Ideal Integrating Bolometer

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We describe a new "ideal integrator" bolometer as a prototype for a new generation of sensitive, flexible far-IR detectors suitable for use in large arrays. The combination of a non-dissipative sensor coupled with a fast heat switch provides breakthrough capabilities in both sensitivity and operation. The bolometer temperature varies linearly with the integrated infrared power incident on the detector, and may be sampled intermittently without loss of information between samples. The sample speed and consequent dynamic range depend only on the heat switch reset cycle and can be selected in software. Between samples, the device acts as an ideal integrator with noise significantly lower than resistive bolometers. Since there is no loss of information between samples, the device is well-suited for large arrays. A single SQUID readout could process an entire column of detectors, greatly reducing the complexity, power requirements, and cost of readout electronics for large pixel arrays.

1. Introduction

A bolometer consists of a thermometer with heat capacity C mounted on an absorbing substrate, weakly coupled to a bath at temperature T_0 via a thermal conductance G (Figure 1). Resistive bolometers (including both composite and transition-edge bolometers) use the temperature dependence of a resistive element to measure the infrared signal incident on the absorber. In steady-state operation, the thermometer heats up until the dissipated power matches the power conducted through the thermal link to the bath,

$$\Delta T_{dc} = \frac{P_{elec} + P_{IR}}{G}, \qquad (1)$$

where P_{elec} and P_{IR} represent the electrical and infrared power, respectively. Larger temperature excursions — a larger signal — can be achieved by reducing the conductivity G of the bolometer to the bath. To mitigate low-frequency (1/f) noise, though, the infrared signal must be modulated at some frequency ω. The synchronous temperature change then becomes

$$\Delta T_{ac} = \frac{\Delta P_{IR}}{G\sqrt{1+\omega^2\tau^2}}, \qquad (2)$$

where $\tau = C/G$ is the time constant of the device. Equation 2 is equivalent to the dc response convolved with a low-pass filter and illustrates a fundamental limitation of resistive devices: the conductance G can not be lowered arbitrarily to increase the dc response without forcing the time constant τ to unacceptably large values. For fixed

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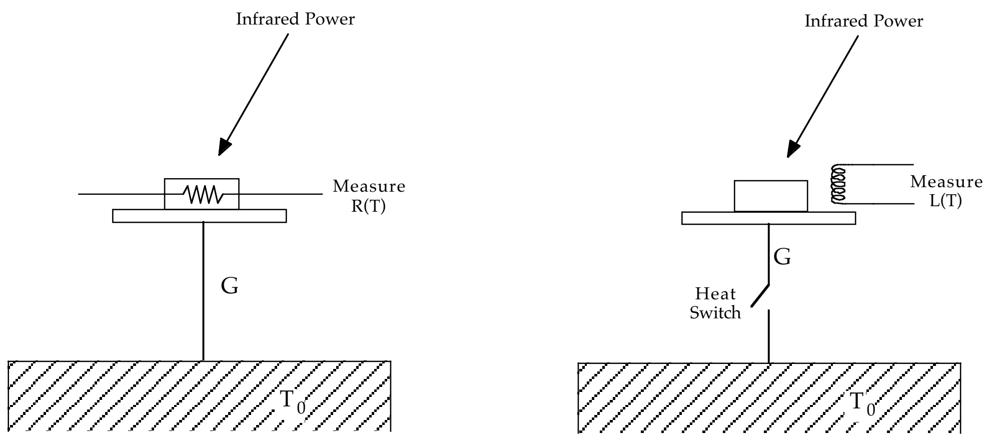
chopping frequency ω, the sensitivity reaches a plateau at $G \approx C\omega$ beyond which further reductions in G bring little improvement.



We have developed a new bolometer concept using a non-dissipative thermometer coupled with a heat switch to break the link between thermal conductance and performance. Penetration-depth thermometers use inductive coupling to measure the temperature of a thin superconducting film without dissipating heat into the system. Temperature changes in the bolometer thus depend *solely* on the integrated infrared power incident on the absorber. The bolometer time constant can then be made arbitrarily long, allowing the device to function as an ideal (lossless) integrator. A heat switch periodically increases the conductance G by a factor of 10^4 or more during short "reset" intervals. This forces the bolometer to the bath temperature on time scales short compared to the intrinsic time constant, reducing effects of 1/f noise and thermal drifts on time scales longer than the period between successive resets.

2. Integrating Bolometer

Figure 1 shows a schematic of the ideal integrating bolometer. It consists of a non-dissipative thermometer on an absorbing substrate, weakly coupled to a thermal bath through a heat switch with conductance ratio

$$\gamma = G_{on}/G_{off} \; . \tag{3}$$

The combination of a non-dissipative sensor with a resettable heat switch breaks the link between conductance and sensitivity that limits resistive bolometers. In the "on" state the conductance is high and the thermometer quickly cools to the bath temperature. In the "off" state the conductance is minimal and the thermometer heats as

$$\frac{dT}{dt} = \frac{P_{IR} - G(T - T_0)}{C} \approx \frac{P_{IR}}{C} \tag{4}$$

Fig 1: Schematic of resistive bolometer (left) and integrating bolometer (right). The integrating bolometer uses a heat switch and non-dissipative thermometer to provide greatly increased sensitivity and lossless integration.

Provided $G\Delta T \ll P_{IR}$, the bolometer responds as an ideal integrator, with temperature change linearly dependent on the integrated infrared power incident on the absorber.

Penetration-depth thermometers are an attractive technology for the lossless thermometer. They use the temperature dependence of the (partial) screening of an external magnetic field by a thin superconducting film to monitor the temperature of the film without dissipative losses or electrical contacts. The Meissner effect in a superconductor generates surface screening currents to block an external magnetic field; the simple case of a bulk superconductor in a parallel magnetic field B_0 leads to an internal field

$$B(x) = B_0 \exp(-x/\lambda) \qquad (5)$$

where λ is the characteristic penetration depth for the field. Near the superconducting transition, the penetration depth has a strong temperature dependence

$$\lambda(T) = \lambda_0 \left[1 - \left(\frac{T}{T_c} \right)^4 \right]^{-1/2} \qquad (6)$$

where T_c is the transition temperature and $\lambda_0 \approx$ 5-20 nm is the penetration depth at T=0. For film thickness $d \sim \lambda_0$, the screening is incomplete and the attenuated magnetic field tracks the thermal dependence of the penetration depth.

Use of a non-dissipative thermometer allows the bolometer to operate as an ideal integrator, with temperature change linearly dependent on the integrated infrared power. The bolometer stays in the linear regime provided that $G\Delta T \ll P_{IR}$ and the integration time Δt is short compared to the time constant $\tau = C / G$. Both of these require small conductance, and hence a long time constant. We recover device speed and avoid unwanted 1/f contributions by using a heat switch to link the absorbing substrate to the bath. The switch effectively produces two time constants: a long time constant in the "off" state while integrating the sky signal, and a short time constant in the "on" state to reset the device to the bath temperature.

The simplest choice for a heat switch uses a thin metal strip toggled between its superconducting and normal states. At temperatures well below the superconducting transition, all conduction electrons are paired and the superconductor has small thermal conductivity. Applying a magnetic field drives the superconductor to its normal state, greatly increasing the thermal conductivity. Conduction ratios $\gamma > 10^4$ can be achieved using aluminum near 100 mK (Mueller 1978).

A superconducting heat switch requires a magnetic field large enough to drive the switch to the normal state, without interfering with the thin film fields nearby. We achieve this by sandwiching a thin aluminum film between niobium layers deposited on one support leg of the bolometer. The top and bottom niobium layers form a continuous circuit, generating an appreciable field within the aluminum strip between them, but cancelling at distances large compared to the 0.4 μm separation of the sandwich. A current 5 mA or less through 10 μm wide niobium strips will generate the 10^{-2} Tesla critical field needed to force the aluminum to the normal state, falling below 10^{-9} Tesla at the penetration depth pickup coil. Since the niobium legs are deposited on top of each other, the fringe field at the coil is primarily parallel to the chip surface and will not affect the perpendicular component sensed by the bolometer. Measurements of cross-talk on a test switch agree well with calculations, providing assurance that cross-talk between the heat switch and the pickup coil will not limit the performance of the bolometer. The niobium remains in the superconducting state throughout the entire reset cycle, adding negligibly to the total thermal conductance. The inductance of the switch is small ($L < 1$ nH), allowing rapid toggling.

The integrating bolometer has a relatively simple readout. A persistent current stored in a superconducting drive coil generates an external field through the thin-film thermometer. As the film temperature changes, the inductance of the coil-film system changes. To conserve flux through the superconducting coil, the coil current changes and can be measured with a SQUID. Figure 2 shows a typical sampling sequence. When the switch is opened, the incident radiation begins to heat the bolometer. A readout SQUID measures the current in the pickup coil, then returns a time Δt later to re-sample the current (using the intervening time to sample other pixels in the array). The difference in measured currents yields the integrated power incident on the detector in the time Δt between samples. After the second sample, we close the heat switch to reset the device. Note that the measured signal depends only on the difference in sampled currents between successive readouts — the technique does not require the bolometer to return to precisely the same temperature each cycle, and is insensitive to drifts on time scales long

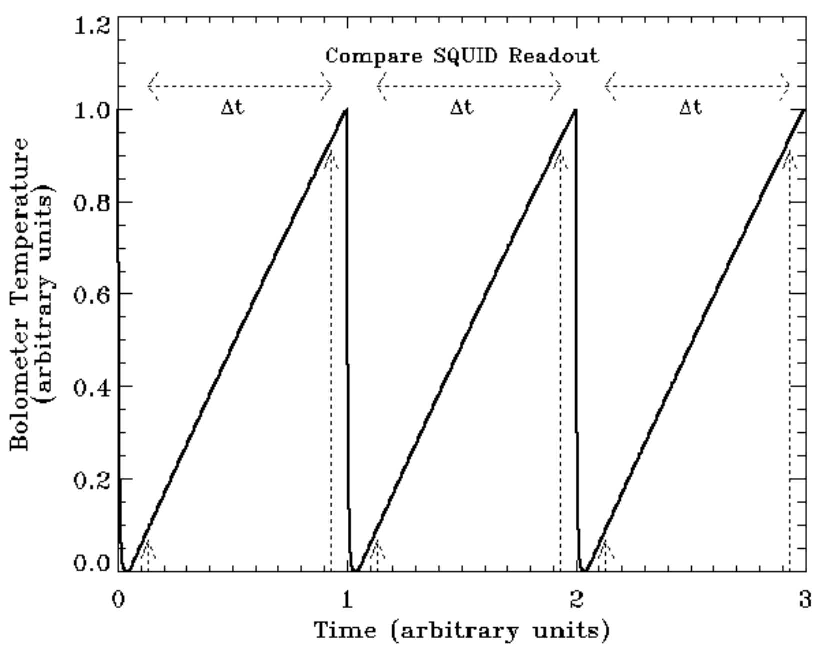


Figure 2: Three successive readout cycles for an integrating bolometer. A SQUID samples the temperature-dependent current after the heat switch opens, then again a time Δt later. The change in current depends on the integrated power absorbed by the detector. After the second sample, the heat switch closes to reset the device.

compared to the reset period Δt.

Figure 3 shows a schematic view of a prototype bolometer developed at GSFC. It consists of a 1 mm × 1 mm silicon nitride membrane 0.5 μm thick, suspended by four silicon nitride legs for low thermal conductance. A Mo-Au film 60 nm thick on the back side of the membrane provides the superconducting film, with a 25-turn niobium pickup coil on the front side. To ensure accurate alignment, the superconducting film and pickup coil are deposited on opposite sides of the same membrane. Niobium leads for the pickup coil occupy two of the four legs, while the niobium-aluminum heat switch ``sandwich'' occupies a third. A thin bismuth film on the membrane provides impedance matching for greater far-IR absorption. The niobium leads for the heat switch make electrical contact with the bismuth film; a final heater lead on the fourth leg allows a bias current to pass through the bismuth film, providing an additional source of heat for calibration and test purposes. The prototype bolometer is optimized for operation at 300 mK; greater sensitivity can be achieved by lowering the temperature to 50 mK.

3. Sensitivity

The sensitivity of a bolometer is described by the noise equivalent power (NEP), the incident infrared power required to produce the minimum detectable signal (see, e.g., Mather 1984 and references therein). The integrating bolometer has several advantages over resistive bolometers. Since it has no dissipative elements, the Johnson noise term vanishes. The heat switch cycle produces an effective response time Δt much smaller than the intrinsic time constant τ, resulting in reduced phonon noise. To see this, consider the spectral density of random thermal fluctuations ΔT within the absorber,

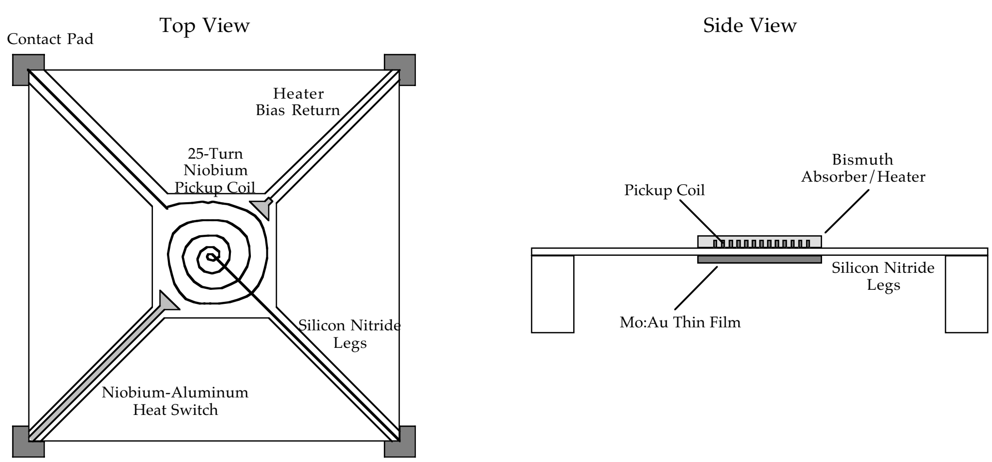


Fig 3: Design for prototype chip built at GSFC. The pickup coil and superconducting film are deposited on opposite sides of a silicon nitride membrane suspended by four legs. The niobium-aluminum heat switch occupies one leg, leads for the pickup coil are on two other legs, while the fourth leg provides a return for the heater current passed through the heat switch leads and bismuth absorber.

$$\tilde{T}(\omega)\,\tilde{T}^*(\omega) = \frac{4\tau kT^2}{C(1+4\pi^2\tau^2\omega^2)}, \tag{6}$$

where $\tilde{T}$ is the Fourier transform of the temperature and * represents complex conjugation (Day et al. 1997). The temperature variance is simply the integral of spectral density over frequency,

$$\left\langle (\Delta T)^2 \right\rangle = \frac{4\tau kT^2}{C}\int_0^\infty \frac{d\omega}{1+4\pi^2\tau^2\omega^2}. \tag{7}$$

The heat-switched bolometer cannot respond to fluctuations on time scales longer than the reset period Δt, imposing a low-frequency cutoff on the integral. With this cutoff, the variance becomes

$$\left\langle (\Delta T)^2 \right\rangle = \frac{kT^2}{C}\frac{2}{\pi}\left(\frac{\pi}{2} - \arctan\frac{2\pi\tau}{\Delta t}\right) \approx 0.1\frac{\Delta t}{\tau}\frac{kT^2}{C}, \tag{8}$$

or

$$\mathrm{NEP}_{\mathrm{phonon}} = \sqrt{0.1\frac{\Delta t}{\tau}4kT^2G}\,. \tag{9}$$

A non-dissipative, heat-switched bolometer is more than an order of magnitude more sensitive than a resistive bolometer. This can be understood intuitively. An unswitched bolometer can have only one statistically independent sample per time interval τ. Activating the heat switch shortens the time constant by a factor $\gamma > 10^4$; hence, the

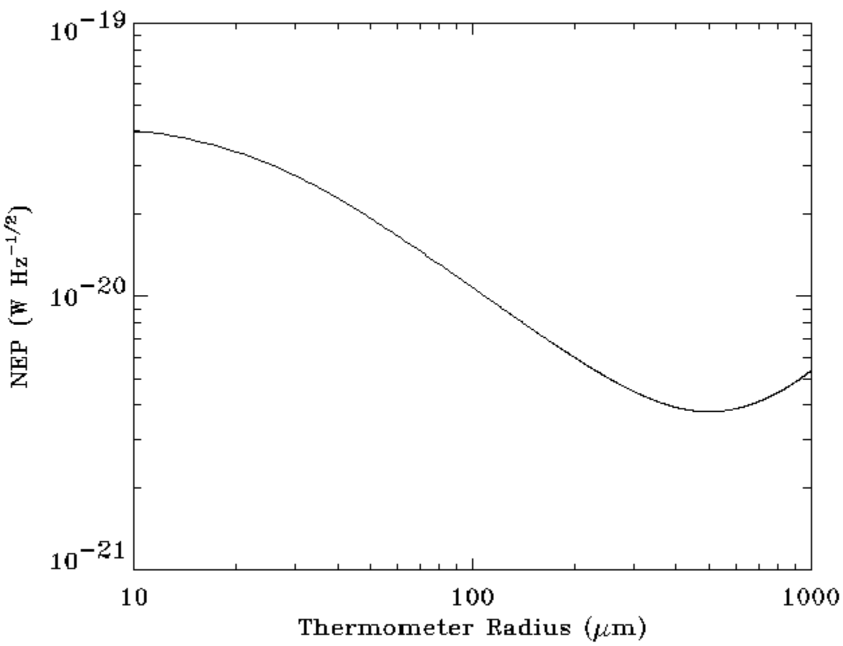


Fig 4: Predicted NEP vs sensor size for ideal integrating bolometer at 50 mK. Phonon noise dominates at small sizes, and SQUID noise for large sizes. A heat switch period Δt = 0.1 ms is shown.

sample taken after the heat switch is turned off again is statistically independent of previous samples. Using a heat switch allows us to acquire $N = \tau/\Delta t$ more samples in a fixed time interval. Since the variance in the mean of N samples scales as 1/N, we thus reduce the phonon noise by a factor $\sqrt{\Delta t/\tau}$. An NEP well below 10^{-20} W $\mathrm{Hz}^{-1/2}$ appears achievable.

Two-stage SQUIDs have typical flux noise below $10^{-6}\ \Phi_0\ \mathrm{Hz}^{-1/2}$ (100 times the quantum limit), with 1/f knee well below the 2 kHz sampling rate of the detector. The amplifier and phonon noise terms scale differently with physical device size. For fixed heat switch period, the phonon noise of an integrating bolometer scales as R^{-2} from the dependence of the cutoff term on the heat capacity C (assuming film thickness independent of radius). The flux resolution of the thermometer scales as R while the heat capacity scales as R^2; hence the amplifier noise ~ C/Φ scales as R. For a device operated at 50 mK, the NEP reaches a minimum below 10^{-20} W $\mathrm{Hz}^{-1/2}$ for sensor size 1 mm to 100 μm (Fig 3), a range easily achieved by photolithographic techniques.

The integrating bolometer has several advantages over resistive devices. The heat switch allows the conductivity to be optimized for sensitivity without sacrificing device speed. The lossless thermometer allows the bolometer to operate as an ideal integrator between resets. The device speed, data rate, and dynamic range depend on the period between heat switch resets and can be changed in real time. *Signal information is derived solely by differencing "snapshot" current measurements, without requiring continuous monitoring throughout the integration period.* A single readout circuit can thus service multiple devices, reducing the complexity, cost, and power consumption of the readout electronics.

References

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