ANALYTICAL EVALUATION OF THE SENSITIVITY OF A DILATOCAPACITOR THERMAL RADIATION RECEIVER

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The volt–watt sensitivity of certain types of capacitor thermal radiation receivers was calculated. It is shown that the sensitivity of one of the variants of the receiver in comparison with other indicators can be quite high, reaching values of 10^8 V · W^{-1}.

When measuring weak thermal fluxes in a wide frequency range it is necessary to solve problems of providing a low level of the intrinsic noise of the receiver. The minimum power recordable by such widely used radiometers as thermocouples and bolometers is limited, as is known [1], by the comparatively high value of thermal and current noises. From this standpoint the dilatocapacitor radiometer, which operates on the principle of conversion of the thermal signal into deformation of the plates of an air or vacuum capacitor and subsequent conversion of the changes of capacitance to current signals, has a considerable advantage. The magnitude of the voltage of the thermal and current noise occurring in such receivers has small values; the magnitude of the noise of the grid currents in the first stage of the measuring circuit also decreases [2].

The idea of using dilatometric methods with solid active elements for recording thermal fluxes is not new. In domestic literature a description [3] is given of a radiometer utilizing a bilayer (quartz–bismuth) active element whose deflection under the effect of radiation was recorded by the optical method. In recent years an article [4] was published in the foreign press in which a dilatooptical receiver with a rather low maximum measurable power ($1.5 \cdot 10^{-11}$ W) is described. A characteristic feature of this receiver is that the principle of mechanooptical amplification is used in it when recording thermal expansion proportional to the flux being measured, which greatly improves the signal–noise ratio at the output of the electrical measuring circuit.

It should be pointed out that in comparison with optical methods, the use of capacitor methods of recording the expansion of active elements has the advantage that in this case heating of the active element from the optical recording system is eliminated, and the liberation of heat as a consequence of dielectric losses can be reduced to negligibly small values.

A simple variant of a dilatocapacitor receiver is considered in [5]. In it the active element, made in the form of a thin metallic or dielectric band, is connected mechanically with the flat movable plate of an air capacitor; irradiation of the active element leads to a change of its length, air gap between the plates, and capacitance of the capacitor. Elementary calculations show that the volt–watt sensitivity of the receiver γ (when recording unmodulated thermal fluxes) will be determined by the formula

$$\gamma = \beta \frac{C}{\lambda} \frac{l\alpha}{\delta}. \tag{1}$$

The term of $l\alpha/\delta$ is regarded as the temperature coefficient of capacitance.

We can show by concrete numerical calculations that γ of the dilatocapacitor receiver with plane-parallel plates can assume values comparable to the volt–watt sensitivity of the other best thermal radiometers.

There exists, however, the possibility of a considerable increase of γ by using another design of the dilatocapacitor, which was proposed in [6] as an indicator of thermal radiation. It has the following design

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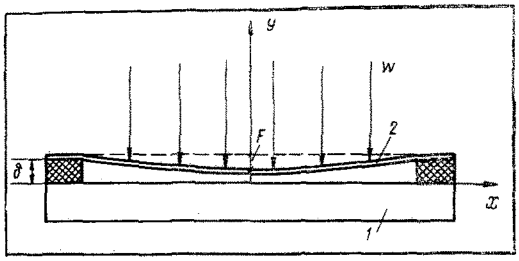

Fig. 1. Schematic diagram of dilatocapacitor.

(Fig. 1). The capacitor plate 1 is made massive, plate 2 is made of very thin foil and is very close to the first plate. By applying a direct or alternating voltage to the indicator it is possible to create a force attracting the plates to each other. When plate 2 is irradiated it elongates, and under the effect of ponderomotive forces it is deflected toward plate 1, which changes the gap and capacitance of the capacitor. In our opinion, the virtue of this dilatocapacitor, besides its simple design, is that the principle of mechanical amplification of the thermal signal is accomplished. Since this problem is important, we will find the temperature dependence of the capacitance of the dilatocapacitor. We will assume that the active element (plate 2) has a rectangular shape and is deflected sinusoidally with amplitude F, half of the sinusoid fitting over length l (Fig. 1). (This form of deflection is used in calculations of bimetallic membranes [7].)

The capacitance of an elementary capacitor of length dx (x is an axis coinciding in direction with l) is

$$dC = \frac{\varepsilon_0 n dx}{\delta - y}. \tag{2}$$

If the form of deflection of the plate is described by the law (see Fig. 1)

$$y = F \cos \frac{\pi}{l} x \tag{3}$$

(where F is the amplitude of the sinusoid), then the capacitance of the dilatocapacitor (for a real case when $\delta^2 > F^2$)

$$C = 2 \int_0^{l/2} \frac{\varepsilon_0 n dx}{\delta - F \cos \frac{\pi}{l} x} = \frac{4 \varepsilon_0 n l}{\pi \sqrt{\delta^2 - F^2}} \operatorname{arctg} \frac{\delta + F}{\sqrt{\delta^2 - F^2}}. \tag{4}$$

Expanding $\arctan \delta + F/\sqrt{\delta^2 - F^2}$ in a series and limiting ourselves to the first term of the expansion, we will have the approximate dependence of the capacitance on the amplitude of deflection

$$C \simeq \frac{4 \varepsilon_0 n l}{\pi (\delta - F)}. \tag{5}$$

It is easy to show that the following relation exists between the amplitude of deflection of the active element and the difference of temperatures of the plates ΔT:

$$F = \sqrt{f^2 + \left(f^2 + \frac{4l^2}{\pi^2}\right) \alpha \Delta T}, \tag{6}$$

where f is the amplitude of the initial deflection corresponding to $\Delta T = 0$ (at the same temperature of the plates).

Substituting Eq. (6) into (5), we obtain

$$C \simeq \frac{4 \varepsilon_0 n l}{\pi \left[\delta - \sqrt{f^2 + \left(f^2 + \frac{4l^2}{\pi^2}\right) \alpha \Delta T}\right]}. \tag{7}$$

The temperature coefficient of capacitance ν (TCC) is the quantity characterizing the thermosensitivity of the capacitor; it is equal to

$$|\nu| = \frac{1}{C} \frac{\partial C}{\partial (\Delta T)} \simeq \frac{1}{2} \frac{\left(f^2 + \frac{4l^2}{\pi^2}\right) \alpha}{\sqrt{f^2 + \left(f^2 + \frac{4l^2}{\pi^2}\right) \alpha \Delta T} \left[\delta - \sqrt{f^2 + \left(f^2 + \frac{4l^2}{\pi^2}\right) \alpha \Delta T}\right]}. \tag{8}$$

Since in comparison with the length of the plate the initial deflection is very small and $f^2 \ll 4l^2/\pi^2$, we obtain

$$|\nu| \simeq \frac{1}{2} \frac{4 \frac{l^2}{\pi^2} \alpha}{\sqrt{f^2 + \frac{4l^2}{\pi^2} \alpha \Delta T} \left[\delta - \sqrt{f^2 + \frac{4l^2}{\pi^2} \alpha \Delta T}\right]}. \tag{9}$$

As we see, ν depends not only on the metric parameters of the capacitor but also on the temperature difference between the plates. Taking into account that ΔT is small, we can write the following expression for the TCC:

$$|\nu| = \frac{2l^2\alpha}{\pi^2 f(\delta - f)}. \tag{10}$$

The ratio obtained permits determining the dependence of TCC on the initial deflection f. From it follows that for small deflections, ν can achieve quite large values. To show that an increase of sensitivity is achieved only by the effect of mechanical amplification and to find the magnitude of the latter, we will take into account that the TCC (1) for a capacitor with plane-parallel plates is equal to $l\alpha/\delta$. Assuming that the parameters of the active element and the initial gap are the same as for a capacitor with a deflecting plate, we have

$$\nu_n = \frac{l\alpha}{\delta - f}. \tag{11}$$

The ratio of (10) to (11)

$$\frac{\nu}{\nu_n} \simeq 0.2\frac{l}{f} \tag{12}$$

should be regarded as the magnitude of mechanical amplification achieved by replacing the translational displacement of the plate by its longitudinal bending.

With consideration of (10) the volt–watt sensitivity (1) of the dilatocapacitor receiver with a longitudinally bending plate will be equal to

$$\gamma_{\text{bend}} = \beta\frac{C}{\lambda}\,\frac{2l^2\alpha}{\pi^2 f(\delta - f)}. \tag{13}$$

For concreteness we present the values of the volt–watt sensitivity of a dilatocapacitor radiometer calculated by Eq. (13), assuming that it is connected into the circuit of an oscillator, and the change of capacitance is produced through deviation of the frequency being recorded by a frequency discriminator. According to the data in [8], a sensitivity of $\beta = 6\ \text{V}\cdot\text{pF}^{-1}$ was secured in such simple schemes not containing amplifier stages. Assuming that the receiver has the data: $l = 4\cdot 10^{-2}$ m, $f = 1\cdot 10^{-6}$ m, $\delta = 1\cdot 10^{-5}$ m, C = 70 pF, $\lambda = 1.06\cdot 10^{-3}\ \text{W}\cdot\text{deg}^{-1}$, we obtain

$$\gamma_{\text{bend}} = 3.3\cdot 10^8\ \text{V}\cdot\text{W}^{-1}.$$

According to the information given in [1, Chapter 3], the volt–watt sensitivity of other thermal receivers is (in $\text{V}\cdot\text{W}^{-1}$):

Schwartz thermocouple	38.5
Andrews superconducting bolometer (at modulation frequency 360 Hz	13.5
Semiconductor bolometer (theoretical data)	28.5–80
Bell Telephone Co. semiconductor bolometer	$25\cdot 10^3$
Opticoacoustic receiver with optical microphone [9]	$(3\text{–}4)\cdot 10^4$
Opticoacoustic receiver with capacitor microphone [10]	$(7.5\text{–}37.5)\cdot 10^2$

Thus the calculated sensitivity of the dilatocapacitor receiver can be the highest of all known radiometers.

To evaluate the capabilities of measuring circuits which can be used together with the dilatocapacitor receiver, we will present the data of [11], where a micrometer with a capacitance transducer connected into the circuit of a radio-frequency oscillator (average frequency 5 MHz) is described. The authors report that the frequency fluctuations were ±3 Hz. If we consider that the dilatocapacitor receiver with the parameters given above is connected into this system, we can show that the frequency fluctuations correspond to a flux power $\Delta W \sim 3\cdot 10^{-11}$ W.

We should mention that in this measuring circuit the frequency bandwidth was rather large. By using the method of modulation of the flux being measured, the bandwidth of the measuring device can be reduced and in so doing the magnitude of the minimum detectable power will be limited only by the fluctuations of heat transfer.

NOTATION

α	is the coefficient of linear expansion;
β	is the coefficient of conversion of capacitance to voltage;
γ	is the volt–watt sensitivity;
δ	is the gap between plates;
$\varepsilon_0 = 8.85 \cdot 10^{-12}$ F/m	is the dielectric constant;
λ	is the thermal conductivity;
ν	is the temperature coefficient of capacitance;
C	is the capacitance of capacitor;
F	is the amplitude of sinusuoid;
f	is the initial deflection;
l	is the length of active element;
n	is the width of plate;
x and y	are the current coordinates.

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