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RESONANCE BOLOMETER

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This paper considers characteristics of a resonance bolometer which is an infrared radiation detector depending for its operation on measuring the temperature dependence of parameters of a reactive element connected into a high-Q oscillatory circuit. The optimal pumping and heat removal conditions are determined with consideration for thermal feedback. The voltage-power sensitivity and noise are measured for microwave-pumped bolometers with active elements (cryogenic dielectric resonators made of potassium tantalate and strontium titanate) included in their circuits.

Resistive bolometers whose active element is a temperature-sensitive resistor are extensively used as infrared radiation detectors. The factors affecting their characteristics and ways of optimizing these instruments have been studied in sufficient detail [1-3]. Several authors [4-7] proposed that systems with temperature-sensitive reactive elements should be used as bolometers. However, the dynamic and noise characteristics of such bolometers have been little studied and this impedes their possible applications.

This study is devoted to the analysis of the performance of a resonance bolometer which is an infrared detector with a temperature-sensitive reactive element connected into its oscillatory circuit. In a high-Q oscillatory system, minor changes in the natural frequency change considerably the forced oscillation amplitude, due to which high sensitivity can be obtained [5]. A resonance bolometer may also be a distributed element, such as a dielectric resonator made of a material with a low loss level and high permittivity essentially depending on temperature.

LOW-FREQUENCY CHARACTERISTICS

The performance of a resonance bolometer is described by oscillation and heat transfer equations. For a lumped system with a temperature-dependent capacitor, the equation describing forced charge oscillations is

$$\ddot{q} + \frac{\omega_f}{Q}\dot{q} + \omega_f^2(1 - a_\varepsilon T_e)q = \frac{U}{L}\cos\omega t, \tag{1}$$

where ω_f is the natural frequency of the oscillatory circuit at temperature $T_e = 0$; Q is its quality factor; $a_\varepsilon = \dfrac{1}{C}\dfrac{dC}{dT}$ is the temperature coefficient of capacitance; L is the inductance, and U is the amplitude of the pump voltage or bias set by the harmonic oscillator at frequency ω. When describing thermal processes we shall neglect nonuniform temperature distribution in the active element and proceed from a heat balance equation in the form

$$C_T\dot{T}_e = -GT_e + P_d + P_c(t), \tag{2}$$

where C_T is the heat capacity, and G is the heat transfer coefficient. The active element is heated by heat power $P_c(t)$ it receives from outside sources and also due to the release of dielectric loss heat P_d which takes place in any real-life reactive element. In the absence of electric oscillations and heat sources, the steady-state temperature $T_e = 0$.

Let the active element receive the heat power

$$P(t) = P_b + P_h\cos\Omega t, \tag{3}$$

where P_b is the permanent background, and P_h is the heat signal amplitude. This causes periodic heating, so that

$$T_e = T_0 + T_h\cos(\Omega t - \varphi_T). \tag{4}$$

Usually for infrared detectors the settling time of electric transients is much smaller than the radiation modulation period:

$$\Omega \ll \omega_f/Q. \tag{5}$$

In this case, the electric regime can be considered quasi-stationary, $q(t) = q_0\cos(\omega t - \varphi_0)$, where the forced oscillation amplitude at a given temperature assumes the steady-state value

$$q_0 = \left(\frac{QU}{L\omega^2}\right)(1+\xi^2Q^2)^{-1/2}, \tag{6}$$

where $\xi = 1 - \omega_f^2/\omega^2$ is the amount of detuning. At the same time, if the thermal characteristics are considered, it can be assumed that

$$P_d = Kq_0^2, \tag{7}$$

where K is the capacitor loss with respect to the total loss in the oscillatory circuit; for a lumped circuit $K = r\omega/2CQ$. In view of (3), (4) and (7), we find from the heat balance equations that

$$\begin{aligned} GT_0 &= P_b + Kq_0^2, \\ P_h &= (G_{ef}^2 + \Omega^2C_T^2)^{1/2}T_h, \end{aligned} \tag{8}$$

where $G_{ef} = G - dP_d/dT_e$. As the temperature-sensitive element is heated not only by the signal power, but also by the power of dielectric loss (which, in its turn, depends on the temperature), there is a thermal feedback in the system. If the dielectric power loss increases with temperature it compensates partially for a higher heat removal from the temperature-sensitive element to the thermostat, i.e., the feedback is positive. In this case, $G_{ef} < G$ and the temperature sensitivity increases: $r_T = dT_h/dP_h$. Conversely, when $dP_d/dT_e < 0$, the feedback is negative: $G_{ef} > G$, and r_T is reduced.

Thermal feedback also occurs in resistive bolometers [2, 8], where it is considered to be a harmful effect that may cause "spontaneous combustion". In resonant systems with temperature-sensitive reactive elements, heating above the temperature determined by the equality $\omega_f(1 - a_\varepsilon T_0) = \omega$ results in detuning of the oscillatory circuit so that there will be no excessive growth of dissipated power. It is not difficult to find that

$$\frac{dP_d}{dT_e} = 2Kq_0\frac{dq_0}{dT_e} = -\frac{2Kq_0^2a_\varepsilon\xi Q^2}{1+\xi^2Q^2}. \tag{9}$$

Thus the thermal feedback level can be controlled through controlling pump voltage and frequency. In particular, heat loss in the system can be compensated for in full if $dP_d/dT_e = G$, provided $a_\varepsilon\xi < 0$. The pumping power at which such compensation is achieved is minimum when $|\xi| = Q^{-1}$ and equals

$$P_{th} = Kq_0^2 = G/|a_\varepsilon|Q. \tag{10}$$

Stationary heating causes a temperature rise to $T_0 = 1/|a_\varepsilon|Q$. As is known, heating which depends on the oscillation amplitude leads to a nonlinear thermal detuning due to which the resonance curves of the oscillatory circuit are typically distorted and in the case of $Kq_0^2 = P_{th}$ become nonunique [9, 10].

The voltage-power sensitivity is given by the equality $r_v = dU_0/dP_h$, where $U_0 = q_0/C$ is the amplitude of pumping voltage at the active element. In view of the identity $r_v = (dU_0/d\xi)(d\xi/dT_e)(dT_e/dP_h)$,

$$r_v = U_c a_e r_T\left[1 + Q^2\xi/(1+Q^2\xi^2)\right], \tag{11}$$

where $U_c = QU/(1+Q^2\xi^2)^{1/2}$ is the amplitude of capacitor voltage at frequency ω. Equation (11) can also be written as

$$r_v = \frac{1}{C}\frac{dq_0}{dT_e}\left[\Omega^2C_T^2 + \left(G - 2Kq_0\frac{dq_0}{dT_e}\right)^2\right]^{-1/2}. \tag{12}$$

The sensitivity threshold for the bolometer is limited by fluctuations, of which temperature variations of the active element and thermal electric noise are fundamental fluctuations that cannot be eliminated. According to [5, 8], power P_n equivalent to the background noise is found from the relation

$$P_n^2/\Delta f = 4kT^2G + \frac{4kT\,\mathrm{Re}\,Z(\omega)}{|r_v|^2}, \tag{13}$$

where $Z(\omega)$ is the oscillatory circuit impedance at the pumping frequency, and Δf is the indicator frequency band.

Consider conditions required to obtain the minimum voltage-power sensitivity $|r_v|$ and the minimum noise level. It is obvious from (11) that local peaks occur both for positive and negative detuning ξ if $|\xi|Q = 1$. The sensitivity of the bolometer is then

$$r_{vm} = r_T U_c a_\varepsilon Q/2. \tag{14}$$

In the case of negative feedback ($a_\varepsilon \xi > 0$), it can be found on the basis of (12) and (9) that maximum voltage-power sensitivity relative to the heat flow modulated at specified frequency Ω is obtained when $Kq_0^2 = P_-$, where

$$P_- = (F^2+1)^{1/2} P_{th}, \tag{15}$$

$F = \Omega C_T/G$. Here, the voltage-power sensitivity is

$$r_v^- = \frac{Q}{2G}\sqrt{\frac{2a_\varepsilon G}{r\omega C}}\,\frac{2}{((F^2+1)^{1/2}+1)^{1/2}}. \tag{16}$$

At low frequencies ($F \lesssim 1$) $r_v^- \sim G^{-1/2}$, whereas at high frequencies ($F \gg 1$) the voltage-power sensitivity is practically independent of G. Therefore, to minimize dielectric fluctuations (the second term in (14)), as well as temperature fluctuations, one should try to obtain the lowest possible heat-transfer coefficient G. The actual range of reducing G proves to be limited not only due to an unremovable radiative heat loss, but also because at low G dissipation of power P_- in the active element causes excessively high heating. As a result, the oscillatory system is heavily detuned and the noise level increases.

For positive feedback, formal analysis based on (12) and (9) shows that maximum r_v is obtained under instability conditions ($G < 2Kq_0\, dq_0/dT_e$), which are unfeasible. If we consider only operation under conditions known for sure to be steady-state, it should be assumed that $Kq_0^2 \to P_{th}$ (but $Kq_0^2 < P_{th}$). Then, there will be no rapid changes on the amplitude vs frequency curve of the nonlinear resonance, i.e., hysteresis-free operation is provided. In this case, the maximum voltage-power sensitivity is

$$r_v^+ = \frac{Q}{2\Omega C_T}\sqrt{\frac{2a_\varepsilon G}{r\omega C}}. \tag{17}$$

As the temperature fluctuation level (the first term in (14)) grows in proportion to G, and the contribution of electric fluctuations diminishes as $|r_v|^{-2} \sim P_{cr}^{-1} \sim G^{-1}$, a minimum P_n is achieved if the heat-transfer coefficient G assumes the optimum value

$$G_0 = \Omega C_T\sqrt{\frac{2r}{a_\varepsilon T Q^3}}. \tag{18}$$

In this case

$$P_n^2/\Delta f = 8kT^{3/2}\Omega C_T\sqrt{\frac{r}{a_\varepsilon Q^3}}. \tag{19}$$

DIELECTRIC RESONATORS USED AS MICROWAVE BOLOMETERS

This section presents estimates for the basic characteristics of resonance bolometers based on dielectric microwave resonators. Their use in infrared detectors offers advantages as against lumped-constant low-frequency circuits, because the resonance properties are concentrated in one dielectric sample, which obviates the necessity of a stable low-loss induction coil and, moreover, no electric contact with high-frequency circuits is required.

A microwave-pumped ferroelectric bolometer was for the first time proposed and implemented in [11]. The sensitive element of this bolometer was a TGS crystal. However, the system had a low Q-factor and low sensitivity on account of a high dielectric loss. Promising crystals for high-sensitivity bolometers are $KTaO_3$ and $SrTiO_3$. Virtual ferroelectrics, these crystals have high permittivity and significant a_ε; their dielectric loss at microwave frequencies and cryogenic temperatures is the lowest among all known ferroelectrics.

The relations of the previous section describe parameters of a lumped oscillatory circuit, whereas a distributed circuit features resonance frequency ω_f, loaded quality factor Q, and circuit coupling factor β. These quantities are converted into parameters of an equivalent series-connected lumped circuit using the formulas $B = (1+\beta)Z_0$, $\omega RC = 1/Q$, $LC = \omega^{-2}$, $r = 4\beta/(1+\beta)^2$, where Z_0 is the characteristic impedance. Besides, in microwave systems it is convenient to consider, instead of q_0 or $U_c = q_0/C$, the power of wave P incident onto the sample from the pumping generator matched with the microwave circuit. Using [12] it is easy to find

$$U_c = \frac{q_0}{C} = \left(\frac{8\beta}{1+\beta}\frac{PZ_0Q_f^2}{1+Q_f^2\xi^2}\right)^{1/2}. \tag{20}$$

In particular, in view of (20) we find from (16) and (17):

$$r_v^+ = \frac{1}{2\Omega C_T}\sqrt{2(1+\beta)Z_0 G a_\varepsilon Q^3}, \tag{21}$$

$$r_v^-/r_v^+ = \frac{F}{((F^2+1)^{1/2}+1)^{1/2}}. \tag{22}$$

Table 1

Design Characteristics of Resonance Microwave Bolometers

Characteristics	$KTaO_3$	$SrTiO_3$
T, K	4.2	78
Q_f	4×10^4	1×10^3
ε	4×10^3	2×10^3
a_ε, K^{-1}	5×10^{-3}	2.5×10^{-2}
V, cm^3	6×10^{-5}	0.5×10^{-3}
C_T, J/K	4×10^{-8}	3×10^{-3}
Ω, Hz	1×10^2	1×10^2
$G_{\rm rad}$, W/K	10^{-12}	3.5×10^{-8}
G_0, W/K	10^{-11}	1×10^{-5}
$G_{\rm calc}$, W/K	2×10^{-8}	1×10^{-5}
P_{th}, W	1×10^{-10}	0.4×10^{-6}
ΔT_{th}, K	5×10^{-3}	4×10^{-2}
r_v^+, V/W	1×10^9	10^3
$P_n^2/\Delta f$, W^2/Hz	2×10^{-29}	7×10^{-24}
r_v^-/r_v^+	12	14

The results of estimating characteristics of bolometers with a dielectric resonator made of virtual ferroelectrics at $f = \omega/2\pi = 10$ GHz are presented in Table 1. Data on the dielectric properties of the crystals (ε, a_ε, Q_f) and their thermal characteristics (G_T) are borrowed from [13], [14] and [15], respectively. To estimate the volume of the active element, it is assumed that $v \approx (1/2)(2\pi c/\omega\sqrt{\varepsilon})^3$, which gives a value close to the volume of a spherical resonator. The value is variable within certain limits depending on the shape of the dielectric resonator. The table presents three values of the heat-transfer coefficient: a minimum one limited by radiation ($G_{\rm rad} = A\sigma T^3$, $\sigma = 5.87\times10^{-12}$ W cm^{-2} K^{-3} is the Stefan-Boltzmann constant, $A \approx (3/2)(2\pi c/\omega\sqrt{\varepsilon})^2$ is the surface area of the dielectric resonator), an optimum value G_0 according to (18) at $\beta = 1$, and also a value G_{calc} adopted for sensitivity and noise estimation. The value of $G_{calc} = G_0$ was taken for a $SrTiO_3$ crystal at 78 K; however, for $KTaO_3$ at 4.2 K G_0 is too small, so that the background radiation, which usually exceeds $P_b \approx 10^{-9}$ W, can cause considerable heating of a dielectric resonator resulting in greater temperature fluctuations. Therefore, strictly speaking, the bolometer parameters can only be optimized at a known background level [3]. To obtain a simple estimate, we have taken the value of G_{calc} which ensures low heating ($\Delta T < 0.05$ K) at a background level of 10^{-9} W.

The sensitivity and the detection threshold obtained for cryogenic bolometers with $KTaO_3$ are similar to those of the best semiconductor and superconducting detectors [8, 16]. It is important that the noise level remains low up to comparatively high frequencies. For example, when Ω increases from 10^2 to 2×10^5 Hz, the level of $P_n^2/\Delta f$ grows by a factor of two, whereas r_v remains high ($r_v \approx 0.5 \times 10^6$ V/W), even though it reduces by three orders of magnitude ($r_v^+ \sim \Omega^{-1}$). Besides, virtual ferroelectric resonators feature high stability to electric and thermal overloads and are insensitive to the magnetic field.

Interestingly, when a negative thermal feedback is employed, the optimum voltage-power sensitivity of a resonance bolometer at a rather high modulating frequency Ω ($F = \Omega C_T/G > \sqrt{3}$) is higher as compared with a positive feedback. The explanation lies in that when a negative feedback is used the compelling force has a larger amplitude ($P_- > P_{cr}$), and the bolometer performance is described by a steeper resonance curve. (In a linear oscillatory circuit, the slope of the resonance curve is proportional to the compelling force amplitude, and due to nonlinear detuning caused by heating r_v^- does not grow indefinitely, but becomes maximum at a final pumping level $Kq_0^2 = P_-$.) Regretfully, the high voltage-power sensitivity obtained with a negative feedback cannot be fully used at high frequency Ω, because $P_- \approx FP_{th}$ for $F \gg 1$ (15) and this causes strong heating of the sensitive element.

The above estimates are certainly idealized and the effect of background illumination W_f and pumping instability should be considered in real-life bolometers.

The regularities established in this paper also hold in the cases when the active element of a bolometer is inductance. Thus, it was proposed in [6, 17] that the temperature sensitivity of the superconducting film inductance should be used in infrared detectors. However, effective connection of a low-inductance element into the oscillatory circuit presents serious difficulties for developing an induction bolometer.

CONCLUSION

This study has elucidated the mechanism of interaction between oscillations in bolometers with temperature-sensitive reactive elements. This interaction is manifested as a thermal feedback for temperature fluctuations and as a nonlinear resonance for electromagnetic oscillations. The analysis has shown that a promising method for developing low-noise bolometers of high sensitivity in a broad frequency range (up to 10^5 Hz) is to use, in microwave-pumped circuits, high-Q cryogenic dielectric resonators made of virtual ferroelectrics: potassium tantalate and strontium titanate. Active elements based on these crystals are resistant to the effect of a magnetic field as compared with semiconductors and superconductors. The not very encouraging results of previous attempts to manufacture such devices are primarily due to failure to take into account their dynamic behavior.

It should be pointed out that the resonance method of increasing the sensitivity of systems with microwave shift has already been studied before on semiconductor photoresistor heat detectors [18, 19]. Yet, their analysis did not include the effect of a thermal feedback, as these detectors do not depend on the thermal effect for their operation. Moreover, as shown above, detectors with a resistive temperature-sensitive element cannot employ a positive feedback. On the other hand, a negative thermal feedback may be useful in resonance detectors with resistive temperature-sensitive elements, because it helps improve sensitivity at high modulating frequencies.

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