Sensors and Actuators, 5 (1984) 207 - 215

BROAD BAND INFRARED THERMAL DETECTOR

AVNER SHAULOV
Philips Laboratories, Briarcliff Manor, NY 10510 (U S A)
(Received March 8, 1983, in revised form January 4, 1984, accepted January 17, 1984)

Abstract

A broad band thermal detector based on pyroelectric materials with temperature-dependent electrical conductivity is described This detector combines the properties, notably the frequency response, of a thermistor bolometer and a pyroelectric detector Suitable choice of the detector parameters provides a uniform frequency response above and below the thermal relaxation frequency

Introduction

Infrared thermal detectors are used in a wide variety of applications which require room temperature operation and uniform sensitivity over a wide spectral range [1, 2] The two most popular types of thermal detectors, the thermistor bolometer and the pyroelectric detector, show a marked difference in frequency response, as shown in Fig 1 The response of the

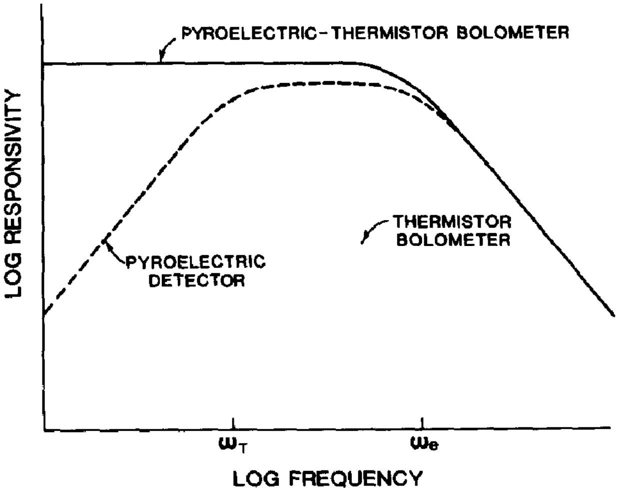

Fig 1 A log–log plot of the frequency response of a thermistor bolometer, pyroelectric detector and tuned pyroelectric–thermistor bolometer

0250-6874/84/$3 00

thermistor bolometer rapidly falls off above its thermal relaxation frequency, ω_T, which typically lies between 1 and 100 Hz Pyroelectric detectors are generally most sensitive above these frequencies [3] In this paper we show that a pyroelectric detector and a thermistor bolometer can be combined in a single detector possessing a uniform frequency response above and below ω_T

The sensing element of this pyroelectric–thermistor bolometer (PTB) is a pyroelectric material whose electrical conductivity is temperature dependent, e g , boracites [4, 5], sodium nitrite ($NaNO_2$) [6], tin-hypothiodiphosphate ($Sn_2P_2S_6$) [7], lead germanate ($Pb_5Ge_3O_{11}$) or lithium ammonium sulfate ($LiNH_4SO_4$) [8] When heated by incident radiation, both the electrical polarization and electrical resistance of the element show a change The change in resistance provides the low-frequency thermistor response, while the change in polarization provides the high-frequency pyroelectric response By suitable choice of the circuit parameters, the thermistor and pyroelectric components of the response can be adjusted to yield a uniform frequency response (see Fig 1) from $\omega = 0$ to a high frequency, ω_e, determined by the electronic time constant for the PTB-load circuit

Device description

The construction of the PTB resembles that of the standard pyroelectric detector It consists of a thin slice of a pyroelectric material whose resistivity is temperature dependent The two opposite faces of the slice are perpendicular to the polar axis and coated with conducting electrodes A voltage source, V_0, and a load resistor, R_L, are connected to the electrodes as shown in Fig 2 The bias voltage provides a steady current through R_L and

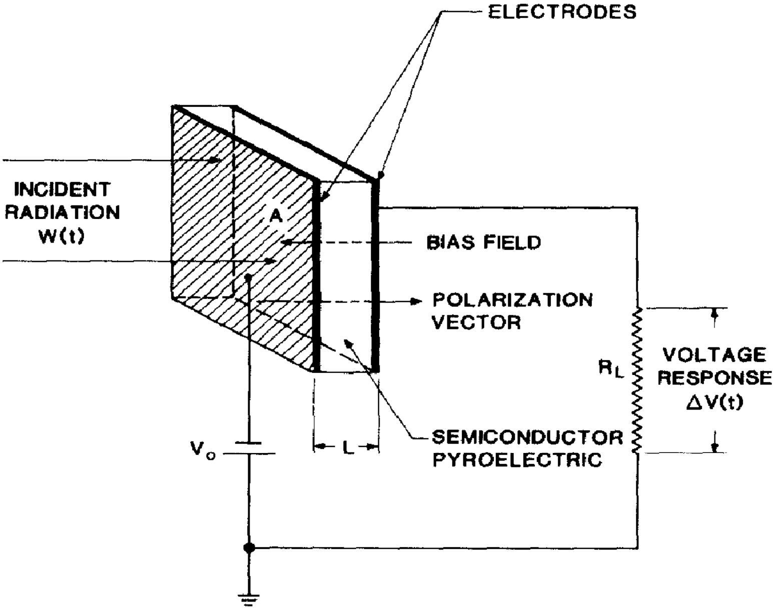

Fig 2 A pyroelectric thermistor bolometer

the sample resistance required for the thermistor response The polarity of the bias voltage must be chosen so that the pyroelectric component and the thermistor component of the PTB signal, due to a given change in temperature, are of the same sign For example, in a situation where an increase in temperature decreases both the spontaneous polarization and the resistance of the PTB element, the bias field direction across the element should be opposite to the spontaneous polarization With small bias fields and materials having high coercive fields, there is little danger of depoling the material

In order to produce a uniform frequency response, both above and below the thermal relaxation frequency, the bias voltage and the load resistor have to be adjusted so that the PTB constant, k (defined below), is approximately unity

Analysis of operation

We assume that the absorbed radiation causes a spatially uniform small temperature rise ΔT of the PTB element Hence, its heating is described by

$$\mathrm{d}(\Delta T)/\mathrm{d}t + \Delta T/\tau_{\mathrm{T}} = W(t)/C_{\mathrm{T}}, \tag{1}$$

where τ_{T} and C_{T} are the thermal time constant and the thermal capacity of the element, respectively, and $W(t)$ is the instantaneous radiation power absorbed in the element [1] The rise in temperature causes a change in the polarization, $\Delta P = -p\Delta T$, and a change in resistance, $\Delta R = \alpha R_0 \Delta T$, of the element, where p is the pyroelectric coefficient, α the temperature coefficient of resistance and R_0 the resistance of the sample at equilibrium These variations in the polarization and resistance change the current through the element and load, causing a voltage signal, ΔV, across the load The current, $\Delta I = \Delta V/R_{\mathrm{L}}$, flowing through the element to the load consists of a conduction current

$$-[\Delta V + V_0 \Delta R/(R_0 + R_{\mathrm{L}})]/R_0,$$

and a displacement current

$$-[C\,\mathrm{d}(\Delta V)/\mathrm{d}t - A\,\mathrm{d}(\Delta P)/\mathrm{d}t],$$

where C is the capacitance and A is the area of the element Hence, we obtain

$$C\frac{\mathrm{d}(\Delta V)}{\mathrm{d}t} + \Delta V\left(\frac{1}{R_{\mathrm{L}}} + \frac{1}{R_0}\right) = -pA\frac{\mathrm{d}(\Delta T)}{\mathrm{d}t} - \frac{\alpha V_0}{R_0 + R_{\mathrm{L}}}\Delta T$$

This equation can be written in the form

$$\mathrm{d}(\Delta V)/\mathrm{d}t + \Delta V/\tau_{\mathrm{e}} = -(pA/C)[\mathrm{d}(\Delta T)/\mathrm{d}t + \Delta T/\tau], \tag{2}$$

where $\tau_{\mathrm{e}} = (1/R_{\mathrm{L}} + 1/R_0)^{-1}\,C$ is the electronic time constant of the circuit and

$$\tau = pA(R_0 + R_L)/(\alpha V_0) \tag{3}$$

Equations (1) and (2) can be solved using the Laplace transform method Assuming initial conditions $\Delta T(0) = 0$ and $\Delta V(0) = 0$, the Laplace transforms of eqns (1) and (2) are

$$(s + 1/\tau_T)t(s) = w(s)/C_T, \tag{1a}$$

$$(s + 1/\tau_e)v(s) = -(pA/C)(s + 1/\tau)t(s), \tag{2a}$$

where $t(s)$, $w(s)$ and $v(s)$ are the Laplace transforms of $\Delta T(t)$, $W(t)$ and $\Delta V(T)$, respectively Substitution of $t(s)$ from eqn (1a) into eqn (2a) yields a direct relationship between the excitation $w(s)$ and the response $v(s)$

$$v(s) = H(s)w(s) \tag{4}$$

where the transfer function, $H(s)$, is

$$H(s) = -(pA/CC_T)\{(s + 1/\tau)/[(s + 1/\tau_e)(s + 1/\tau_T)]\} \tag{5}$$

Using this relationship, the response $\Delta V(t)$ to any excitation function $W(t)$ can be obtained by taking the inverse Laplace transform of $v(s)$

As seen from eqn (5), the response of the PTB is characterized by three time constants τ_T, τ_e and τ The thermal time constant, τ_T, characterizes the response of any thermal detector Pyroelectric detectors are additionally characterized by the electronic time constant, τ_e The third time constant, τ, which appears in the response of the PTB is given in eqn (3) as the charge per degree, due to change in polarization, divided by the current per degree, due to a change in resistance Thus, τ reflects the relative contributions to the output signal of the pyroelectric effect and the thermistor effect

From eqn (5) is follows that when $\tau = \tau_T$ the PTB is characterized only by the electronic time constant, τ_e In this case the PTB acts as a fast response thermistor or as a pyroelectric detector with a d c response This is illustrated in the following examples

Response to a step function

For step irradiation, $W(t) = 0$ if $t < 0$ and $W(t) = W_0$ if $t > 0$, one obtains,

$$\Delta V(t) = [\xi W_0 \tau_T \theta/(1 - \theta)][(1 - k)\exp(-t/\tau_T) - (1 - k\theta)\exp(-t/\tau_e) + k(1 - \theta)], \tag{6}$$

where $\xi = -pA/CC_T$, $\theta = \tau_e/\tau_T$ and $k = \tau_T/\tau$ The response as a function of time is plotted in Fig 3 together with the separate contribution of the pyroelectric and thermistor components The curves shown are calculated for $\theta = 0\ 01$ and $k = 1$ While the thermistor component of the response rises slowly with time constant τ_T to a steady value, the pyroelectric component rises quickly with time constant, about τ_e, to a peak value and then decays slowly with time constant τ_T When the load resistor and the bias voltage

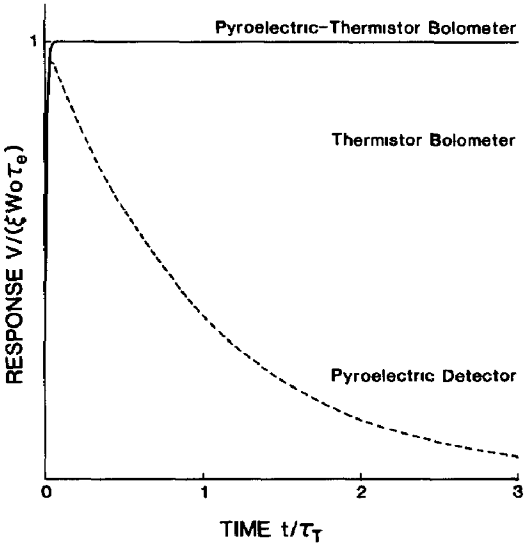

Fig 3 Responses of a thermistor bolometer, a pyroelectric detector and a tuned pyroelectric–thermistor bolometer to a step function

V_0 are chosen so that $k = 1$, the slow decay of the pyroelectric response is compensated by the slow rise of the thermistor response, so that the combined response rises quickly to a steady value The fast rise of the step response to a steady value is an outstanding trait of the PTB among thermal detectors

Frequency response

The steady-state response of the PTB to a sinusoidal input of frequency ω, is also a sinusoidal with frequency ω The ratio of the amplitude of the response to that of the input is the magnitude of the transfer function $H(s)$ when $j\omega$ is substituted for s Hence, the responsivity, $r(\omega)$, of the PTB is given by

$$r(\omega) = |H(j\omega)| = \xi\tau_e(k^2 + \omega^2\tau_T^2)^{1/2}[(1 + \omega^2\tau_e^2)(1 + \omega^2\tau_T^2)]^{-1/2} \quad (7)$$

Figure 4 shows $r(\omega)$ as a function of ω for $\theta = 0\ 01$ When $k \ll 1$, the PTB acts as a pyroelectric detector and maximum responsivity is obtained at frequencies lower than $1/\tau_e$ and higher than $1/\tau_T$ For $k \gg 1$, the PTB acts as a thermistor and maximum response is obtained at frequencies lower than $1/\tau_T$ When $k = 1$, the low-frequency response of the thermistor component and the high-frequency response of the pyroelectric component are combined to yield a flat frequency response from $\omega = 0$ to a high frequency determined by τ_e

Experimental results

Experimental results were obtained for a PTB made of a thin slice of $Cu_3B_7O_{13}Cl$ crystal (thickness 60 μm, area 0 04 cm^2) The faces of this slice

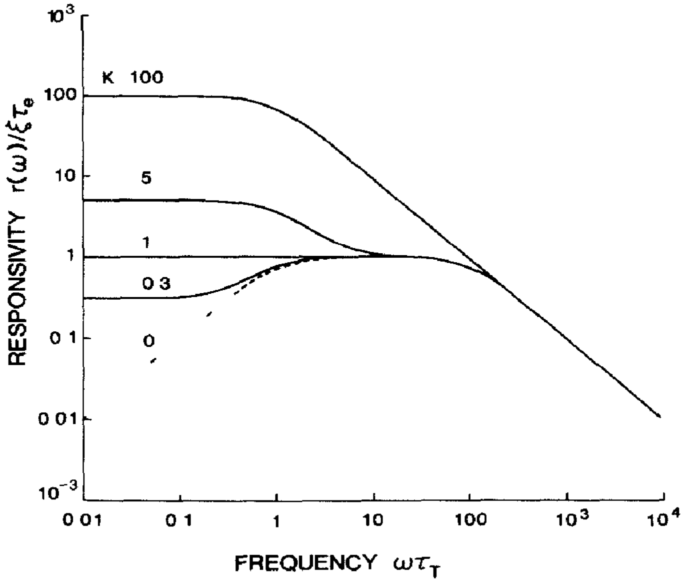

Fig 4 Frequency response of a pyroelectric–thermistor bolometer for $\theta = 0\ 01$ and different values of k

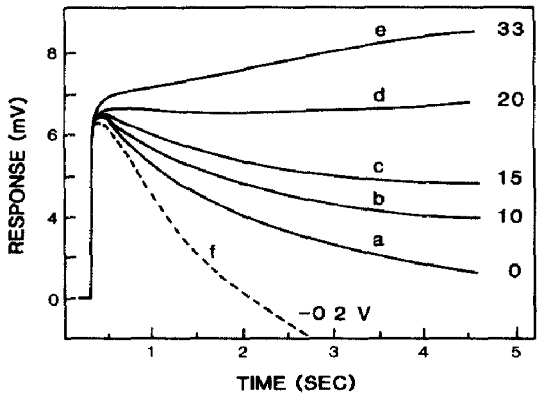

Fig 5 Oscillograms of the output voltage of a $Cu_3B_7O_{13}Cl$ PTB in response to a step illumination for different bias voltages

were perpendicular to the pyroelectric axis and covered with evaporated gold electrodes Attached to the electrodes were 75 μm silver leads from which the sample was suspended The voltage response to a step illumination was measured across a 50 M Ω load resistor for different bias voltages Oscillogram (a) in Fig 5 shows the response in the absence of a bias voltage This pure pyroelectric response rises fast initially and then decays slowly with the thermal time constant $\tau_T = 1\ 85$ s When a bias voltage is applied the thermistor component contributes a slowly rising voltage to the response and as a result, the decay is suppressed (oscillograms (b) and (c)) At a bias voltage of 0 2 V, the decay of the pyroelectric component of the response is compensated by the rise of the thermistor component and an approximately flat response is obtained (oscillogram (d)) The bias voltage V_0' necessary to obtain this compensation (a value of $k = 1$) can be calculated from eqn (3)

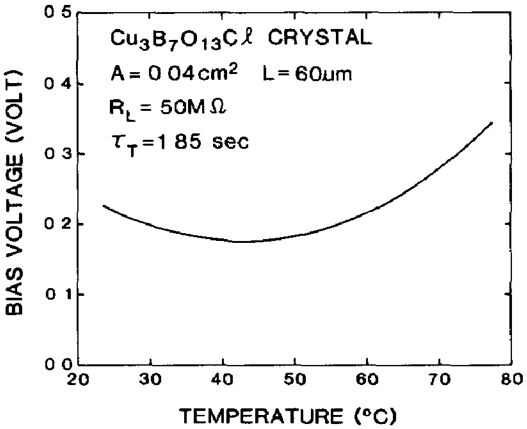

Fig 6 Temperature dependence of the bias voltage required for a uniform frequency response in a $Cu_3B_7O_{13}Cl$ PTB

$$V_0' = pA(R_0 + R_L)/(\alpha\tau_T) \qquad (8)$$

For $Cu_3B_7O_{13}Cl$ at room temperature, $p = 4\ 5 \times 10^{-9}$ C/cm² K, $\alpha = 8\ 8\%/K$ and the measured resistance of this sample is $R_0 = 1\ 5 \times 10^8$ ohm Using this formula with $R_L = 5 \times 10^7$ ohm, $A = 0\ 04$ cm² and $\tau_T = 1\ 85$ s, we obtain $V_0' = 0\ 22$ V, which closely agrees with the observation in Fig 5 When a higher voltage is applied (*e g* , 0 33 V), the slowly rising response of the thermistor component overcomes the pyroelectric decay and as a result the total response continues to rise slowly after the initial fast rise (oscillogram (e)) The importance of the polarity of the bias voltage is illustrated in oscillogram (f) where the bias voltage was reversed The pyroelectric component and the thermistor component now have opposite signs, and as a result the response quickly decays and crosses the zero line

The bias voltage V_0' (eqn (8)) required to achieve a flat frequency response ($k = 1$) may vary with temperature since the sample resistance, R_0, as well as the coefficients α and p are temperature dependent Figure 6 shows the temperature dependence of V_0' for the demonstrated example of $Cu_3B_7O_{13}Cl$ The curve shown was calculated from eqn (8) using experimental data for the temperature dependence of the resistivity [5] and pyroelectric coefficient in $Cu_3B_7O_{13}Cl$ [9] The temperature dependence of τ_T was not taken into account because it is very weak compared to that of p, α and R_0 far from the transition temperature It is noted that in the range 25 - 60 °C V_0' varies between 0 18 V and 0 22 V Consequently, for a constant bias voltage, *e g* , $V_0 = 0\ 2$ V, the PTB constant $k = \tau_T/\tau = V_0/V_0'$ (see eqn (3)) can vary between 1 1 and 0 9 Such variations can cause deviations from a flat response of ±10% as indicated by eqn (7) and Fig 4

Temperature stability of the PTB can be a problem at elevated temperatures approaching the ferroelectric–paraelectric transition point (about 93 °C in $Cu_3B_7O_{13}Cl$) where V_0' varies strongly with temperature However, even without this, a PTB cannot be operated close to the transition temperature because of the depoling effect of the bias field

Discussion and conclusions

Acting simultaneously as a thermistor and as a pyroelectric detector, the PTB combines the advantages of both detectors Specifically, in the PTB the thermistor component provides the low-frequency response while the pyroelectric component provides the high-frequency response As a result, a flat frequency response can be obtained over a broad band The bandwidth of the PTB is limited only at the high-frequency side by the electrical time constant of the detector-load circuit The bandwidth can be increased by decreasing the load resistance R_L with a corresponding loss of responsivity

In the arrangement described in Fig 2, changes in the ambient temperature can cause false signals This problem is conventionally solved by employing two identical elements in a bridge circuit [1] One of these elements is exposed to the radiation while the other, shielded from radiation, serves to compensate for changes in the ambient temperature The bridge is balanced when no excess radiation is incident on the exposed element

Large changes in the ambient temperature can also affect the balance between the thermistor and pyroelectric components of the PTB response, since the former depends on the temperature, T, and the latter depends on dT/dt Consequently, the bias voltage V_0 has to be re-adjusted to achieve $k = 1$ as required for a flat frequency response However, fine adjustment is not crucial for obtaining a broad frequency response As shown in Fig 4, a broad frequency response, though not perfectly flat, can be obtained with a wide range of k values between 0 5 and 2

This paper has focused on an outstanding trait of the PTB among thermal detectors — its broad frequency response This characteristic was demonstrated with a PTB made of a $Cu_3B_7O_{13}Cl$ crystal With such a stable crystal, reproducibility and time stability are ensured However, other less expensive materials in the form of ceramics or thin films can also be considered [7, 8] Full characterization of the PTB requires further study of noise characteristics and optimization of materials and circuit parameters

Acknowledgements

The author is grateful to W A Smith for helpful discussions, and to J Hannes and D Dorman for helpful assistance

References

1 R A Smith, F E Jones and R P Chasmar, *The Detection and Measurement of Infrared Radiation*, Oxford, 2nd edn , 1968, Ch III
2 E H Putley, Thermal detectors, in R J Keyes (ed), *Topics in Applied Physics Vol 19 Optical and Infrared Detectors*, Springer-Verlag, Berlin, 2nd edn , 1980, p 71
3 E H Putley, The pyroelectric detector, in R D Willardson and A C Beer (eds), *Semiconductors and Semimetals*, Vol 5, Academic Press, New York, 1970

4 H Schmid, P Chan, L A Pétermann, F Teufel and M Mandly, Spontaneous polarization, dielectric constant, d c resistivity, and specific heat of orthorhombic boracite $Fe_3B_7O_{13}I$, *Ferroelectrics, 13* (1976) 351 - 352

5 H Schmid and L A Pétermann, Dielectric constant and electric resistivity of copper chlorine boracite, $Cu_3B_7O_{13}Cl$, *Phys Status Solidi (a), 41* (1977) K147 - K150

6 Yutaka Takagi and Kazuo Gesis, Electrical properties of $NaNO_2$ single crystals in the vicinity of the ferroelectric Curie temperature, *J Phys Soc Jpn , 22* (1967) 979 - 986

7 A P Buturlakin, M I Gurzan and V Yu Slivka, Ferroelectric properties of $Sn_2P_2S_6$ crystals, *Sov Phys Solid State, 19* (1977) 1165 - 1167

8 M Potomska, B Hilczer and M Michalczyk, Electric conductivity of some ferroelectric crystals, *Ferroelectrics, 39* (1981) 1217 - 1220

9 W A Smith, M E Rosar and A Shaulov, Analysis of pyroelectric and dielectric measurements on boracites, *Ferroelectrics, 36* (1981) 467 - 470

Biography

Avner Shaulov received his B Sc , M Sc , and Ph D (1974) degrees in physics from the Hebrew University of Jerusalem From 1973 to 1976, as a senior instructor at Ben-Gurion University, Beer Sheva, Israel, he investigated magnetic phase transitions using ultrasonic methods From 1976 to 1978 he engaged in studies of improper ferroelectrics as a visiting scientist at Yeshiva University, New York In 1978 he joined the technical staff of Philips Laboratories (North American Philips Corporation) where he is currently investigating applications of ferroelectrics in infrared detectors and ultrasonic transducers