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Microcalorimeters and Large-Scale Cryogenic Multiplexer Arrays – the Promise and the Pitfalls

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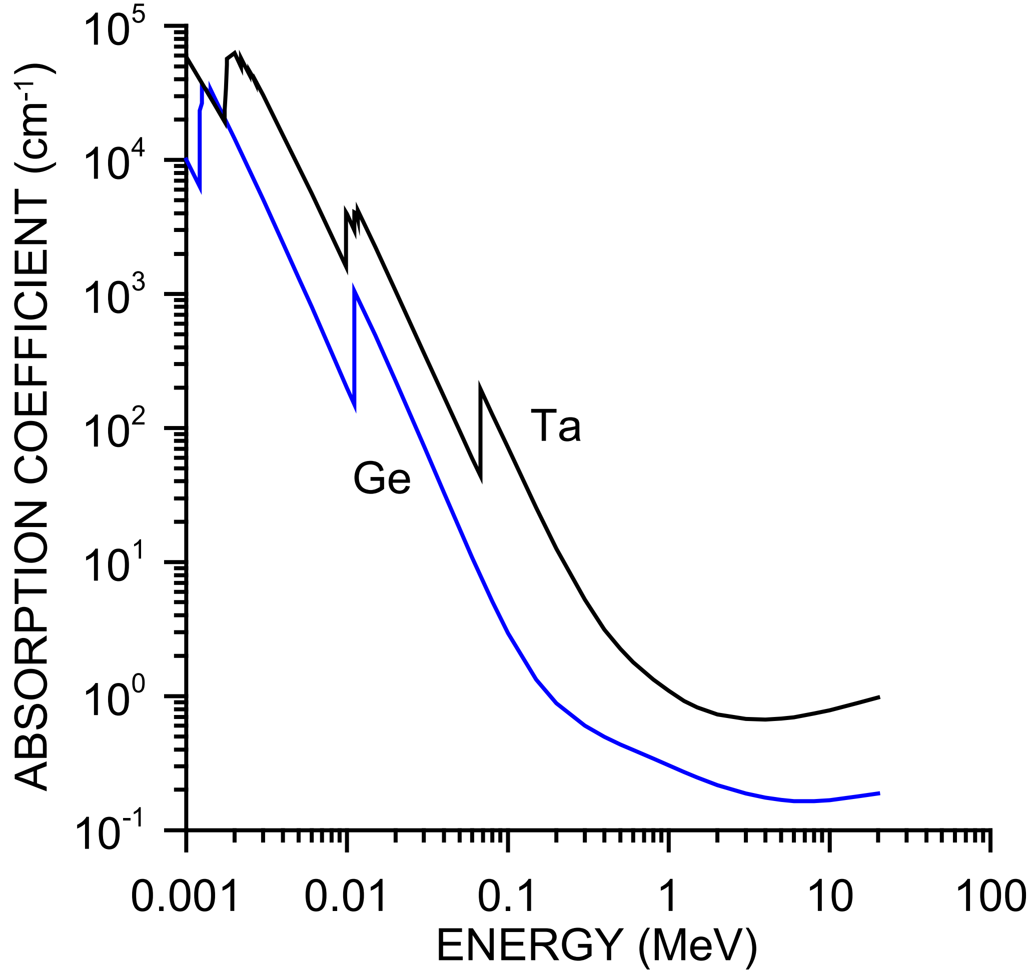
Quest for Enhanced Energy Resolution

- Improved energy resolution would open many avenues in science, industrial applications, and nuclear non-proliferation.
- Currently, silicon and germanium detectors provide the optimum combination of energy resolution and efficiency at keV and MeV energies.
- High-Z materials would reduce the required sensor size for high full-energy measurement efficiency.
- Although remarkable progress has been made in developing new semiconductor materials and readout techniques that mitigate materials shortcomings, none of them surpass the energy resolution of silicon or germanium.
- Microcalorimeters operating at sub-Kelvin temperatures can provide superior energy resolution, but suffer from small size and rate capability.
- New developments alleviate these problems.
- Different material requirements than in semiconductors extend the range of suitable materials.

Material requirements differ significantly from semiconductors.

Not necessarily easier, but different requirements open possibilities with different materials, e.g. Ta.

Gamma Absorption Coefficients of Ge and Ta



Microcalorimeters

- Energy per signal quantum ~meV, rather than ~eV in semiconductors

  Statistical energy resolution: $\sigma_E = \sqrt{kTE_\gamma}$

- In addition fluctuations in number of phonon modes, dependent on heat capacity C, so

$$\sigma_E = \sqrt{kT\left[TC(T) + E_\gamma\right]}$$

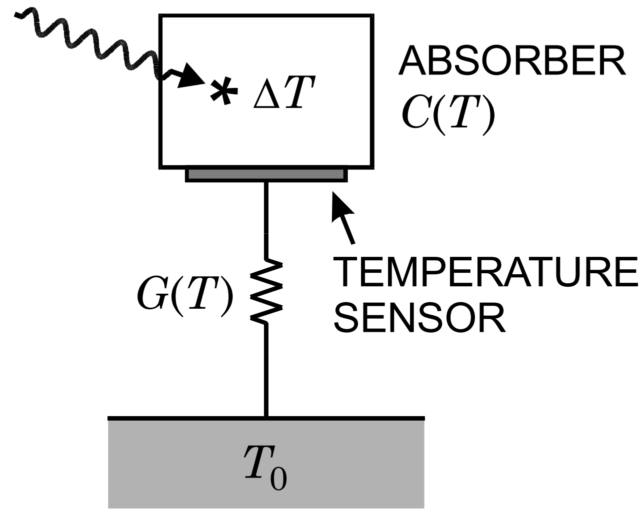
High resolution requires

- Operation at low temperatures
- Low heat capacity (small sensors + operation at low temperatures)

Key developments

- Monolithic integration of large sensor arrays + cryogenic multiplexing
  $\Rightarrow$ increase detection efficiency and rate capability
- Cooling systems that don't require liquid cryogens

Microcalorimeter Principle



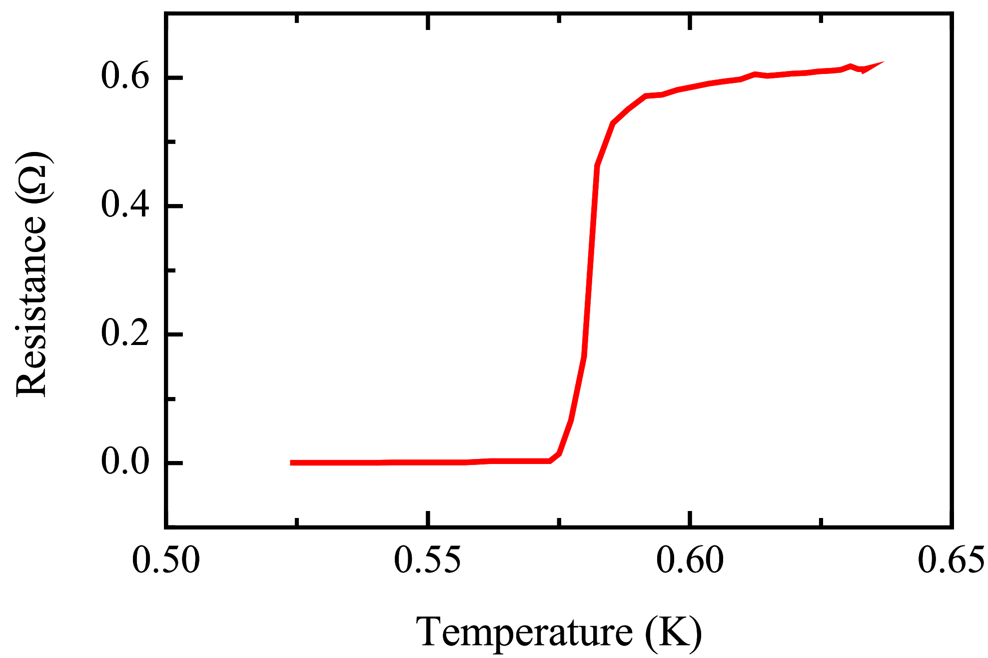
One type of sensor implementation:

Superconducting Transition Edge Sensor (TES)

Thin film superconductor at transition temperature

Bias sensor in transition

small $\Delta T \;\Rightarrow\;$ large ΔR



Electrothermal Feedback

Required power is of order pW, i.e. voltage of order μV
current of order μA

Simplest to bias device with a **constant current** and measure change in voltage

Problem: power dissipated in sensor $P = I^2 R$

Increasing R $\Rightarrow$ Increasing P $\Rightarrow$ Increasing R $\Rightarrow$ Increasing P

$\Rightarrow$ **thermal runaway**

When biased with a **constant voltage** $P = \dfrac{V_b^2}{R}$

Increasing R $\Rightarrow$ Decreasing P $\Rightarrow$ Decreasing T $\Rightarrow$ Decreasing R

$\Rightarrow$ **negative feedback**

Analogous to fedback op-amps:

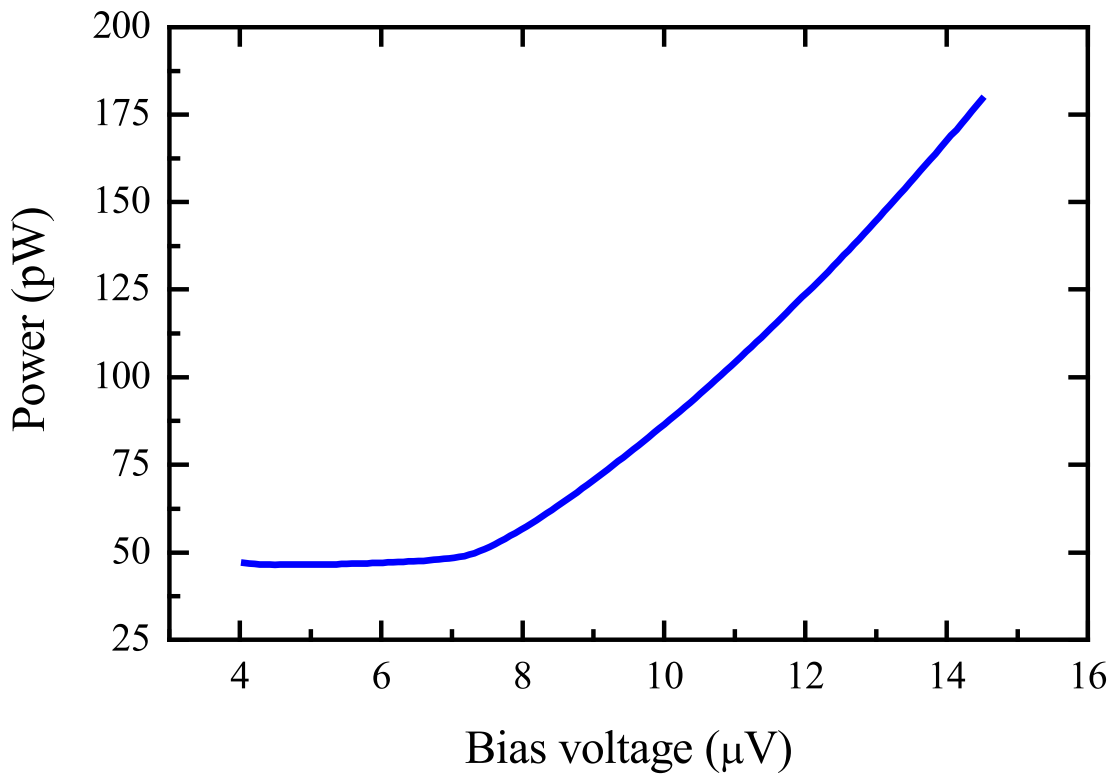
Loop gain stabilizes operating point, increases linearity, and bandwidth.

Additional phase shifts can lead to instability.

Operate with constant voltage bias

$\Rightarrow$ "Constant power operation":

Change in absorbed power is balanced by change in electrical power: $\Delta I / \Delta P = 1 / V_{bias}$



Constant Voltage Bias requires that total resistance in bias loop is much smaller than the bolometer resistance (typ. 1 ohm)

Key Developments

- Monolithic fabrication of bolometers

  ⇒ wafer-scale integrated arrays

- Cryogenic multiplexing

  1. Time domain (NIST)
  2. Frequency domain (this work)

     Zero add'l power at cold stage

- Systems in 2nd year of operation:

  1. South Pole Telescope (SPT)

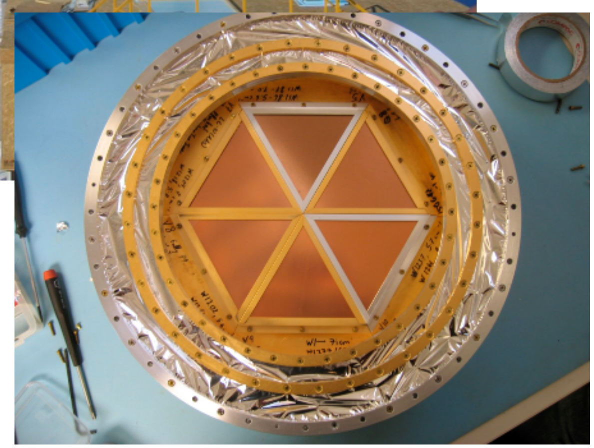
     970 bolometer array

  2. APEX-SZ

     320 bolometer array

- Cryogen-free cooling

  No refilling of liquid cryogens required



SPT bolometer array

Principle of Frequency-Domain Multiplexing

1. High-frequency bias (~100 kHz – 1 MHz)

   Each bolometer biased at different frequency

2. Signals change sensor resistance

   $\Rightarrow$ Modulate current

   $\Rightarrow$ Transfer signal spectrum to sidebands adjacent to bias frequency

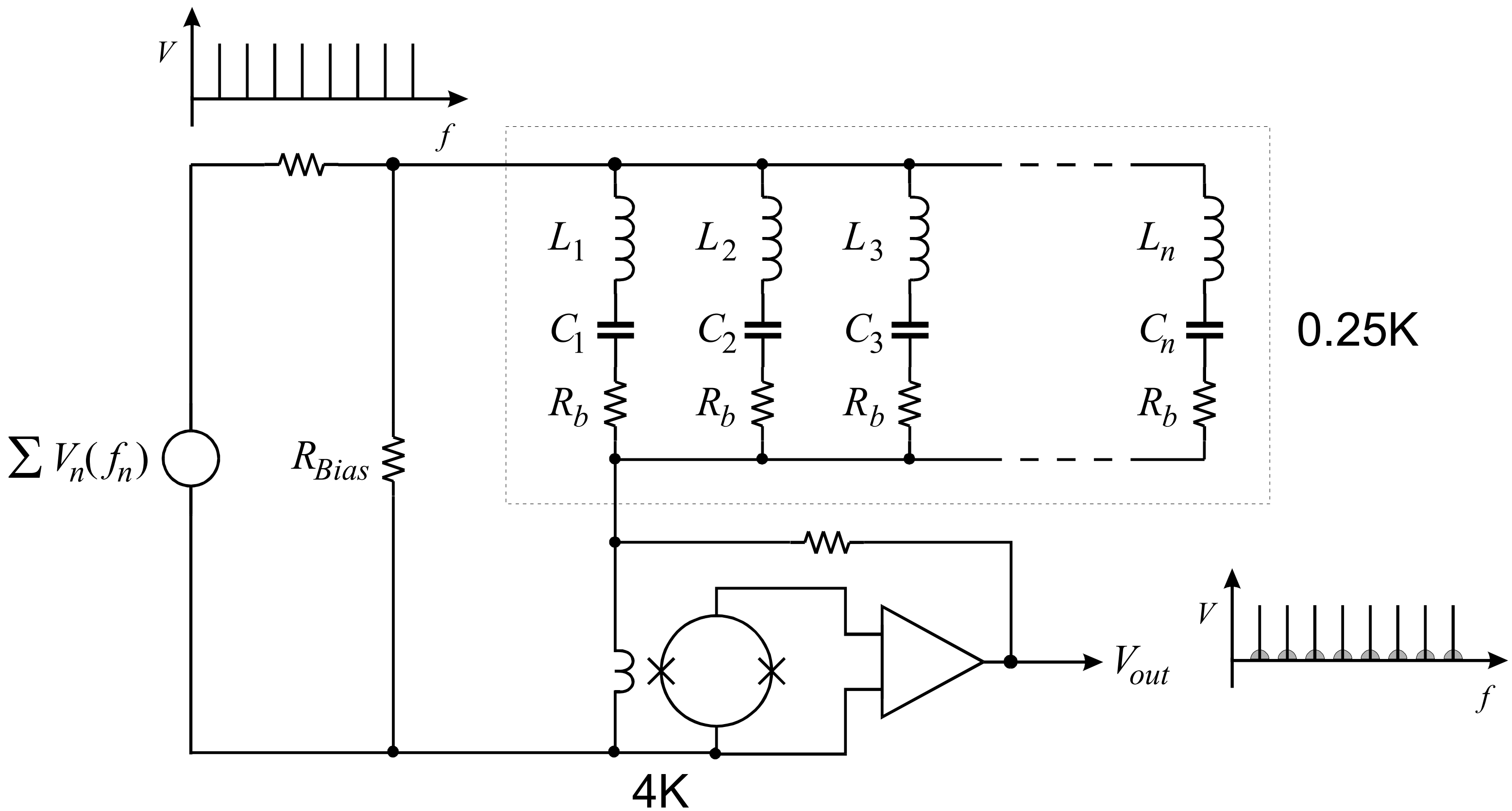
   $\Rightarrow$ Each sensor signal translated to unique frequency band

3. Combine all signals in common readout line

4. Retrieve individual signals in bank of frequency-selective demodulators

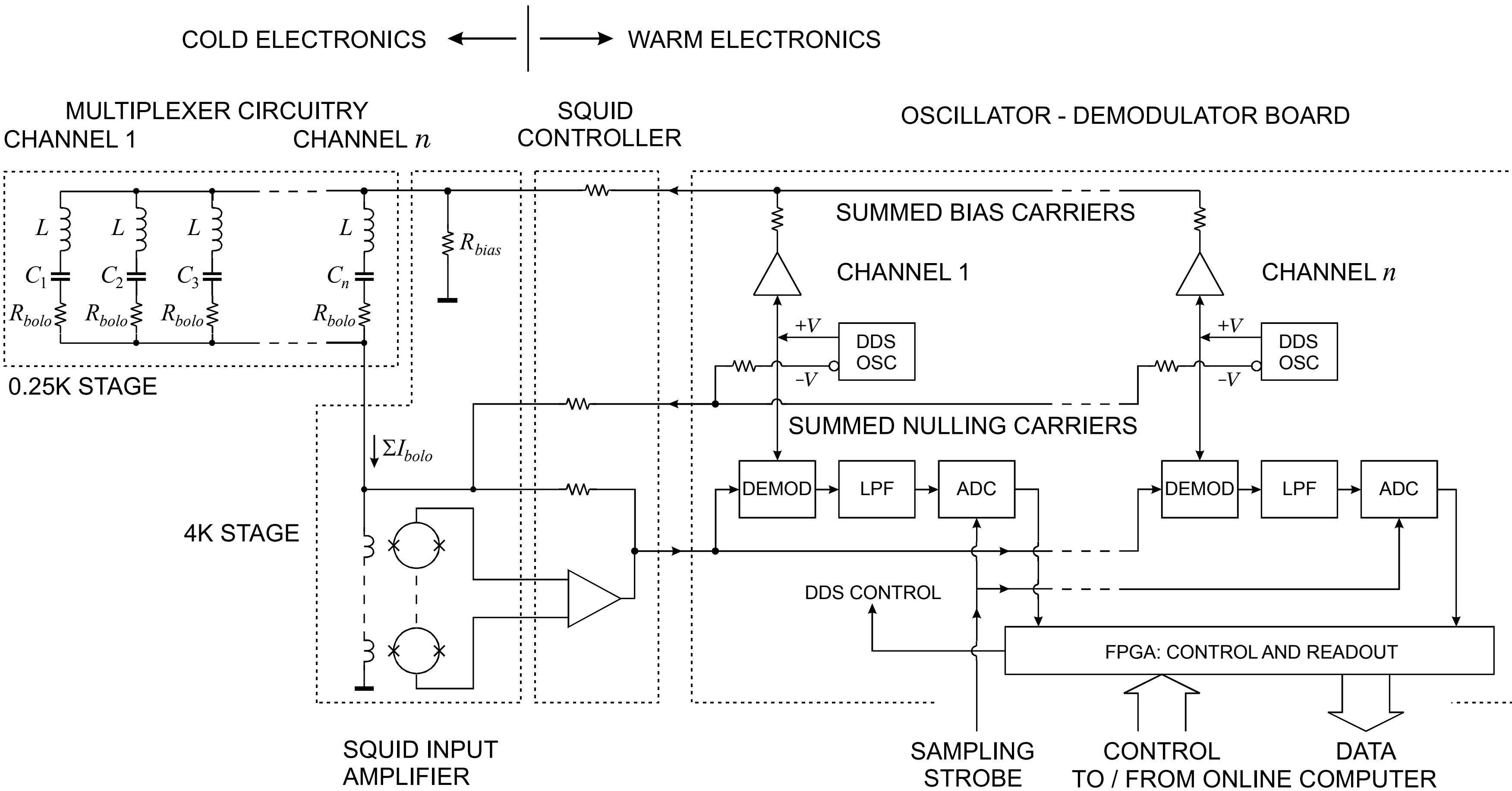
High-frequency bias greatly reduces sensitivity to microphonics.
(no noise increase due to mechanical pulse tube cooler)

MUX circuit on cold stage



- "Comb" of all bias frequencies fed through single wire.
- Tuned circuits "steer" appropriate frequencies to bolometers and limit noise bandwidth.
- Current return through shunt-fedback SQUID amplifier (low input impedance).
- No additional power dissipation on cold stage (only bolometer bias power).

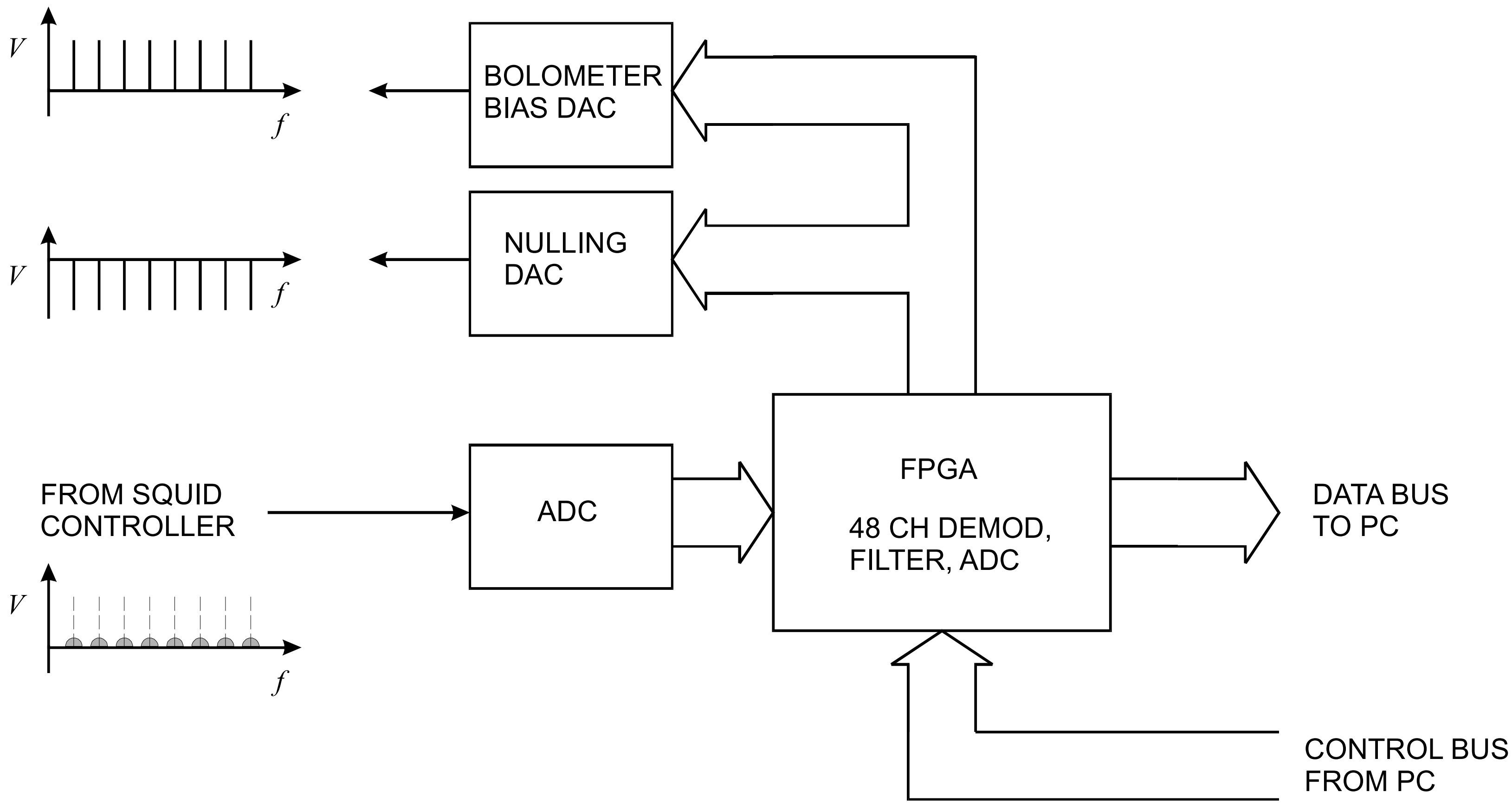
Readout



Bias frequencies are nulled at SQUID input to reduce maximum signal level.
(does not affect signal, which is only in the sidebands)

Note: SQUID feedback loop includes room-temperature amplifier.

Recent improvements in fast ADCs and FPGAs enabled
"Fully Digital" Demodulator (Matt Dobbs et al., LBNL/McGill)



- Substantial reduction in power $\Rightarrow$ Balloon-borne experiments (e.g. EBEX)
- Baseline readout for CMB polarization experiments PolarBear and EBEX (balloon)

Challenges

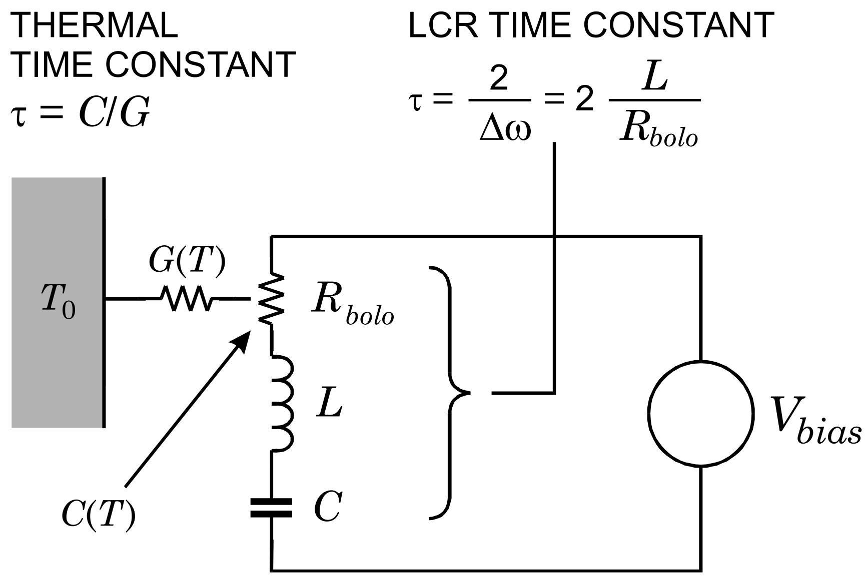
Bolometer time constants

Both the bolometer's thermal time constant

$$\tau_{th} = C / G$$

and the time constant introduced by the resonant circuit bandwidth

$$\tau_{LCR} = 2\frac{L}{R_{bolo}}$$



introduce poles and phase shifts into the electrothermal feedback loop.

For a given selectivity ($\Rightarrow$ channel spacing), the bolometer time constant must be sufficiently large to maintain feedback stability.

The bolometer time constant was increased by introducing additional mass (increase C). Thermal interfaces introduced additional time constants! Solved in refined design.

Primary challenge: Convincing detector designers that electronics cannot solve all problems and that detectors must be tailored to the readout.

SQUID Feedback Amplifier

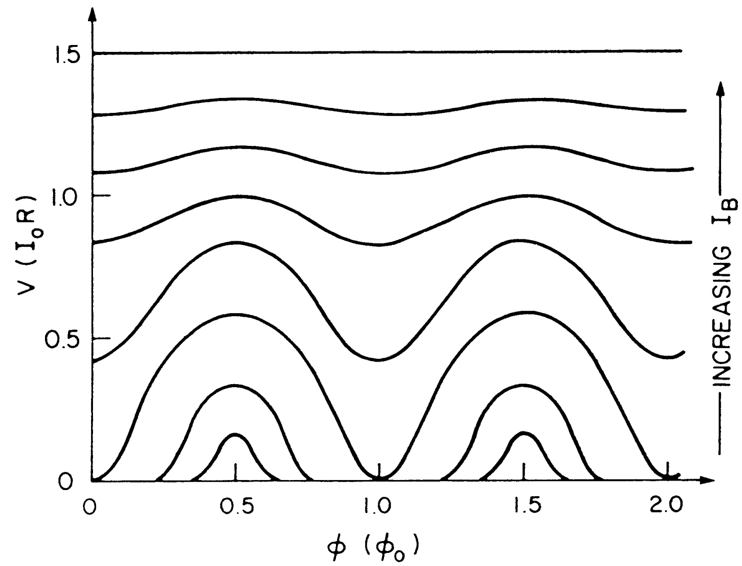
1. SQUIDs have periodic output

    Maximum signals must remain within monotonic range

    Dynamic range extended by

        SQUID array (100 SQUIDs in series) (allows small input inductance)

        Shunt feedback



2. Feedback must be active to maximum bias frequency (~MHz)

    ⇒ High loop gain-bandwidth product of 10s of MHz required

    ⇒ Limits wiring length to maintain phase margin for stability

3. In-situ characterization of individual SQUIDs required to determine operating point.

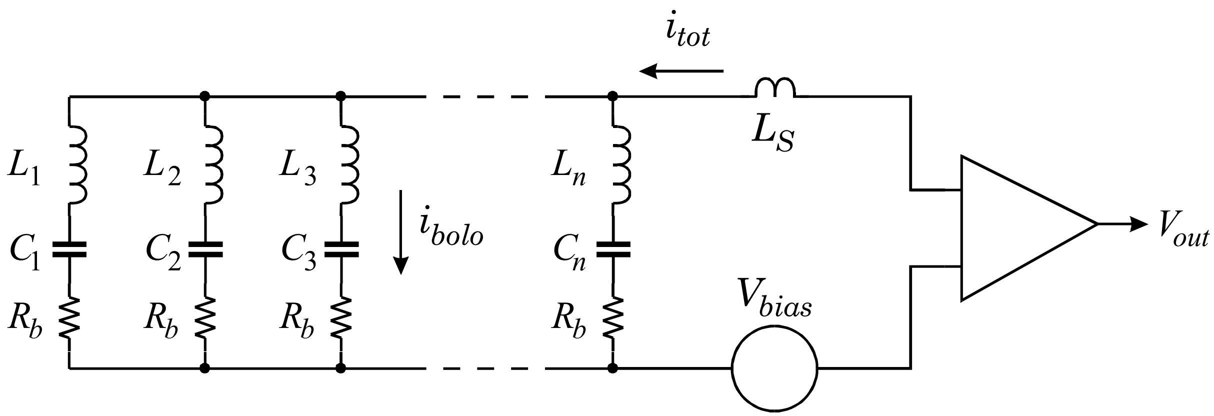
    ⇒ Digitally controlled bias scan and bias point

4. SQUIDs extremely sensitive to high-frequency RF pickup

    ⇒ Digital crosstalk big problem as wide bandwidth connections are required to maintain phase shift in feedback loop.

Parasitic Inductances and Capacitances

1. Series inductance in the wiring between the MUX and the SQUID

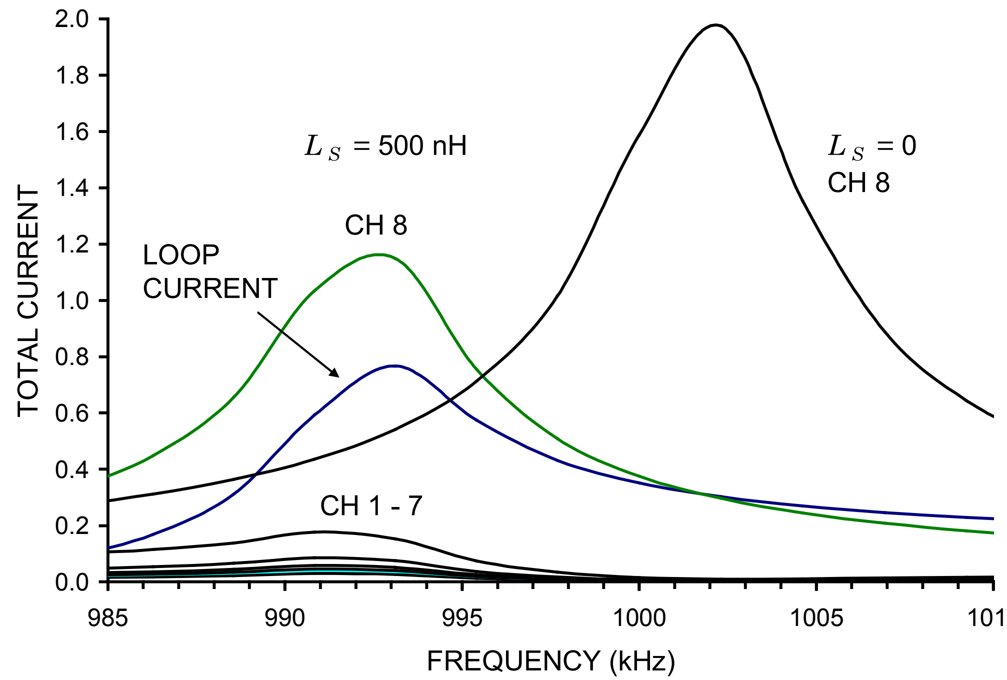


Series inductance introduces shift in current maximum between input loop i_{tot} and bolometer current.

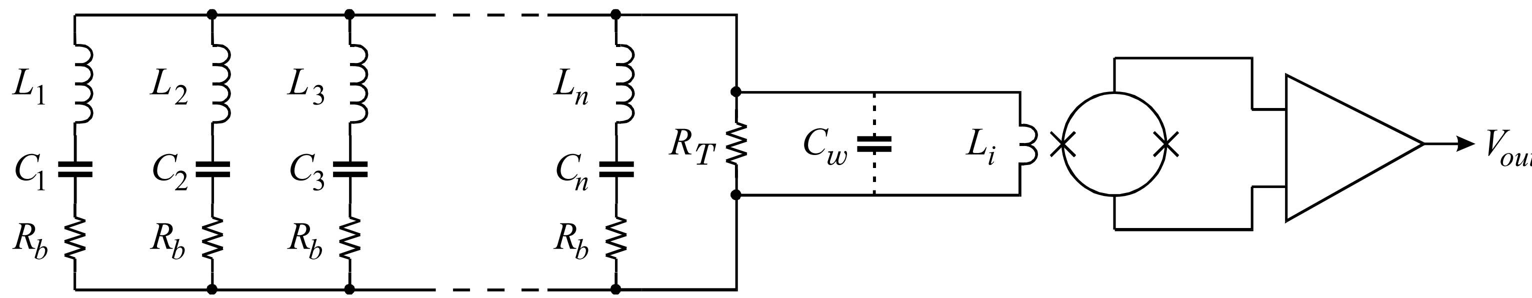
Special tuning procedure required:

Network analysis $\Rightarrow$
Calculate freq offset

Series inductance also increases bias source impedance and reduces electrothermal loop gain.



2. Resonance formed by SQUID input inductance and wiring capacitance



Low-inductance wiring increases capacitance. Compromise required.

$\Rightarrow$ Resonance well within feedback loop gain-bandwidth product.

$\Rightarrow$ Damp resonance by termination resistor R_T.

3. Parasitic Resonances

1. Additional resonances due to distributed capacitance of spiral inductors in MUX circuit. (10 – 20 MHz)

2. Multiple series resonant circuits connected in parallel also form parallel resonances.

   When a bolometer goes superconducting, the associated parallel resonance assumes such a high Q that the resonant impedance and phase shift lead to self-oscillation at a frequency close to the series resonance.

   $\Rightarrow$ Requires

   - uniformity of superconducting transition temperatures
   - stable control of bias levels

Parasitic resonances lead to self-oscillation because SQUIDs require a high bandwidth feedback loop to

- extend SQUID's maximum signal capability over full range of bias frequencies,
- reduce SQUID's non-linearity over full range of bias frequencies (intermodulation of bias carriers generates spurious signals)

Alternatives to SQUIDs

- Suppression of RF pickup/digital crosstalk to SQUID major challenge in prototyping
- Regular retuning required (added electronic functions required)
- Changes in temperature cause significant changes in SQUID characteristics
- Limited signal capability requires feedback at MUX frequencies (~MHz) well beyond signal bandwidth (~kHz)
- Eliminating SQUIDs would greatly simplify design and operation

Assessment of amplifier noise temperature points towards alternatives

The noise temperature is the temperature for which the thermal noise of the source resistance is equal to the amplifier noise.

$$T_N = \frac{e_n i_n}{2k},$$

where e_n and i_n are the amplifier's input voltage and current noise densities

1. SQUIDs

The noise temperature of optimized SQUIDs in the He temperature range is typically

$$T_N \approx \frac{f}{10^8 \ \text{[Hz/K]}}$$

so at 1 MHz $T_N \approx$ 10 mK.

2. Bipolar Transistor

$$T_N = \frac{T}{\sqrt{\beta_{DC}}}$$

excludes room temperature operation

BJTs not functional at required temperature

3. JFETs and MOSFETs

At the relevant temperatures the channel noise capacitively coupled to the gate dominates the input current noise.

$$T_N \approx T\omega \frac{g_m}{I_D} \frac{L^2}{\mu}$$

MOSFETs provide

1. Low temperature operation (T = 4K)
2. High g_m / I_D
3. Small channel lengths L

Practical MOSFETs should provide $T_N <$ 50 mK at 1 MHz and room temperature.

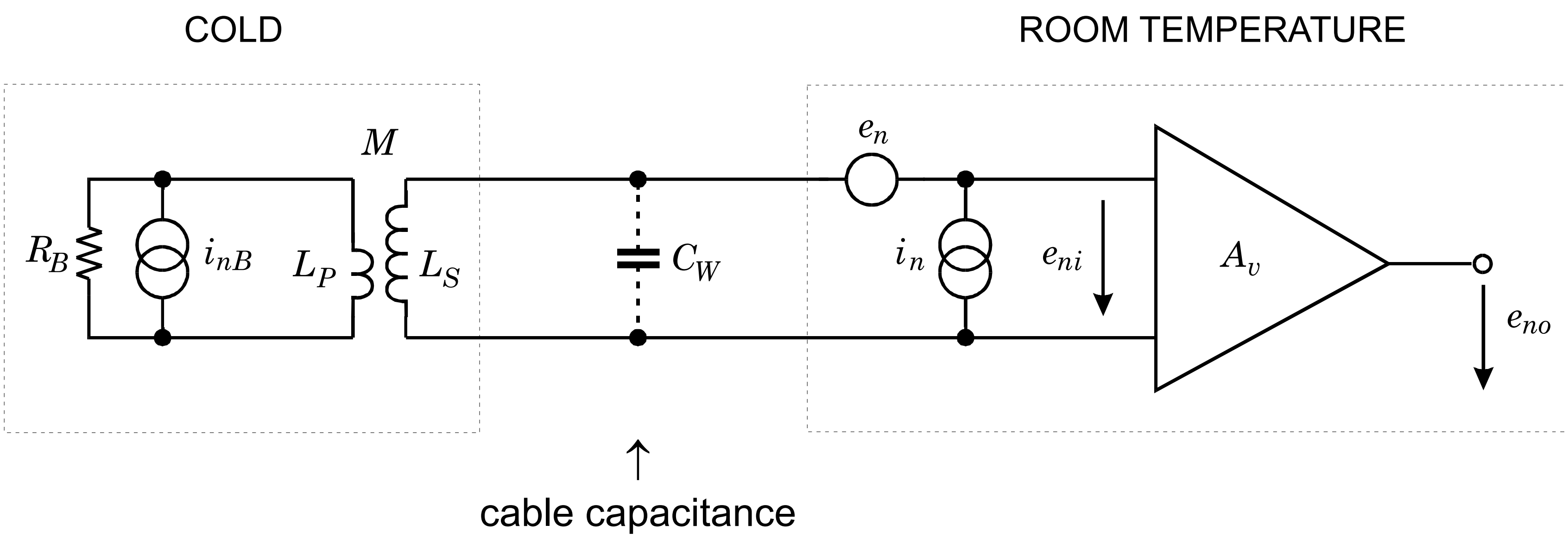
However ...

MOSFET noise matching requires high source resistance (voltage signal)

$\Rightarrow$ Input transformer required

Would this configuration work?

Superconducting transformer on 4K stage to reduce wire resistance (thermal noise).



Bolometer noise at transformer secondary: $e_{niB} = \mathbf{i}\omega M i_{nB}$

Must override amplifier noise voltage $e_{niB} > e_n$, so $M > \dfrac{e_n}{\omega i_{nB}}$

Typical values: $\omega = 10^7$

$e_n = 1\ \mathrm{nV}/\sqrt{\mathrm{Hz}}$

$i_{nB} = 10\ \mathrm{pA}/\sqrt{\mathrm{Hz}}$ $\qquad M > 10\ \mu\mathrm{H}$

Primary impedance $X_P = \omega L_P$ must be much smaller (<10%) than the bolometer resistance to maintain voltage bias.

$R_B = 1\ \Omega$ $\Rightarrow$ primary inductance $L_P \leq 10$ nH

Since $M = \sqrt{L_P L_S}$, secondary inductance $L_S > 10$ mH

Maximum frequency is limited by the resonance formed by wiring capacitance and L_S.

Assume wiring capacitance of 25 pF (50 cm from 0.25K to 300K): resonance at 300 kHz

Increase frequency $\omega = 10^8$ $\Rightarrow$ primary inductance $L_P \leq 1$ nH

$M > 1\ \mu\mathrm{H}$ secondary inductance $L_S > 1$ mH

mH inductors not compatible with monolithic integration (spiral inductors)
+ self-resonances in MHz regime.

Initial Summary

Increasing frequency reduces transformer size

Reduce capacitance at transformer secondary

$\Rightarrow$ place transformer adjacent to amplifier

$\Rightarrow$ capacitance set by amplifier (MOSFET) input capacitance

$\Rightarrow$ Superconducting transformer to reduce resistance (thermal noise)

$\Rightarrow$ Transformer and MOSFET at 4K

Practical monolithic transformers: Spiral inductors with $L_S < 100\ \mu\text{H}$

Desirable to reduce required secondary inductance to increase resonant freq.

Mutual inductance can be maintained by increasing primary inductance.

$$M = \sqrt{L_P L_S}$$

Can constant voltage bias be maintained with

transformer's primary impedance > bolometer resistance?

External Electrothermal Feedback

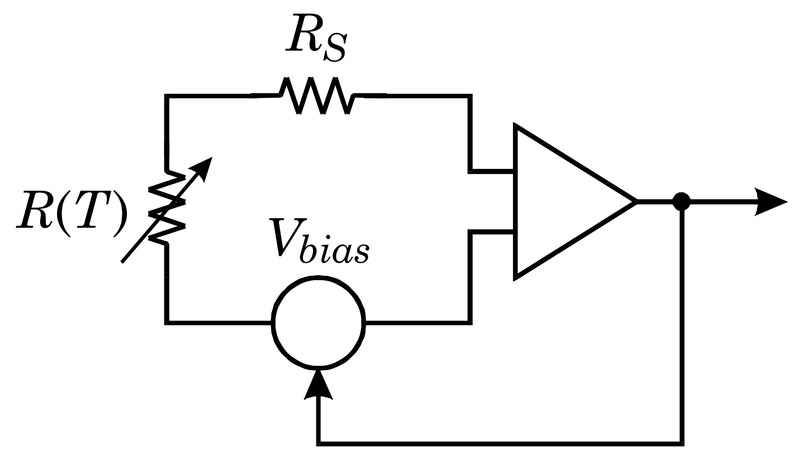
For constant voltage bias the change in temperature vs. signal power

$$\frac{\Delta T}{\Delta P_S} = \frac{\dfrac{1}{G + \mathbf{i}\omega C}}{1 - \dfrac{V^2}{G + \mathbf{i}\omega C}\dfrac{dG_B}{dT}} = \frac{A_0}{1 - A_L}$$

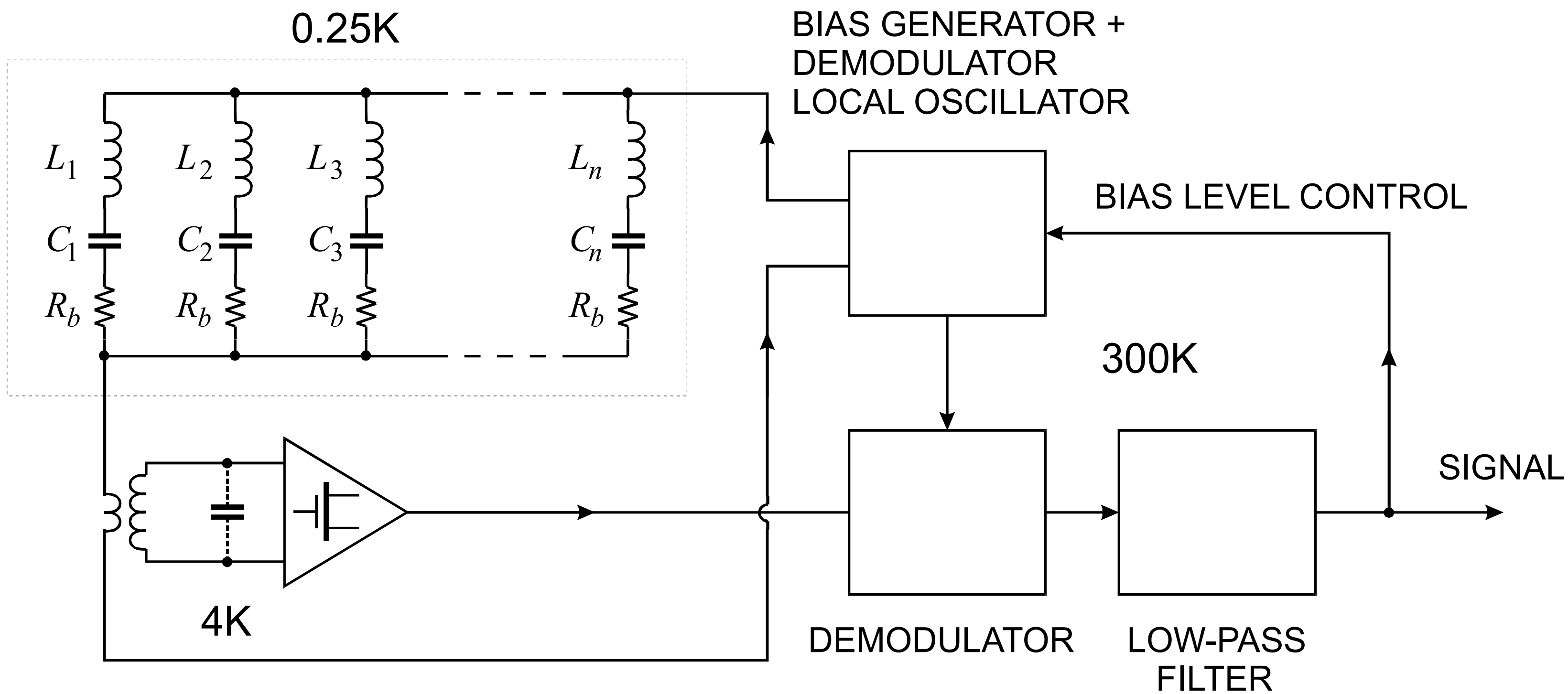
as in a feedback amplifier ($A_0 =$ amplifier open loop gain, $A_L =$ loop gain).

Instead of controlling the bolometer's heat flow only by the thermal link, the bias power can be electronically controlled.

Even with a significant series resistance in the bias loop, this allows adjustment of the bias to maintain constant voltage across the bolometer.



Implementation in digital demodulator



The low-pass filter suppresses components from the neighbor channels.

It adds a pole in addition to the LC filter in each bolometer leg, so its cutoff must be sufficiently high.

This places an additional limit on the channel spacing, but higher bias frequencies increase frequency range for MUXing.

Summary

- Large-scale microcalorimeter arrays increase efficiency and rate capability.
- Monolithic integration and cryogenic multiplexing make this practical.
- Robust readout systems essential – eliminate SQUIDs.
- External electrothermal feedback loop allows practical monolithically integrated transformers.
- MOSFETs on high-resistivity silicon fabricated at LBNL have demonstrated improved noise and low power at 4K.
- In contrast to SQUIDs, MOSFETs provide reproducible operation with well-controlled operating points.
- Operation in 10 – 30 MHz regime reduces size of inductors and capacitors.
- Detailed simulations indicate that this could indeed work.
- Systems must be designed as a whole, not detectors and readout separately!