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THE DIELECTRIC BOLOMETER, A NEW TYPE OF THERMAL RADIATION DETECTOR

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SUMMARY

Thermal detectors for the infrared, such as thermocouples and bolometers, are limited in their ultimate sensitivity predominantly by Johnson noise rather than temperature noise. Low noise figures are hard to achieve since Johnson noise preponderates temperature noise, which is the only essential noise for thermal detectors.

The dielectric constants of some materials are sufficiently temperature dependent to make a new type of bolometer feasible. The basic theory of a dielectric bolometer, as shown here, promises noise figures below 3 decibels even at chopper frequencies well above the $1/\tau$ value of the detector. Ferroelectrics such as barium-strontium titanate and others seem to be well suited for radiation-cooled dielectric bolometers.

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INTRODUCTION

Infrared detectors can be divided into two major groups. The first group, known as quantum detectors, is based on the freeing of electrons from the lattice structure. The second group, called thermal detectors, respond to the heating that a body undergoes when exposed to radiation. The change in temperature of the usually very small black body is then obtained by measuring a changing characteristic parameter of the body. Suitable detector materials exhibit strong temperature dependence of one of their physical parameters: resistance in the bolometer, thermoelectric voltage in the thermocouple, and gas pressure in the pneumatic detector.

This report shows that in some materials the temperature coefficient of the dielectric constant is high enough to make a dielectric bolometer feasible. Such a bolometer promises a variety of advantages, especially with respect to noise. Johnson noise, the greatest obstacle in achieving the ultimate sensitivity in resistance bolometers and thermocouples, is practically nonexistent in capacitive elements. The dielectric bolometer approaches the ultimate sensitivity of thermal detectors to an unprecedented degree.

A list of the more important symbols used in this report is given in Appendix A.

THERMAL DETECTORS

Thermal detectors can be made uniformly sensitive over wide segments of the spectrum, very closely approaching the absorption characteristic of a black body. At present, they are the only detectors that show good sensitivity at wavelengths greater than 5 microns and that do not require cooling. However, thermal detectors have a common limitation. Their ultimate sensitivity is restricted by a type of noise called temperature noise (References 1, 2, 3), which is peculiar to the mode of energy conversion and normally is not found in quantum detectors. The temperature of the detector is determined by random emission and absorption processes. Even at equilibrium, the temperature shows small fluctuations about a mean value. The inherent property of thermal detectors, namely to convert temperature to electrical signals in most cases, transfers the random temperature fluctuation into voltage or current fluctuations in the output circuit.

Temperature noise must be distinguished from Johnson noise, which is caused by velocity fluctuations of electrons in the conduction band. Both types of noise have the same physical origin; Johnson noise is also called thermal or Nyquist noise. To illustrate the difference between temperature noise and Johnson noise, consider a two-terminal network connected to an ideal current source. At a particular temperature, Johnson noise (mean-square voltage) is determined by the real part of the electrical impedance. Temperature noise is completely absent if none of the network parameters depends on temperature or if the bias current is zero. If the real part of the electrical impedance is zero — but not the imaginary part, of course — and if some of the network parameters depend on temperature, then temperature noise alone is detectable. Such a network can be realized by, for example, an electrical capacitance that exhibits a high temperature coefficient of the dielectric constant.

Temperature noise is essential to thermal detectors; whereas Johnson noise cannot be considered essential, although it is always present to some extent in electrical circuits. The goal in the development of thermal detectors has been a temperature-noise-limited detector (Reference 4). Theoretically, it should be possible to produce metal-strip and semiconducting bolometers so that temperature noise and Johnson noise are in the same order of magnitude (Reference 5). All available resistive bolometers, however, are limited by Johnson noise rather than by temperature noise (Reference 6). In semiconductor bolometers another type of noise, called current noise, sometimes has to be considered (Reference 7).

THE DIELECTRIC BOLOMETER

Johnson noise can be made negligible compared with temperature noise if the temperature dependence of the dielectric constant is chosen as the means of physical conversion from temperature to the indicated electrical property. In a dielectric bolometer, Johnson noise is reduced to the small amount generated by dielectric polarization losses. At a particular frequency of the bias current, the bolometer can be represented by an ideal capacitance and a series resistor that incorporates dielectric losses as well as leakage.

The basic theory of the dielectric bolometer, as given here, indicates the capabilities and limitations of the technique. The bolometer element is connected to a constant current source i_c as shown in Figure 1.

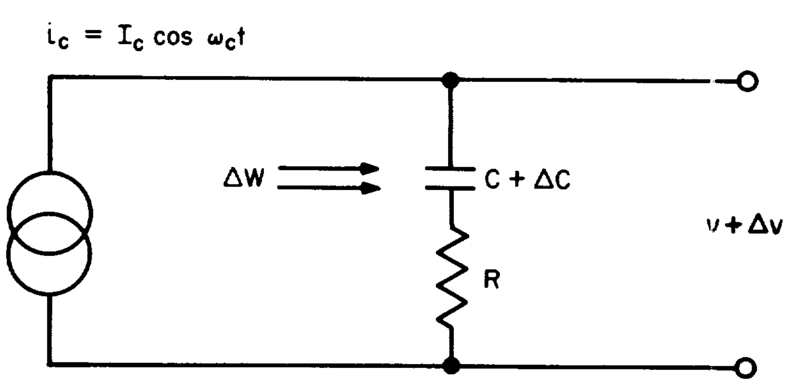


Figure 1 - Basic circuit of a dielectric bolometer

The variations Δv in the amplitude of the carrier, caused by variations in the capacitance ΔC, are

$$\Delta v = - \frac{i_c}{j\omega_c C} \frac{\Delta C}{C} . \tag{1}$$

The relative change in the dielectric constant with temperature is called the temperature coefficient α. It is equal to a change in capacitance if the physical dimensions of the capacitance are temperature-independent:

$$\alpha = \frac{1}{\epsilon} \frac{\Delta\epsilon}{\Delta T} = \frac{1}{C} \frac{\Delta C}{\Delta T} . \tag{2}$$

The temperature rise ΔT of the capacitive element exposed to the radiation ΔW is governed by:

$$C \frac{d}{dt} \Delta T + G \Delta T = e \Delta W . \tag{3}$$

The thermal conductance G incorporates heat conduction as well as reradiation. If ΔW is a periodic function, then Equation 3 is solved by

$$\Delta T = e \Delta W G^{-1} (1 + \omega_s^2 \tau^2)^{-\frac{1}{2}} . \tag{4}$$

The responsivity of the detector is normally defined as the ratio of output voltage and available power. Equations 1 to 4, combined, yield

$$r = \frac{i_c \alpha e}{\omega_c C G (1 + \omega_s^2 \tau^2)^{\frac{1}{2}}} . \tag{5}$$

The responsivity is proportional to the bias current i_c, which cannot be increased beyond certain limits. Nonlinearities in the dielectric material, such as breakdown and saturation, limit i_c as well as the average temperature increase ΔT_0 that can be allowed in a particular application. Thermal dissipation in the loss resistor determines ΔT_0:

$$i_c^2 R = G \Delta T_0 . \tag{6}$$

Substitution of i_c in Equation 5 yields

$$r = e \alpha Q \left(\frac{\Delta T_0 R}{G (1 + \omega_s^2 \tau^2)} \right)^{\frac{1}{2}} . \tag{7}$$

Besides the loss resistance R and thermal properties G and τ of the bolometer assembly, responsivity depends on e and on the product αQ. Temperature coefficient and quality factor are both material constants; they will serve as one criterion in the selection of suitable dielectrics.

where τ_r is the thermal time constant of the bolometer cooled by radiation only.

It is desirable to operate at a signal frequency ω_s below ω_1. The noise figure is then

THE ULTIMATE SENSITIVITY OF DIELECTRIC BOLOMETERS

Responsivity and ultimate sensitivity are the most important properties of a radiation detector. The ultimate sensitivity is achieved when detector noise is reduced to the minimum of essential noise. The temperature noise, which is the essential noise in thermal detectors, is given by the mean square of the fluctuation of power flow to the detector (References 8, 9):

$$\overline{\Delta W_T^2} = 4\,k\,T^2\,\mathcal{G}\,\Delta f\ . \tag{8}$$

The Johnson noise in the loss resistor is

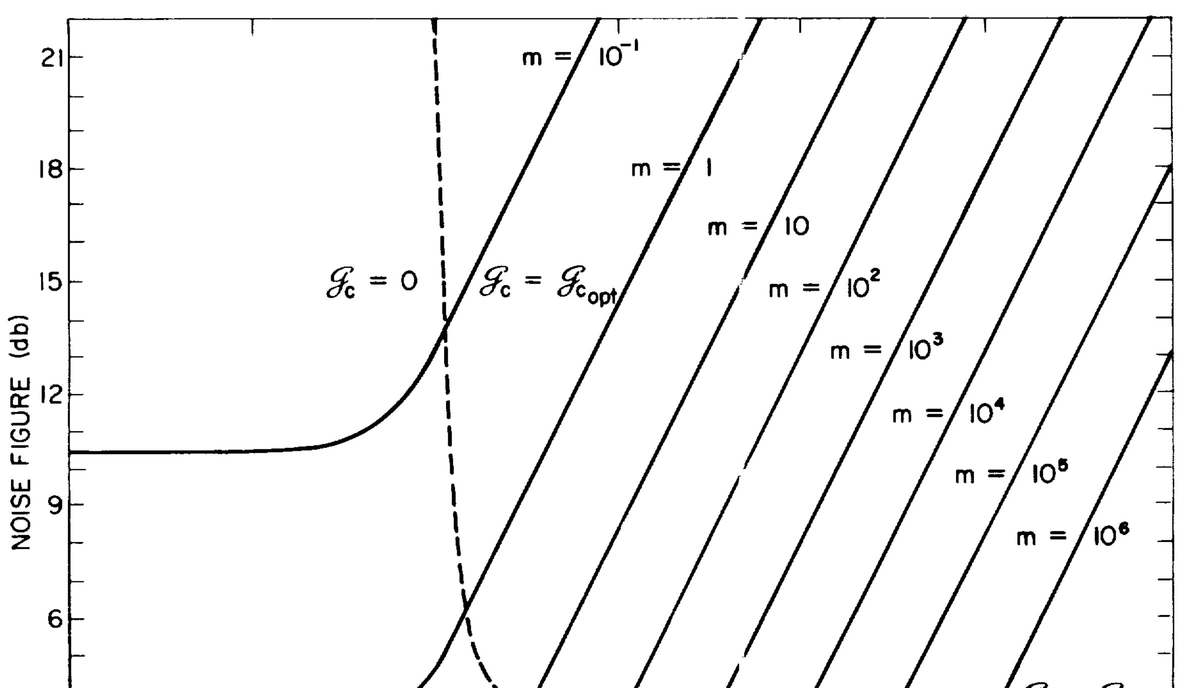
$$\overline{v_J^2} = 4\,kTR\,\Delta f\ . \tag{9}$$

Johnson noise can be converted into thermal units by dividing by the square of the responsivity. The total detector noise, expressed as power flow to the detector, then becomes

$$F_{(\omega_s \leq \omega_1)} = 1 + (1 + \omega_s^2 \tau_r^2)\, m^{-1}\ ,$$

$$F_{(\omega_s \geq \omega_1)} = 2(1 + m)^{\frac{1}{2}}\, \omega_s\, \tau_r\, m^{-1}\ . \tag{22}$$

Figure 2 shows quite clearly that noise figures below 3 db can be achieved only in radiation-cooled bolometers. Here, even at chopper frequencies much higher than the one corresponding to the time constant τ_r of the detector, a low noise figure can be obtained if the parameter m can be made high enough.



usually accompanied by maxima in the loss angle, and the product αQ is relatively small (Reference 11). One group of materials however, the ferroelectrics, which are widely known for their piezoelectric properties, show rapid changes of ϵ in the vicinity of the Curie point. Potassium dihydrogen phosphate (which has the trade name KDP) has a temperature coefficient of 0.25 and a Q of 40 at -147°C, while its Curie point is at -150°C (Reference 12). Rochelle salt exhibits drastic variations in dielectric constant near -18°C and +25°C; unfortunately its physical instability makes the practical use of Rochelle salt difficult.

Barium titanate has excellent mechanical properties (Reference 13). Its Curie point is at +120°C, but can be lowered to room temperature and even below by means of strontium titanate additions (Reference 14). For small bias currents, αQ values in the order of 25 can be expected over a useful temperature range of about 5°C. Positive and negative temperature coefficients can be utilized by operating just below or just above the Curie temperature. A much wider range of operation is possible with titanate ceramics; they often serve as temperature-compensating elements in high-frequency circuits.* Readily obtainable are αQ values of 7 to 10 (α up to 0.03; Q up to 500).

Without a thorough search in dielectric materials it is reasonable to expect that αQ values in the order of 7, at least, are obtainable. If the restriction to smaller ranges in the operating temperature can be tolerated, αQ values of 20 to 30 may be reached. This estimate of αQ permits estimation of values for the parameter m, which was defined by Equation 11. The bolometer emissivity e will be assumed as 0.8, the operating temperature as 300°K, and the temperature rise ΔT_0 as 1°C. Values for m will range between 10,000 ($\alpha Q = 7$) and 100,000 ($\alpha Q = 23$). This indicates that noise figures below 3 db are feasible even at chopper frequencies 100 to 300 times the $1/\tau_r$ value.

OTHER NOISE SOURCES

Thus far it has been shown that in dielectric bolometers Johnson noise can be made negligible compared with thermal noise. It remains to be shown that other noise sources are also very small compared with essential noise. It is sufficient to demonstrate that none of the other noise sources exceeds the level of Johnson noise. A brief and rather limited attempt will now be made to show this.

Current noise, often an important factor in resistive bolometers, is absent in a dielectric element since direct current does not flow in the detector circuit.

Flicker noise in the preamplifier tube and possibly $1/f$ noise in transistors can be avoided by choosing a bias frequency well above the range where flicker noise predominates. Bias frequencies in the audio range, perhaps a few kilocycles per second, will serve the purpose.

*Barium-strontium titanate samples were kindly supplied by the Massachusetts Institute of Technology Laboratory for Insulation Research.

Shot noise in tubes is conventionally represented by an equivalent noise resistor. Good preamplifier triodes have equivalent noise resistors in the order of one kilohm. The bolometer impedance should be chosen so that the loss resistor is higher than the equivalent noise resistor of the tube; the tube then contributes practically nothing to the total noise. Materials of higher α and lower Q will be more suitable to match a noisy input stage. High α values make the use of transistor preamplifiers possible.

Generator noise is caused by fluctuations in the bias current. In most applications two bolometer elements will be used: one exposed and the other shielded, or preferably both exposed alternately to the incoming radiation. Although the bridge circuit reduces the requirements on amplitude and frequency stability of the bias source, a good phase shift or tuning fork oscillator will be necessary to utilize the ultimate sensitivity of the detector.

Dielectric noise may be an important factor in the performance of a dielectric bolometer. Dielectric noise is analogous to Barkhausen noise in magnetic materials; it is caused by the spontaneous alignment of molecular groups in the electric field. The magnitude of the effect will depend on the temperature range and on the materials used. Further investigations may show that antiferromagnetic materials such as $PbZrO_3$ may behave better in this respect, since they do not show spontaneous polarization (References 15, 16). Presently the Curie point of $PbZrO_3$ is too high for this material to be useful as a dielectric bolometer. Further research in this field will help to evaluate the importance of dielectric noise in a capacitive bolometer.

CONCLUSION

This theoretical study of the dielectric bolometer promises an uncooled thermal detector restricted by temperature noise only. Such a detector has reached the ultimate sensitivity of thermal detectors. Measurements have been initiated to show the feasibility of this approach experimentally.

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Appendix A

LIST OF SYMBOLS

A = area

C = capacitance

$\mathcal{C}$ = thermal capacitance

e = emissivity

F = noise figure

f = frequency

$\mathcal{G}$ = thermal conductance

i_c = bias current

j = $\sqrt{-1}$

k = 1.38×10^{-23} joule/deg = Boltzmann constant

m = $e^2 \alpha^2 Q^2 T \Delta T_0$

Q = $1/\omega RC$ = quality factor

R = resistance of dielectric loss resistor in series with capacitance

r = responsivity

T = temperature

t = time

v = voltage

W = radiant power

α = temperature coefficient of dielectric constant

ϵ = dielectric constant

σ = 5.67×10^{-8} watt m^{-2} deg^{-4} = Stefan-Boltzmann radiation constant

τ = $\mathcal{C}/\mathcal{G}$ = thermal time constant

ω = $2\pi f$ = radian frequency

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