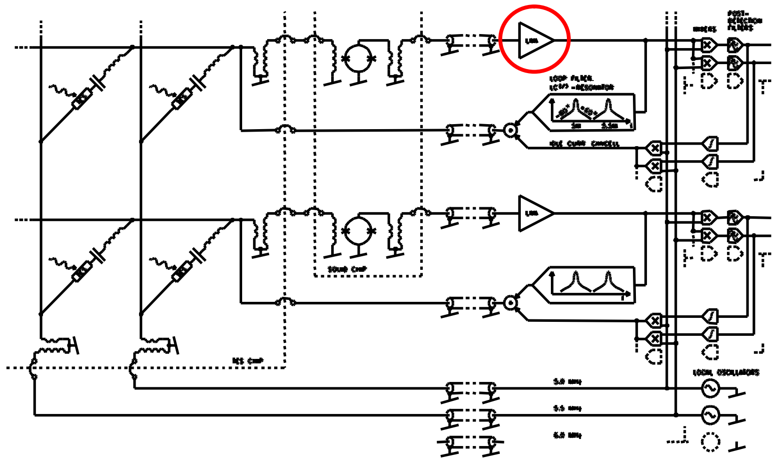
An ac-coupled post-SQUID semiconductor amplifier

Mikko Kiviranta, (*) Antti Virtanen, Heikki Seppä, Jari S. Penttilä, Juha Hassel and Panu Helistö
VTT Microsensing, 02150 Espoo, Finland; and (*) GE Healthcare Technologies, 04301 Tuusula, Finland

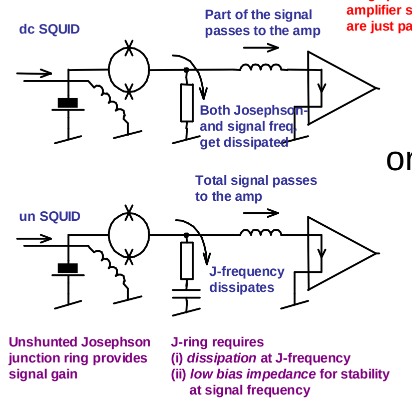
Motivation: frequency-domain multiplexing



Noise temperature $T_n = \frac{u_n i_n}{2k_B}$ Noise matching resistance $Z_n = \frac{u_n}{i_n}$ (u_n: V / Hz$^{1/2}$, i_n: A / Hz$^{1/2}$)

At SQUID output T_n ~ 2.5 × bath temperature

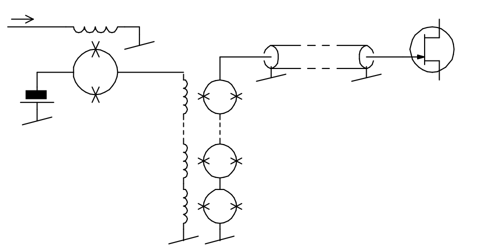
How to see this:



or

$$\Phi_n = \sqrt{24 k_B T L \sqrt{LC}}$$
$$\frac{\partial I}{\partial \Phi} = \frac{1}{L}$$
$$P_{out} = I_{out}^2 R_{dyn} / 2$$
$$R_{dyn} = \sqrt{\frac{L}{2\pi C}}$$
$$T_n \approx 2.4 \times T$$

Single SQUID at 4.2K: T_n~10K room-temp amplifier doable but difficult
SQUID array at 4.2K: same T_n as single SQUID, just different R_n
Single SQUID at 0.4K: T_n~1K room-temp amplifier very difficult
Single SQUID read with single SQUID: 2nd SQUID limits dynamic range
Single SQUID read with a *k*-SQUID array:
- Choose coupling such that one Φ_0 in 1st SQUID corresponds to Φ_0 in each SQUID in the array
- Then the dominant non-linearity is the same for 1st and 2nd SQUID…
- …but T_n at the array output is *k* times the T_n at the 1st SQUID output.



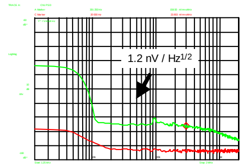
Candidates for the semiconductor device

Bipolar transistors

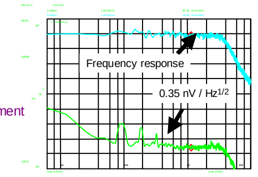
$u_n = \sqrt{4 k_B T R_{BB}}$ $u_n = \sqrt{\frac{2e}{I_C}} \times \frac{kT}{e}$ $i_n = \sqrt{\frac{2eI_C}{h_{fe}}}$

SSM2220, MAT03, AD797: regularly used

FZT690: very large h_{fe} ~ 1400
Not promising



BFP650: very low R_{BB} ~ 1 Ω
Tn ~ 50 K, Zn ~ 90 Ω, High-bandwidth replacement for SSM2220, MAT03



JFETs

$u_n = \sqrt{\frac{8k_BT}{g_m}}$ $i_n = \omega C_g \sqrt{\frac{k_BT}{g_m}}$ $i_n = \sqrt{2eI_g}$

⟹ $T_n = \sqrt{2/3}\,\omega \frac{C_g}{g_m} T$

2SK147, IF1320: has been used previously

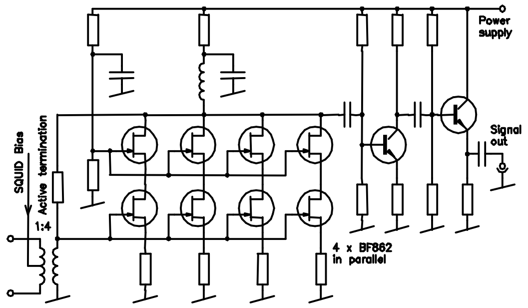
The largest C_g - g_m ratio we found: BF862
- T_n = 5.5 K, Z_n = 4.2 kΩ @ 10 MHz (theory)
- Must couple devices in parallel, use transformer to match source resistance

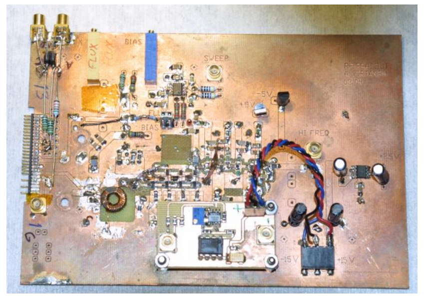
HEMTs / MESFETs

- Tend to have too high 1/f noise corner (100 MHz or more)

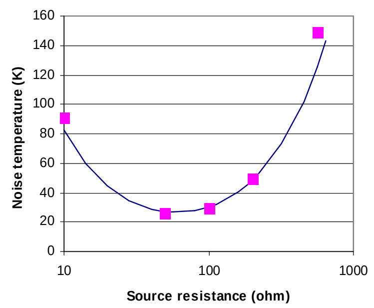
Our JFET amplifier prototype

Simplified schematics

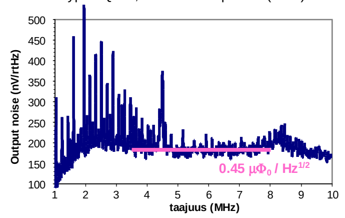




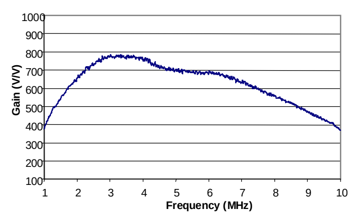
Noise temperature at 5 MHz



Noise spectrum with a SQUID
Washer type SQUID, SUST vol.17 p.S285 (2004)



Frequency response
-3dB bandwidth 1.8 - 7.9 MHz

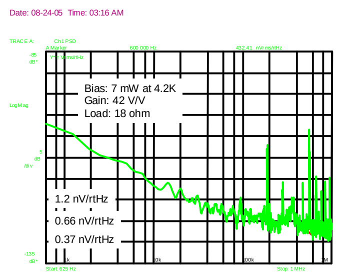


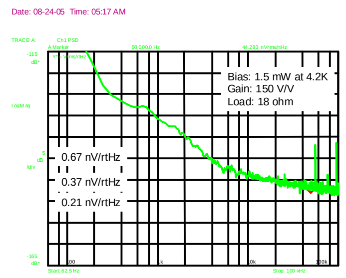
What about a cryogenic amplifier?

- Short feedback to the SQUID input
  ⟹ large dynamic range at a large bandwidth
- Johnson noise from cabling becomes negligible

We have some promising 4.2K results

A quick functionality check for semiconductor device D2





A quick functionality check for semiconductor device D5

7 mW bias point
- 3 MHz cutoff due to cable capacitance
- With matched circuits >1 GHz bandwidth feasible
- Theoretical estimate for current noise 3 pA/rtHz. Observed load dependence is consistent with u_n = 0.135 nV/rtHz, i_n = 4 pA/rtHz.
- Getting rid of the 250 kHz interference may lead to lower noise.

1.5 mW bias point
- Lower cutoff, due to higher cable-driving impedance