Superconducting Quantum Arrays for Wideband Antennas and Low Noise Amplifiers

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Outline

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• 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 $\sim kT\approx 10^{-22}$ 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)

\[ S_B = 3 \text{ fT} \cdot \text{Hz}^{-\frac{1}{2}} \]

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

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

Readout Electronics

SQUID Array (SQIF Receiver)

Flux Concentrator (antenna)

\[ V \quad \delta V/\delta \phi \quad \phi \quad \delta \phi/\delta B \quad B \]

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

(a) L1 L3b J2 J1 L2
L3a J3
(b)

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

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-SQUID 2D Array Samples

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

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

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 ~ 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 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

Copper Bump for MCM

R3
M3
M2
M1
M0
M-1
M-2

JJ
resistor
wiring

SUBSTRATE

HYPRES fab process
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

Flux Concentrators

SQUID array

SQUID array

SQUID array

Digital-RF Rx

DSP

Room-temperature module

SQIF Sensor/LNA

Digital-RF Receiver

Fixed or Shipboard deployment

superstructure surface

\(~10 \text{ cm}\)

\(~50 \text{ cm}\)

SQUID array chip-size (1-cm scale) antenna
SQIF-based Receiver

4 K Refrigerator

SQIF Array Incorporated into Tapered Slot Flux Concentrators

Incident TEM Field

Primary Flux Concentrator
Superconducting Digital Receivers

XTAR Satellite

Successful operation with X-band satellites using conventional dish antennas

X-band Transmitter

COTS Digital Modem

COTS Digital Modem

X-band Digital-RF Receiver
Today’s Digital RF Receiver System

Based on superconducting RSFQ digital technology

RSFQ chip: 1 cm², 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

SQUID 2D array for Superconducting Quantum Antennas

Sensitive compact RF system based on Superconductor Quantum Antennas

Flux Concentrator

SQIF Sensor/LNA

SQUID array

Rx channels

DSP

Digital-RF Receiver

Room-temperature module

Sensitive compact RF system based on Superconductor Quantum Antennas

WFB: Frequency agile antennas and sensors using advanced control materials
**Semiconductor Receiver versus SQIF Receiver (E vs. B)**

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

<table>
<thead>
<tr>
<th>Conventional Receiver</th>
<th>SQIF Superconducting Receiver</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mars link at 64 MBPS</td>
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</tr>
<tr>
<td><strong>EIRP = 84 dBW ($\approx 2.5 \times 10^8$ W)</strong></td>
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</tr>
<tr>
<td>Assumes 100 W TWT, 12 m aperture</td>
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</tr>
<tr>
<td>Range=3.7X$10^8$ km</td>
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</tr>
<tr>
<td><strong>Power density at receiver $\approx 2.8X10^{-16}$ W/m$^2$</strong></td>
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</tr>
<tr>
<td>Electric Field $\approx 4.6 \times 10^{-7}$ V/m</td>
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<tr>
<td>Displacement flux density $\approx 10^{-18}$ C/m$^2$</td>
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<tr>
<td><strong>Receive Antenna Aperture</strong></td>
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</tr>
<tr>
<td>QPSK, Block Turbo Code, 3 dB margin</td>
<td>Flux Concentrator</td>
</tr>
<tr>
<td>Required $E_b/N_0 = 4.6$ dB</td>
<td>Mechanical refrigerator at 4K</td>
</tr>
<tr>
<td>Aperture size 72 meters</td>
<td>Aperture Size $\sim ???$</td>
</tr>
</tbody>
</table>
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

\[ \varphi(f) = \frac{S_f(f)}{2L}, \text{ where } f \text{ is frequency, } L \text{ – inductance of bi-SQUID calculated from the measured separately, } \Delta l_c \text{ modulation of IV curve defined as } L = \phi_0/2\Delta l_c. \]  
Noise temperature is defined as \[ T_N = \frac{\pi f \varphi(f)}{k_B}, \text{ where } k_B \text{ is Boltzmann’s constant.} \]
RF Coupling to SQIF array

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

RF-signals modulate magnetic flux threading loop areas

\( \Rightarrow \) 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 \( \phi \).

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

Typical Critical Current:

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

Time constant:

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

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

1st Gen ADR-1/2

2nd Gen ADR-3/4

3rd Gen ADR-5/6/7

Low-pass ADR

X-band ADR

L-band ADC + Deserializer

X-band ADC + Deserializer

Dual LP ADC + Decimation

Dual LP ADC + Decimation

Filters

X-band Multi-threshold \( \Delta \Sigma \) Deserializer

X-band Multi-threshold \( \Delta \Sigma \) Channelizer