Ravindranadh J, Vol 3(1), pp 45-53
https://doi.org/10.55306/CJDTES.2026.030104
e-ISSN: 3048-8389
Ci-STEM Journal of Digital Technologies and Expert Systems

A Study of the Principles and Applications of Superconducting Quantum Sensors for Microwave and Magnetic Sensing

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Open Access
Review Article
Received: 07/04/2026
Accepted: 21/05/2026
Published: 07/06/2026
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Citation:
Ravindranadh J, "A Study of the Principles and Applications of Superconducting Quantum Sensors for Microwave and Magnetic Sensing" Ci-STEM Journal of Digital Technologies and Expert Systems, Vol. 3(1), pp. 45-53, 2026
doi: 10.55306/CJDTES.2026.030104
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Published By:
Ci-STEM Global Services Foundation, India.

Abstract:
Superconducting quantum sensors use flux quantization, the Josephson effect and low-loss microwave circuits to measure magnetic flux, microwave signals and photon flux close to fundamental limits. In this review we follow the field from the Bardeen–Cooper–Schrieffer theory and the discovery of Josephson tunnelling to SQUID magnetometers, microwave kinetic inductance detectors and quantum-limited parametric amplifiers. We explain how dc and rf SQUIDs, superconducting resonators, and Josephson and kinetic-inductance amplifiers work, and we describe one measurement chain that covers them all, with separate excitation, response, amplification, control and readout paths and a flux-locked-loop variant for SQUIDs. Flux and field noise, noise-equivalent power, added noise, bandwidth and dynamic range are defined and compared using numbers taken directly from the primary literature, together with the conditions under which they were measured. We then survey applications in biomagnetism, astronomical imaging, qubit readout and dark-matter searches, and close with the open problems of scalability, environmental noise and fair benchmarking.

Keywords:
Josephson junctions, kinetic inductance detectors, magnetometers, parametric amplifiers, quantum limit, SQUID, superconducting sensors.

1. INTRODUCTION

Two properties make superconductors attractive for sensing. They dissipate very little energy, so resonators keep a high quality factor and amplifiers can be built that add almost no noise. They also carry a coherent macroscopic quantum state, in which magnetic flux comes in units of the flux quantum, $\Phi_0 = h/2e \approx 2.068 \times 10^{-15}$ Wb [1]. Add the Josephson junction, a nonlinear inductance with essentially no loss [2], and the main ingredients of this review are in place: superconducting quantum interference devices (SQUIDs), superconducting microresonators and kinetic inductance detectors, and parametric amplifiers built from Josephson junctions or kinetic inductance.

SQUIDs are the oldest of these and have been covered in detailed reviews and a handbook [3], [4]. Resonant detectors [5], [6] and quantum-limited amplifiers [7]–[9] matured later, pushed along by astronomy and by the need to read out superconducting qubits [10], [11]. They are usually discussed separately, yet they have the same skeleton. A cryogenic quantum element is probed, its response is amplified as close to the quantum limit as possible, and the result is digitized and passed back to the control electronics. We use that common skeleton to organize the paper.

We make four contributions. First, a short history built on primary sources. Second, a physical description of each sensor class with the relations that matter. Third, a block diagram that handles both resonator-based and SQUID flux-input measurements. Fourth, a comparison of performance in which

every plotted number can be traced to a cited source and to the conditions under which it was obtained. Applications and open challenges follow.

2. HISTORICAL EVOLUTION

The story starts with the microscopic theory of Bardeen, Cooper and Schrieffer [12]. Experiments on superconducting cylinders soon showed that trapped flux is quantized [1]. Josephson then predicted in 1962 that a supercurrent can tunnel across a thin barrier between two superconductors [2], and the effect was observed not long afterwards [13]. In 1964, quantum interference between two junctions in a superconducting loop was demonstrated [14]. That is the physical basis of the SQUID (Fig. 1).

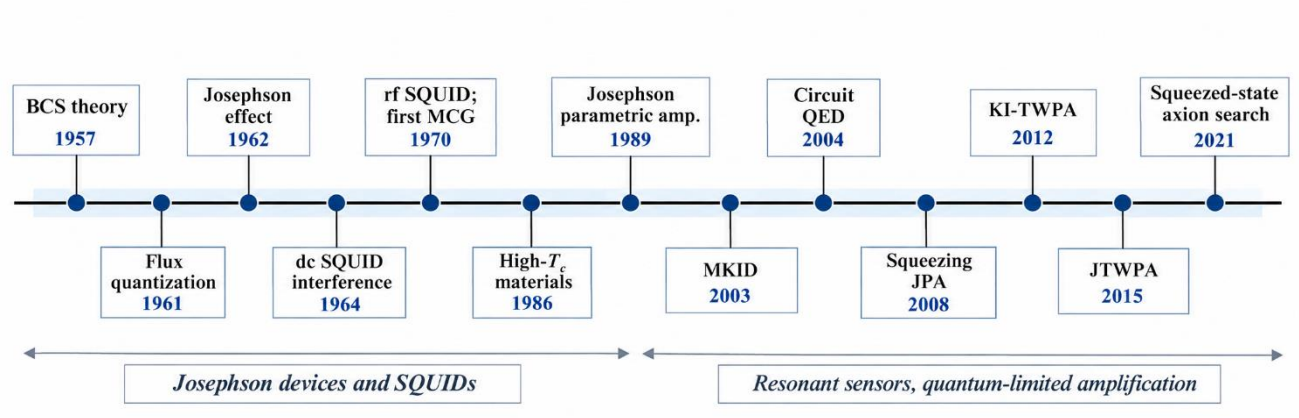


Fig. 1. Timeline of key developments in superconducting quantum sensing. Events and dates are from [12], [1], [2], [14], [15], [16], [17], [18], [5], [10], [7], [8], [9] and [19]; the 1964 entry refers to dc-SQUID-type quantum interference between two junctions [14].

Practical magnetometry took off with the rf-biased point-contact devices of Zimmerman *et al.* [15], who reported a sensitivity of the order of 10^{-9} G/√Hz. In the same year Cohen *et al.* used a point-contact magnetometer to record magnetocardiograms inside a shielded room [16], which gave biomagnetism its first strong motivation. After the discovery of high-T_c materials [17], SQUIDs that run at liquid-nitrogen temperature became possible; they are reviewed in [20]. Low-T_c dc SQUIDs meanwhile kept getting quieter and easier to use [21].

Resonant detectors came along in parallel. Day *et al.* introduced the microwave kinetic inductance detector (MKID), in which absorbed radiation changes the kinetic inductance of a thin film and so shifts the resonant frequency of a microresonator; many such resonators can be read out together by frequency multiplexing [5]. The physics and applications were later reviewed in [6]. On the amplifier side, Yurke *et al.* demonstrated Josephson parametric amplification [18], and in 2008 a tunable Josephson metamaterial was used to amplify and squeeze quantum noise [7]. Circuit quantum electrodynamics [10] created strong demand for such amplifiers, and travelling-wave designs based on kinetic inductance [8] and on Josephson junctions [9] widened their bandwidth. One recent milestone is the use of squeezed-state receivers in a search for dark-matter axions [19].

3. PHYSICAL PRINCIPLES AND SENSOR ARCHITECTURES

3.1. SQUIDs

A dc SQUID is a superconducting loop broken by two Josephson junctions. Each junction follows the current–phase relation

$$I_J = I_c \sin \varphi \tag{1}$$

where I_c is the critical current and φ is the gauge-invariant phase difference [2]. Flux quantization fixes the total phase change around the loop, so the critical current of the pair, and with it the voltage across the biased device, varies periodically with applied flux. The period is Φ_0 [14]. In a flux-locked loop the SQUID works as a null detector and gives a linear output over many flux quanta. Its sensitivity is quoted as a flux-noise spectral density, $S_\Phi^{1/2}$, which is converted to a field noise through the effective area A_{eff} of the pick-up structure:

$$B_n = \frac{S_\Phi^{1/2}\,\Phi_0}{A_{eff}} \tag{2}$$

with $S_\Phi^{1/2}$ in units of $\Phi_0/\sqrt{\text{Hz}}$. Equation (2) is what Fig. 3(b) plots. An rf SQUID has a single junction coupled to a tank circuit; it was the type used in the early practical magnetometers [15]. The trade-offs between the two types, including readout electronics and system integration, are discussed in [3], [4].

3.2. Superconducting Resonators and Kinetic Inductance Detectors

The resonant frequency of a superconducting microresonator depends on its geometric inductance L_g, its kinetic inductance L_k and its capacitance C:

$$f_r = \frac{1}{2\pi\sqrt{(L_g + L_k)C}} \tag{3}$$

Absorbed photons or quasiparticles change L_k and the dissipation, which moves f_r and lowers the quality factor Q. Because every resonator has its own frequency, thousands of pixels can share one transmission line [5], [6]. A kilo-pixel MKID imaging system for far-infrared space observatories has been demonstrated, with noise-equivalent power, yield and crosstalk characterized in [22]. What the sensor reports is therefore a shift of a microwave resonance, not a voltage.

3.3. Parametric Amplifiers

A Josephson parametric amplifier (JPA) pumps a nonlinear resonator, at twice the signal frequency in degenerate operation or at a detuned frequency in non-degenerate operation, and obtains gain from it [18], [7]. A phase-preserving linear amplifier cannot add less than half a quantum of noise referred to its input [23], [24]; in terms of the added photon number,

$$N_{add} \geq \frac{1}{2} \tag{4}$$

Resonant JPAs are held back by a gain–bandwidth product. Impedance engineering [25] and strong coupling to the environment [26] have both been used to get around it. Travelling-wave parametric amplifiers (TWPAs) spread the nonlinearity along a transmission line, using either Josephson junctions [9] or the kinetic inductance of a superconducting film [8]. SQUIDs can also serve as near-quantum-limited microwave amplifiers [27].

3.4. Hybrid Architectures

The pieces can be combined. In dispersive SQUID magnetometry, the flux-dependent inductance of a SQUID shifts the resonance of a microwave resonator, and a quantum-limited SQUID parametric amplifier reads it out [28]. Such a scheme borrows the multiplexing of Section III-B and the near-quantum-limited gain of Section III-C, and swaps the low-frequency flux-locked loop for a microwave measurement.

4. MEASUREMENT ARCHITECTURES

Fig. 2 shows the generic chain. In the resonant case (Fig. 2a) a room-temperature source supplies a probe tone, the *excitation path*, which is attenuated and filtered inside the cryostat before it reaches the sensor. The sensor changes the transmitted or reflected signal in response to the measurand (*response path*). A quantum-limited amplifier, normally followed by a cryogenic HEMT amplifier, sets the noise of the whole system (*amplification path*). The signal is then amplified again at room temperature, demodulated into in-phase and quadrature parts and digitized (*readout path*). A controller supplies flux bias and pump tones and closes any feedback loop from the processed data (*control path*).

In the SQUID flux-input variant (Fig. 2b) the measurand is a flux fed into the SQUID through a pick-up loop and input coil. The SQUID is dc biased, and the flux-locked-loop electronics integrate the amplified voltage and return a feedback current that cancels the applied flux, so the feedback signal is proportional to the input flux [3], [4]. The same split of paths applies: the bias source takes the role of

excitation and the feedback current that of control. A SQUID array or other cryogenic amplifier is often added so that the room-temperature preamplifier is less critical.

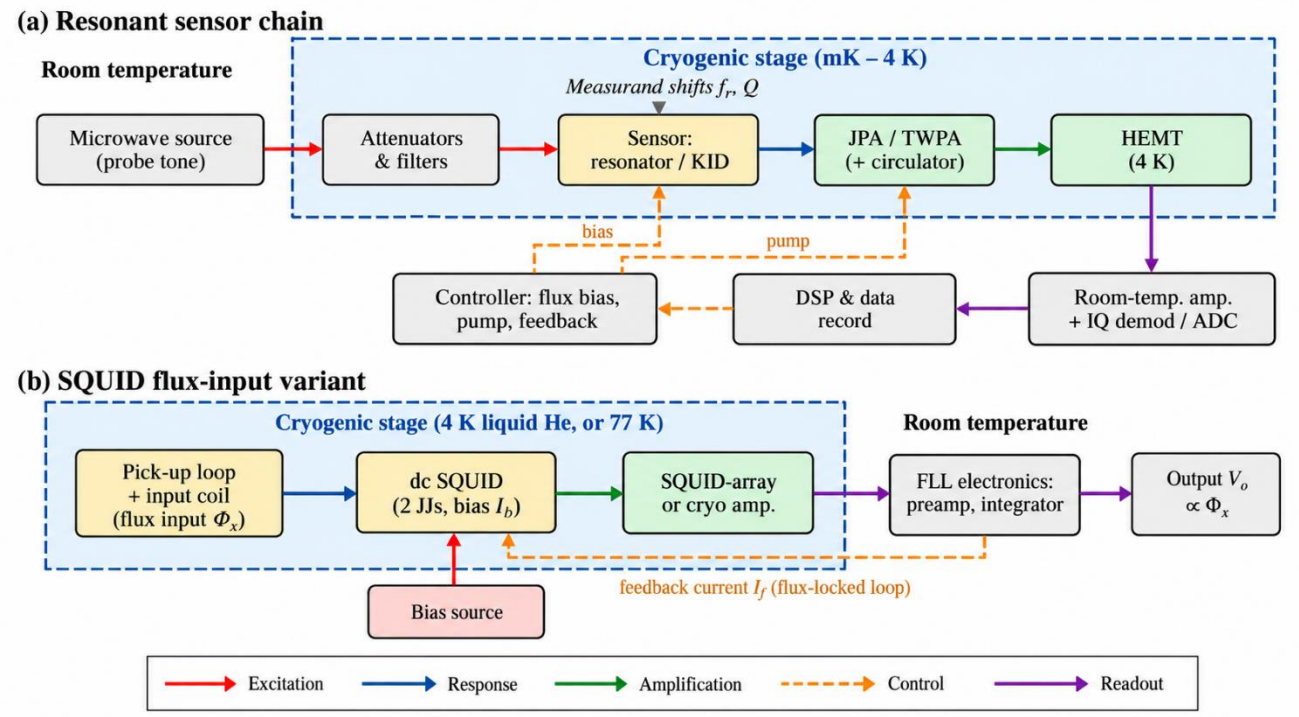


Fig. 2. Measurement architecture. (a) Resonant-sensor chain with excitation (red), response (blue), amplification (green), control (orange, dashed) and readout (purple) paths and an enclosing cryogenic stage. (b) SQUID flux-input variant with flux-locked-loop feedback. Schematic; no numerical data.

5. PERFORMANCE METRICS

Which metric matters depends on the device. For magnetometers it is the white-noise floor, given either as flux noise in $\Phi_0/\sqrt{\text{Hz}}$ or as field noise in T/√Hz through (2). For resonant detectors it is the noise-equivalent power (NEP), together with the multiplexing yield [22]. For amplifiers it is gain, bandwidth, added noise (in photons or as a noise temperature) and dynamic range, usually expressed by the 1-dB compression point [23], [24]. These numbers cannot be swapped between device classes, and any quoted value depends on temperature, bias, pick-up geometry and bandwidth. Table I lists the sensor classes, and Table II collects the specific values used in this paper, each as stated in its source.

Table 1: Sensor Classes And Their Measurement Principles

Device	Measurand	Transduction	Representative source
dc SQUID	Magnetic flux	Flux-periodic critical current; flux-locked loop [3], [4]	[21], [29]
rf SQUID	Magnetic flux	Single junction coupled to rf tank circuit [15]	[15], [16]
MKID / resonator	Quasiparticle or photon flux	Shift of resonant frequency and Q via kinetic inductance [5]	[5], [6], [22]
JPA	Weak microwave signal	Parametric gain of a pumped Josephson resonator [18], [7]	[7], [25]
TWPA	Weak microwave signal	Distributed nonlinearity (Josephson or kinetic inductance) [9], [8]	[8], [9]
Dispersive SQUID	Flux via microwave resonance	SQUID inductance shifts a resonator; JPA readout [28]	[28]

Table 2: Performance Values Used In This Paper

Device	Metric	Reported value	Condition / caveat	Source
rf point-contact SQUID	Field noise	Order of 10^{-9} G/√Hz (≈100 fT/√Hz)	Order of magnitude as stated; unit-converted here	[15]
dc SQUID	Field noise	< 4 fT/√Hz	Upper bound; 3 mm × 3 mm chip, 4.2 K	[21]
dc SQUID (state of the art)	Flux noise	≈ 1 $\mu\Phi_0$/√Hz	Typical level, not a single device	[29]
SERF atomic magnetometer	Field noise	0.54 fT/√Hz	Non-superconducting reference	[30]
Impedance-engineered JPA	Gain / bandwidth	Flat 20 dB over 640 MHz	Mean 1-dB compression −110 dBm; near quantum-limited noise	[25]
Kinetic-inductance TWPA	Gain bandwidth / added noise	Gain over ±2 GHz about 11.56 GHz pump; ≤ 3.4 photons at 9.4 GHz	Added noise is an upper limit	[8]
Josephson TWPA	Bandwidth / efficiency	"Several GHz"; quantum efficiency 75 % (70 % with following amp.)	Dynamic range sufficient for 20 qubits	[9]

Fig. 3(a) plots the three field-noise values from Table II. The Zimmerman value is a unit conversion of the order-of-magnitude figure in [15] (10^{-9} G ≈ 100 fT). The Drung value is an upper bound, reported for a 3 mm × 3 mm chip at 4.2 K [21]. The atomic magnetometer [30] is not superconducting and appears only for context. The devices differ in pick-up geometry and conditions, so the panel should not be read as a ranking. Fig. 3(b) instead shows how flux noise translates into field noise through (2). At 1 $\mu\Phi_0$/√Hz, which Drung quotes as the level of state-of-the-art SQUIDs [29], field noise falls in inverse proportion to the effective area, so a larger pick-up structure is the main route to lower field noise.

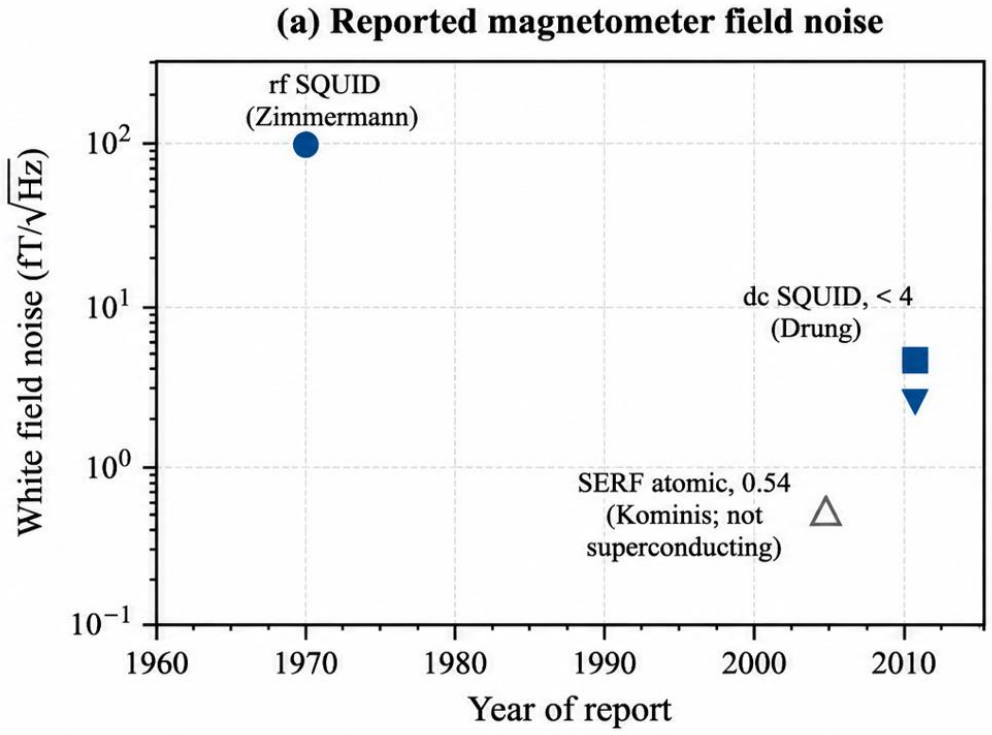


Fig. 3. (a) Reported magnetometer field noise: rf SQUID [15] (≈100 fT/√Hz, converted from 10^{-9} G/√Hz), dc SQUID [21] (upper bound, < 4 fT/√Hz; 3 mm × 3 mm chip, 4.2 K) and a SERF atomic magnetometer [30] (0.54 fT/√Hz, non-superconducting reference). Pick-up geometries and conditions differ.

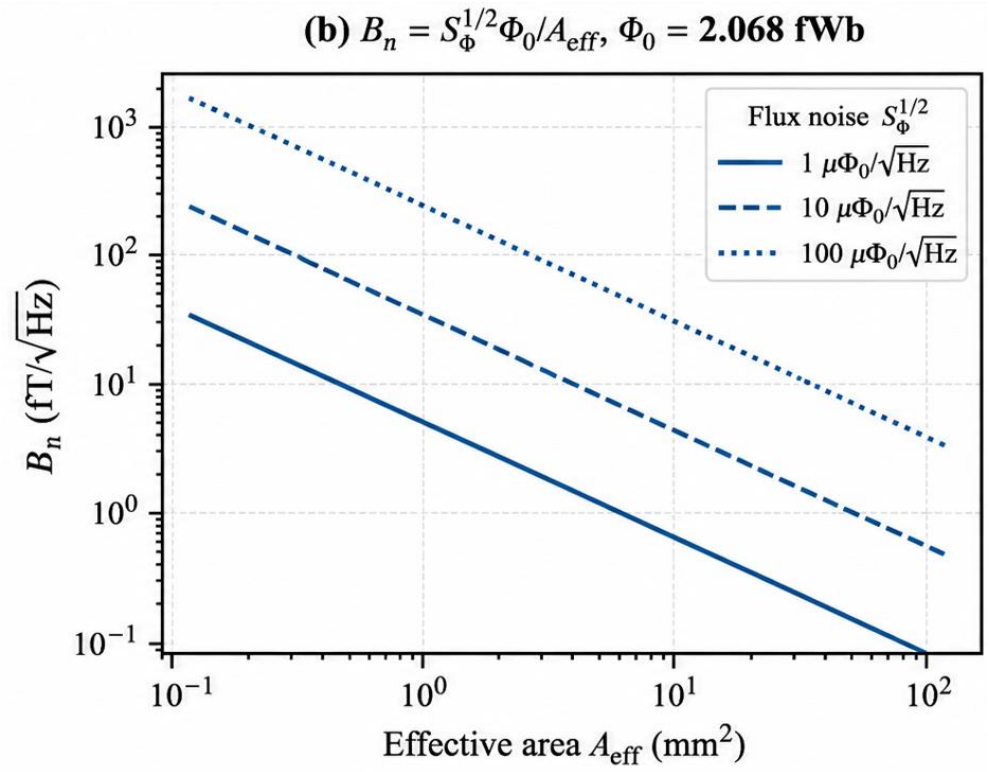


Fig. 3. (b) Field noise from (2) with Φ_0 = 2.068 fWb for flux noise of 1, 10 and 100 $\mu\Phi_0/\sqrt{Hz}$; the 1 $\mu\Phi_0/\sqrt{Hz}$ level is the state-of-the-art figure quoted in [29]. Curves are calculated.

Fig. 4 compares the gain bandwidths reported for two amplifiers. Their gains and measurement conditions differ (Table II), so the figure shows the scale of bandwidth that has been reached and is not a like-for-like comparison. The impedance-engineered JPA gives a flat 20 dB over 640 MHz [25], whereas the kinetic-inductance travelling-wave amplifier shows gain over about 4 GHz [8]. The Josephson travelling-wave amplifier also covers several GHz [9], but its abstract gives no number, so it is not plotted.

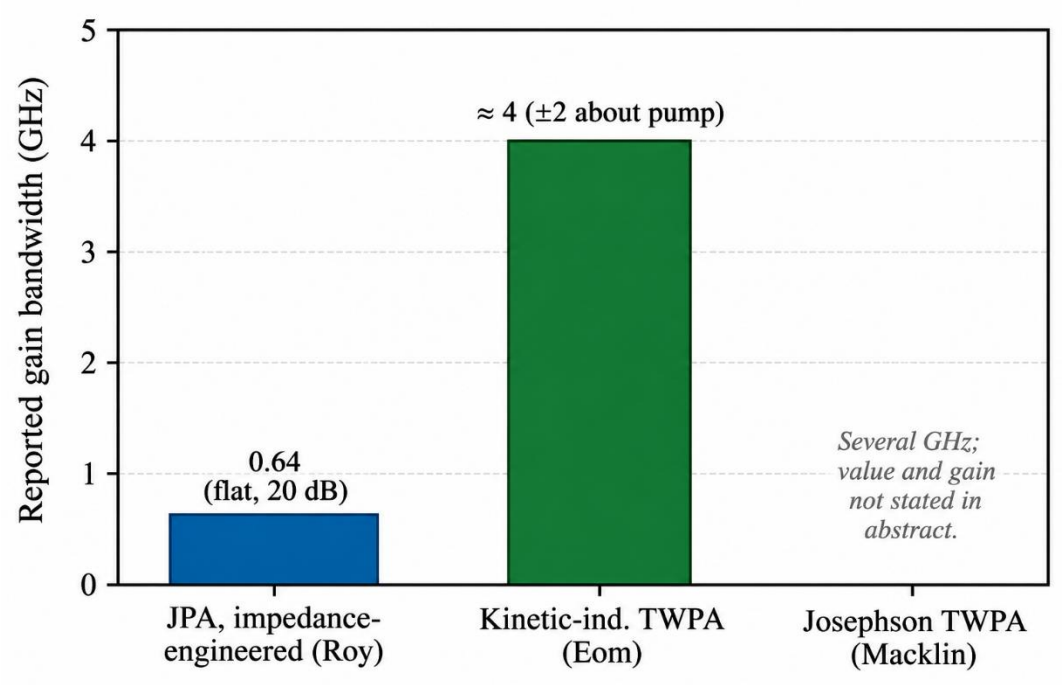


Fig. 4. Reported gain bandwidth: impedance-engineered JPA, flat 20 dB over 640 MHz [25]; kinetic-inductance TWPA, gain over ±2 GHz about the pump (≈ 4 GHz span, gain level not stated in the abstract) [8]; Josephson TWPA [9] reported only as “several GHz” and not plotted.

https://doi.org/10.55306/CJDTES.2025.030103

6. APPLICATIONS

Biomagnetism. The first magnetocardiograms [16] showed that SQUIDs can pick up the weak fields of the human body. Success depends on low white noise and on working in a shielded or gradiometric setup [3]. Atomic magnetometers now compete: a multichannel device has reached sub-femtotesla sensitivity [30], so the choice between the two technologies increasingly comes down to cryogenic cost and bandwidth.

Astronomical imaging. MKIDs suit large focal planes because of frequency-domain multiplexing [5], [6], and the kilo-pixel system of [22] is aimed at far-infrared space observatories. *Quantum information.* Quantum-limited amplifiers make single-shot dispersive readout of qubits possible in circuit QED [10], [11]; the travelling-wave amplifier of [9] was reported to have enough dynamic range to read out 20 qubits. *Fundamental physics.* Squeezed-state receivers have been used in a search for dark-matter axions [19], and SQUID-based dispersive magnetometry [28] links the magnetic and microwave domains.

7. CHALLENGES

Scalability. Reading out many qubits or pixels takes wideband amplifiers with high dynamic range and low loss. Impedance engineering [25] and travelling-wave designs [8], [9] help with part of this, but circulators and isolators are still bulky. *Environmental noise.* Material and magnetic-noise effects near micro-sized SQUIDs have been studied [31], and outside the laboratory shielding or gradiometry is needed. *Benchmarking.* The values in Table II were measured under different conditions, and no single standard compares flux, power and amplifier noise. Reporting full measurement conditions with each figure of merit, as we have tried to do here, would make later comparisons more reliable. *Cryogenics.* Operation at 4 K or below limits where these sensors can be deployed and keeps interest in high-T_c devices alive [20].

8. CONCLUSION

The sensors reviewed here rest on the same physics and, as Fig. 2 shows, fit one measurement architecture. From the first rf SQUID magnetometers [15] to multiplexed MKID arrays [22] and wideband parametric amplifiers [8], [9], progress has come from combining flux quantization, the Josephson effect and kinetic inductance with careful cryogenic readout. Because reported figures depend so strongly on measurement conditions, traceable reporting matters as much as the numbers themselves. Promising directions include broadband amplifiers with higher saturation power, integrated flux-to-microwave readout of SQUIDs, and benchmarking that works across device classes.

DECLARATIONS:

Acknowledgments	:	Not applicable.
Conflict of Interest	:	The author declares that there is no actual or potential conflict of interest about this article.
Consent to Publish	:	The authors agree to publish the paper in the Global Research Journal of Social Sciences and Management.
Ethical Approval	:	Not applicable.
Funding	:	Author claims no funding was received.
Author Contribution	:	Both the authors confirms their responsibility for the study, conception, design, data collection, and manuscript preparation.
Data Availability Statement	:	The data presented in this study are available upon request from the corresponding author.
Use of Generative Artificial Intelligence	:	AI-assisted tools have been used to improve the diagrams, language editing or grammatical clarity; the authors take full responsibility for the content of the final version.

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