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FEATURES OF GENERATING THE OUTPUT SIGNAL OF THE INFRARED RADIATION SENSOR

The paper deals with infrared radiation detectors that can register the thermal radiation of a living organism. The human body has a temperature in the range from 31°C to 42°C, depending on the heat exchange between the skin and the environment, and infrared radiation in the wavelength range from 4 to 50 microns. The analysis of the phenomenon of the pyroelectric effect and the features of the use of pyroelectric sensitive elements, which are the basis of the operation of the sensors, has been carried out. The principles of the formation of thermal radiation in the detection zone of the sensor are given, and the formulas for determining the amount of radiation of the thermal flux are presented. The process of forming the output signal during the action of thermal energy on the sensor was studied. It has been established that for the rational use of methods and algorithms for improving the interference immunity of an infrared sensor, it is necessary to know the main parameters of the signal, namely the amplitude, shape, duration, dependence on the speed of human movement, and background temperature. Experimental graphs of the shape and spectrum of the signal at the input of the pyroelectric sensor under different input conditions are presented. The influence of temperature contrast on the formation of the sensor output signal is analyzed.
Keywords: *sensitive element, pyroreceiver, IR radiation, signaling, sensitivity zone.*

Introduction. Sensors based on a pyroelectric sensitive element are widely used for various needs. These are security alarms, automatic lighting systems, etc. The basis of the operation of such sensors is the registration of infrared radiation (IR) of a living body using a sensitive element. Infrared radiation is a type of electromagnetic wave, the wave-length of which is longer than that of visible light (0.74 μm), but shorter than that of radio waves (1...2 mm). Such radiation cannot be seen by the human eye, but it has thermal energy that can be recorded [1].

The human body has a temperature in the range of 31°C to 42°C, which depends on the heat exchange between the skin and the environment. It is a source of IR radiation in the wavelength range from 4 to 50 μm [2]. At the same time, the radiation density of the skin of the human body is: with a wavelength of up to 5 μm – up to 1%; with a wavelength from 5 to 9 μm – 20%; with a wavelength from 9 to 16 μm – 30%; with a wavelength over 16 μm – over 41% (Fig. 1). The human body emits infrared energy with a peak wavelength of 9 μm to 10 μm. In addition, the peak wavelength of infrared rays emitted by a heated object becomes shorter as the temperature increases [3].

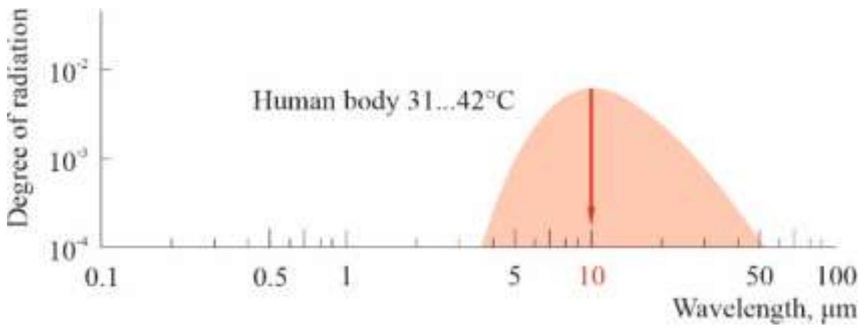

Figure 1 – Distribution of human body radiation by wavelength [3]

To understand the possibilities of using pyroelectric sensors for specific cases, it is necessary to analyze the pyroelectric effect, the principles of the formation of heat flows in the detection zone, and how the output signal is formed when thermal energy acts on the sensor [4].

Literature revive. The principle of operation of the sensitive sensor element is that some crystalline materials are characterized by the property of being polarized under the influence of IR radiation. Along with the change in radiation intensity, polarization is carried out and, as a result, a dipole moment is created in a crystal made of materials called pyroelectrics [2, 5]. By detecting the difference in potentials formed as a result of polarization between different regions of the pyroelectric crystal, it is possible to observe the amount of thermal IR radiation (Fig. 2). The principle of operation of IR sensors consists of the registration of thermal signals emitted by objects in the area of the sensor. The useful signal at the output of a single-surface receiver, depending on the radiation, is determined by the formula (1) [6]:

$$S(t) = S_U \Delta Q(t) \tag{1}$$

where S_U is the voltage sensitivity of the radiation receiver; $\Delta Q(t)$ is a change in the amount of heat flow that enters the input hole of the optical system and occurs in the event of movement of the object in the area of the sensor.

The maximum value of $\Delta Q(t)$ occurs if the object completely falls into the detection zone of the IR sensor. Let's take this value as ΔQ. Consider the option if the losses in the optical system are small enough to be neglected. Let's determine ΔQ through the object's parameters and the environment's background. Suppose that within the background (the absolute temperature of the surface of which is T_b and the emissivity E_b), an object with the absolute temperature T_{ab} and the emissivity E_{em} appears [7, 8].

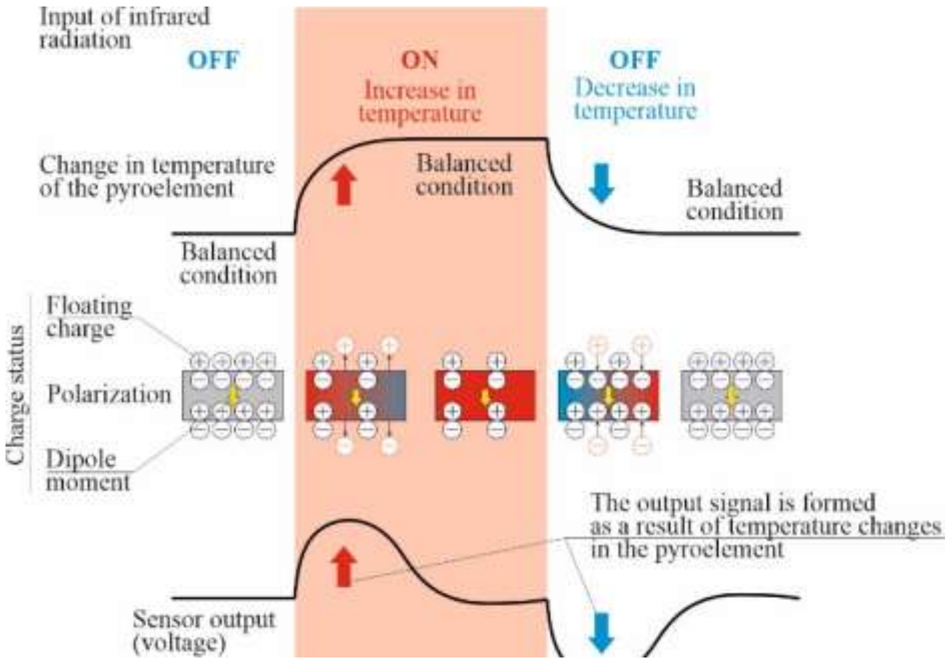

Figure 2 – The phenomenon of the pyroelectric effect [7, 8]

We will denote the area of the projection of the object on the plane that is perpendicular to the direction of radiation by S_{em}, and the area of the projection of the background in the field of view by S_b [9]. For such a case, the amount of heat flow that enters the optical system inlet before the observation object appears is determined by the formula (2):

$$Q_b = L_b \frac{S_b S_{in}}{l_b^2} \tag{22}$$

where l_b is the distance from the entrance hole to the background surface; L_b – is background brightness; S_{in} – is the area of the entrance hole of the optical system.

The value of the heat flow, which is created by the object of observation, is determined by formula (3):

$$Q_{ab} = L_{ab} \frac{S_{ab} S_{in}}{l^2} \tag{3}$$

where l is the distance from the sensor to the observation object; L_{ab} is the brightness of the observation object.

In the presence of an object of observation, the total heat flow entering the inlet created by the object and a separate part of the background surface not shielded by the object is determined by the formula (4):

$$Q_\Sigma = L_b \frac{S_b S_{in}}{l_b^2} + L_{ab} \frac{S_{ab} S_{in}}{l^2} = L_b \frac{S_{in}}{l_b^2}\left(S_b - \frac{S_{ab}}{l^2} l_b^2 \right) + L_{ab} \frac{S_{ab} S_{in}}{l^2} \tag{4}$$

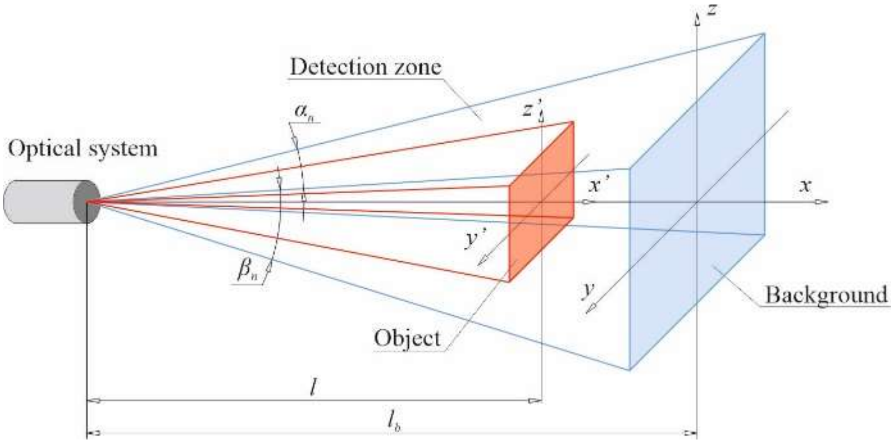

Figure 3 – Scheme of the detection zone of the infrared pyroelectric sensor [8]

The change in heat flux radiation ΔQ is determined by formula (5):

$$\Delta Q = \frac{S_{ab} S_{in}}{l^2}\left(L_{ab} - L_b\right) \quad (6)$$

Let's accept the statement that Lambert's law is fulfilled for the object of observation and the background, so we determine the luminances L_{ab} and L_b through the emissivity and absolute temperatures:

$$L_b = \frac{\delta_0 E_b T_b^4}{\pi}, \quad L_{ab} = \frac{\delta_0 E_{em} T_{ab}^4}{\pi} \quad (7)$$

where δ_0=5.67·10^{-8} W/(m^2·K^4) is the Stefan-Boltzmann constant.

Substitute formula (6) into formula (5) and get the expression for ΔQ taking into account the absolute temperature and emissivity of the observation object and the background:

$$\Delta Q = \frac{\delta_0 S_{in} S_{em}}{\pi l^2}\left[E_{em} T_{ab}^4 - E_b T_{ab}^4\right] = \Delta E S_{in} \quad (8)$$

Given the given parameters of the optical system and the radiation receiver, the signal value is completely determined by the change in the irradiance of the sensitive element. It is known that the emissivity of human skin is very high and is on average 0.99 relative to a completely black body at wavelengths longer than 4 μm [10]. In the IR region of the spectrum, the optical properties of skin radiation are quite close to the characteristics of black body radiation [11].

The temperature of the skin depends on the heat exchange between the skin and the environment. Thus, at an air temperature of +25°C, the temperature on the surface of a person's palm varies within the range of +32...+34°C, and at an air temperature of +19°C, it varies within the range of +28...+30°C. The presence of clothing reduces the thermal radiation of the object because the temperature of the clothing is lower than the temperature of bare skin. If the temperature around the object is +25°C, then the average temperature of the body surface of a clothed person is approximately +26°C. Other parameters included in the formula (7) can take on different values that depend on the specific situation and/or input data [12].

Research methodology. To establish relationships between the structural elements of the infrared sensor and the influence of external environmental factors on the output signal from the sensor, theoretical research methods were used, in particular, the phenomenon of the pyroelectric effect and the dependence of the sensitivity of the receiver on thermal radiation were analyzed [13].

Observation, measurement, and experiment methods were used to confirm the de-scribed phenomena. In particular, infrared transmitters with two-element pyroreceiv-ers were used. The movement of an object emitting infrared (thermal) radiation was simulated in the detection zone of the sensor. A spectroanalyzer was used to remove the output signal from the sensor. The resulting spectrogram was analyzed by shape and spectrum. To obtain data based on which the output signal was analyzed, an experimental study of the movement of a thermal object was carried out at different speeds at different distances from the pyroelectric receiver [14].

Results. We will analyze the process of generating signals for the sensor, the main types of interference, and extraneous influences that cause false operation of the IR sensor.

Signal generation. To understand the methods and algorithms for improving the in-terference immunity of the IR transmitter, it is necessary to know the main parameters of the signal – amplitude, shape, duration ΔE, dependence on the speed of human movement, and background temperature:

$$\Delta E = \frac{\delta_0 S_{em}}{\pi l^2}\left[E_{em} T_{ab}^4 - E_b T_b^4\right] \quad (9)$$

Consider, for example, one detection zone, the length of which is 10 m, and the beam's diameter at the base of the cone is 0.3 m. Let us assume that a person crosses the zone normally with different speeds (V_{max}, V_{min}) at a distance from the receiver of 10.5 and 1 m. The signal's shape in the case of crossing the beam at a distance of 10 m has a triangular shape with a maximum when the detection zone is completely covered (Figure 4a). Figure 4b shows the spectrum of this signal. If the beam crossing occurred at a shorter distance, the signal acquires a trapezoidal shape with steep fronts (Figure 5a) and the spectrum of this signal takes on the form shown in Figure 5b.

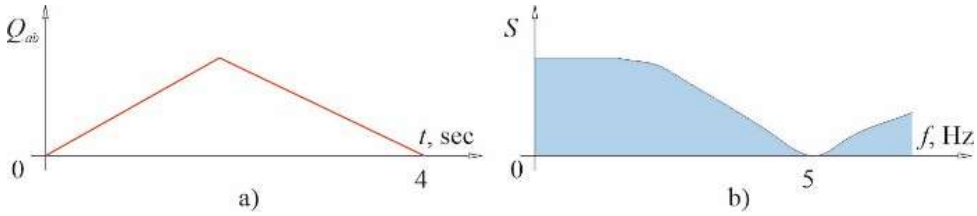

Figure 4 – The shape and spectrum of the signal at the input of the pyroelectric sensor under the conditions of D_{max}, V_{min}.

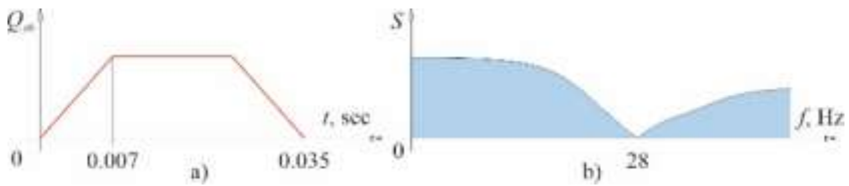

Figure 5 – The form and spectrum of the signal at the input of the pyroelectric sensor under the condition of D_{min}, V_{max}.

It was found that the duration of the output signal is inversely proportional to the speed of the object and the distance to the sensor. The real output signal differs from the ideal due to various distortions introduced by the amplification path and the influence of chaotic noises created by various temperature fluctuations in the background. Recordings of real signals obtained using a passive IR detector are shown in Figure 6. The figure also shows its spectral characteristics, which were obtained using a spectroanalyser.

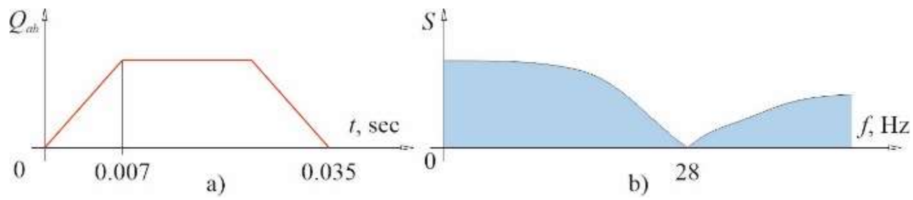

Figure 6 – Graphs of the change in the signal at the output of the pyroelectric sensor (a) and spectrograms of the signals (b).

The analysis of the graphs established the spectral range that is necessary for the transmission of signals generated when crossing the detection zone in the entire range of object speeds from 0.1 to 15 Hz. At the edges of the range, there is a possibility of weakening the signal, since the pyroreceiver has a frequency response with a drop in the region of 5...10 Hz. For its compensation, it is necessary to introduce an amplifier into the signal processing path, which provides a rise in the frequency response in the region of 5...20 Hz.

Usually, the amplitude of the output signal is determined by the temperature contrast between the human body and the background on which the detection beam is directed. Since the background temperature changes with the room temperature, the output signal also changes, which is proportional to their difference. At the point where the temperature of the person and the background coincide, the value of the output signal is zero. In the region of higher temperatures, the signal changes sign. The background temperature in the room reflects the temperature of the air outside the room with some delay, which is due to the thermal inertia of the wall materials and the way the building is insulated.

Temperature contrast depends on the temperature of the outer surface of a person, which is affected by clothing. Moreover, it is necessary to take into account that if a person enters a room where an IR motion detector is installed, for example, from a cold street, then at the first moment the thermal contrast is quite significant. Gradually, as the temperature of the clothes adapts to the temperature of the room, the signal decreases significantly. However, even after a long stay indoors, the amount of the input signal depends on the type of clothing. Figure 7 shows experimental dependences of the temperature contrast of a person on the temperature around the object. The dashed line shows the extrapolation of experimental data for temperatures above +40°C.

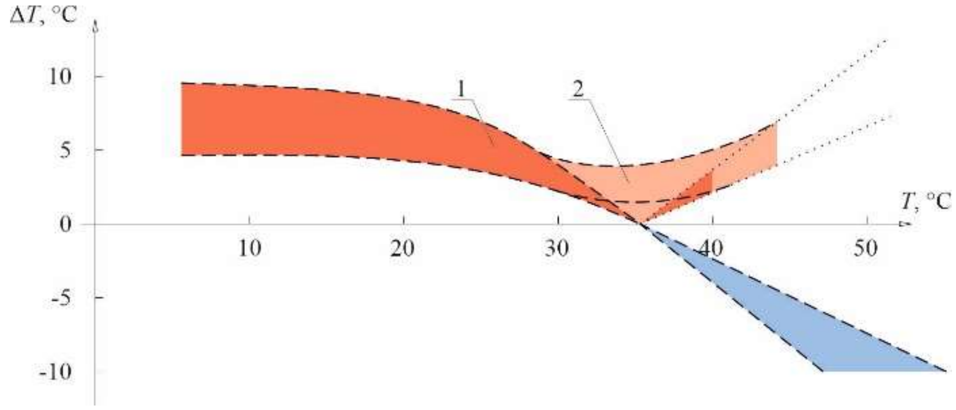

Figure 7 – Dependence of the temperature contrast of a person on the temperature of the environment.

Area 1 is a range of contrasts depending on the shape of the clothes, the type of background, the size of the person, and the speed of his movement. The transition of the value of the temperature contrast through zero occurred only if in the temperature range of 30...39.5°C the measurements were carried out after the adaptation of the object in the heated room for 15 minutes. In the case of the invasion of an object that was previously in a room with a temperature below 30°C or outdoors with a temperature of 44°C, into the sensor's sensitivity zone, the signal levels in the temperature range of 30...39.5°C lie in regions 2 and do not reach zero.

The temperature distribution on the human surface is not uniform. It is closest to 36°C on exposed parts of the body - the face and hands, and the temperature of the surface of clothes is closer to the background of the room. Therefore, the signal at the input of the pyro receiver depends on which part of the body overlaps the radiant zone of sensitivity.

Let's analyze the influence of interference that causes false operation of passive IR sensors. These are the effects of the external environment or internal noises of the receiving device of the transmitter, which are not related to the movement of the object in the sensitivity zone.

There is the following classification of obstacles:

- thermal, which is caused by heating the background of the room under the influence of solar radiation, convection air flows from the operation of radiators, air conditioners, drafts, etc.;
- electrical, caused by guidance from sources of electrical and radio radiation on individual elements of the electronic part of the IR sensor;
- own, which are caused by the noise of the pyroreceiver and the input signal amplification path;
- extraneous, which is associated with the movement of small animals or insects on the surface of the input optical window in the sensitivity zone of the IR sensor.

Conclusions. As a result of the analysis of the process of formation of the output signal, it was established that the amplitude of the signal is determined by the temperature contrast of the surface of the detection object and the surrounding background, which can range from a fraction of a degree to tens of degrees. The shape of the signal has a triangular or trapezoidal appearance, the duration of the signal is set by the intersection of the detection zone and, when moving normally to the beam, can be 0.05...10 s. During movement at an angle to the normal, the duration of the output signal increases.

The maximum spectral density of the output signal is in the range of 0.15...5 Hz; when a person moves along the beam, the signal is minimal and is determined only by the temperature difference of individual areas of the person's surface and is less than 1°C. During the movement of the object between the beams, the signal is practically absent; at a temperature in the room, which is close to the temperature of the surface of the human body, the signal is minimal, i.e. the temperature difference is less than 1°C. Signal amplitudes in different beams of the detection zone can differ significantly from each other, as they are determined by the temperature contrast of the human body and the area of the background to which this beam is directed, the difference can reach less than 10°C.

The spectral range of interference covers the range of the signal and lies in the region from one to tens of hertz. The most dangerous type of interference is background sunlight, the effect of which increases the background temperature by 3...5°C. The influence of sunlight for close areas of the background is strongly correlated with each other and can be weakened when using a two-beam scheme for the construction of detection means. Convective disturbances from thermal household devices take the form of fluctuating random temperature fluctuations that reach 2...3°C in the frequency range from 1 to 20 Hz with a weak correlation between beams.

Electrical disturbances take the form of short pulses or step functions with a steep front, the applied voltage can be hundreds of times higher than the input signal. The intrinsic noise of the pyroreceiver, corresponding to the signal when the temperature changes by 0.05...0.15°C, lies in the frequency range that overlaps the range of the input signal and increases proportionally to the temperature by about half for every 10°C.

References

1. S. Moroz, A. Tkachuk, V. Zablotskyi, S. Prystupa, V. Lyshuk and V. Talakh, "Analysis of Technical Characteristics of Temperature Sensors for the Design of Medical Thermometers," 2023 13th International Conference on Dependable Systems, Services and Technologies (DESSERT), Athens, Greece, 2023, pp. 1-4, doi: 10.1109/DESSERT61349.2023.10416501.
2. S. A. Moroz, M. V. Khvyshchun, A. A. Tkachuk, V. V. Lyshuk and S. O. Prystupa, "Investigation of Features of Functioning of the Pyroelectric Sensors in Electronic Security Devices," 2021 IEEE 12th International Conference on Electronics and Information Technologies (ELIT), Lviv, Ukraine, 2021, pp. 27-32, doi: 10.1109/ELIT53502.2021.9501138.
3. Yu Z, Yuan L, Luo W, Feng L, Lv G. Spatio-Temporal Constrained Human Trajectory Generation from the PIR Motion Detector Sensor Network Data: A Geometric Algebra Approach. Sensors. 2016; 16(1):43. https://doi.org/10.3390/s16010043.
4. A. Zviagintsev, I. Brouk, I. Bloom and Y. Nemirovsky, "Voltage and current integrated readout for uncooled passive IR sensors based on CMOS-SOI-NEMS technology," 2014 IEEE 28th Convention of Electrical & Electronics Engineers in Israel (IEEEI), Eilat, Israel, 2014, pp. 1-5, doi: 10.1109/EEEI.2014.7005758.
5. Danaci, K.I., Akagunduz, E. A survey on infrared image & video sets. Multimed Tools Appl 83, 16485–16523 (2024). https://doi.org/10.1007/s11042-023-15327-8.
6. Wang, Y., Peng, L., Schreier, J. et al. Silver telluride colloidal quantum dot infrared photodetectors and image sensors. Nat. Photon. 18, 236–242 (2024). https://doi.org/10.1038/s41566-023-01345-3.
7. Pang, X., Wang, Y., Zhu, Y. et al. Non-volatile rippled-assisted optoelectronic array for all-day motion detection and recognition. Nat Commun 15, 1613 (2024). https://doi.org/10.1038/s41467-024-46050-z.
8. T. Salzmann and M. Magno, "A Low Power Infrared Sensor for Direction, Speed, Distance Finding for Contextual Intelligence," 2022 IEEE Sensors, Dallas, TX, USA, 2022, pp. 1-4, doi: 10.1109/SENSORS52175.2022.9967162.
9. K. Sureeya, C. Karupongsiri and K. Chetpattananondh, "Implementation of a IR Sensor as a Measurement Device for Smart Farming," 2021 18th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON), Chiang Mai, Thailand, 2021, pp. 742-745, doi: 10.1109/ECTI-CON51831.2021.9454671.
10. Q. S. Hamad, M. S. Croock and S. Al Qaraawi, "Efficient infrared sensor and camera based monitoring system," 2013 International Conference on Electrical Communication, Computer, Power, and Control Engineering (ICECCPCE), Mosul, Iraq, 2013, pp. 20-25, doi: 10.1109/ICECCPCE.2013.6998764.
11. S. A. Daud, S. S. Mohd Sobani, M. H. Ramiee, N. H. Mahmood, P. L. Leow and F. K. Che Harun, "Application of Infrared sensor for shape detection," 2013 IEEE 4th International Conference on Photonics (ICP), Melaka, M, 2013, pp. 145-147, doi: 10.1109/ICP.2013.6687095.
12. S. Singh, B. K. Shukla and S. Moses Santhakumar, "Infra-Red Sensor-Based Technology for Collecting Speed and Headway Data on Highways Under Mixed Traffic Conditions," 2020 7th International Conference on Signal Processing and Integrated Networks (SPIN), Noida, India, 2020, pp. 607-611, doi: 10.1109/SPIN48934.2020.9070829.
13. B. Mustapha, A. Zayegh and R. K. Begg, "Ultrasonic and Infrared Sensors Performance in a Wireless Obstacle Detection System," 2013 1st International Conference on Artificial Intelligence, Modelling and Simulation, Kota Kinabalu, Malaysia, 2013, pp. 487-492, doi: 10.1109/AIMS.2013.89.
14. Xu, D., Wang, Y., Xiong, B. et al. MEMS-based thermoelectric infrared sensors: A review. Front. Mech. Eng. 12, 557–566 (2017). https://doi.org/10.1007/s11465-017-0441-2

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ОСОБЛИВОСТІ ФОРМУВАННЯ ВИХІДНОГО СИГНАЛУ ДАТЧИК ІНФРАЧЕРВОНОГО ВИПРОМІНЮВАННЯ

У статті розглядаються детектори інфрачервоного випромінювання, які можуть реєструвати теплове випромінювання живого організму. Тіло людини має температуру в діапазоні від 31°C до 42°C залежно від теплообміну між шкірою та навколишнім середовищем та інфрачервоне випромінювання в діапазоні довжин хвиль від 4 до 50 мікрон. Проведено аналіз явища піроелектричного ефекту та особливості його використання. Наведено принципи формування теплового випромінювання в зоні виявлення датчика та наведено формули для визначення величини випромінювання теплового потоку. Досліджено процес формування вихідного сигналу під час дії теплової енергії на датчик. Встановлено, що для раціонального використання методів і алгоритмів підвищення завадостійкості інфрачервоного датчика необхідно знати основні параметри сигналу, а саме амплітуду, форму, тривалість, залежність від швидкості руху людини і фонова температура. Наведено експериментальні графіки форми та спектру сигналу на вході піроелектричного датчика за різних умов входу. Проаналізовано вплив температурного контрасту на формування вихідного сигналу датчика.

Ключові слова: *чутливий елемент, піроприймач, ІЧ-випромінювання, сигналізація, зона чутливості.*