Investigation of Features of Functioning of the Pyroelectric Sensors in Electronic Security Devices

S.A. Moroz
Department of electronic and telecommunication
Lutsk National Technical University
75 Lvivska Str., Lutsk 43018, Ukraine
s.moroz@lntu.edu.ua

M. V. Khvyshchun
Department of electronic and telecommunication
Lutsk National Technical University
75 Lvivska Str., Lutsk 43018, Ukraine
mykolaxmv@ukr.net

A.A. Tkachuk
Department of electronic and telecommunication
Lutsk National Technical University
75 Lvivska Str., Lutsk 43018, Ukraine
a.tkachuk@lntu.edu.ua

V.V. Lyshuk
Department of electronic and telecommunication
Lutsk National Technical University
75 Lvivska Str., Lutsk 43018, Ukraine
vlyshuk@gmail.com

S.O. Prystupa
Department of electronic and telecommunication
Lutsk National Technical University
75 Lvivska Str., Lutsk 43018, Ukraine
s.prystupa@lntu.edu.ua

***Abstract*— The article reviews and studies the operation of pyroelectric sensors in electronic security devices. The main focus is on pyrodetectors that detect infrared radiation from the human body. To eliminate background thermal radiation, the pyroreceiver must consist of two crystals. In addition, pyroreceivers must have internal correction circuits that attenuate the high-frequency components of the signals. Establishing the main parameters of thermal radiation, which is perceived by the pyroreceiver.**

***Keywords*— pyroelectric sensor, security device, infrared radiation, output signal**

I. Introduction

Due to the widespread use of modern electronic devices, there is a significant "intellectualization" of technical means of protection. These tools are no longer just ancillary and acquire new properties, which has a significant impact on the organization of security and its level in the context of the development of Smart City technologies. A striking example of the development of security detection means is infrared (IR) detectors, the principle of which is based on the registration of thermal radiation of the human body [1-3]. As is known, [4] infrared are electromagnetic waves with a wavelength $\lambda > 0.76$ µm. Since the level of radiation of the human body is extremely low, the technical means of detection, due to their design, are several orders of magnitude more sensitive. Any IR passive detector consists of three parts: the optical system, the IR radiation receiver (PIR), and the processing unit (PU).

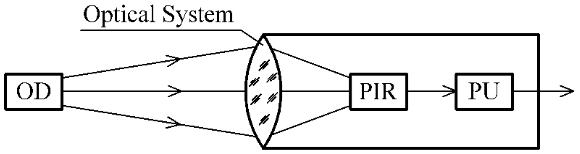

Fig. 1. Block diagram of the IR passive detector

The optical system concentrates the radiation coming from the object detection (OD), collecting it from the inlet of a large area and directing it to the PIR - an element that is sensitive to heat rays. Fresnel lenses are used as an optical system, which has a wide pattern - 100-120° vertically and horizontally. Thus (conditionally) one half of space is "seen" by one crystal, the other - another. That is, it turns out a kind of cone, which is dissected by a plane, the direction of which depends on the relative position of the crystals. Usually, this plane is vertical. With the help of a lens from two half-cones, two relatively narrow "beams" of the pattern are formed. This increases the sensitivity of the sensor by distance and reduces parasitic noise.

PU amplifies the electrical signal from the PIR output, filters it in the band of useful signals, selects informative features (amplitude, pulse polarity, duration of emissions, and their number), and activates the alarm when the values of these features within certain limits.

Pyroelectric sensors (pyroreceiver) have become widespread as receivers of infrared radiation. Pyroreceivers have a low speed, but it is enough to perceive human radiation. Pyroreceivers are highly sensitive, operate in the ranges of received power W = 1 nW ... 1 mW and wavelength λ = 7 ... 14 µm, the level of its own noise at the output is 10… 30 µV, the output resistance is 5 kOhm, simple and cheap [5, 6]. It is with their appearance associated with the widespread use of IR passive detection means (DM)

The pyroreceiver consists of a miniature ceramic radiation absorber. As absorbers are used lithium tantalate ($LiTaO_3$), lead titanate ($PbTIO_3$), lead niobate ($PbNbO_3$), lithium niobate ($LiNbO_3$), lead zirconate titanate (PZT). These substances are polarized when the irradiating energy flux changes, ie charges of the opposite sign are formed on opposite faces of the ceramic element. The magnitude of the charge is proportional to the current change in power absorbed. The principle of operation of the pyroelectric sensor is similar to the principle of operation of the piezoelectric sensor: the charge is generated only at the moment of change of physical influence.

Researches of infrared sensors as intelligent security detectors were considered in [7, 8, 9]. As noted in these works, infrared sensors are multifunctional and can be used in various fields. This can apply to both industrial lighting and smart home maintenance systems. However, an important element in these sensors are pyrodetectors, which

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are insufficiently considered. Therefore, the study of pyroelements in terms of physical perception of thermal radiation is relevant. The design of PIR sensors needs to determine the energy parameters that fall on the pyroelement and the level of the output signal, which is obtained from the output of the pyroreceiver.

II. Experimental Results And Discussion

Consider in more detail the mentioned pyroelectric effect. Pyroelectrics are crystalline dielectrics with spontaneous polarization in the absence of external influences, which increases or decreases with temperature change, accompanied by the formation of an electric field (pyroelectric effect) [5].

At a constant temperature, the polarization of the pyroelectric is neutralized due to the interaction of surface charges with free electric charges of air. If the temperature of the material increases, for example, when absorbing any visible or invisible radiation, the polarization also increases, which is observed as an electrical signal, usually when connecting electrodes to form a capacitor (Fig. 2).

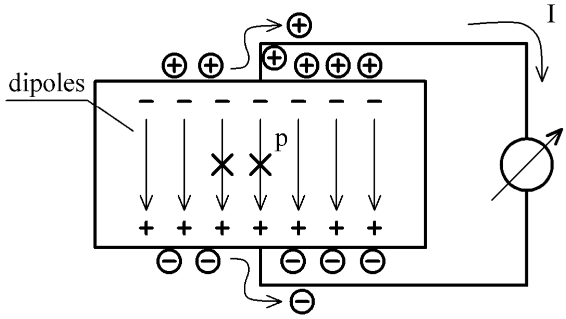

Fig. 2. The scheme of polarization of pyroelectrics

During a change in temperature, the pyroelectric is polarized, ie on opposite sides of it, there are different charges. This is possible in substances with spontaneous or residual polarization when the available polarization depends on the ambient temperature T_0. Due to the electrical conductivity, the associated polarization charges are usually compensated by free charges of the opposite sign, and the presence of polarization is not manifested. In the process of heating, the polarization value p changes, and part of the free charges are released. These free charges are detected by an external indicator - pyroelectric polarization, which is a function of temperature [4].

The appearance of the charge Δq on the faces of the pyroelectric (Fig. 3, a) is associated with the emergence of a temperature gradient T and additional polarization of the pyrocrystal when heated by light (heat) flux

$$\Delta q = \gamma \cdot S \cdot \Delta T \quad (1)$$

where γ – the pyroelectric coefficient of charge (depends on the absolute temperature), $C/(m^2 \cdot K)$; S – the area of the pyroelectric.

In the process of polarization, there is an intermediate conversion of light flux into heat. The value of ΔT is determined by the equations of a heat balance between the input Q_1 and the allocated Q_2 heat fluxes.

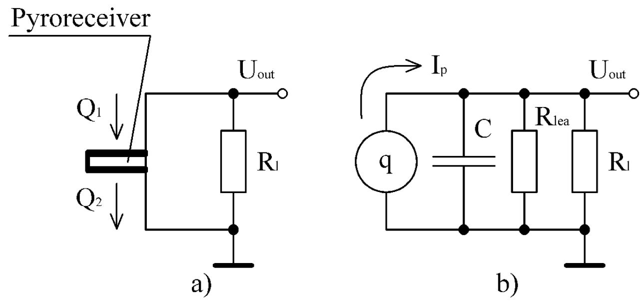

Fig. 3. Pyroelectric receiver (a) and its equivalent circuit (b)

From the electrical point of view, the pyroelectric can be represented as a capacitor C with a leakage resistance R_{lea} = 10^{11}-10^{12} Ohm, which is charged from the heat flow by a current I_p = dq / dt and discharged to a load resistance Rn (Fig. 3, b). The peak voltage removed from the capacitor plates is

$$U_0 = \Delta q / C = \gamma \cdot d \cdot \Delta T / (\varepsilon_0 \cdot \varepsilon) = \chi \cdot d \cdot \Delta T \quad (2)$$

where ε – the dielectric constant of the material; ε_0 = $8{,}854 \cdot 10^{-12}$ F/m; d – the thickness of the pyroelectric; χ – the coefficient of pyroelectric potential, V/(m·K).

Because the charge is generated in response to a temperature gradient, the pyroreceiver has a unique property, detecting only moving objects and does not respond to a stationary background. In other words, the pyroelectric is an active dynamic sensor.

The reaction of the pyroreceiver to the heat pulse is shown in Fig. 4. The leading edge of the output pulse is quite steep, and the decay of the pulse is gentle according to the expression

$$q(t) = q_0 \cdot exp(-t/\tau_\theta) \quad (3)$$

as determined by the thermal constant

$$\tau_\theta = \rho \cdot S \cdot d \cdot R_\theta \quad (4)$$

where q_0 – the peak value of the charge; ρ – the specific heat; R_θ – thermal resistance of the crystal - environment; S·d – the volume of pyroelectric.

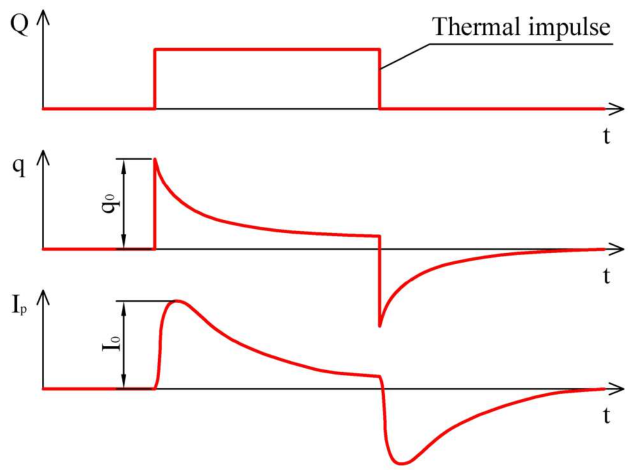

Fig. 4. Oscillograms of pyroelectric output signals under the influence of a thermal pulse

The temperature gradient and hence the output signal ultimately depend on the heat flux coming to the pyroreceiver. The heat flux density reaching the pyroelectric, proportional to its area S_1, is inversely proportional to the square of the distance to the object L and according to Stefan-Boltzmann's law is defined as

$$\psi \approx ((\sigma/(2\cdot\pi\cdot L^2))\cdot S_1\cdot(T_1^4 - T_0^4) \quad (5)$$

where $\sigma = 5{,}67\cdot10^{-8}$ W/(m$^2\cdot$K^4) – Stefan-Boltzmann constant, T_1, T_0 – absolute temperature of the object and the environment.

The magnitude of the flux Q_p, which is absorbed by the pyroelectric, is determined by the area S_2 of the input pupil of the optical system (or the area of the pyroelectric), its transmission μ, and the absorption coefficient of the input flux ε_p:

$$Q_p \approx (2\cdot\sigma\cdot\varepsilon_p/(\pi\cdot L^2))\cdot S_2\cdot\mu\cdot T_0^3\cdot\Delta T \quad (6)$$

where $\Delta T = T_1 - T_0$.

The peak voltage at the output of the pyroelectric can be calculated by the formula:

$$U_0 = \beta\cdot Q_p \quad (7)$$

where β – pyroelectric sensitivity factor, V/W.

A typical form of the useful signal at the output of the sensor, taking into account its amplification has the form shown in Fig. 5.

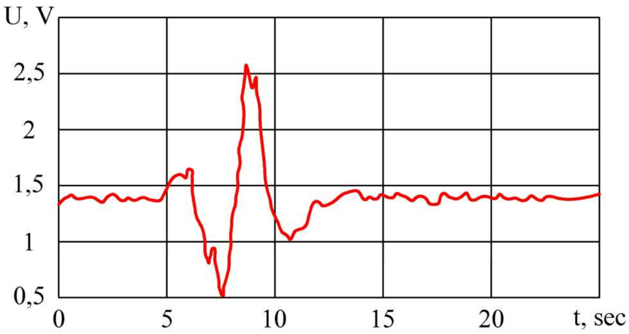

Fig. 5. The signal of the IR sensor when a person moves in the area of sensitivity

Usually, inside the pyroreceiver, there are two elements that are included opposite. Natural oscillations of background thermal radiation equally affect both elements and the charges generated by them mutually compensate each other.

When the sensitivity zone of the sensor is crossed by a person, it will be in the field of view of one crystal, and it will generate a voltage pulse according to the change in the level of infrared radiation. When an object enters the field of view of another crystal, it will also create a pulse, but of a different direction. The two-element sensitive element generates a bipolar (bipolar) symmetric signal when a person moves across the beam.

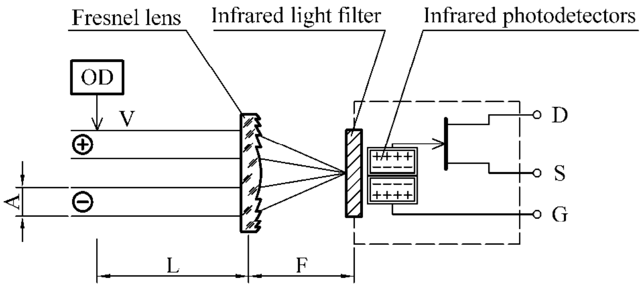

Fig. 6. Scheme of pyroreceiver

Its duration depends on how far a person is from the sensor and how fast it is moving. At a human speed of 0,2 ... 5 m/s, the duration of the useful signal can vary in the range of 0,02 ... 10 s.

The counter-inclusion scheme largely suppresses numerous interfering influences of a general nature. To spread the charge is an internal resistor that provides self-discharge with a time constant of about 1s. The charge signal is amplified by a field-effect transistor, which is built into the sensor.

From the point of view of the zones of sensitivity, we can assume that the rays are two; from the point of view of detection - one, as only the appearance of a bipolar signal $U_{out}(t)$ leads to the operation of the sensor (Fig. 7).

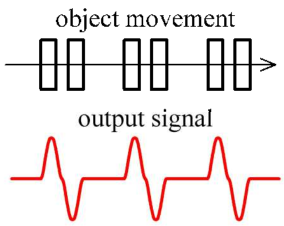

Fig. 7. The type of signal at the output of the pyroreceiver

However, in addition to the useful signal in the transmitter, there is an internal noise, which is a random signal with an average value of about 1.42 V, due to the operation of the preamplifier (Fig. 8).

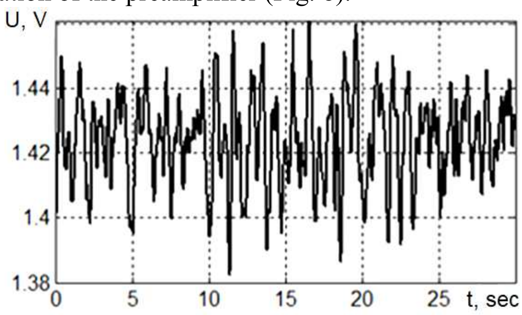

Fig. 8. Fragments of recorded noise signals

The power spectrum of the presented noise signals without their constant component is shown in Fig. 8.

From fig. 9 it follows that the internal noise is the low frequency with an effective frequency band in the range of 0.2 ... 3 Hz.

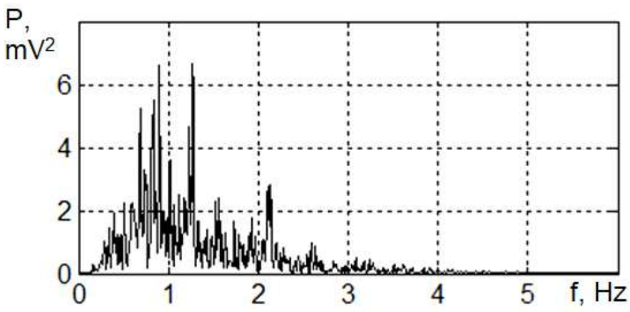

Fig. 9. Power spectrum of noise signals

The energy flux density increases as a person approach the sensor and the spectrum of useful signals shifts toward higher frequencies.

Consider in more detail the features of radiation that are perceived by a pyroelectric sensor.

The power distribution of electromagnetic radiation of a body having a temperature T along the wavelength λ obeys Planck's law:

$$dW = ((2\cdot\pi\cdot h\cdot c^2)/\lambda^5)\cdot((S/(exp(h\cdot c/(k\cdot\lambda\cdot T) - 1))d\lambda) \quad (8)$$

where dW – the radiation power in the wavelength range (λ, λ + dλ), *W;* h – Planck's constant, $h = 6{,}63\cdot10^{-34}$ J·s; s – speed of light, $c = 3\cdot10^8$ m/s; k – the Boltzmann constant, $k = 1{,}38\cdot10^{-23}$ J / K; T – the temperature of the radiating body, K; S – the surface area of the radiating body.

Planck's law holds exactly if the emitter is a so-called completely black body. In other cases, the radiation power is slightly lower, which is taken into account by introducing a coefficient ε, which is called the emissivity or radiation coefficient (ε = 0 ... 1). In general, the value of ε depends on the wavelength λ, temperature, angle of observation, and other factors, but many radiating surfaces can be roughly described by average values in the range λ = 5 ... 14 µm. All qualitative and quantitative estimates of the radiation characteristics of different bodies are based on the analysis of Planck's law [4].

First of all, differentiating the formula of Planck's law by *λ* and equating the derivative to zero, we obtain an expression for the wavelength corresponding to the maximum radiation of a body with temperature *T*. It is called Wine's law and

$$\lambda_{max} = h\cdot c/(4{,}97\cdot k\cdot T) = A/T \quad (9)$$

where A – a constant coefficient, $A = 2{,}898\cdot10^{-3}$ m·K.

The temperature range of the human body can range from 30 ... 42 ° C (T = 303 ... 315 K*)* and radiation at a wavelength of λ_{max} = A/T = 9.2 ... 9.6 µm. The maximum radiation varies within narrow limits, but the power itself is distributed over a wide range of wavelengths (Fig. 10). In the graph, the power is calculated relative to the maximum value, which is taken as a unit. For the PIR transducer to work effectively, it must receive radiation in the widest possible range of wavelengths. The interval λ = 4 .... 36 µm contains more than 90% of the total power. However, creating a wide-range infrared receiver is technically difficult. In addition, broadband reception with a small increase in the useful signal is accompanied by a significant increase in the interference signal. Therefore, it is much more important to cut off radiation with a wavelength less than 5… 7 µm and more than 14 ... 20 µm using special filters. Residual power is sufficient for the stable operation of the PIR converter. The interval λ = 7 .... 14 µm contains 43% of the power emitted over the entire wavelength range. In this interval all sensors reacting to the heat of a human body function.

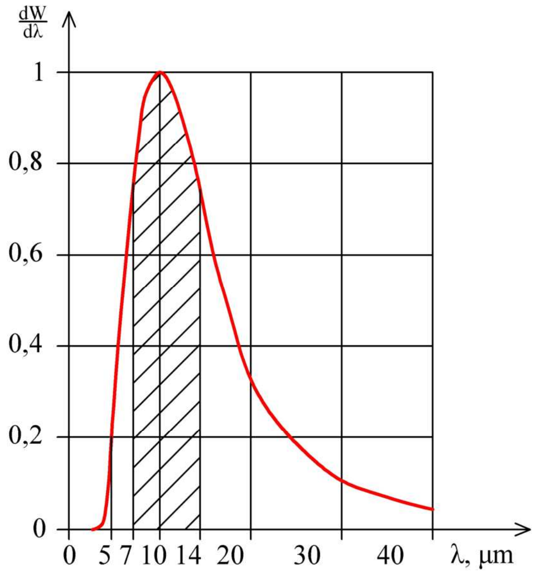

Fig. 10. Power distribution of human thermal radiation along the wavelength λ

The full power of infrared radiation can be found by integrating the expression of Planck's law over the entire wavelength range. The obtained dependence is called the Stefan-Boltzmann law:

$$W = \sigma\cdot\varepsilon\cdot S\cdot T^4 \quad (10)$$

where σ - Stefan-Boltzmann constant, $\sigma = 5{,}67\cdot10^{-8}$ W/(m²·K⁴).

Radiation of the human body having a temperature of T occurs against the background of radiation of surrounding objects with a temperature of T_{sur}. When a person appears, the change in power ΔW (compared to the surrounding background) will be equal to the difference between what is emitted by the body and what is absorbed by it from the surrounding space:

$$\Delta W = \sigma\cdot\varepsilon\cdot S\cdot(T^4 - (T_{sur})^4) \approx 4\cdot\sigma\cdot\varepsilon\cdot S\cdot(T_{sur})^3\Delta T \quad (11)$$

where $\Delta T = T - T_{sur}$.

The PIR sensor converts the power of the incident heat rays into a proportional electrical signal. Since the heat flow comes from all objects with non-zero temperatures, the sensor should only register its change. Let's estimate the power which is absorbed by the PIR converter at the emergence of the violator of perimeter protected. The surface area of the human body (his skin) is on average equal to S = 2.0 m²; it can vary within S = 1.4 ... 2.5 m². Clothing weakens the flow of electromagnetic radiation emitted by it. Part of the body (head, hands) are always open. The minimum value of the area can be taken equal to S = 1.0 m². Assuming ε = 0.9*,* the temperature in the room T_{sur} = 288… 308 K (15 C 35° C), the temperature difference ΔT = 1 … 20 K, we obtain the range of changes in radiated power $\Delta W = 4\cdot\sigma\cdot\varepsilon\cdot S\cdot (T_{sur})^3\cdot\Delta T$ = 5 .... 300 Вт.

Obviously, in the case of ΔT = 0 K a person completely "merges" with the background, so it is necessary to somehow set the minimum value of T. Natural temperature fluctuations in the room are at the level of hundredths of a degree, on the street in a quiet environment they reach 0.1 °C; to reliably detect useful signal changes, the detection threshold should be set at 1.2 °C.

The obtained range ΔW = 5… 300 W is consistent with the data on the overall energy balance of man. An adult at rest emits a power of about 120 watts into the environment; at light work, it grows to 250 W, and at heavy - to 500 W. At the same time, up to 55% of power is spent on direct radiation; the rest is removed by convection and evaporation.

The energy flux density (that is the energy passing per unit time through a unit area perpendicular to the direction of propagation) of human thermal radiation at the location of the sensor will be

$$P = \Delta W / (4 \cdot \pi \cdot L^2), \quad (12)$$

where L – the distance from the person to the sensor.

For distances L = 2 ... 10 m, the energy flux density is in the range P = ΔW / (4·π·L2) = 0.005 ... 6 W/m^2.

The power W_{rec} absorbed by the PIR converter is equal to the product of the energy flux density P and the area S_{rec} of the optical system that directs heat rays to the sensitive element. Then the expression for power will look like this

$$W_{rec}=K_\lambda \cdot K_s \cdot K_a \cdot \Pi \cdot S_{rec} = K_\lambda \cdot K_s \cdot K_a \cdot \sigma \cdot \varepsilon \cdot S \cdot (T_{sur})^3 \cdot \Delta T \cdot S_{прм}/(\pi \cdot L^2) \quad (13)$$

There are three additional factors that reduce the power absorbed by the PIR converter. Each of them corresponds to its coefficient K_λ, K_s or K_a ($0 < K_\lambda < 1$, $0 < K_s < 1$, $0 < K_a < 1$). The coefficient K_λ is equal to the fraction of power per band of wavelengths λ, which is absorbed by the PIR converter; for the interval λ = 7 ... 14 μm it is K_λ = 0.43. The coefficient K_s takes into account that the image area of the object of detection of S_{od} may exceed the area of the PIR-converter S_{PIR}, and then $K_s = S_{PIR}/S_{od}$, otherwise K_s = 1. The value of the coefficient K_a decreases with the increasing angle a between the flow direction *P* and normal to the area of the optical system; K_a = cosα. For single-beam detection objects, the value of $K_a = 1$.

If K_λ = 0,43, K_s = 1, K_a = 1, S = 0,0001 .... 0,0004 m^2, then the power that is received is $W_{rec} = K_\lambda \cdot K_s \cdot K_a \cdot \sigma \cdot \varepsilon \cdot S \cdot (T_{sur})^3 \Delta T \cdot S_{rec}/(\pi \cdot L^2) = 2 \cdot 10^{-7} ... 1 \cdot 10^{-3}$ W. To work with the effects of such levels, PIR must have a very high sensitivity. The level of received power decreases sharply with increasing distance *L*, with the only possibility of increasing the power - increasing the area of S_{rec}.

Let's estimate the frequency range of useful signals. The signal will have the longest duration if the person moves at the maximum distance L_{max} = 50 m with the minimum speed v_{min} = 0,3 m/s at an angle ϕ to a beam (sinϕ ≈ 1/2), then the time of increase of a signal

$$T_{max} = B / (v_{min} \cdot \sin\phi) \quad (14)$$

because the sensitive element captures only the change in heat flux.

The minimum frequency of the useful signal $f_H \approx 1 / (2 \cdot \pi \cdot T_{max}) \approx v_{min} \cdot \sin\phi / (2 \cdot \pi \cdot B) = 0{,}3 / (4 \cdot 3{,}14 \cdot 0{,}35) = 0{,}07$ Hz. The signal changes the fastest when a person moves with a maximum speed v_{max} = 5 m/s near the sensor at a distance $L_{min} = 2$ m perpendicular to the beam (sinϕ = 1). Then the signal rise time $T_{min} = A_{min}/v_{max} = a \cdot L_{min} / (F \cdot v_{max}) \approx 0{,}007$ c. The maximum frequency of the useful signal will be $f_B \approx 1/(2 \cdot \pi \cdot T_{min}) = Fv_{max}/(2 \cdot \pi \cdot a \cdot L_{min}) = 0{,}06 \cdot 5/(2 \cdot 3{,}14 \cdot 0{,}001 \cdot 2) = 24$ Hz. Value f_H and f_B determine the filter band in the PU.

The energy flux density increases as a person approach the sensor and the spectrum of useful signals shifts toward higher frequencies. Most pyroreceivers have internal correction circuits that attenuate the high-frequency components of the signals. Usually, their sensitivity γ decreases evenly in the frequency range above 0.1 Hz (Fig. 11). As a result, the level of useful signals at the output of the pyroreceiver is weakly dependent on the distance to the sensor and the speed of movement.

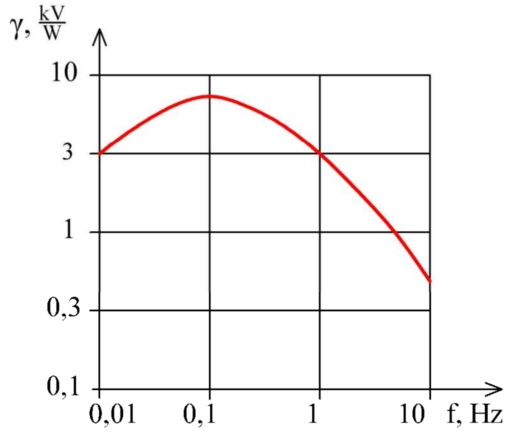

Fig. 11. Frequency response of the pyroreceiver

Estimation of parameters (level of the received power of thermal radiation and a range of frequencies of useful signals) for multibeam DT is carried out on the same parity, as for a single beam. The compact dimensions of the device are provided when using lenses of small area, for one beam $S_{rec} \approx 0.0002$ m^2, respectively, and their focal length is in the range F = 20 ... 40 mm. For the average values of V = 0.3 ... 3 m / s, a = 1 mm, L = 1.5 ... 15 m, F = 25 mm, sinϕ = 0.5… 1 we obtain the frequency range of useful signals $f = F \cdot v \cdot \sin\phi / (2 \cdot \pi \cdot a \cdot L) = 0.04 ... 8$ Hz. The value of the minimum radiation power received by the pyroreceiver will be $W_{rec} = K_\lambda \cdot K_s \cdot K_a \cdot \sigma \cdot \varepsilon \cdot S \cdot (T_{sur})^3 \cdot \Delta T \cdot S_{rec} / (\pi \cdot L^2) = 170$ nW. It corresponds to the minimum level of the useful signal $U_{out} = \gamma \cdot W_{rec} = 4000 \cdot 170 \cdot 10^{-9} = 680$ μV.

The amplitude of the intrinsic noise of the pyroreceiver is about 20 μV. The area of the radiating surface within one beam is equal to

$$S = 2 \cdot a \cdot b \cdot L^2/F^2 \quad (15)$$

The power of N independent emitters is proportional to $(N)^{1/2}$. The number of rays N is approximately equal to N ≈ 20. Therefore, the dependence of the received power on the temperature changes of the background *T* is described by the expression

$$W_{rec} = K_\lambda \cdot K_s \cdot K_a \cdot \sigma \cdot \varepsilon \cdot S \cdot (T_{sur})^3 \Delta T \cdot S_{rec} / (\pi \cdot L^2) = K_\lambda \cdot K_s \cdot K_a \cdot \sigma \cdot \varepsilon \cdot 2 \cdot a \cdot b \cdot (N)^{1/2} (T_{sur})\ 3 \cdot \Delta T \cdot S_{rec} / (\pi \cdot F^2) \quad (16)$$

The expression does not include the range L. For the typical indoor level of temperature fluctuations T = 0.01 ...

0.02 °C associated with natural convection, we obtain an estimate of the power level W_{rec} = 11 ... 22 nW and the amplitude of the interference fluctuation signal Uout = $\gamma \cdot W_{rec}$ = 40 ... 90 μV.

III. Conclusion

The shape of the output signal from the pyroreceiver has a triangular or trapezoidal shape, the duration of the signal is determined by the intersection of the radial zone and when moving normally to the beam can be from 0.05 to 10 s. When moving at an angle to normal, the signal duration increases. The maximum spectral density of the signal is in the range from 0.15 to 5 Hz; when a person moves along the beam, the signal is minimal and is determined only by the temperature difference of individual parts of the human surface and is a fraction of a degree.

The frequency range of the useful signal from the pyroreceiver, which is formed due to the influence of thermal radiation is from 0.07 Hz to 24 Hz. The signal is affected by the speed of movement of the cell of infrared radiation and its distance to the pyroreceiver.

The use of a single-element pyrodetector in electronic security devices is impractical because it does not provide adequate operation for thermal radiation of the human body. A two-element sensitive element is required for efficient operation, which generates a bipolar (bipolar) symmetrical signal when a person moves across the beam. The pyroelements are included opposite each other. Such an inclusion scheme greatly suppresses numerous general interfering influences.

It is established that the pyroelectric sensor can perceive the power of infrared radiation in the range from 5 to 300 watts. Since the average human body emits more than 120 watts into the environment, this type of sensor is very well suited for security devices to detect the presence of a person in the security zone.

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