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Authors
Nahum, M.
Richards, P.L.

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DESIGN ANALYSIS OF A NOVEL LOW TEMPERATURE BOLOMETER*

M. Nahum and P. L. Richards

Department of Physics, University of California at Berkeley,
and Materials and Chemical Sciences Division, Lawrence Berkeley Laboratory,
Berkeley, CA 94720.

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M. Nahum and P. L. Richards
Department of Physics, University of California at Berkeley,
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Abstract

We propose a novel antenna-coupled superconducting bolometer which makes use of the thermal boundary resistance available at low temperatures. The radiation is collected by a planar self-complementary antenna and thermalized in a small thin film resistor. The resulting temperature rise is detected by a transition edge thermometer which can be (but need not be) a separate film. All components are deposited directly on a substrate so that arrays can be conveniently produced by conventional lithographic techniques. The active area of the bolometer is thermally decoupled by its small size and by the thermal resistance of the boundaries with the substrate and the antenna terminals. Design calculations based on a 2x2 μm square film of a superconductor with $T_c \approx 0.1$ K give an NEP$\approx 10^{-18}$ WHz$^{-1/2}$, time constant $\approx 10^{-6}$ s and responsivities up to $\approx 10^9$ V/W. These specifications meet the requirements for NASA's Space Infrared Telescope Facility and Sub-Millimeter Moderate Mission. Useful applications also exist at ^{3}He and ^{4}He temperatures. The calculated NEP scales as $T^{5/2}$. Materials, architectures, and readout schemes will be discussed.

Introduction

In the last thirty years, the device architecture of the bolometers that are actually used for detecting millimeter and submillimeter waves has gone through several stages of evolution. In the 1960's, the carbon resistance bolometer introduced by Boyle[1] gave way to doped germanium bolometers with soldered wire leads introduced by Low.[2] Subsequently, the composite bolometer[3] with dielectric substrate suspended on polymer fibers, metal film radiation absorber, and doped semiconducting thermometer with ion implanted contacts and metal leads has been used for many successful experiments including the COBE satellite. A more recent development has been to use metalized fiber leads in place of metal wires in order to achieve small values of thermal conductance. An alternative approach introduced by Weiss[4] and developed by Mosely[5] is to etch the bolometer and the supporting legs from a Si wafer and to implant the thermometer and sometimes the absorbing surface. This monolithic approach can yield arrays of bolometers with uniform properties.

The goals of this evolution are to obtain efficient absorption of the incident radiation, to absolutely minimize the heat capacity of the portions of the bolometer that respond thermally to the incoming radiation, and to provide the minimum thermal conductance consistent with the background power loading and the required speed of response. It has also been necessary to optimize the temperature readout and amplifier systems so that they introduces no additional noise. Once this optimization is complete, the only way to improve sensitivity is to lower the operating temperature. All of the recent bolometer concepts have been operated at ^{4}He temperatures, ^{3}He temperatures, and at ≈ 100 mK using adiabatic demagnetization refrigerators.

Despite this extensive development there remain opportunities to improve bolometer performance at millimeter and submillimeter wavelengths. The key is to further reduce the heat capacity of the material which responds thermally to the input radiation thus allowing further reduction in the thermal conductance and increased sensitivity. The work of Hwang et al[6] and Hu and Richards[7] on antenna coupled microbolometers for use at 300 and 90 K respectively, suggests a way in which this can be done. Following this approach, we propose to make high sensitivity antenna-coupled superconducting microbolometers at LHe and

lower temperatures. To reduce the heat capacity of the thermally active region we reduce its size to micron dimensions. The reduced thermal conductance is due to the thermal boundary resistance and to the small contact area of the thermally active region with the substrate. Efficient radiation coupling is achieved by means of a planar lithographed antenna. The radiation is thermalized in a small thin film resistor and the resulting temperature rise is detected by a transition edge thermometer which can (but need not be) a separate film. All of the components are deposited directly on the substrate and can be produced in arrays using standard photolithographic techniques. We estimate NEP$\approx 10^{-18}$ W/Hz$^{-1/2}$ with time constant $\tau \approx 10^{-6}$ s at 100 mK temperatures for a 2x2 μm square active region. Other superconducting readout schemes, such as measurements of the temperature dependence of the kinetic inductance,[8] could be used if their complexity is justified by benefits to the overall optimization for the actual experimental conditions. The performance of the proposed bolometer, however, is controlled primarily by the thermal design rather than by the temperature readout scheme.

Thermal Isolation

As will be discussed, the sensitivity of the bolometer is limited by its thermal isolation from the environment. In our geometry the absorbed radiation is dissipated via two paths. The first is direct heat flow from the superconducting thermometer into the dielectric substrate. At relatively high temperatures (typically above 10 K), this flow is limited by the bulk thermal conductivity of the substrate. Solving the thermal diffusion equation yields a frequency dependent thermal conductance given by[7]

$$G(f) = \kappa\sqrt{2\pi A}\left[(1 + \sqrt{\tau f})^2 + \tau f\right]^{1/2} \qquad (1)$$

where $\tau = cA/2\kappa$ is an effective time constant, κ is the thermal conductivity of the substrate, A is the contact area, c is the specific heat of the substrate and f is the modulation frequency. The frequency dependence is due to the intrinsic time constant of the substrate.

At lower temperatures, the thermal boundary resistance across the interface between the film and the substrate contributes significantly to the thermal isolation. This effect becomes very pronounced below several Kelvin and can be several orders of magnitude larger than the bulk contribution to the thermal resistivity. Acoustic mismatch theory has been very successful in explaining the boundary resistance.[9] The main points are that at low temperatures the phonon wavelengths are long (≈ 400Å at 1 K)[10] so that the bulk material properties can be used to characterize the heat flow across the interface. Phonons are reflected from this interface due to a mismatch in the acoustic properties across the boundary. The standard analysis yields

$$G = \frac{AT^3}{B} \qquad (2)$$

where A is the contact area, T is the temperature and B is a materials dependent parameter which depends on integrals over the transmission probabilities of the various acoustic phonon modes. The parameter B depends on the densities and the sound velocities of the materials and usually has a value of about 20 K^{4}cm^2/W.

The contact area between the superconducting thermometer and the antenna terminals provides an alternate path for heat dissipation. In addition to the phonon conduction, there exists the possibility that unpaired electrons in the superconducting thermometer (which is maintained at the center of the resistive transition) can also transfer energy across this interface. However, if the antenna is made of a superconductor whose T_c is higher than the operating temperature of the superconducting thermometer, then

the Andreev reflection of electrons at this interface reduces the thermal conduction of electrons to a negligible value.[11] The physical explanation is that electrons whose energy is smaller than the superconducting energy gap have zero transmission probability while those whose energy is larger than the energy gap have a very small occupation probability.

Another effect which may be of importance at very low temperatures (≤ 1 K) is the electron-phonon thermal resistance[12] in the superconducting thermometer itself. At such low temperatures the energy transfer between the electrons and phonons is less than perfect because there are a finite number of electrons attempting to transfer energy to phonons with a low occupation probability. The result being that the normal electrons in the superconducting thermometer absorb the radiation and are heated above the lattice temperature. The thermal resistance between the electrons and phonons has been measured in copper[13] with the result that $G = 5\times10^3 VT^4$ W/K, where V is the volume in cm^3. This effect can dominate the thermal boundary resistance at low enough temperatures for small film volumes (for a 1000 Å Cu film the effects are comparable at ≈ 1K). We are not aware of similar measurements on superconducting films, which have a stronger electron-phonon interaction, but do expect a reduction in the total effective thermal conductance. Estimates of this effect, however, will not be included in the design calculations; our calculated sensitivities thus represent a conservative limit.

Radiation Coupling

It has long been recognized that millimeter to far infrared radiation can be coupled to very small devices by means of an antenna.[14] Planar lithographed antennas such as log-periodic[15] and log-spirals[16] are very attractive candidates for our applications. These antennas are self complementary in that the shape of the regions covered by metal is the same as the regions of bare dielectric. These self complementary antennas are all very broadband and have a frequency independent real antenna impedance $R=377[2(1+\epsilon)]^{-1/2}$ Ω that depends only on the dielectric constant ϵ of the substrate. When deposited on quartz, the antenna impedance is ≈ 120 Ω. The short wavelength behavior of these devices is not well understood but response has been observed at 119 μm.[6] Since planar antennas located on a dielectric surface radiate primarily into the dielectric, the signals are introduced through the back surface of the dielectric which is often placed on the back side of a dielectric lens, as shown in Fig. (1), or on a dielectric filled paraboloidal reflector.[17] The efficiency of this quasi-optical coupling scheme has been estimated at 50% and higher at millimeter waves.[15,16]

Design Calculation

The figures of merit commonly used to characterize bolometers are the noise equivalent power (NEP), the time constant τ and the voltage responsivity S. If we model the thermal circuit as a heat capacity C coupled to a heat bath through a conductance G then $\tau=C/G$ and

$$S = \frac{I \, dR/dT}{G(1 + \omega^2\tau^2)^{1/2}} \qquad (3)$$

where I is the bias current, dR/dT is the temperature coefficient of resistance and $\omega = 2\pi f$ is the modulation frequency. To avoid thermal runaway due to self bias heating, the bias current must satisfy

$$\alpha \equiv \frac{I^2 \, dR/dT}{G} < 1 \qquad (4)$$

For design purposes we pick a nominal value of $\alpha = 0.3$. The optical NEP is computed by summing the squares of statistically independent contributions

$$NEP = \frac{1}{\eta}\left[4k_BT^2G + \frac{4k_BTR}{S^2} + \frac{4k_BT_nR}{S^2}\right]^{1/2} \qquad (5)$$

where η is the optical efficiency. The first term is due to temperature fluctuations, or phonon noise in the thermometer, the second term is from the Johnson noise in the resistance R of the thermometer and the last term is due to an amplifier with noise temperature T_n. If the transition width is a fraction β of the operating temperature then, neglecting amplifier noise, we can write

$$NEP = \frac{1}{\eta}\sqrt{4k_BT^5\frac{A}{B}(1+\frac{\beta}{2\alpha})} \qquad (6)$$

In Fig. (2) we plot estimates of the Johnson noise and phonon noise contributions to the NEP as well as the total NEP, all as a function of operating temperature (neglecting amplifier noise). We assume the heat flow to be limited by the thermal boundary resistance due to a 2x2 μm square total contact area (including contact with the antenna edges). We set the optical efficiency at 50% and $\beta=0.1$.
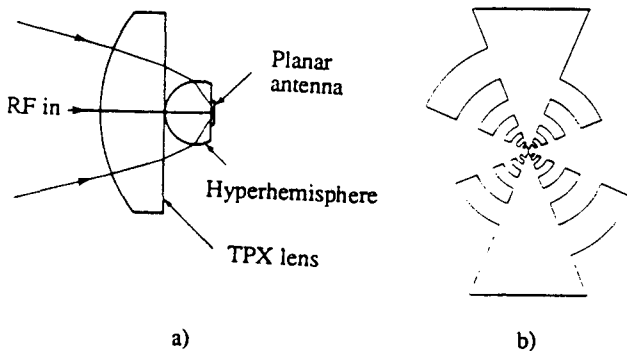

Figure 1. Quasi-optical coupling scheme. a) Cross section. The substrate is mounted on the flat side of a hyperhemispherical lens. A TPX lens is used to further narrow the beam. b) Planar log-periodic antenna. This self complementary structure gives a frequency independent real antenna impedance and very broadband response. In addition, it has a nearly Gaussian beam pattern.
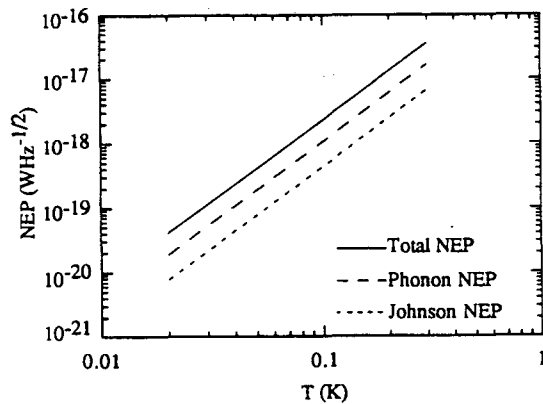

Figure 2. Estimates of the Johnson, phonon and total NEP as a function of operating temperature. We assume the heat flow to be limited by the thermal boundary resistance from a 2x2 μm square contact area and pick B=20 K^{4}cm^2/W. The optical efficiency is assumed to be 50%, the stability factor 0.3 and the superconducting transition width 10% of the operating temperature. Under these conditions the sensitivity is limited by the phonon noise.

The time constant is calculated from $\tau = C/G$ where C is the total heat capacity of the thermometer. At temperatures of interest (T<4 K), the electronic contribution to the heat capacity dominates the lattice contribution so that in general τ is inversely proportional to the temperature. A crude estimate is $\tau \approx 10^{-6}$ s at 100 mK. The very fast calculated speed of response suggests that additional improvements in NEP could be obtained if it were possible to further reduce the thermal contact of the thermometer to its surroundings. Large gains in NEP may not be possible, however, because of the background power limits to the smallest acceptable thermal conductance. In Fig. (3) we plot the maximum power that can be absorbed without heating the thermometer above the transition (for β=0.1 and 0.5). Improvements in the dynamic range can be obtained by artificial broadening of the superconducting transition width (for instance, by addition of magnetic impurities or the use of alloy films with graded profiles). The resulting sensitivity is not expected to degrade significantly since the transition width has to increase to 60% of the operating temperature (i.e. β = 0.6) for the Johnson noise limit to equal the phonon noise contribution.
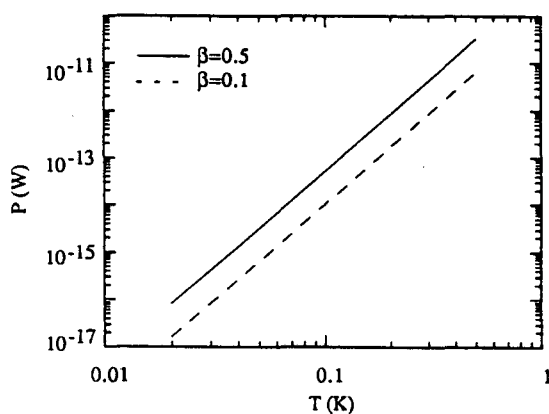

Figure 3.   Temperature dependence of the maximum power that can be absorbed without losing sensitivity. The dynamic range can be increased by optimization of the transition width.

In order to use the same element to thermalize the infrared current and to measure the resulting temperature rise, the thermometer impedance must match the antenna impedance of ≈100 Ω. Since pure metals have relatively low resistivities, they are not very suitable for this purpose; A better choice is to use alloys of transition metal superconductors. Published data show that a wide range of transition temperatures can be obtained using Mo/Ge alloys ($T_c \approx 0.05$-8 K) which also have very suitable resistivity values.[18] Other alloys, such as Nb/W (T_c<9.2 K) and Nb/Ta ($T_c \approx 4.3$-9.2 K) are also suitable for our purposes.[19]

Although excellent performance has been obtained from conventional transition edge bolometers,[20] problems with the readout of a low impedance thermometer have hampered applications. This is no longer a serious problem because of developments in the use of the DC SQUID as an amplifier with very low noise temperature. Thin film lithographed SQUIDs with operating temperatures ≤1 K can be used to read out signals from a resistance of 100 Ω or less with a noise temperature ≈ 10^{-7} K. The amplifier occupies a square millimeter of substrate space and dissipates less than 100 pW of power.[21] A less elegant approach is to use a cooled low noise transformer and an FET amplifier.

Applications

Potential applications of this device can be understood by reference to applications of conventional composite bolometers. Unlike a conventional bolometer which accepts any throughput, the antenna coupled bolometers are limited to a single spatial mode with throughput equal to the square of the wavelength. Consequently their use is favored for applications to diffraction limited imaging or spectroscopy.   Our estimates indicate that the antenna coupled bolometer can, in principle, achieve much higher sensitivities than conventional bolometers operated at the same

temperature in applications where the background power loading is very low. There are two NASA astrophysical spacecraft which are proposed for this decade and which require bolometers with very high sensitivities operating in low backgrounds. The Space Infrared Telescope Facility (SIRTF) will have a single bolometer for λ≈1 mm and a four bolometer array for shorter wavelengths, all operate at 100 mK. Backgrounds will be very low because the optics will be cooled to ≈1.5 K. The Submillimeter Moderate Mission (SM³) which will have low emissivity ≈200 K optics will require large format bolometer arrays for diffraction limited imaging which will probably operate near 300 mK as well as 100 mK arrays for spectroscopy. In addition, bolometers are used for important astrophysical applications at millimeter and submillimeter wavelengths from ground based (mountain top or south pole), airborne, balloon, and sounding rocket platforms. Important scientific goals include observations of molecular line emission from interstellar gas and planetary atmospheres, continuum emission from interstellar dust, and observations of the cosmic background radiation.

Because of the relative ease of fabrication into arrays, this antenna coupled bolometer may also find applications in relatively high background measurements which view 300 K sources. Such bolometers might operate at 4.2 K or even at higher temperatures. The sensitivity would then be limited by phonon noise in the thermal conductance required to keep the bolometer cold. In such applications it would be necessary to broaden the transition significantly to achieve comparable dynamic range of bolometers with doped semiconductor thermometers.

In most applications, external filters are used to limit the detected bandpass. At submillimeter wavelengths, high frequency filter leakage is a major problem since the power from a thermal source detected by a conventional bolometer with constant throughput increases as the square of the frequency. For an antenna coupled bolometer, the single mode throughput decreases as the frequency squared, so that the spectrum of detected power is flat and the filtering task is easier. In addition, the antennas can also incorporate lithographed filter and tuning elements. Several such elements have been developed to impedance match SIS mixers.[22] Conventional lumped elements can be used if their dimensions are small compared with the wavelength. The impedance matching properties of resonant structure would permit the use of thermometers with resistance <100 Ω.

As the properties of antenna coupled bolometers become better understood, it appears possible that they will become the detector of choice for important astrophysical measurements. They would either give higher absolute sensitivity or give the required sensitivity at a more convenient operating temperature than required for more conventional bolometers.

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UNIVERSITY OF CALIFORNIA
INFORMATION RESOURCES DEPARTMENT
BERKELEY, CALIFORNIA 94720