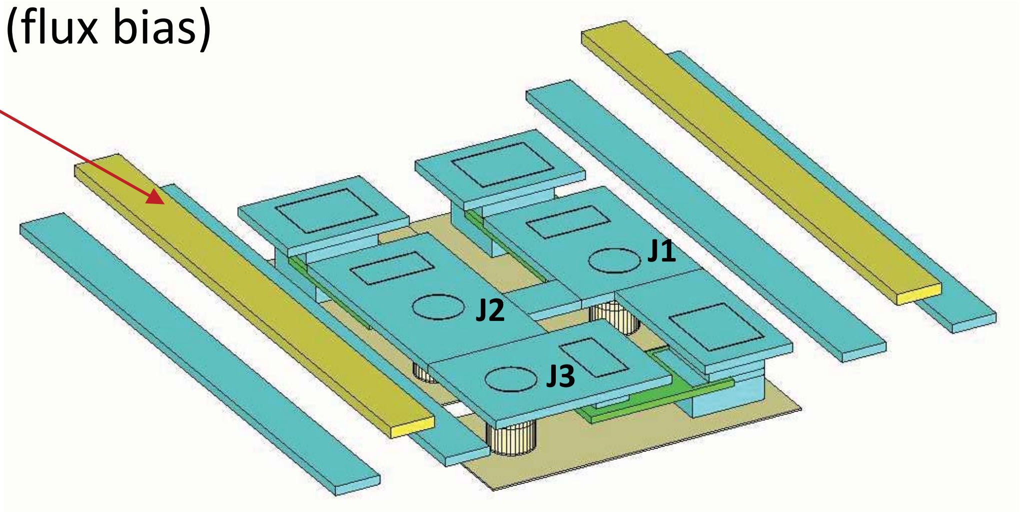
(b)

bi-SQUID cell

3-turn control line (flux bias)

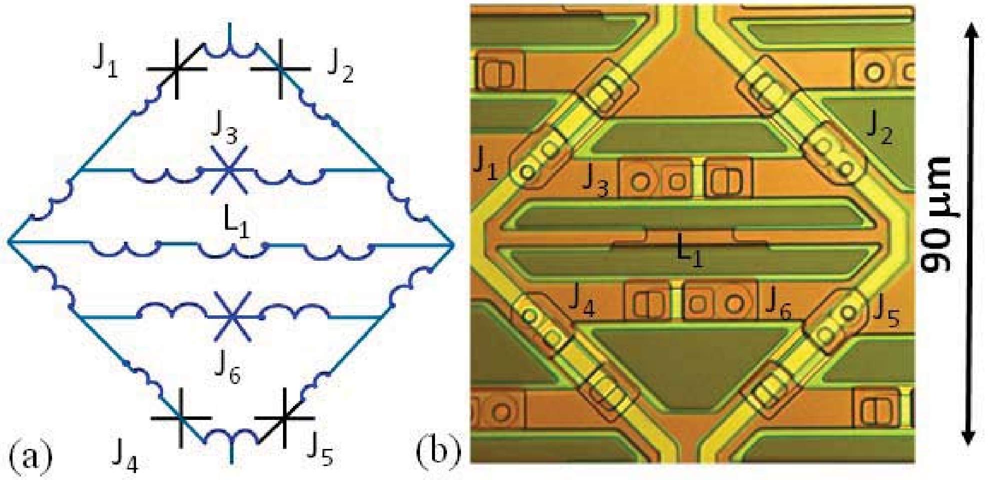


cell area is varied

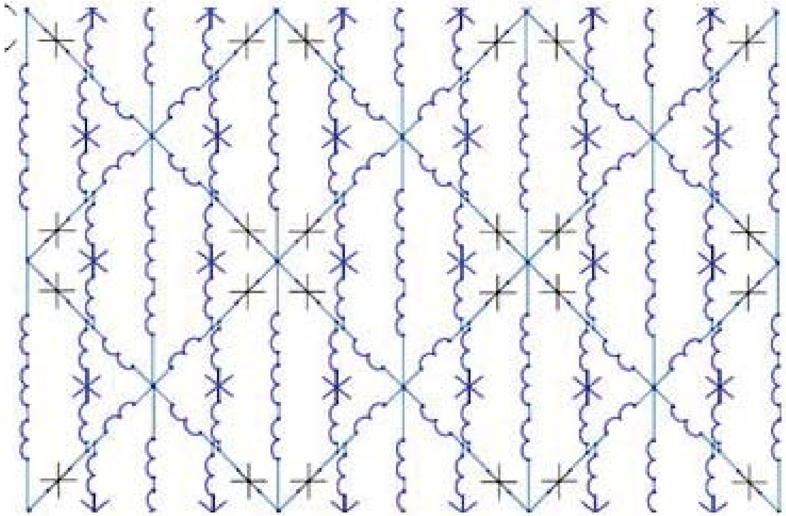


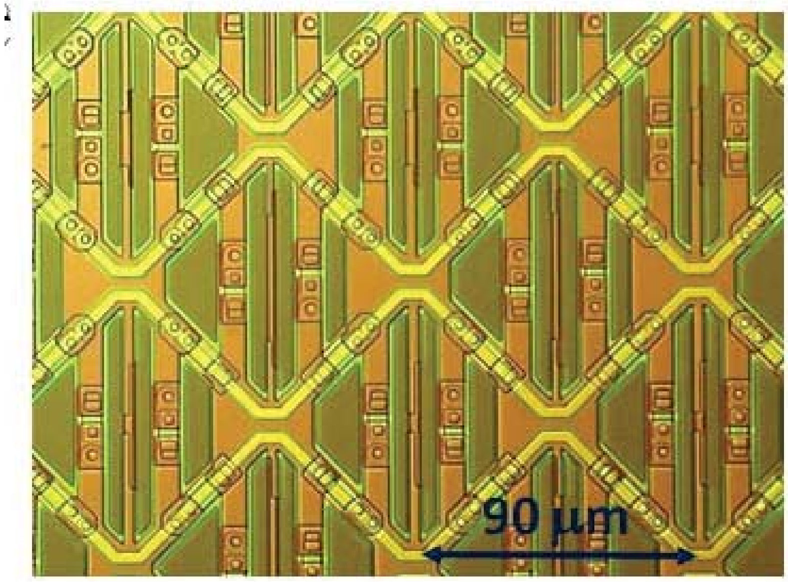
SQUD 2D Array Integration

Objectives:
- Preserve linearity
- Maximize area efficiency
- Ensure uniform dc current bias distribution



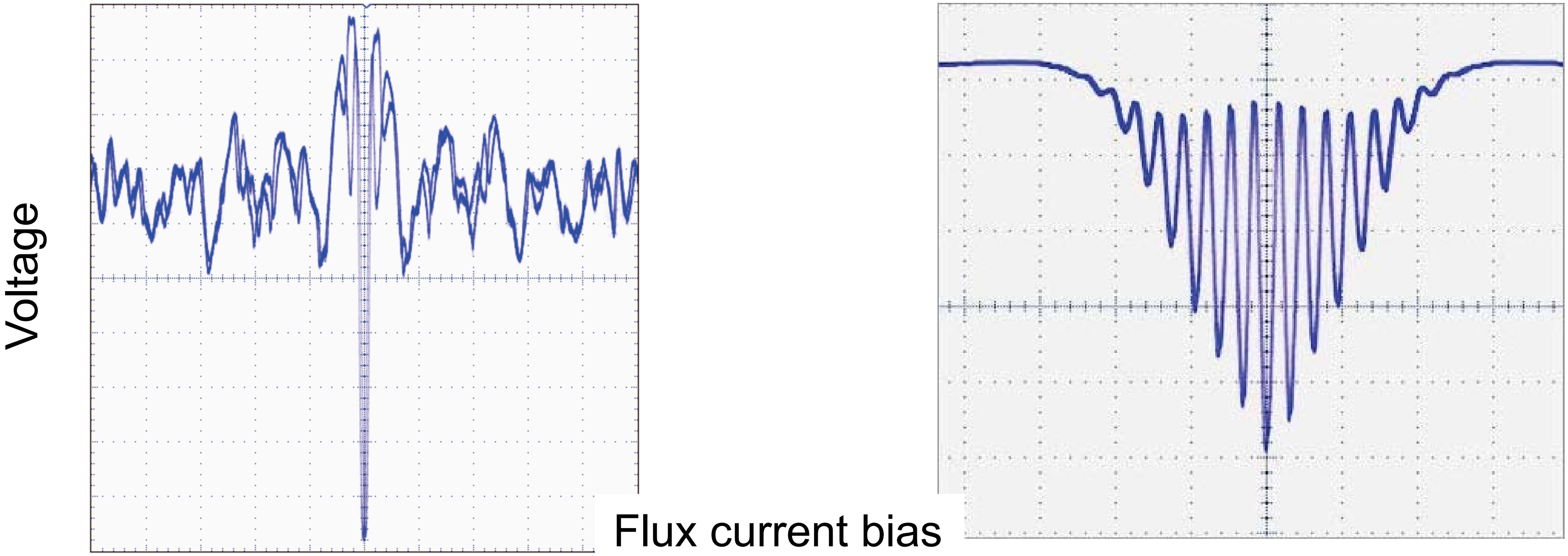
Diamond-shaped double bi-SQUID cell





Bi-SQUD 2D Array: Degree of SQIF

Flux/voltage characteristic



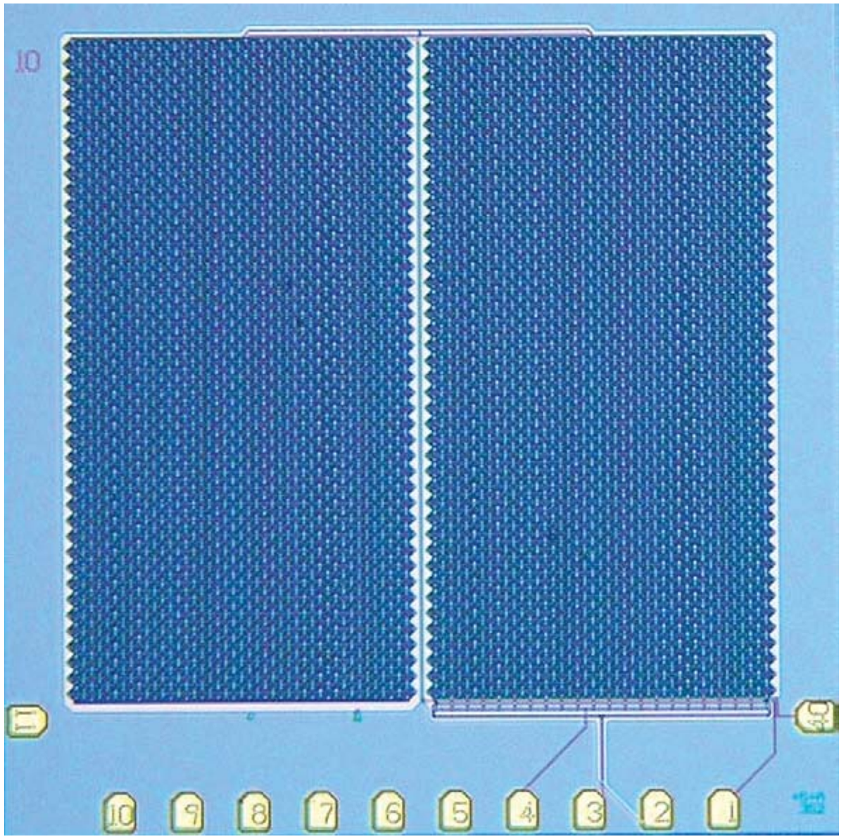
15 × *80 cell dual bi-SQUID SQIF array σ ~ 70% of inductance spread*

2 mV/div, 0.5 mA/div
(max voltage ≈*18 mV, ΔV/ΔI (flux bias) ≈170 V/A)*

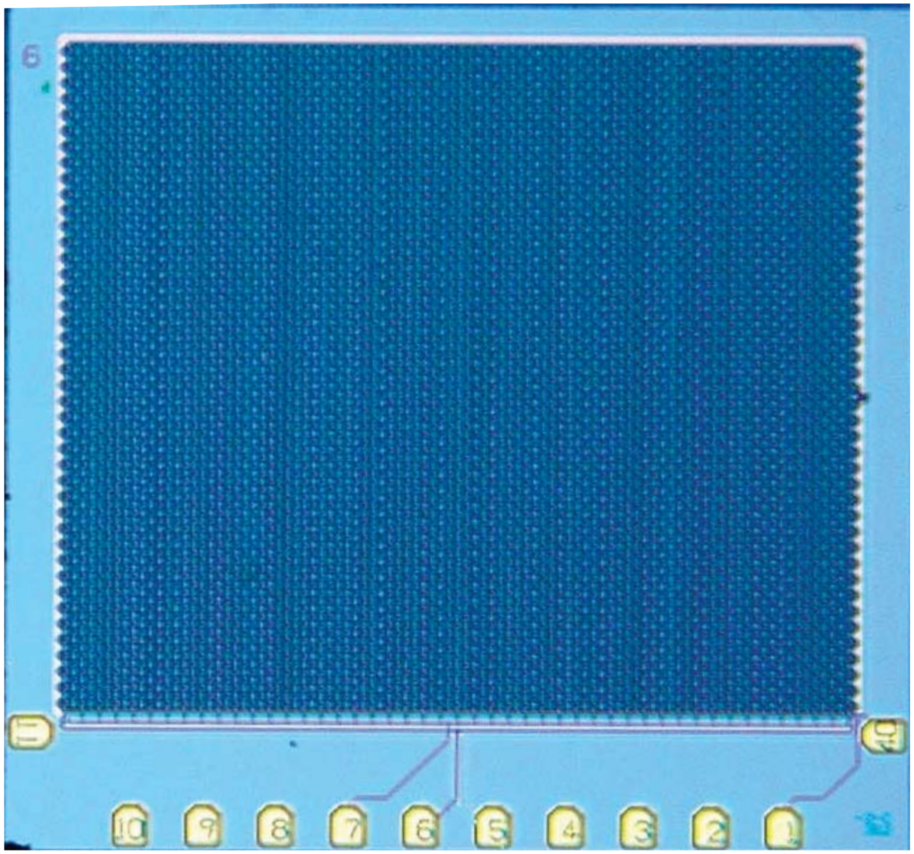
15 × 40 dual bi-SQUID array with *σ* ~ *30%.*

5 mV/div, 10 mA/div

Bi-SQUD 2D Array Samples



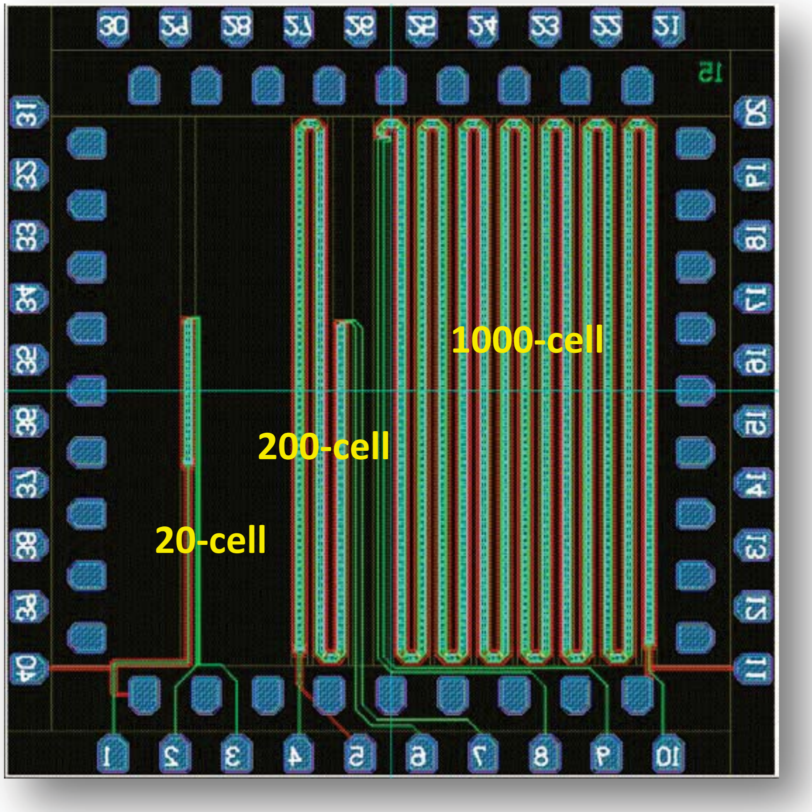
two serially connected 2D arrays
(2 x 43 x 85) arrays with 7310 cells

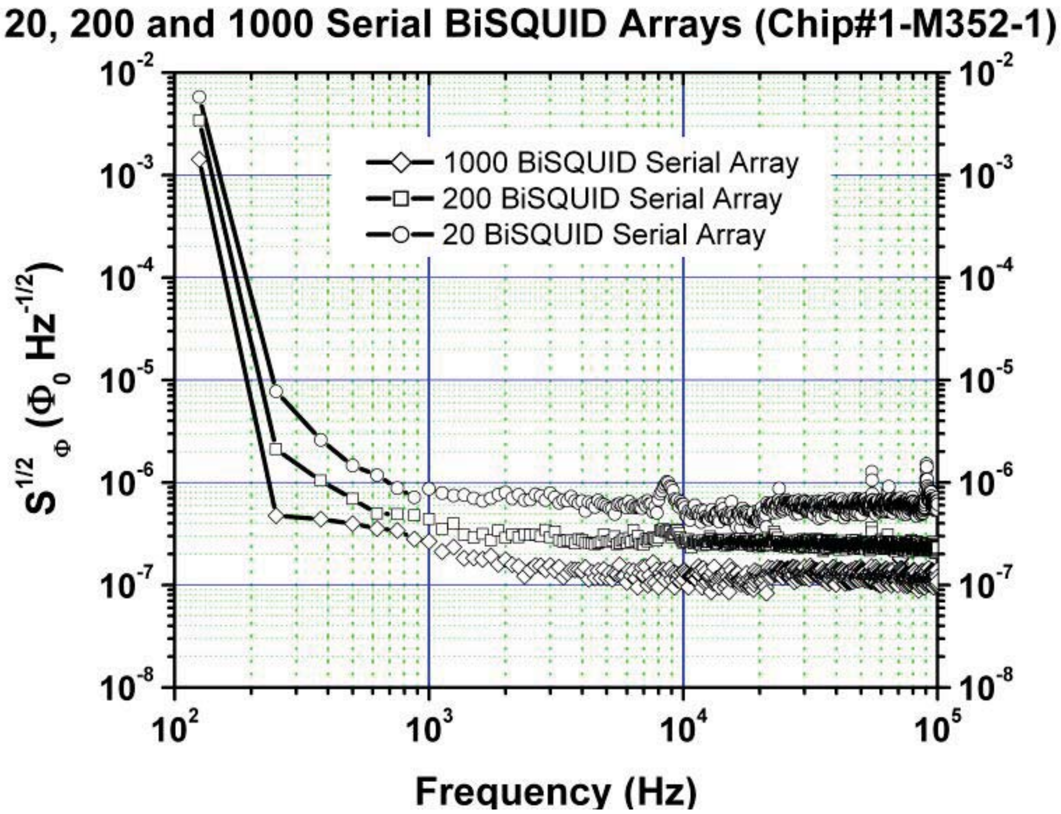


a single 7820-cell (92 x 85) 2D array

Fabricated 5 mm x 5 mm chips using HYPRES Nb-AlOx-Nb Josephson junction process. Diamond-double bi-SQUID arrays.

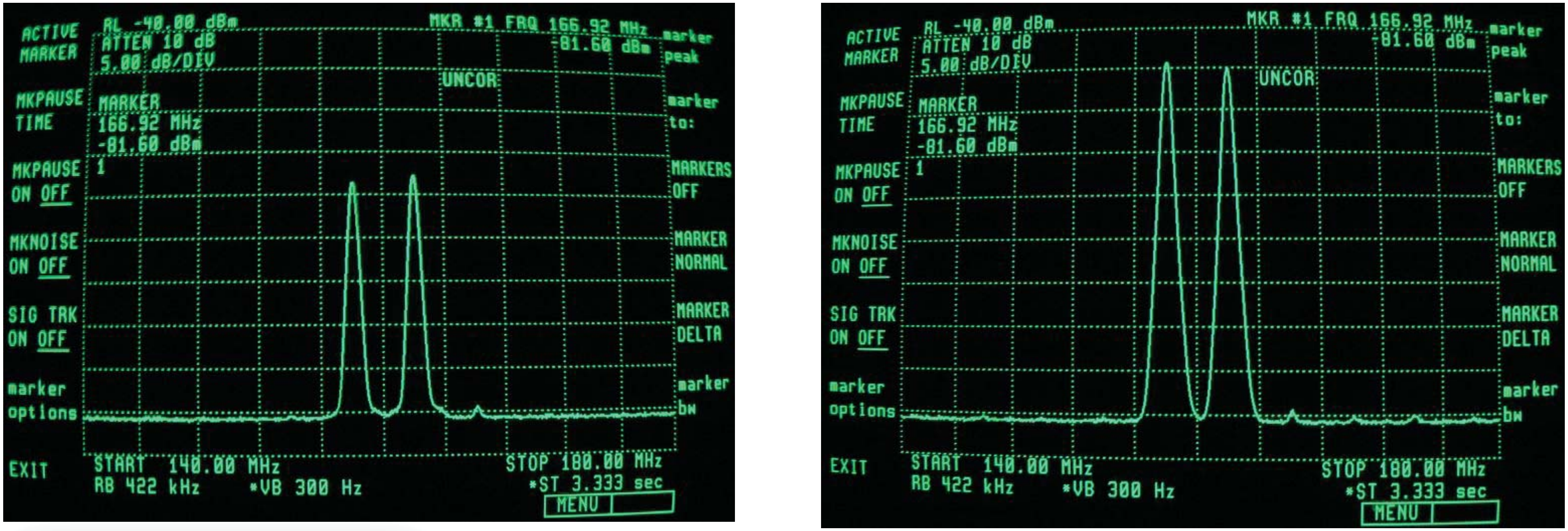
Array Noise Improvement

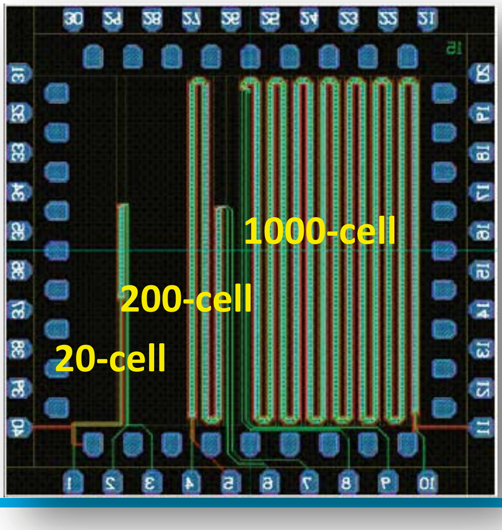




Comparison of the measured flux noise spectral densities for the 20-, 200- and 1000-cell arrays. It is evident that noise is getting reduced for 1000-cell array compared to 20-cell array as ~ $N^{1/2}$ or ~7 times as theoretically expected

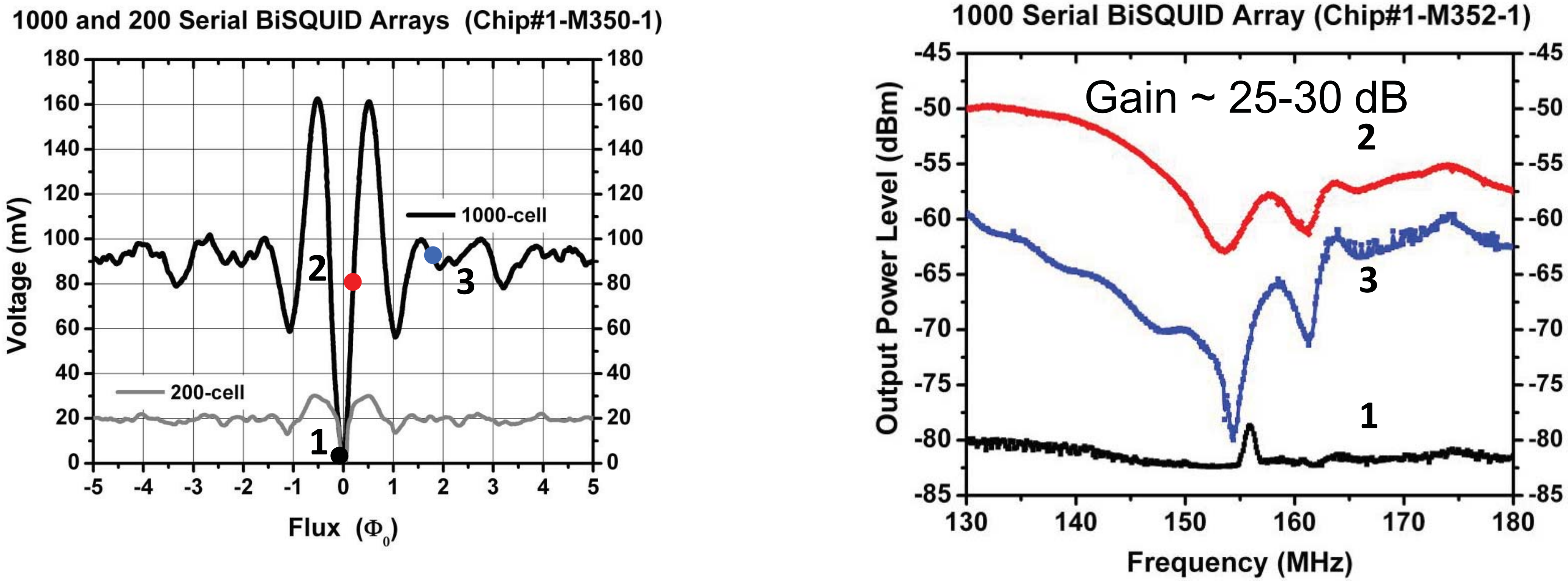
Array Linearity Improvement





Measured two-tone (158 MHz and 162 MHz) response for (left) 200-cell and (right) 1000-cell serial bi-SQUID array at dc bias level placing operation point at a midpoint of anti-peak SQIF slope with 5 dB/div

Measured Amplification


1000 and 200 Serial BiSQUID Arrays (Chip#1-M350-1)

1000 Serial BiSQUID Array (Chip#1-M352-1)

Measured output power level of a 1000-cell serial bi-SQUID arrays at three dc bias levels placing the array operation point at **1** – near the tip of the anti-peak, **2** – a midpoint of the anti-peak slope (optimum), **3** – outside of the anti-peak (saturation region)

Superconductor Circuit Fabrication

- **Two types of Superconductor Materials**
  - Low Temperature Superconductors (**LTS**)
    - for 4K operation
    - Industrial-grade Nb-AlOx-Nb Josephson junctions
    - Available commercially (HYPRES, AIST (Japan), IPHT (Germany))
  - High Temperature Superconductors (**HTS**)
    - For ~70 K operation
    - Research grade YBCO Josephson junctions
    - Available from research labs (UCSD (San Diego), CSIRO (Australia), etc.)

LTS Fabrication Process

Nb-AlOx-Nb junctions for 4 K operation

HYPRES Fabrication Process

~6 mask releases per year (current number is 350)

~400 chips per wafer

High J_c (20 kA/cm^2) with MoN resistors – *under development*

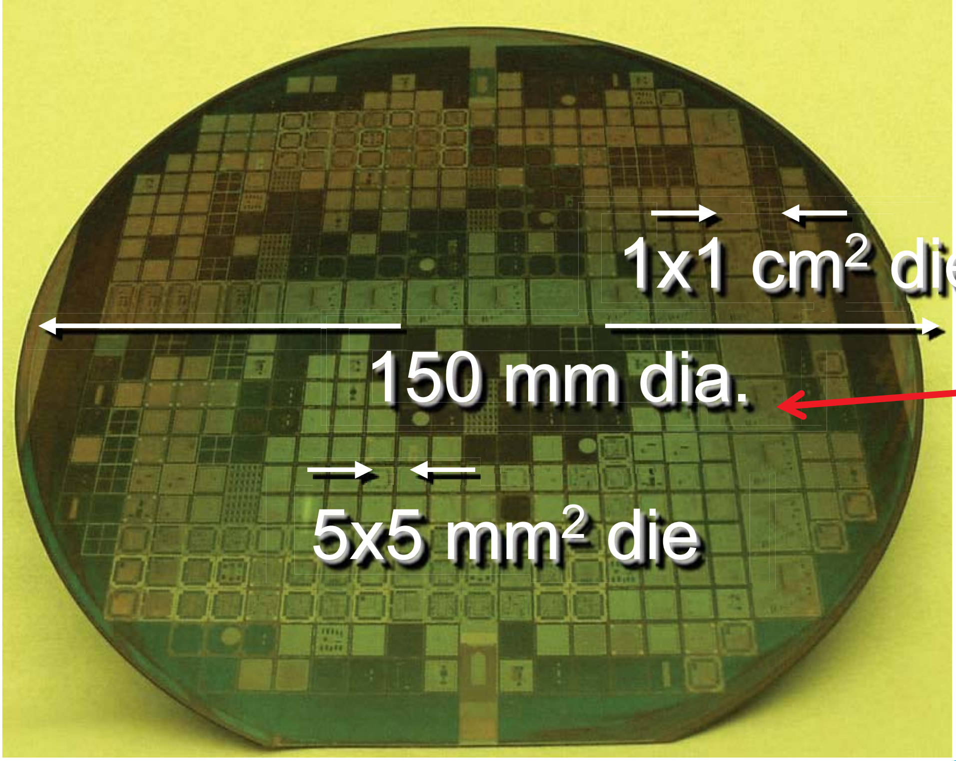
- RSFQ (Digital & Mixed-signal)

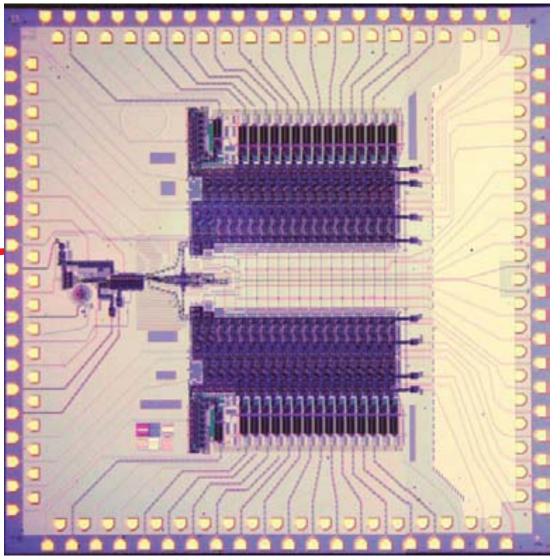
Medium J_c (1 kA/cm^2 and 4.5 kA/cm^2) with Mo resistors

- RSFQ (Digital & Mixed-signal)

Low J_c (30 A/cm^2) with Al, Mo, or Ti/PdAu resistors

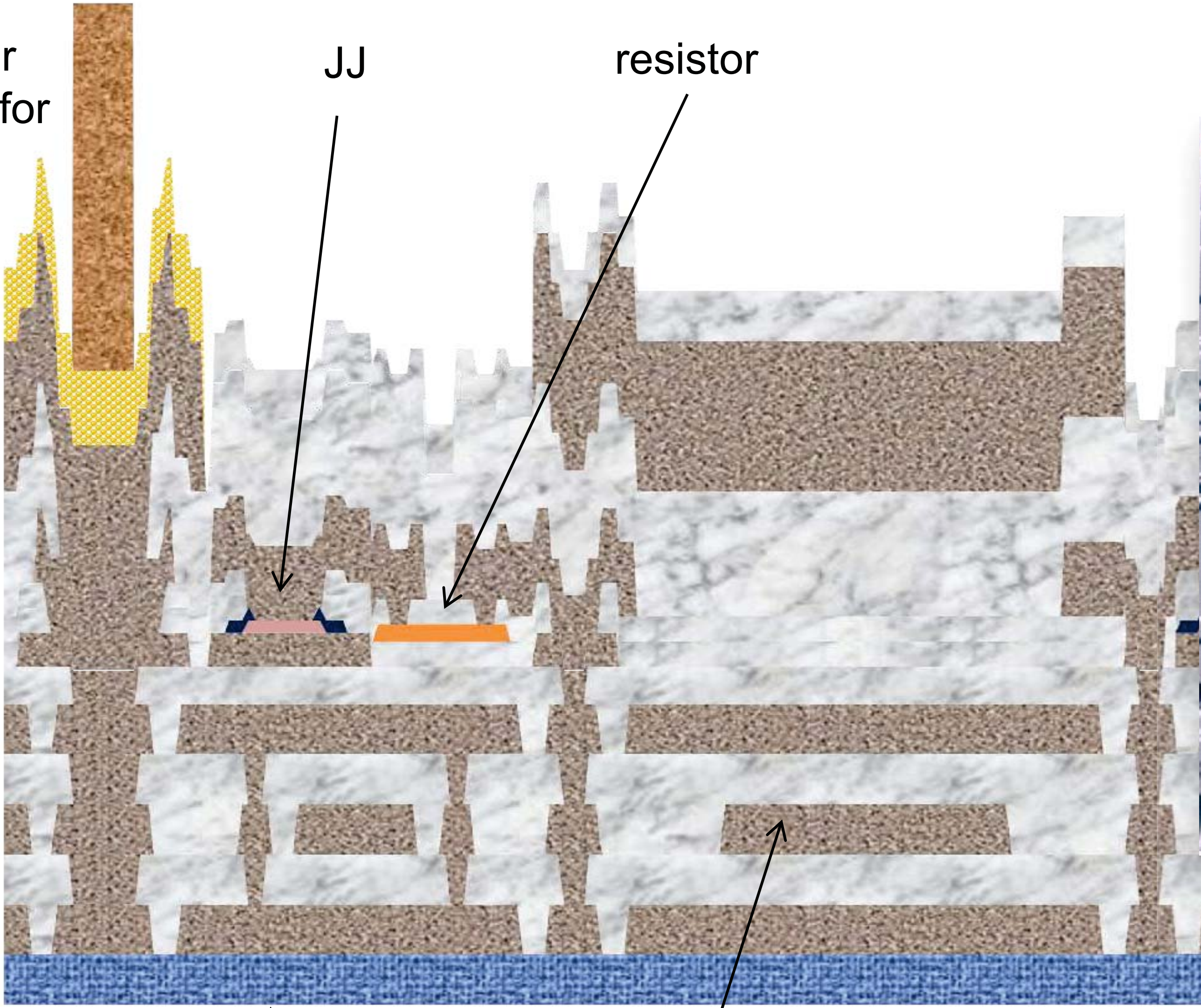
- SQUID applications
- 1 V and 10 V Voltage Standard
- QC circuits for mK operation



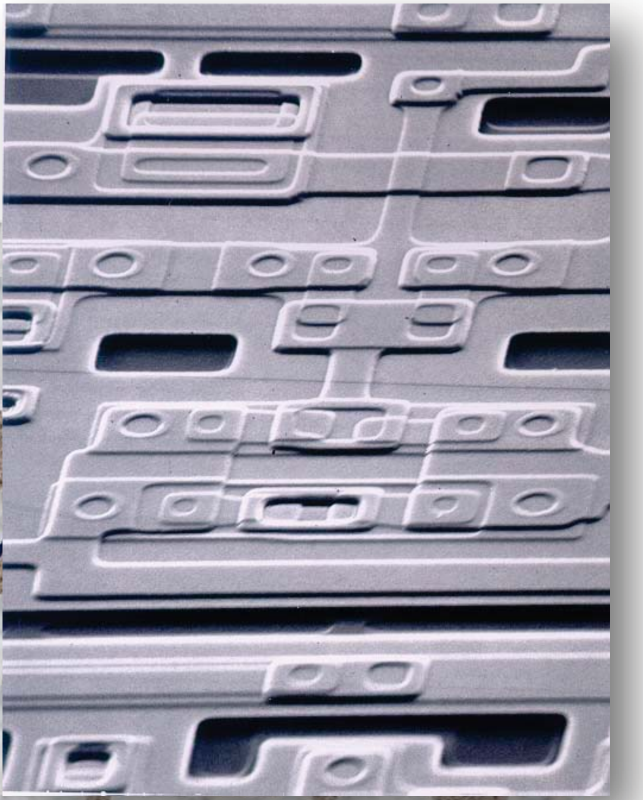


All-Digital Receiver (ADR) – 12,000 JJs

LTS Fab: Process Cross section



HYPRES fab process



Cryocooling for 4 K operation

4″x9″x18″

Coldhead

13″x18.4″x18.4″

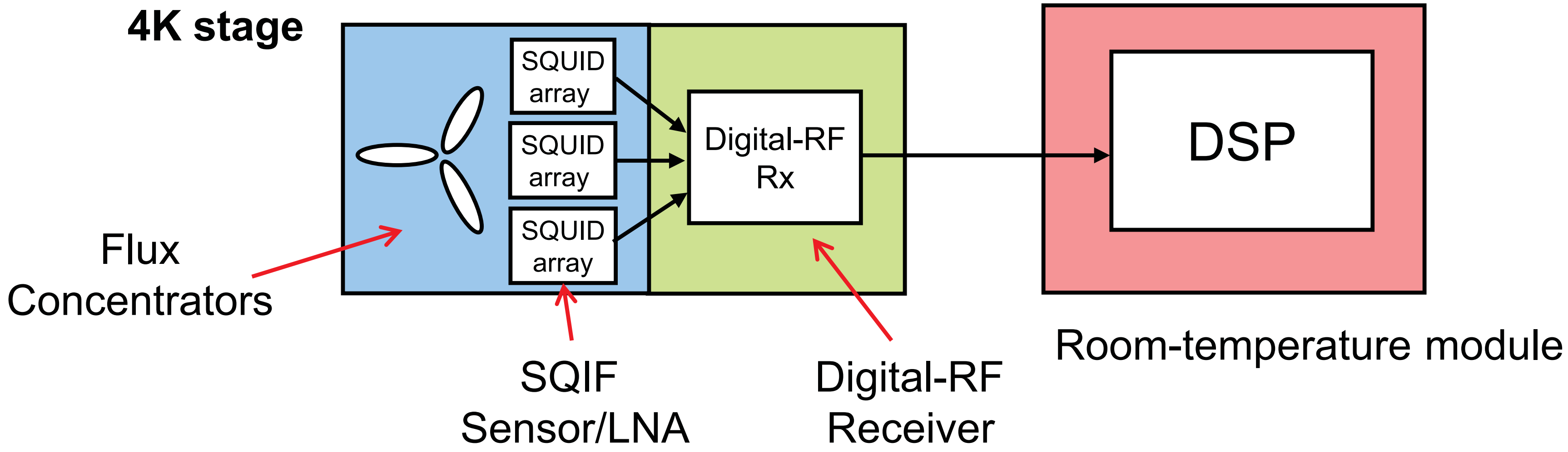
Compressor

- Weight: 7.2 kg (for coldhead only)
- Input Voltage: 18-28 VDC
- Maximum Input Power: 1.5 kW (compressor power)
- Cooldown Time (300 to 4K): 150 min (unloaded).
- Cooling Capacity: 0.2W @4.2K and 3-5W@45K

Integrate radome onto a cryocooler

Commercially available from multiple sources

Platforms for LTS-based systems



4K stage

SQUID array

SQUID array

SQUID array

Digital-RF Rx

DSP

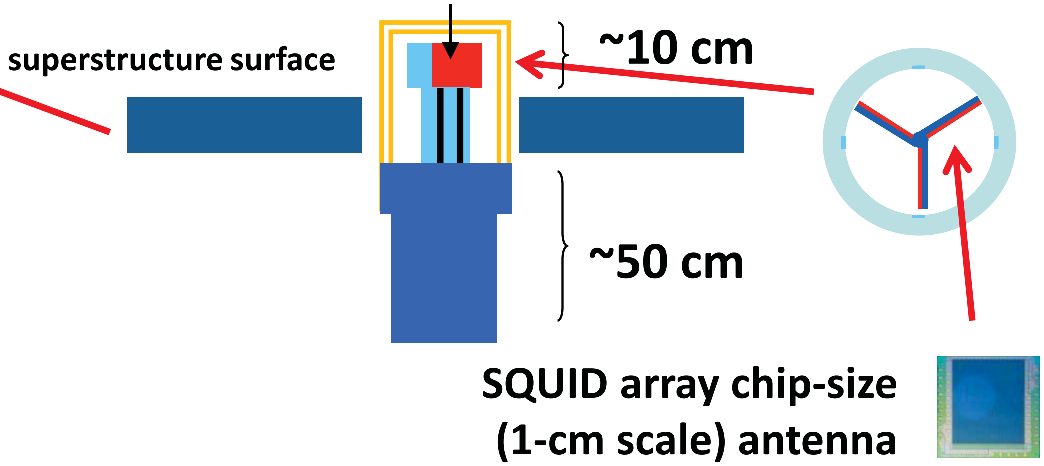
Flux Concentrators

SQIF Sensor/LNA

Digital-RF Receiver

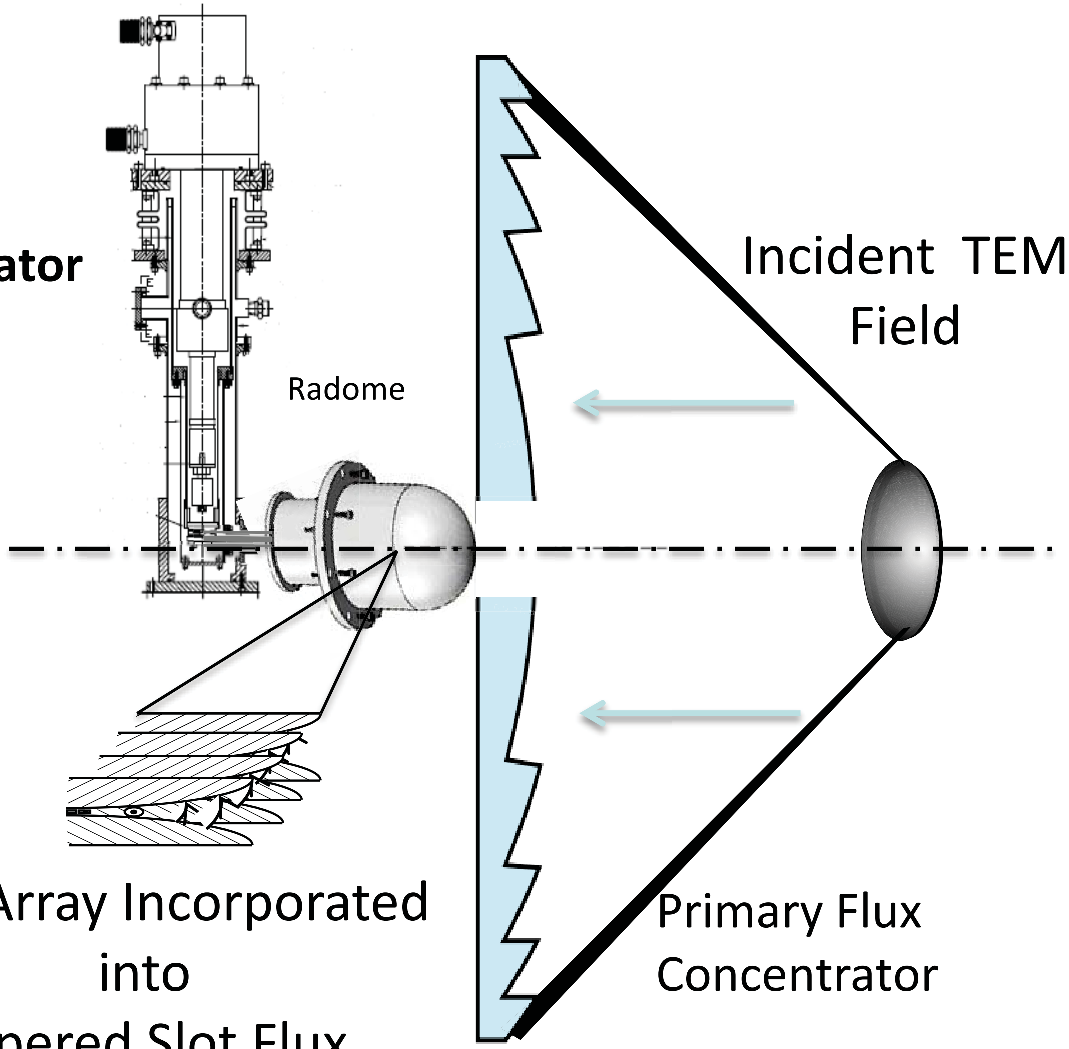
Room-temperature module

Fixed or Shipboard deployment



SQUID array chip-size (1-cm scale) antenna

SQIF-based Receiver



4 K Refrigerator

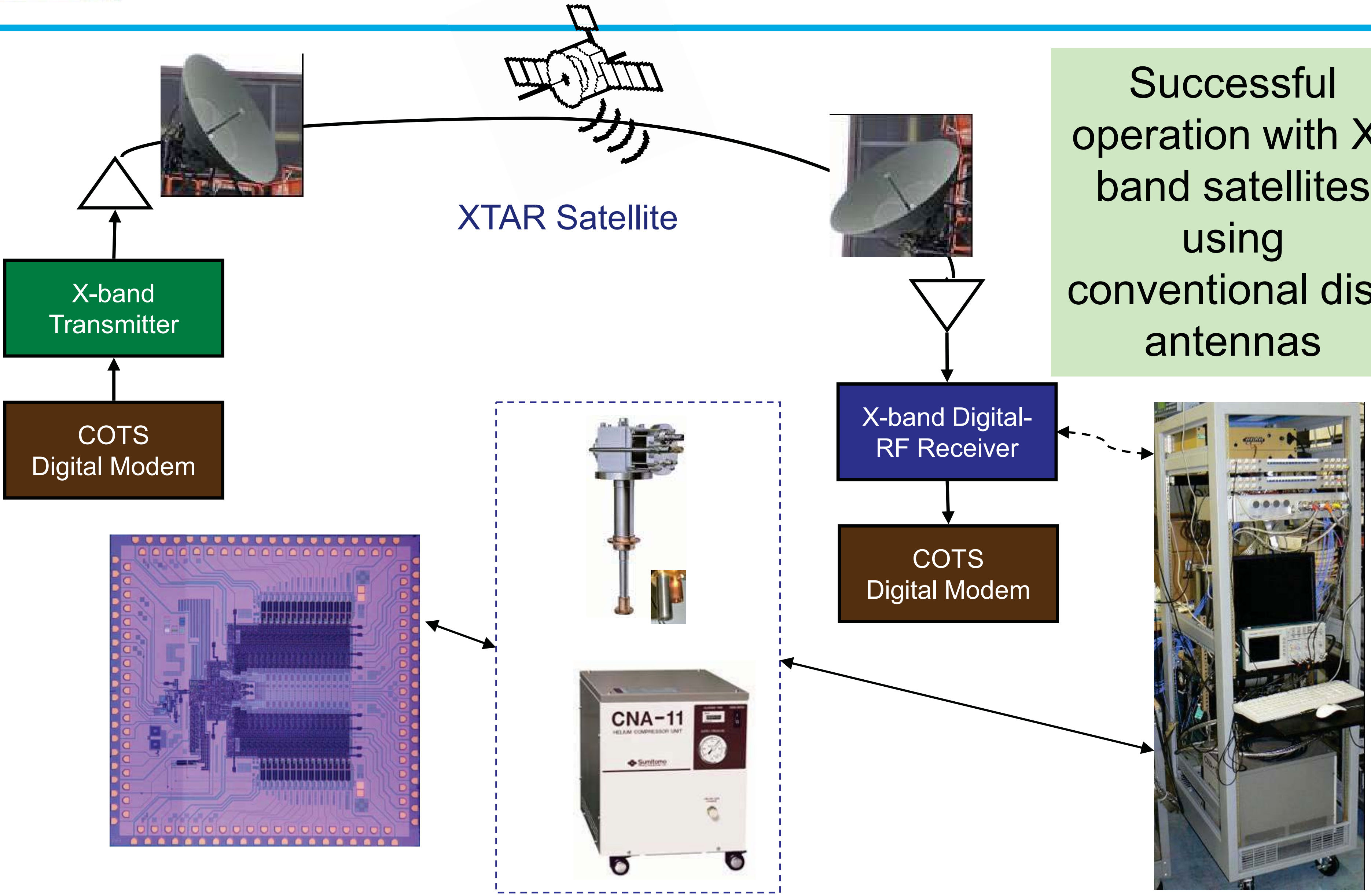
Radome

Incident TEM Field

Primary Flux Concentrator

SQIF Array Incorporated into Tapered Slot Flux Concentrators

Superconducting Digital Receivers



XTAR Satellite

X-band Transmitter

COTS Digital Modem

X-band Digital-RF Receiver

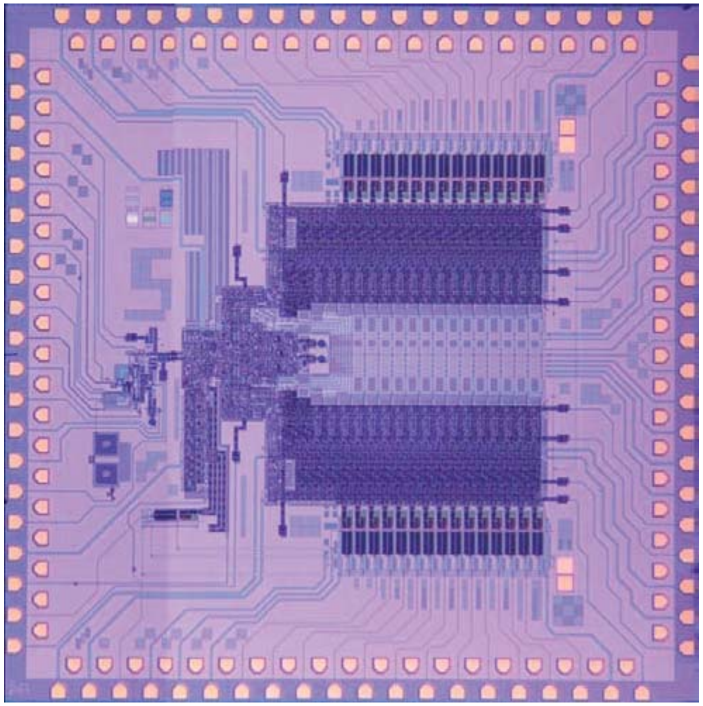
COTS Digital Modem

Successful operation with X-band satellites using conventional dish antennas

Today’s Digital RF Receiver System

Based on superconducting RSFQ digital technology

RSFQ chip: 1 cm^2, 11K JJs, 30 GHz clock
Band-pass ADC integrated with digital signal processor



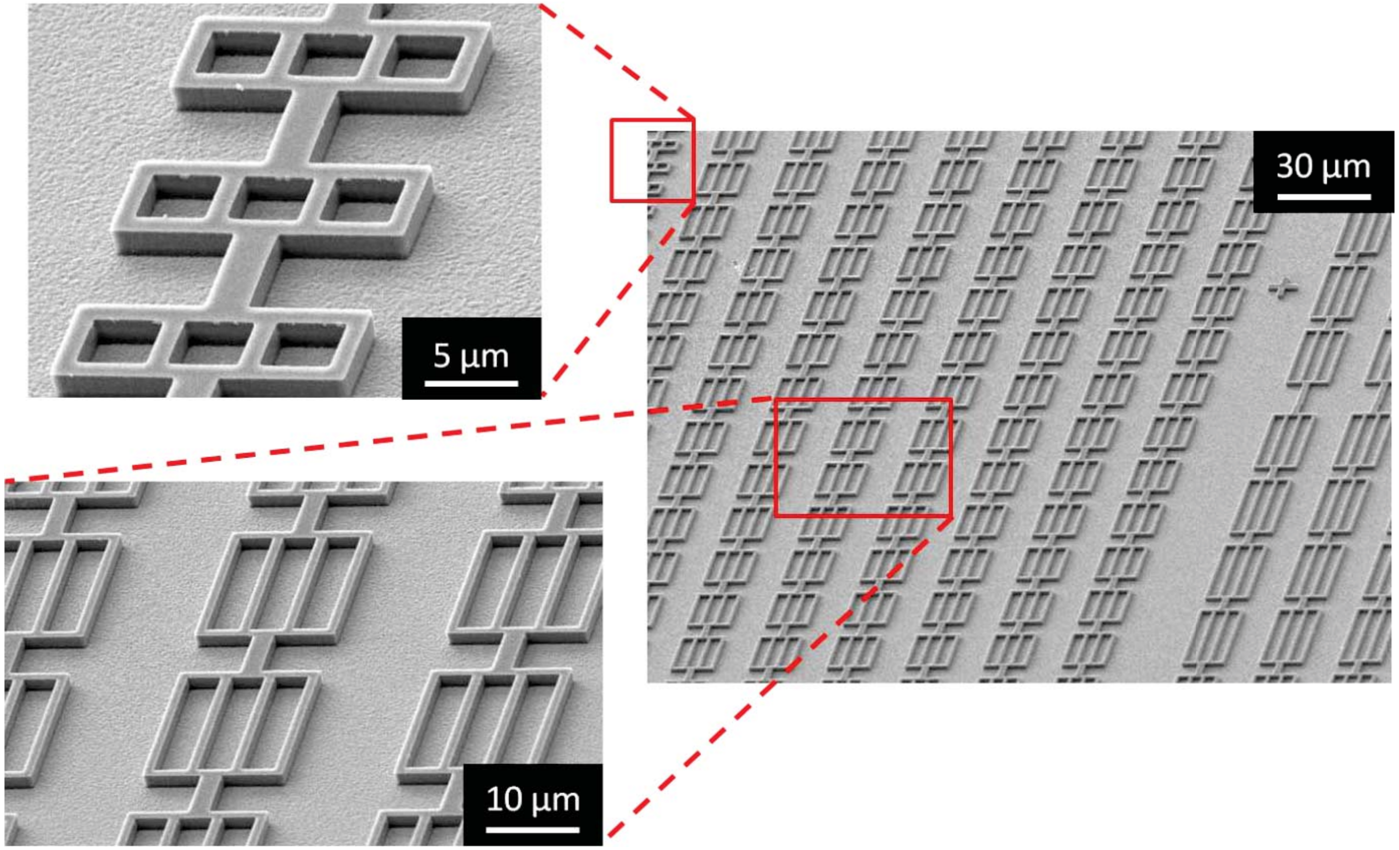
30 Gs/s wideband digital receiver for satellite communications

ADR-7 – Complete cryogenic Digital-RF satellite communication receiver system (takes input from conventional dish antenna)

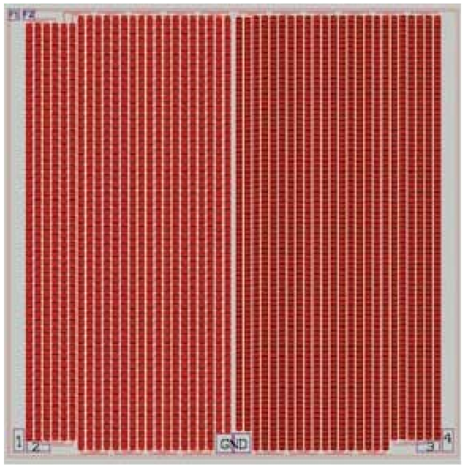
HTS Fabrication Process

YBCO junctions for ~70 K operation

Univ. California San Diego (UCSD) fabrication process



Based on Ion Damage Josephson Junction (IDJJ) fabrication technique



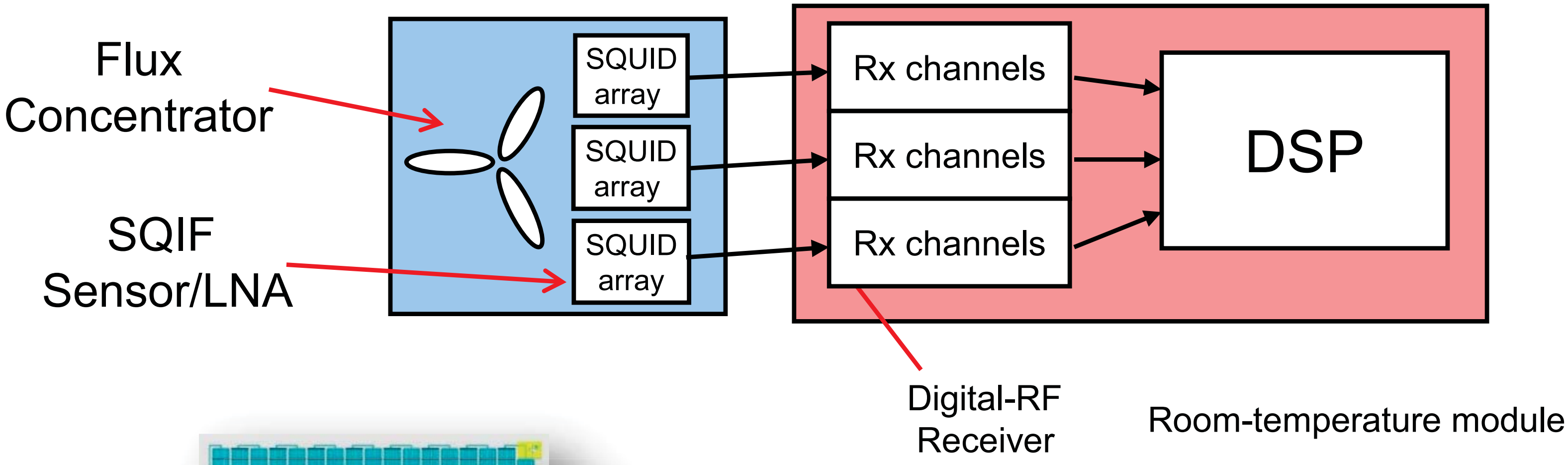
Cryocooling for 70-77 K operation

Integral Stirling 1W Micro Cooler RICOR K543

- Weight: 715 g
- Input Voltage: 18-28 VDC
- Steady State Input Power (1000mW @77K): 20W Typ. @23°C
- Maximum Input Power: 45W
- Ambient Temperature Range
- Operational: -40°C...+71°C
- Non-Operational: -56°C...+85°C
- Cooldown Time (500J @23°C): 4 min. Typ.
- Cooling Capacity: 1W @77K @71°C
- MTTF > 15,000 Hours (Goal)
- Meets Environmental Conditions per MIL-STD-810

Commercially available from multiple sources

Platforms for HTS-based systems



Flux Concentrator

SQIF Sensor/LNA

SQUID array

SQUID array

SQUID array

Rx channels

Rx channels

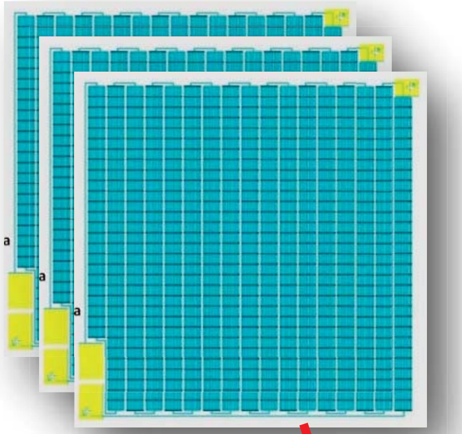
Rx channels

DSP

Digital-RF Receiver

Room-temperature module

SQUID 2D array for Superconducting Quantum Antennas



Sensitive compact RF system based on Superconductor Quantum Antennas

Semiconductor Receiver versus SQIF Receiver ($\mathcal{E}$ vs. $\mathcal{B}$)

SQUIDs can detect magnetic fields lower than one flux quantum $h/(2e) \approx 10^{-15}$ Wb, 10^{-18} Wb reported in the literature

Conventional Receiver

Mars link at 64 MBPS

- EIRP = 84 dBW (≈2.5×10^{8} W)
  - Assumes 100 W TWT, 12 m aperture
  - Range=3.7×10^{8} km
- Power density at receiver ≈ 2.8×10^{-16} W/m^2
  - Electric Field ≈ 4.6×10^{-7} V/m
  - Displacement flux density ≈ 10^{-18} C/m^2
- Receive Antenna Aperture
  - QPSK, Block Turbo Code, 3 dB margin
  - Required E_b/N_o=4.6 dB

Aperture size 72 meters

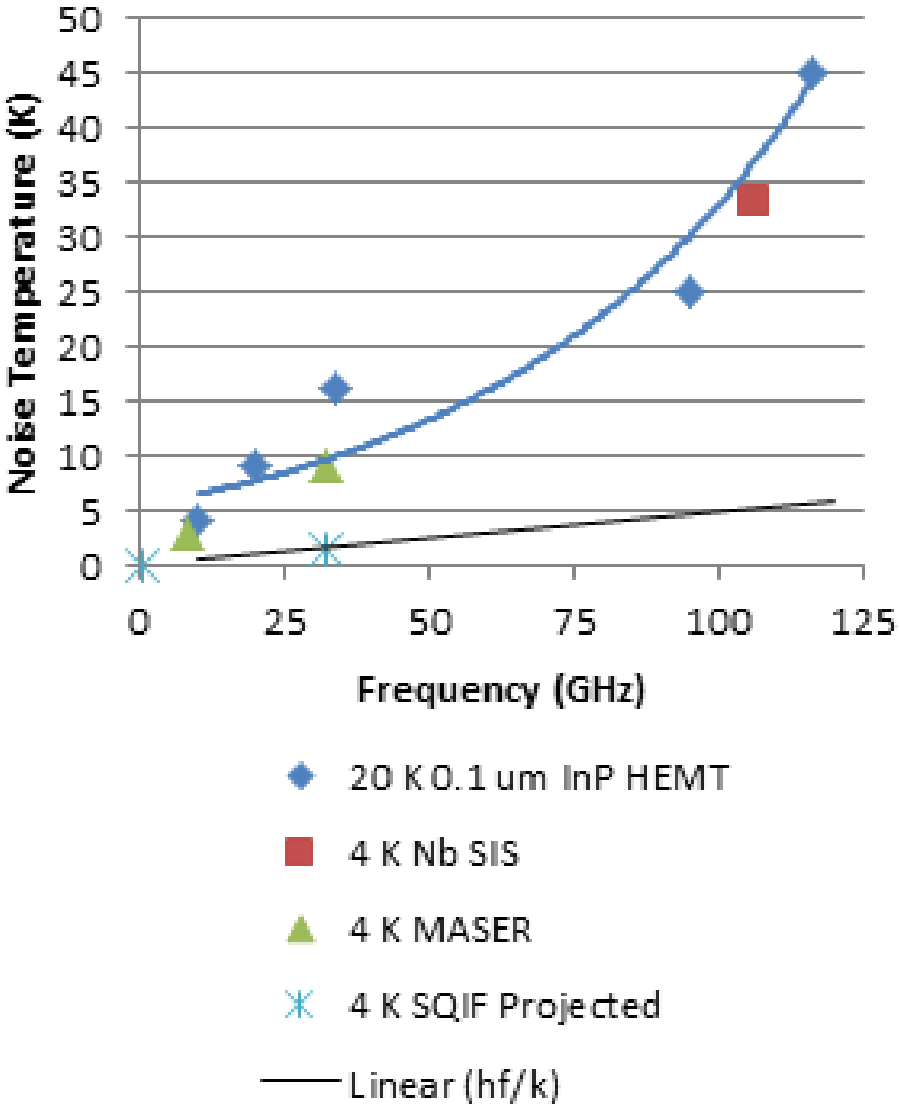
SQIF Superconducting Receiver

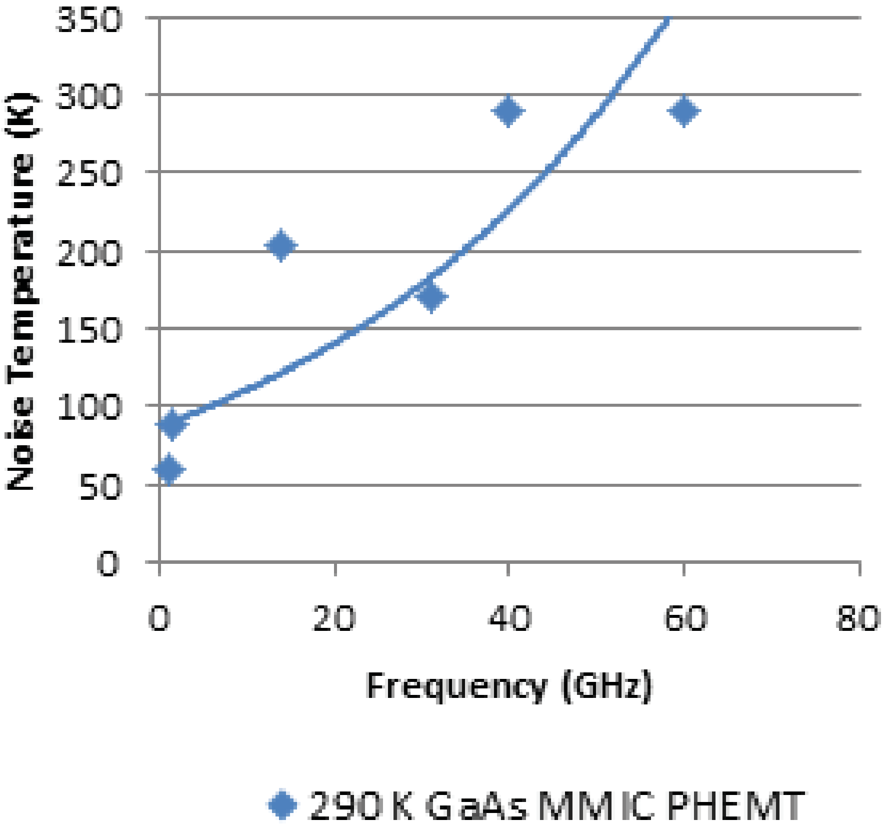
Mars link at 64 MBPS

- EIRP = 84 dBW (≈2.5×10^{8} W)
  - Assumes 100 W TWT, 12 m aperture
  - Range=3.7×10^{8} km
- Power density at receiver ≈ 2.8×10^{-16} W/m^2
  - Electric Field ≈ 4.6×10^{-7} V/m
  - Displacement flux density ≈ 10^{-18} C/m^2
  - Magnetic Field ≈ 10^{-9} A/m
  - Magnetic flux density ≈ 10^{-15} Wb/m^2
- Receive Antenna Aperture
  - Flux Concentrator
  - Mechanical refrigerator at 4K

Aperture Size ~ ???

State-of-the-Art LNA Technology



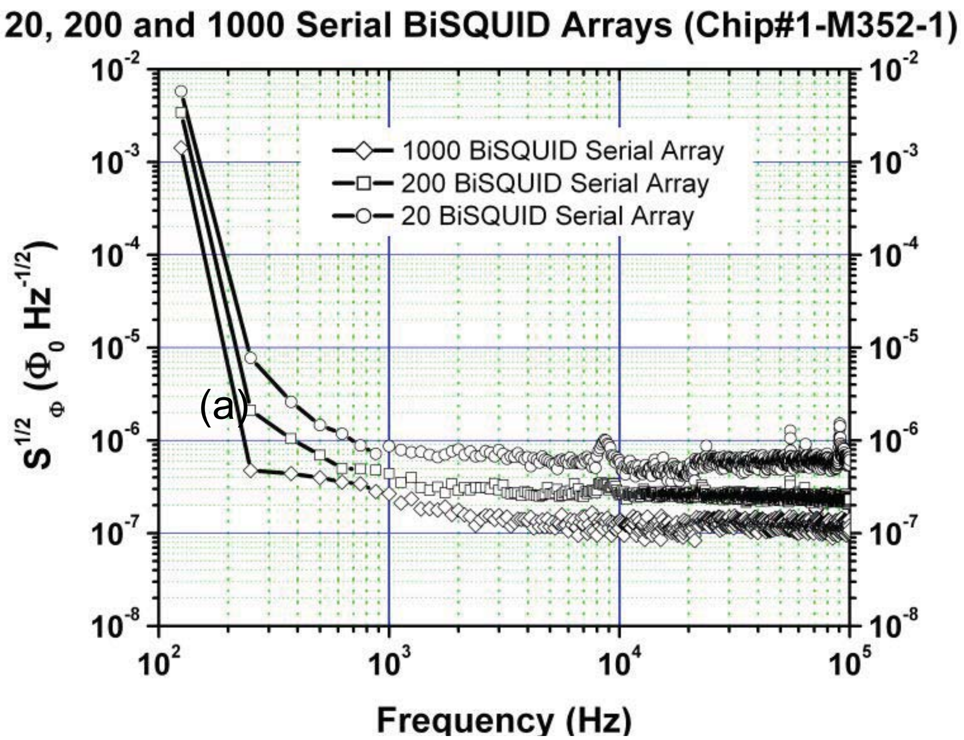


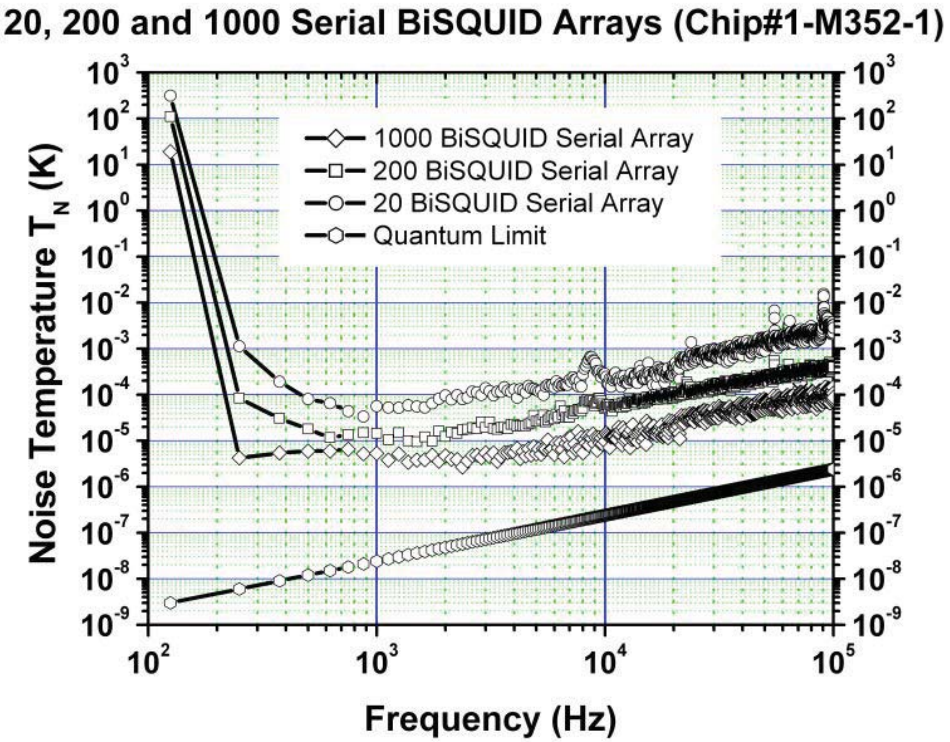
Conclusions

- SQUID arrays have the potential to detect extremely weak magnetic fields to enable a new type of signal detection processing
- Can potentially lead to the development of antenna with quantum-limited sensitivity
- Electrically small broadband communication or direction finding system with high sensitivity, dynamic range, linearity, dynamic programmability, high angular accuracy

Backup

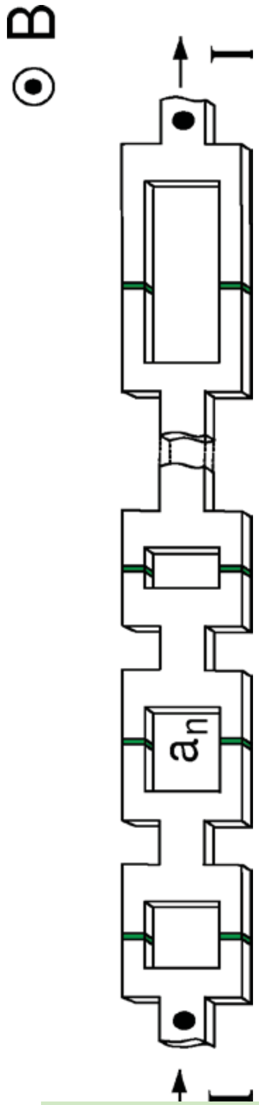
Measured Noise





$\varepsilon(f) = S_F(f)/2L$, where f is frequency, L – inductance of bi-SQUID calculated from the measured separately, ΔI_c modulation of IV curve defined as $L = \Phi_0/2\Delta I_c$. Noise temperature is defined as $T_N = \pi f \varepsilon(f)/k_B$, where k_B is Boltzmann's constant.

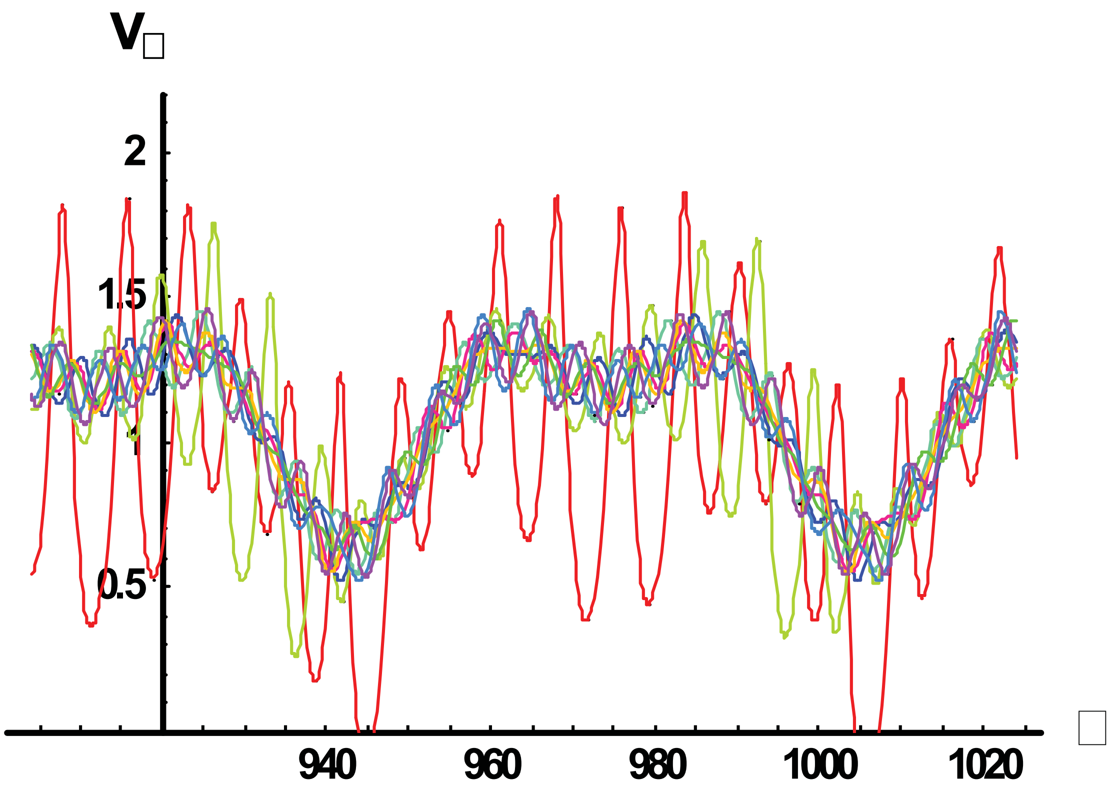
RF Coupling to SQIF array



$$B(t)=B_0+B_{rf}\left(t\right)$$

RF-signals modulate magnetic flux threading loop areas

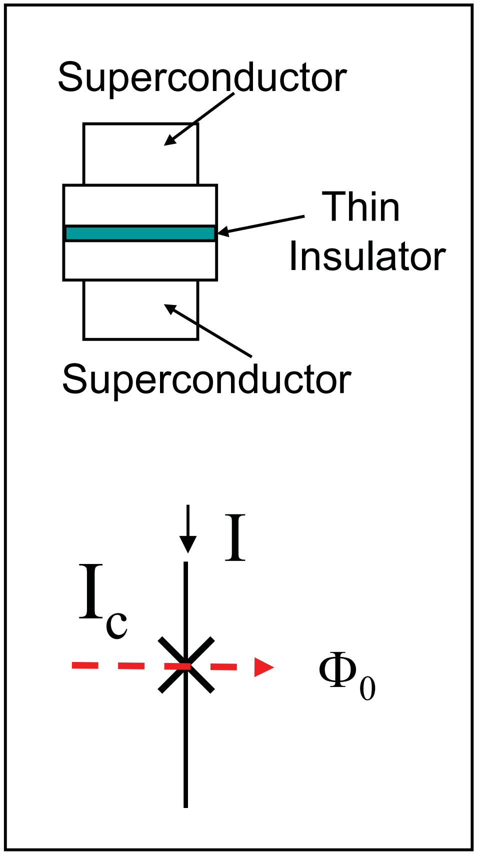
➔ copy of signal transferred into beat pattern of high frequency Josephson voltage output V(t)



Electrically small multi-loop antenna based on direct reception of magnetic field by individual loops

Josephson Junction

Active component (switch) in superconductor electronics



Josephson Junction

Below critical current "Ic"

$I < I_c$

Current flows through JJ at $V = 0$

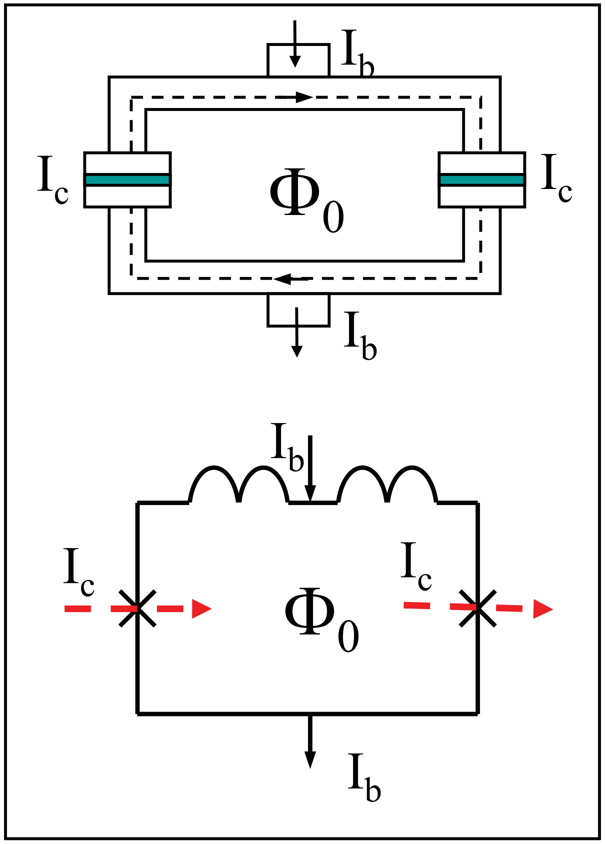
$$I = I_c \sin(\phi)$$

$I > I_c$

$V \neq 0$, and JJ passes magnetic flux through at rate $\dot{\phi}$

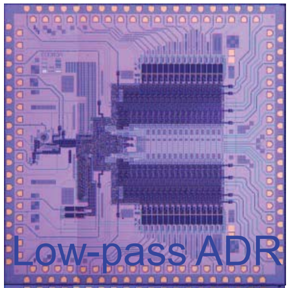
$$\dot{\phi} = \Phi_0 / V_c$$

Typical Critical Current:
$I_c \sim 0.1$ mA
Time constant :
$\tau \sim 1$ ps (3-µm process)
$\tau \sim 0.1$ ps (0.2-µm process)



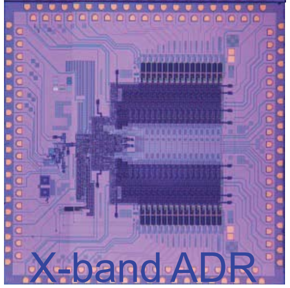
Matured Nb-based Digital Rx

1st Gen
ADR-1/2



Low-pass ADR

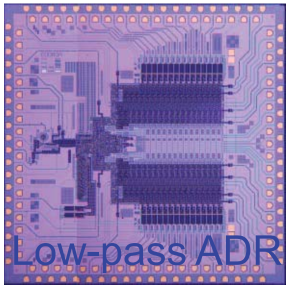
10 mm



X-band ADR

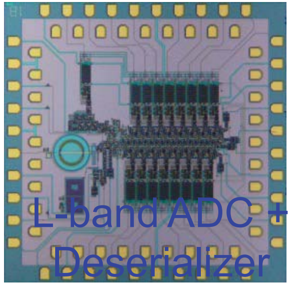
10 mm

2nd Gen
ADR-3/4



Low-pass ADR

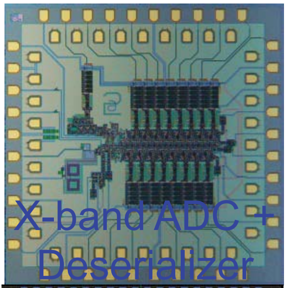
10 mm



L-band ADC + Deserializer

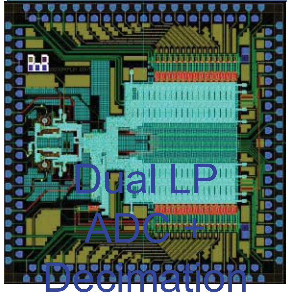
5 mm

3rd Gen
ADR-5/6/7



X-band ADC + Deserializer

5 mm

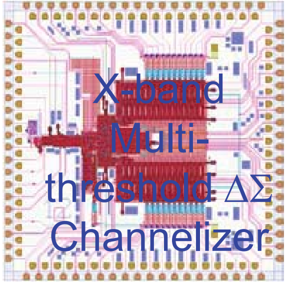


Dual LP ADC + Decimation Filters

10 mm

X-band Multi-threshold ΔΣ Deserializer

10 mm



X-band Multi-threshold ΔΣ Channelizer

10 mm