Superconducting Quantum Arrays for Wideband Antennas and Low Noise Amplifiers

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Outline

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Motivation: Sensitivity, Size, Bandwidth

- Conventional semiconductor electric field detection limited at about $kT \approx 10^{-22} \text{ J}$
- 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 $10^6 \text{ h or } \approx 10^{-28} \text{ J}$.
- Conventional semiconductor electric field detection threshold of $\sim kT\approx 10^{-22} \text{ J}$. 

![Ideal Receiver Noise](image)
SQUID – magnetic field sensor

Superconducting Quantum Interference Device (SQUID) invented in 1964 (50 years ago), R.Jaklevic, J.Lambe, J.Mercereau, A.Silver (US)

\[ \Phi_0 = \frac{h}{2e} = 2.07 \times 10^{-15} \text{ mV ps (Wb)} \]

Can measure fields as low as 5 aT (5×10^{-18} T) (a few days of averaged measurements)
Non-linear inductance of additional junction \( I_{c3} \) linearizes the SQUID response.

**Bi-SQUID – linearized SQUID**

Bi-SQUID – a 3-junction dc SQUID

- dc SQUID response
- bi-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** : **Superconducting Quantum Interference Filter** - 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

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

(a) L1, L3a, L3b, J1, J2, L2

(b) control line

bi-SQUID cell

3-turn control line (flux bias)

cell area is varied
SQUID 2D Array Integration

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

Diamond-shaped double bi-SQUID cell
Bi-SQUID 2D Array: Degree of SQIF

Flux/voltage characteristic

15 × 80 cell dual bi-SQUID SQIF array \( \sigma \sim 70\% \) of inductance spread
2 mV/div, 0.5 mA/div
(max voltage \( \approx 18 \) mV, \( \Delta V/\Delta I \) (flux bias) \( \approx 170 \) V/A)

15 × 40 dual bi-SQUID array with \( \sigma \sim 30\% \).
5 mV/div, 10 mA/div
Bi-SQUID 2D Array Samples

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

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

a single 7820-cell (92 x 85) 2D array
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 $\sim N^{1/2}$ or $\sim 7$ 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 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

- High $J_c$ (20 kA/cm²) with MoN resistors – under development
  - RSFQ (Digital & Mixed-signal)
- Medium $J_c$ (1 kA/cm² and 4.5 kA/cm²) with Mo resistors
  - RSFQ (Digital & Mixed-signal)
- Low $J_c$ (30 A/cm²) with Al, Mo, or Ti/PdAu resistors
  - SQUID applications
  - 1 V and 10 V Voltage Standard
  - QC circuits for mK operation

~6 mask releases per year (current number is 350)
~400 chips per wafer

All-Digital Receiver (ADR) – 12,000 JJs
LTS Fab: Process Cross section
Cryocooling for 4 K operation

- 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

Room-temperature module

Flux Concentrators

SQIF Sensor/LNA

Digital-RF Receiver

Fixed or Shipboard deployment

superstructure surface

~10 cm

~50 cm

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

Platforms for LTS-based systems
SQIF-based Receiver

4 K Refrigerator

Radome

SQIF Array Incorporated into Tapered Slot Flux Concentrators

Incident TEM Field

Primary Flux Concentrator
Superconducting Digital Receivers

Successful operation with X-band satellites using conventional dish antennas

X-band Transmitter

COTS Digital Modem

XTAR Satellite

X-band Digital-RF Receiver

COTS Digital Modem

Digital Modem

Digital Modem

COTS

Successful
everation 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

- 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

Integral Stirling 1W Micro Cooler RICOR K543

Commercially available from multiple sources
Platforms for HTS-based systems

- Flux Concentrator
- SQIF Sensor/LNA
- SQUID 2D array for Superconducting Quantum Antennas
- Sensitive compact RF system based on Superconductor Quantum Antennas
Semiconductor Receiver versus SQIF Receiver ($E$ vs. $B$)

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

### Conventional Receiver
Mars link at 64 MBPS

- EIRP = 84 dBW ($\approx 2.5 \times 10^8$ W)
  - Assumes 100 W TWT, 12 m aperture
  - Range = $3.7 \times 10^8$ km
- Power density at receiver $\approx 2.8 \times 10^{-16}$ W/m$^2$
  - Electric Field $\approx 4.6 \times 10^{-7}$ V/m
  - Displacement flux density $\approx 10^{-18}$ C/m$^2$
- Receive Antenna Aperture
  - QPSK, Block Turbo Code, 3 dB margin
  - Required $E_b/N_0 = 4.6$ dB

Aperture size 72 meters

### SQIF Superconducting Receiver
Mars link at 64 MBPS

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

Aperture Size $\approx$ ???
State-of-the-Art LNA Technology

![Graphs showing noise temperature vs frequency for different materials.]

- 20 K 0.1 um InP HEMT
- 4 K Nb SIS
- 4 K MASER
- 4 K SQIF Projected
- Linear (hf/k)
- 290 K GaAs MMIC PHEMT
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
Measured Noise

\[ \varepsilon(f) = \frac{S_F(f)}{2L}, \text{ where } f \text{ is frequency, } L \text{ – inductance of bi-SQUID calculated from the measured separately, } \Delta I_c \text{ modulation of IV curve defined as } L = \frac{\Phi_0}{2\Delta I_c}. \]

Noise temperature is defined as \[ T_N = \frac{\pi f \varepsilon(f)}{k_B}, \text{ where } k_B \text{ is Boltzmann’s constant.} \]
RF Coupling to SQIF array

\[ B(t) = B_0 + B_{rf}(t) \]
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

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 \( \phi \).

\[ \dot{\phi} = \Phi_0 / V_c \]

Typical Critical Current:

\( I_c \sim 0.1 \text{ mA} \)

Time constant:

\( \tau \sim 1 \text{ ps} \) (3-\( \mu \text{m} \) process)

\( \tau \sim 0.1 \text{ ps} \) (0.2-\( \mu \text{m} \) process)
Matured Nb-based Digital Rx

1\textsuperscript{st} Gen
ADR-1/2

2\textsuperscript{nd} Gen
ADR-3/4

3\textsuperscript{rd} Gen
ADR-5/6/7

Low-pass ADR

L-band ADR

X-band ADR

X-band ADR + Deserializer

Dual LP, ADC + Decimation

Filters

X-band Multi-threshold ΔΣ Deserializer

X-band Multi-threshold ΔΣ Channelizer