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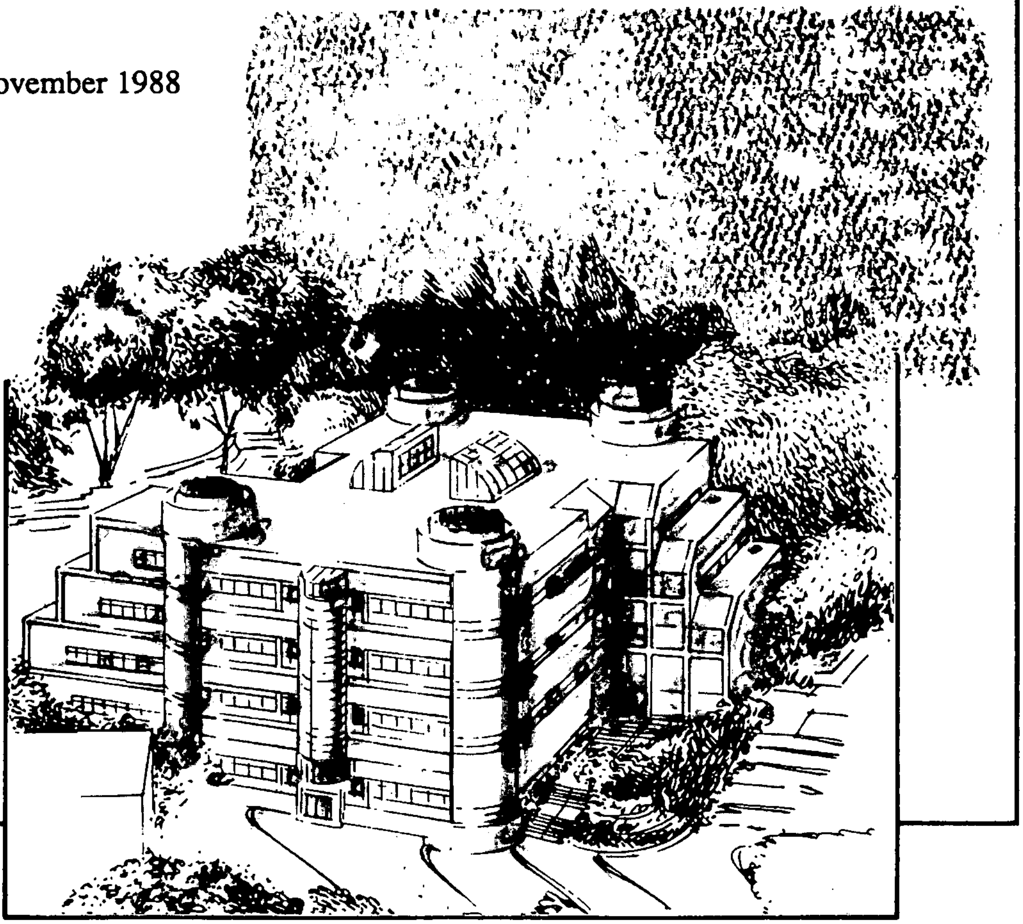

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We have developed a bolometer readout circuit which dramatically improves the low frequency stability of bolometric detectors. In astronomical applications, the readout allows for qualitatively different observation modes (e.g. staring or slow drift scanning) which are particularly well suited for space observations and for the use of arrays. In many applications the new readout can also increase sensitivity. We present noise spectra for ^{4}He temperature bolometers with no excess noise at frequencies greater than 0.1 Hz. The optical responsivity of a bolometer operated with the new readout is measured to be the same as that of the bolometer operated with a conventional readout.

Introduction

Bolometric detectors are widely used in applications ranging from microcalorimetry [1] to infrared astronomy [2]. Bolometer theory has been treated in detail in the literature [3,4]; here we discuss only the relevant results.

A bolometer consists of an absorber which converts the incident signal into heat, a thermometer (typically a thermistor), and a weak thermal coupling to a heat sink at temperature T_0 (Fig. 1). The performance of the bolometer is determined by the absorption efficiency of the absorber, the heat capacity of the detector (C), the thermal conductivity of the thermal link (G), and the sensitivity of the thermistor. Typical thermistor materials are doped semiconductors such as gallium doped germanium (Ge:Ga) [5]. The low temperature conductivity for semiconductors with doping densities in the range of typical bolometer materials (10^{15} dopants/cm^3) is dominated by hopping conductivity, which leads to a temperature dependent resistance of the form [6]

$$R(T) = R_0 \exp[(\Delta/T)^s] \qquad (1)$$

where R_0 and Δ are constants which depend on the doping density and $1/4 \leq s \leq 1$, depending on the temperature range of interest and the doping density. We fit R(T) for our ^{4}He temperature Ge:Ga thermistors using $s = 1/2$. The sensitivity of the thermistor is characterized by $\alpha = d\ln R/dT$; for our thermistors $\alpha \sim \Delta^{1/2}T^{-3/2}$.

The sensitivity of the bolometer can be described in terms of the noise equivalent power (NEP), which is the power incident on the detector that produces a signal to noise ratio of unity in a one hertz bandwidth. There are four contributions to the NEP, which add in quadrature [4]:

$$(NEP)^2 = (NEP)^2_{photon} + 4kT^2G + 4kTR(Z+R)^2/4R^2S^2 + (NEP)^2_{excess} \qquad (2)$$

where R is the resistance, Z is the dynamic resistance dV/dI, and S is the voltage responsivity. The first term, due to random arrival of photons, is the ultimate limit we would like to reach in detector development. The second and third terms, statistical fluctuations in the energy transport through the thermal link and Johnson noise in the thermistor, are fundamental noise sources which are a function of the bolometer characteristics and the operating temperature. The final term includes contact noise, amplifier noise and other sources of excess noise. The main form of excess noise we will be concerned with is amplifier noise.

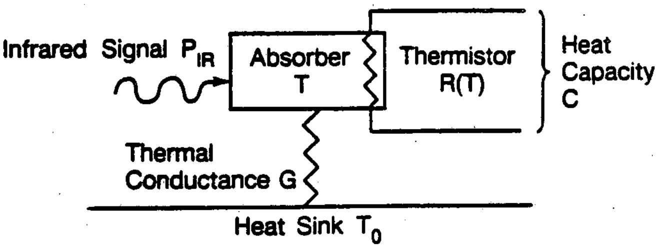

Figure 1. Bolometer thermal circuit.

For semiconductor thermistor bolometers operated at 300 mK and at frequencies greater than 5 Hz, the contribution to the NEP from a good junction field effect transistor (JFET) amplifier is small in comparison to the fundamental noise sources. At frequencies less than 3-5 Hz, however, generation-recombination noise in the JFET causes significantly worse amplifier performance [7]. In order to prevent amplifier noise from dominating the NEP, the signal of interest must appear at frequencies greater than 3 Hz. In infrared astronomy, this is usually accomplished by modulating the optical signal using a mechanical device such as a wobbling mirror or shutter.

For a semiconductor thermistor with an electrical bias power chosen to minimize the NEP, the phonon and Johnson noise contributions to the NEP are roughly equal. In this case we can approximate the electrical NEP (the optical NEP without the phonon noise term) as

$$(\mathrm{NEP})_E^2 = 2(4kT^2C/\tau) + (\mathrm{NEP})^2_{\mathrm{excess}} \qquad (3)$$

where we have rewritten the thermal conductivity G in terms of the thermal time constant $\tau = C/G$. Decreasing G, and hence increasing τ, decreases the bolometer NEP. The minimum value of G is determined by the requirement that τ be less than or similar to the optical modulation period which, in the absence of observational constraints, is determined by the necessity of avoiding 1/f noise. In this case, the ultimate sensitivity of the bolometer could be improved by eliminating 1/f noise and employing slower optical signal modulation.

Bolometer Bridge Circuit

The use of bridge circuits in measurements with extreme stability requirements has a long tradition in experimental physics [8]. Bridge techniques have not, however, been applied to infrared bolometric detectors. We have developed a bridge readout for bolometers (Fig. 2) which dramatically reduces 1/f noise. Instead of relying on modulation of the incident optical signal, the bridge circuit uses an ac bias voltage to modulate the detector signal.

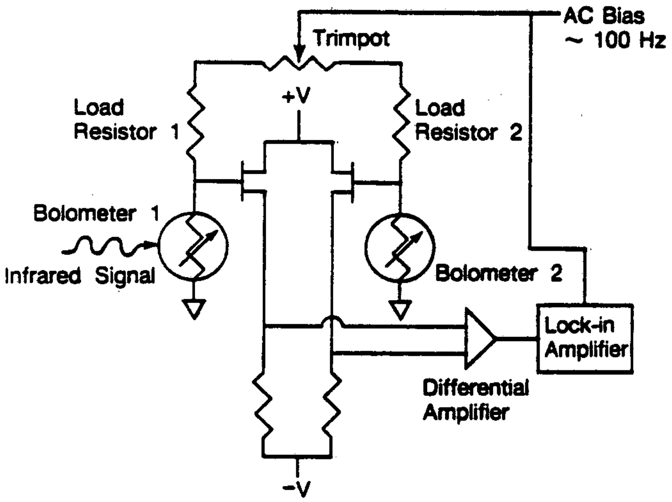

Figure 2. Bolometer bridge circuit. The two bolometers are biased with an ac voltage to provide a modulated signal for amplification. Infrared power is incident on bolometer 1. The signals from the bolometers are buffered by matched JFET source followers. The differential amplifier removes the common mode signal, and the lock-in amplifier returns a dc voltage proportional to the difference in resistance of the bolometers, which is proportional to the infrared power.

The ac bias used in the bridge circuit can take two forms: (1) a sinusoidal voltage at a frequency much higher than the bolometer thermal rolloff frequency ($\omega_{\mathrm{bolo}} = 1/2\tau$) such that the bolometer cannot thermally follow the varying power, or (2) a square wave voltage symmetric about ground such that the electrical power across the bolometer is constant. In either case, the response of the bolometer is equivalent to a bolometer with a dc bias power equal to the average power of the ac bias. The bolometer signals are buffered by JFET source followers and the common mode signal is removed by a differential amplifier. A lock-in amplifier provides phase sensitive detection, producing a dc output voltage proportional to the difference in resistance of the two bolometers. When one of the bolometers is illuminated by an infrared signal, as shown in Fig. 2, the circuit produces a dc output voltage proportional to the infrared power. Alternatively, both bolometers may be illuminated, in which case the output voltage is proportional to the difference of the power incident on the two bolometers.

Because the bolometer time constant can be long compared to the ac bias frequency, significant gains in sensitivity are possible. The maximum value of τ, and hence the smallest NEP, are now determined purely by observational constraints. The noise from the two bolometers is uncorrelated, and thus adds in quadrature. For matched bolometers the spectral noise density at the lock-in output is

$$S_n = 2(4kTR) + 2(4kT^2GS^2) = 4(4kTR) . \qquad (4)$$

There is a factor of $2^{1/2}$ increase in noise level with respect to a conventionally coupled bolometer because we measure the difference signal of two bolometers. In any real observation this degradation in performance is offset by the increased modulation efficiency, which is 100% as opposed to $\leq$ 50% for conventional optical modulation schemes. Excess 1/f noise from the amplifiers and 1/f drifts in the JFET offset are eliminated by the phase sensitive detection. Low frequency current noise is eliminated provided that the noise is additive. With perfectly matched bolometers, noise due to 1/f cold plate temperature fluctuations and bias voltage fluctuations is also eliminated since each bolometer will respond identically to these system drifts. The only source of excess low frequency noise that can couple through the system is a differential change in the resistivities of the two thermistors.

In practice, the bolometers will not be perfectly matched. The germanium thermistors will be of different sizes and doping densities, so that the Δ and R_0 parameters used to describe the bolometer R(T) (equation 1) will be different. In addition, the length of the electrical leads will vary, which results in a mismatch in thermal conductivity. Each of these mismatches can couple low frequency system drifts into the circuit, producing an unstable output.

Three sources of excess noise which can be coupled into the bridge circuit by bolometer mismatches are cold plate temperature fluctuations, bias voltage fluctuations and fluctuations on the background optical power in the case where both bolometers are illuminated. We can adjust the bridge operating point by (1) adjusting the impedance of the bolometer load resistors, (2) adjusting the dc power on the bolometers, and (3) independently controlling the base temperature of each bolometer. Using these adjustments we can minimize the circuit sensitivity to the various system drifts mentioned above. Cold plate temperature fluctuations place the most serious requirements on bolometer matching; thus we would like to adjust the bridge to an operating point such that the sensitivity to temperature fluctuations is zero to first order ($dV_{\mathrm{out}}/dT = 0$). Given this condition, we can calculate how closely matched the bolometers must be in order to make the excess noise due to temperature fluctuations small in comparison with Johnson and phonon noise.

Table 1 gives the requirements on the matching of Δ, R_0 and G for a ^{3}He temperature bolometer with thermistor sensitivity $\alpha = 25$, assuming a flat spectrum of temperature fluctuations with amplitude 1 mK/Hz$^{1/2}$. In this example the $dV_{out}/dT = 0$ condition is achieved by adjusting the load resistor impedances. The NEP of the bolometer is 2×10^{-17} W/Hz$^{1/2}$. The requirements on bolometer matching scale approximately as α^{-1}.

TABLE I. Required Matching of Two Bolometers in the Bridge Circuit.

MAXIMUM ALLOWED PARAMETER MISMATCH*
(for 1 mK/√Hz temperature fluctuations)

Δ	R_0	G
2%	20%	15%

*Calculated for semiconductor thermistor bolometers with α=25 operated at 300 mK. Bolometer bias set to minimize NEP. Requirements keep excess noise due to temperature fluctuations below fundamental bolometer noise.

Experimental

We have constructed the bridge circuit described in the previous section using neutron transmutation doped (NTD) thermistors [5] with 25 μm diameter brass leads. The bolometers are mounted in separate light-tight cavities on a thermally isolated stage attached to the cold plate of a ^{4}He dewar. We used a Siliconix [9] U401 matched, dual JFET mounted in a self-heating package on the dewar cold plate. The essential features of the U401 are good matching of the two JFETs, high common mode rejection and good noise characteristics for source impedances in the 10-30 MΩ range. We used a Princeton Applied Research [10] model 124A lock-in amplifier to provide phase sensitive detection and to provide a stable ac bias voltage. The lock-in output was monitored either with a Hewlett Packard [11] model 3582A spectrum analyzer or a Hewlett Packard series 300 computer programmed to measure low frequency power spectra.

Dynamic Bolometer Response

One concern with the operation of the bridge circuit is that the responsivity of a bolometer with an ac bias voltage will differ from that of a bolometer with a dc bias voltage. In silicon a frequency dependent effect has been observed which increases the conductivity of the material significantly for frequencies in the 100-1000 Hz range [12]. If this effect is present in the Ge:Ga thermistor the bolometer load curves should be shifted toward lower resistances as the frequency of the bias voltage increases.

We measured a series of load curves with ac bias frequencies from 0 Hz to 800 Hz. By minimizing the capacitance in the bolometer heat sinks we were able to make capacitive (RC) rolloff effects negligible over this frequency range. We see no significant deviations in the load curves as the frequency of the bias voltage is increased. Thus we expect the electrical responsivity of a bolometer with an ac bias voltage at a frequency greater than the thermal rolloff frequency to be the same as the responsivity of a dc biased bolometer.

We directly measured the optical responsivity using a small optical source. The bolometers were optically isolated in separate cavities. We placed the optical source in one of the cavities and modulated the power delivered to the source at a frequency less than 1 Hz. We compared the signal from the bolometer operated in the bridge circuit to the signal from the same bolometer operated in a conventional readout with a dc bias power equal to the average of the ac bias power used in the bridge measurement. In these tests, the power delivered to the source bolometer not only produced an optical signal but also heated the bolometer mounting structure significantly. Because the response to the thermal and optical signals are difficult to separate, the test is only accurate to the 10% level. The measured signals were less than 5% different. We conclude that the optical responsivities in the two cases were very similar, as we would expect from bolometer theory.

Circuit Performance

The first set of tests of the circuit were made with room temperature metal film resistors in place of bolometers. These tests verified that the circuit performed as expected and eliminated low frequency noise from the JFET and other amplifiers. The spectrum for the bridge circuit was flat down to 0.016 Hz, the lowest frequency that the spectrum analyzer can measure. The spectrum for the conventional amplifier began to rise above the white noise level around 3 Hz and by 0.5 Hz was 100 times larger than the noise from the bridge circuit.

As mentioned in section II the matching of the thermistor temperature dependence is crucial. To date, our experimental results have been limited by thermistor mismatches which couple temperature drifts into the circuit. Figure 3a shows the best spectrum obtained using ^{4}He temperature bolometers. The noise level at frequencies above 0.1 Hz is about 50 nV/Hz$^{1/2}$, which is the level expected from Johnson and phonon noise for bolometer impedances of 20 MΩ. The spectrum was measured using badly mismatched bolometers (10% mismatch in Δ and 50% mismatch in R_0). As a result the

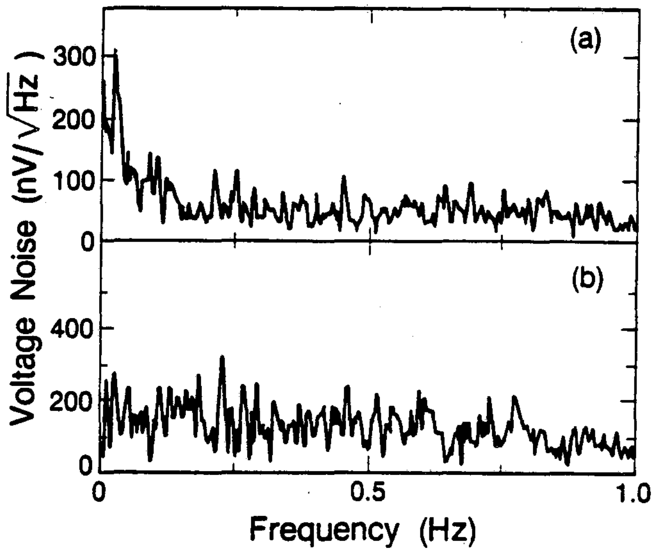

Figure 3. Noise spectra measured at 1.4 K for the bridge circuit using 20 MΩ Ge:Ga bolometers with 25 μm brass leads. (a) Noise spectrum measured without any regulation of the cold plate temperature. There is no excess noise for frequencies greater than 0.1 Hz. (b) Noise spectrum for the same bolometers with simple temperature regulation.

circuit was very susceptible to temperature changes, resulting in excess noise below 0.1 Hz. To decrease the effect of fluctuations in the cold plate temperature we used a simple feedback scheme to regulate the temperature of the isolated stage. Figure 3b shows a noise spectrum for the same bolometers with temperature regulation of the isolated stage. The temperature regulation significantly reduced the very low frequency noise in the circuit, but increased the noise at frequencies in the 0.1 to 0.6 Hz range (to a little over twice the fundamental noise limit). This extra noise was probably due to oscillations in the temperature of the stage induced by the simple feedback circuit (the stage thermal time constant was about 1 second).

In another experiment, where the measured noise spectra were similar to those above, we were able to show that all the excess noise could be accounted for by temperature fluctuations. We changed the cold plate temperature and measured the derivative of the output voltage with respect to temperature. We also measured the voltage noise spectrum and the spectrum of the cold plate temperature fluctuations. The spectrum of the voltage noise was consistent with the measured dV_{out}/dT and the spectrum of cold plate temperature fluctuations. The value of dV_{out}/dT calculated from independently measured bolometer parameters agreed closely with the measured value (Table 2).

TABLE II. Circuit Susceptibility to Temperature Fluctuations for ^{4}He System.

	dV_{out}/dT (mV/K)
Ratio of Voltage Noise to Temperature Noise (.05 Hz)	0.5 ± 0.2
Measured Directly	0.5 ± 0.1
Calculated from Bolometer Parameters	0.60 ± .05

Conclusions

We have constructed a bolometer readout circuit employing an ac bias voltage and two matched bolometers that allows stable dc bolometer operation for integration times $\gtrsim 10$ seconds. The low frequency stability is currently limited by cold plate temperature fluctuations coupled into the circuit by thermistor mismatches. Greater stability can be achieved by careful selection of matched thermistors, regulation of the cold plate temperature, and careful adjustment of the bridge operating point.

The advantages in sensitivity and stability offered by the bridge circuit should allow construction of more effective instruments both for ground-based and space-based astronomical observations. The bridge circuit is an essential technology for the Far Infrared Photometer which will be flown on the Japanese Infrared Telescope in Space in early 1993. In this application we hope to achieve an optical NEP = 2×10^{-17} W/Hz$^{1/2}$ for a ^{3}He bolometer. We are also developing a bolometer array based on the bridge concept for use at the Caltech Submillimeter Observatory. The array will incorporate ^{3}He temperature bolometers with background-limited NEPs of 5×10^{-17} W/Hz$^{1/2}$.

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