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PHYSICAL MODELS OF OPTICAL-ELECTRONIC SYSTEMS OF THE IR SPECTRUM RANGE WITH THERMOELECTRIC COOLING (REVIEW)

The paper considers the main physical models of optical-electronic systems in the IR spectrum range with thermoelectric cooling. The features and advantages of these models are analyzed. It was established that the simplest and the one that is practically used in industrial samples of IR devices is a model of a thermoelectric module built into a metal case with photosensitive elements that are cooled. Such a model with cascade thermoelectric coolers (TEC) made of materials based on $Bi_2 Te_3$ ensures the level of operating temperatures of IR devices up to 195 K. It has been shown that expanding the cooling range to temperatures of 140-150 K is possible by using functionally graded materials and additional stages of low-temperature thermoelectric materials, for example BiSb-based materials, for TEC. It has been established that the energy efficiency of a TEC significantly depends on the optimization of its design, which should take into account the electrical and thermal resistance of contacts, interconnect and insulation plates, as well as the influence of the thermal resistance of the IR detector case, its connections with the TEC, heat sinks and heat exchangers used in the system for heat removal from TEC. Therefore, the TEC design must take into account all system components, and the choice of the physical model of the optical-electronic system with TEC is important. Bibl. 32, Fig. 11, Tabl. 2.
Key words: optical-electronic system, IR device, thermoelectric cooler, physical model.

General information about optical-electronic systems of the IR range

Optical-electronic systems are widely used for recording IR radiation and forming IR images in modern ground-based and space-based equipment. But the leading place among the many uses of infrared optical-electronic technology is occupied by its application in military affairs. IR systems are used to detect and track ground, surface and underwater targets, in night vision and thermal reconnaissance devices, in forward inspection systems for aircraft, combat vehicles, in mine detectors, range finders, in weapon and projectile control systems and many other military instruments equipment necessary for protection and safety.

The main element of IR systems and devices is a photodetector, that is, a radiation detector with an internal photoelectric effect. In general, the simplest photodetector is a photosensitive element located in a sealed protective housing with an input window made of transparent material for radiation. As a photosensitive element, photoresistor, photodiode, phototransistor and photothyristor structures made of semiconductor material sensitive to radiation in the operating (for a given device) spectrum range are used. Modern photodetectors, as a rule, are multi-element, that is, they contain a number of photosensitive elements.

The problem is that the photosensitive element needs to be cooled in order for IR photodetectors to work. In order to increase the detection ability, it is necessary to suppress the own radiation of the sensitive element. This is achieved by cooling to temperatures at which self-radiation noise becomes negligible. In addition, the cooling of small sensitive elements with a low heat capacity makes it impossible for them to heat up too much under the influence of intense radiation. Cooling is also necessary to reduce the thermal generation of charge carriers in the semiconductor photosensitive element. The heat spreaders of the carriers compete with the optical transitions, which leads to a large amount of dark noise in uncooled devices.

The operating temperature of the photodetector is related to the operating wavelength range of the IR detector and depends on the material and technology of the photosensitive element. Photocells made of different semiconductor materials will also have different operating temperatures which can reach the cryogenic level [1]. Four cooling methods are used:

- liquefied gases;
- due to the Joule-Thomson effect;
- cryogenic machines;
- thermoelectric cooling.

The choice of method depends on the requirements for the operating temperature of the receiver and on the surrounding conditions. In particular, the method of liquefied gases is used in the conditions of laboratory research, in industry, medicine, but it is absolutely not suitable for military equipment. Other methods, on the contrary, are mainly developed for military affairs, but are also used in other fields.

To cool the IR detectors to cryogenic temperatures, micro cryogenic systems based on the Stirling gas machine [2], which is connected to the photodetector in a single structure, are specially developed and used. They ensure the cooling temperature of the photodetector at the level of 75 - 150 K. These are energy-efficient coolers. With a cooling capacity in the range of 100 - 600 mW, their coefficient of performance reaches the values of 10^{-2} – 3 10^{-2}. The main disadvantage of such systems is their high cost. Such mechanical cooling systems make optoelectronic devices bulky, expensive, and unreliable, which prevents the widespread practical use of IR devices.

However, not all IR devices need such deep cooling. For example, medium-wave (3 – 5 μm) and long-wave (5 – 30 μm) IR detectors, which are required for many important practical applications, usually work without cryocooling [1]. Scientific studies have shown that sufficiently high characteristics of sensors in the medium and long-wave IR range are provided at operating temperatures of photodetectors significantly higher than cryogenic ones [3, 4]. These temperatures are achieved using thermoelectric cooling [5, 6], which in this case is more rational compared to the machine method of cold generation.

Thermoelectric cooling is widely used to ensure the required operating temperature of IR detectors [1]. Operating temperatures of IR detectors up to 190 K are achieved using thermoelectric coolers [1, 5, 6], which have no moving parts, are compact, reliable, and have a long service life. The operating temperature of such devices is related to the operating range of the IR detector and depends on the material and manufacturing technology of the photosensitive element. The most common elements for IR detectors are photoresistors based on *PbS* and *PbSe*, photodiodes made of InGaAs, photodiodes and photoresistors based on *InSb* and *HgCdTe*. Modern materials for IR detectors are, for example, *GaAs*/*AlGaAs* quantum well materials [7] and *InAs*/*GaSb* superlattices [8], which serve as an alternative to *HgCdTe*, because the use of *Hg* and *Cd* toxic elements in electronic devices is limited by European Union directives. The operating temperatures of photosensitive elements made of all these materials are compatible with the temperature range provided by thermoelectric cooling. Single-stage thermoelectric modules are used for temperature stabilization and shallow cooling of IR detectors. Two-stage modules are used for IR detectors with an operating temperature of 230 K, three-stage modules are cooled to an operating temperature of 210 K, and four-stage modules are cooled to 195 K. The industrial manufacturer of IR detectors based on *HgCdTe* with built-in 2-, 3- and 4-stage thermoelectric modules is the European company Vigo Photonics [6].

Main physical models of optical-electronic systems with thermoelectric cooling

Let us consider the physical models of optical-electronic systems with thermoelectric cooling. The simplest model contains a photo-receiving device placed on the heat-absorbing face of a thermoelectric cooling module, which is usually mounted in a sealed case, the base of which is in thermal contact with the heat exchanger.

This simplest model was used in the period 1973 – 1975 for airborne infrared technology [9]. An IR detector with a *PbSe*-based photosensitive element and a single-stage thermoelectric cooler (TEC) was installed in the device case with a lens pumped at a given solid angle. The physical model of the device is shown in Fig. 1.

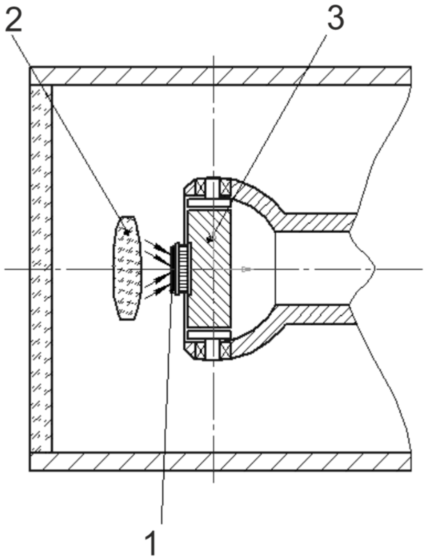

Fig. 1. The simplest model of IR device with TEC [9].
1 – IR detector with TEC, 2 – lens, 3 – hear-receiving base

The cooler consumed less than 0.6 W of power and lowered the temperature of the sensitive element by 35-45 K. The necessary sensitivity and heat resistance of the device was ensured both in the barrage mode and under the conditions of the peak temperature value of the air flow approaching the device. The device was used in the former USSR until the 90s.

In the simplest model of optoelectronic systems, cascade coolers are often used. The technology for developing a 4-stage TEC for cooling an IR receiver based on a 2D focal array of sensitive elements with *HgCdTe* to a temperature of 200 K is described in [10]. Materials based on Bi_2Te_3 with a quality factor of $2.95\cdot10^{-3}$ K^{-1} in *n*-type and $2.9\cdot10^{-3}$ K^{-1} in *p*-type were used. Experimental samples of a cooler were manufactured, containing in stages, respectively, 2-5-12-31 thermocouples with crystals measuring 1.5 1.5 1.8 mm. At a heat exchanger temperature of 333 K, the average value of the maximum temperature difference was 147 K. In operating mode with a cooling capacity of 100 mW, the TEC provided cooling to 200 K. The average value of power consumption was 10.5 W, and the coefficient of performance in operating mode reached 0.0093.

In [11], Marlow Industries proposed a physical model of a TEC integrated into the body of an IR detector array to stabilize its temperature. Thermoelectric temperature stabilization is often used in cooling-free infrared imaging systems due to the temperature sensitivity of the detector array. These infrared systems operate under changing ambient temperatures. The TEC is used to heat or cool the detector array to an optimal temperature.

Infrared detector arrays must operate in a hermetically sealed enclosure. Typically, the TEC is mounted in a metal case, and the detector array is mounted directly on top of the TEC. The metal case has several input/output contacts, through which the signal received from the detector is transmitted to the electronic components of the system. The window is attached to the top of the case. With this approach, the TEC, which has two ceramic plates, is soldered into the case or filled with epoxy resin. The leads from the TEC are attached to the power contacts on the case.

The concept of built-in TEC facilitates the installation method. Instead of a metal case, the TEC is built into a case made of multilayer ceramics (Fig. 2). Metallization platforms are located at the base of the case, which allow p- and n-elements to be soldered directly to the base of the case. The power supply wires of the TEC are attached to the pins on the outside of the case with metallized transition holes and tracks that eliminate the additional process of soldering the wires.

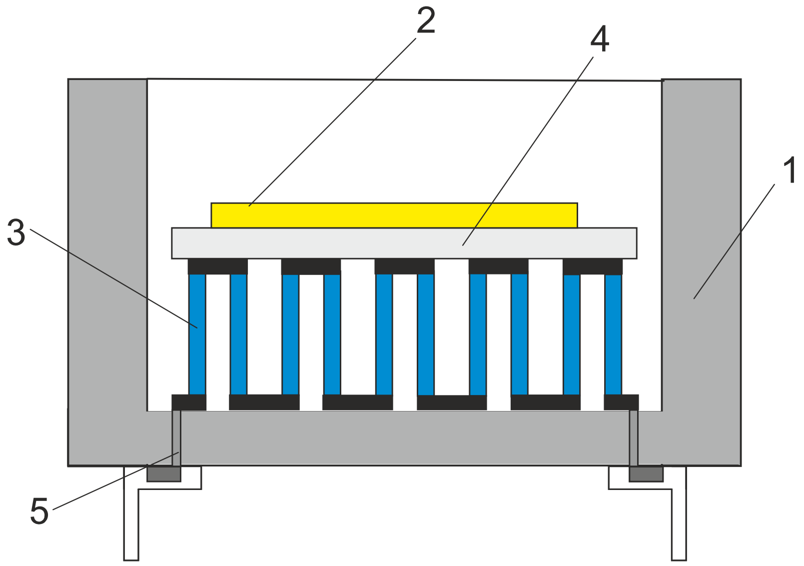

Fig. 2. Model of TEC embedded into a ceramic case [11]. 1 – ceramic case, 2 – cooling object, 3 – thermoelements, 4 – ceramic plate, 5 – metallized holes for power wires

Thus, the concept of embedded TEC involves soldering individual thermoelements directly into the base of the ceramic base with built-in electric wires for both TEC and the detector array. Integrating the cooler directly into the case offers many advantages. This reduces the number of component parts in the system, the number of soldering and connection operations, eliminates the TEC assembly operation for detector manufacturers.

[11] provides an overview of the thermal, electrical, and dimensional requirements needed to effectively design an integrated cooler for an uncooled infrared system. The embedded TEC must be designed based on operating parameters such as power, temperature difference, size and reliability.

An example of the characteristics of the built-in TEC for cooling to 25 C an array of detectors with an active heat release of 0.5 W at an ambient temperature of 75 C and a thermal resistance of the heat sink of 2 C/W is given. The TEC power in this mode is 1.89 W [11].

In [12], a physical model of a cascade TEC with a separate supply of stages is proposed (Fig. 3). Such a model is advisable to use for so-called planar microcoolers, which are located in the same plane as a miniature optical-electronic device that is cooled. As a rule, specially developed microelectronics technologies, namely MEMS technologies, are used for the manufacture of such TECs. A feature of the physical model is that thermal matching in the stages is carried out due to the ratio of the areas of the stages and the length of the thermoelements in the stages.

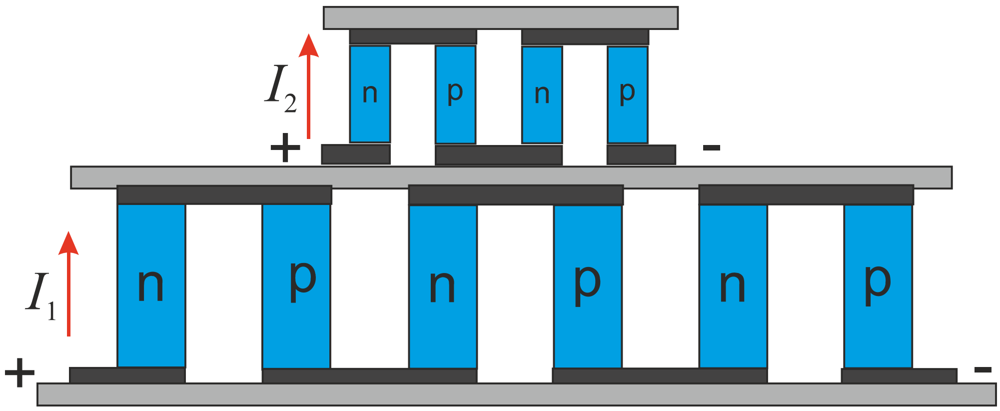

Fig. 3. Model of TEC with a separate power supply to stages

In [12], the principle of calculating the maximum temperature difference for a given refrigerating capacity of a two-stage TEC with separate power supply of the stages is proposed. An example of designing and calculating the characteristics of a planar two-stage TEC for an IR laser with a heat output of 10 mW is given. The problem of heat loss is also discussed as the most important mechanism of deterioration of the characteristics of miniature TECs. In particular, to reduce heat losses caused by the presence of interstage thermal resistance and heat removal through wires, instead of the TEC model shown in Fig. 3, a physical model with parallel power supply of stages is proposed, the configuration of which is illustrated in Fig. 4. In this model, there is no interstage insulating plate and only one pair of electrical wires is used, but both stages can operate at optimal current as a result of adapting the areas of the stages to the height of the thermoelectric legs.

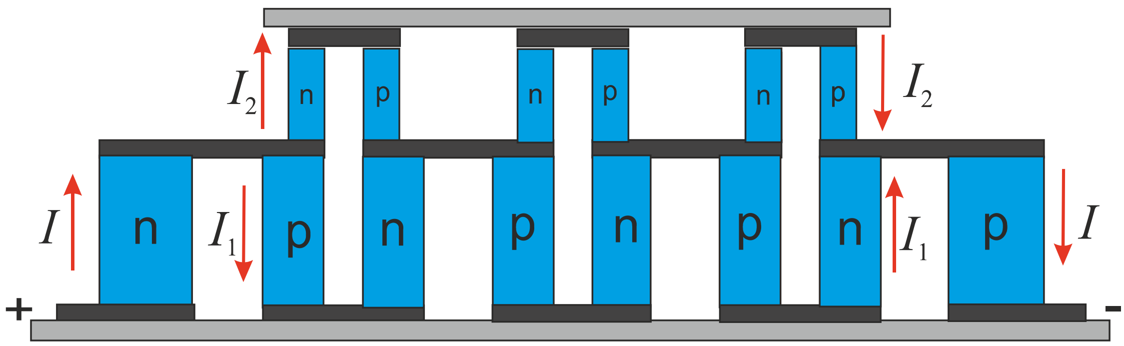

Fig.4. Model of TEC with a parallel power supply to stages

In [13], a three-dimensional (3D) physical model of the system is considered, which consists of an optical-electronic object, an array of thermoelements with ceramics on the cold and hot sides, and a heat sink (Fig. 5).

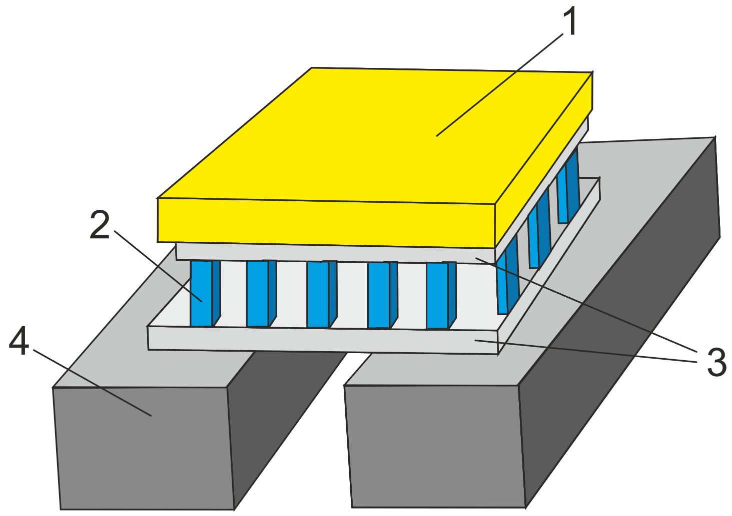

Fig. 5. Structure of a 3D physical model of a thermoelectric cooling system for an optical-electronic object. 1 – optical-electronic object, 2 – thermoelements, 3 – ceramics, 4 – heat sink with a hole

One-dimensional models do not provide information in directions perpendicular to thermoelements. Therefore, they are not suitable for systems with heat sinks with uneven temperature distribution over the surface, or in the case of incomplete contact of ceramics with the heat sink. In such cases, 3D models are used. In [13], the model takes into account transient and three-dimensional effects, the temperature dependence of the characteristics of the model materials, as well as convective and radiative heat exchange between ceramics and is used to determine the following values: time and electric power of the TEC to reach the required temperature of the object, power in steady-state mode to maintain the set temperature, the maximum TEC power, at which the maximum temperature difference between ceramics, temperature gradients on the object and other components of the system is achieved. The computer simulation uses a finite element method with a feedback control loop to correlate the power supply to the TEC in order to regulate the temperature of the object. An example of using the model to calculate the parameters of a thermoelectric temperature stabilization system for an IR detector, which is used in uncooled night vision cameras with a heat sink that is not completely in contact with the hot ceramics of the TEC due to the large hole for electrical wires, is described.

A series of works [14 – 18] are devoted to the problems of cooling optical-electronic devices. As heat sources, optical-electronic components can be divided into three groups. Devices of the first group have low heat generation power and small dimensions. Traditional TEC configurations successfully solve the problem of their thermal regulation.

The second group includes optoelectronics devices with intense heat generation (powerful diodes, infrared lasers, etc.). To ensure their reliable operation, miniature TECs with high cooling capacity are required. It is known that reducing the length of thermoelements leads to an increase in the cooling capacity of TECs. However, there are physical limitations that hinder the miniaturization of TEC. Such limitations are irreversible losses caused by the electrical contact resistance, as well as the electrical and thermal resistance of the interconnects and ceramic plates of TEC. Therefore, the physical model of TEC (Fig. 6) for such optical-electronic devices must take into account these factors, which cannot be eliminated in principle.

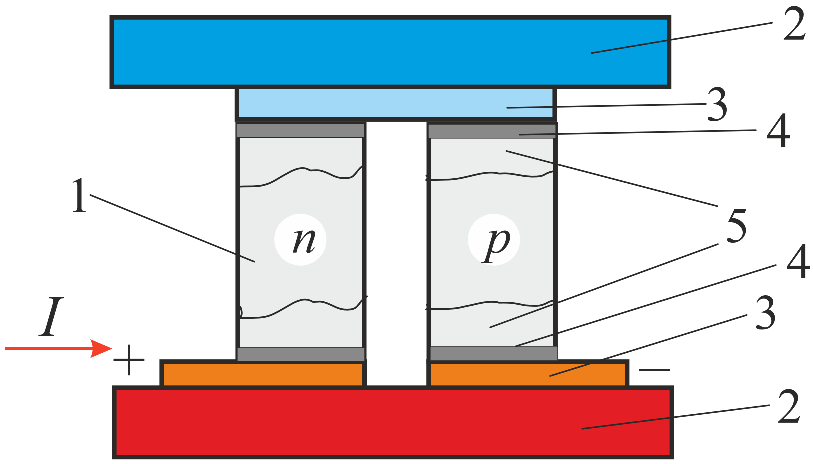

Fig. 6. Physical model of a thermoelectric miniature converter. 1 – thermoelectric material, 2 – insulation ceramic plate, 3 – interconnect plate, 4 – anti-diffusion metal layer, 5 – contact zone

The quality of electrical contacts is the most important factor that significantly affects the operation of cascade TECs. In [18], the characteristics of low-temperature cascade TECs were analyzed depending on the value of the electrical contact resistance. Two key characteristics are considered: the maximum coefficient of performance at a given temperature difference and the maximum cooling achieved for a TEC with a fixed configuration. To maintain the coefficient of performance at an acceptable level, it is necessary to provide a contact resistance r_c in the range from 10^{-7} Ohm см^2 to 10^{-6} Ohm cm^2, while with higher resistance the coefficient of performance of the TEC sharply decreases, especially for TEC with thermoelectric legs with a height of 0.5 mm or less. Irreversible losses caused by the electrical resistance of the interconnect metal plates were also analyzed, and their thicknesses were determined, which should provide an acceptable low level of resistance for various cascade TECs with typical sizes of thermoelectric legs and the distance between them.

In [17], the influence of the thermal properties of insulating ceramic plates on the operation of cascade TECs was studied. A mathematical model has been developed for the analytical calculation of the thermal resistance of interstage ceramics associated with three-dimensional heat transfer from a smaller cascade to a larger cascade. The model is used to determine the maximum temperature difference for standard multi-stage TECs with different ceramics. The TEC with the length of thermoelectric legs in the range from 0.3 mm to 2 mm was considered. A comparative analysis of the obtained results was carried out and recommendations were formulated for choosing the appropriate material for insulation plates.

The third group includes large-sized planar optical-electronic devices, for example, multi-element arrays of IR detectors and imagers, charge-coupled devices (CCDs), etc. These are typically low-intensity distributed heat sources that require low operating temperatures, typically 200 K and below. Here the problem arises: how to provide the necessary deep cooling in conditions of minimum cooling capacity. Typically, a few thermocouples are usually sufficient in the upper stage. Therefore, its surface area is small compared to the object being cooled. As a result, it is difficult to meet the requirements of temperature uniformity and mechanical strength. A low-temperature, multi-stage TEC is needed, in which the increased dimensions of the cold stage are combined with minimum power and mechanical strength. Traditional pyramidal stages are not suitable here. Special low-temperature cascade TECs with increased dimensions of the cold surface, but with a small cooling capacity, are needed.

Two physical TEC models are used to solve the problem. The first model, the traditional one, consists in the uniform distribution of thermoelectric legs in cold stages to increase the area. This model is used only if the total required number of thermoelectric legs in the cold stage is sufficient to withstand the applied mechanical and thermal loads. The second model is the use of an increased number of legs in cold stages with their mixed series-parallel connection. Thus, two or more legs are arranged in parallel, forming a separate thermoelectric leg, the height of which increases proportionally to maintain the optimal geometry of the legs. In this way, it is possible to significantly increase the number of legs and obtain TEC with almost the same area of stages. This model has the advantages of increased packing density of legs, which means increased mechanical strength. The results of testing such modules are given in [15, 16]. Despite the greatly increased dimensions of the upper stages, these TECs provide $\Delta T_{\max}$ values at the level of the best pyramid modules.

In [15, 16], a physical model of an optical-electronic device with TEC, which is placed in a small-sized metal case, whose own thermal characteristics affect the operation of TEC, is considered. The case made of kovar has a significant thermal resistance and affects the temperature of the hot surface of the TEC. In addition, additional heat enters through the case cover. As a result, the actual characteristics of the TEC may differ significantly from the expected ones.

Fig. 7 shows a physical model of a device with thermoelectric cooling. A substrate with an optical-electronic element on top is installed on the cold surface of the TEC. The structure is located inside a metal case on a base plate which is fixed on the heat sink. The entire system is closed with a lid thermally connected to the base.

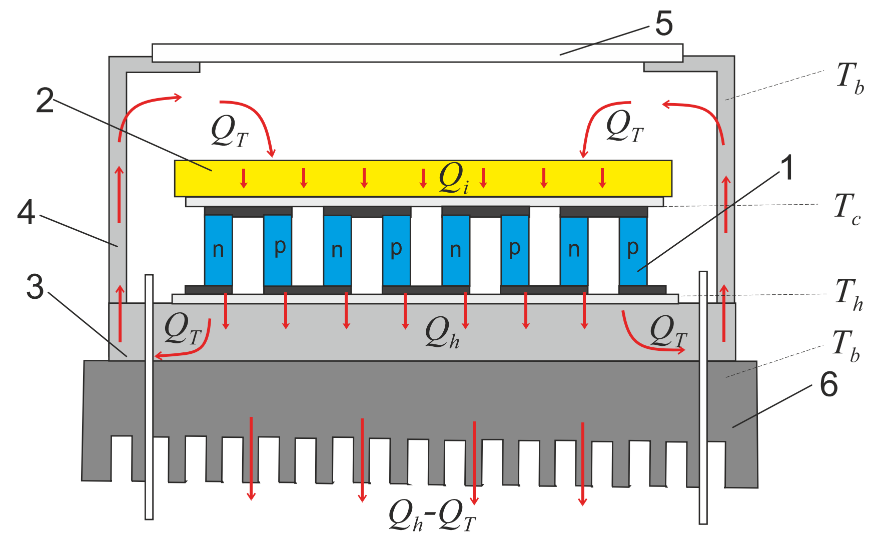

Fig. 7. Physical model of an optical-electronic device with TEC in a metal case [16].
1 – TEC, 2 – optical-electronic element, 3 – case base plate, 4 – case cover,
5 – window, 6 – heat exchanger base

The stationary thermal model of the system is described by the following equations:

$$Q_c = A(\alpha T_c i - 0.5 i^2(\rho + 2r_c / L)L - \frac{\kappa}{L}(T_h - T_c)), \tag{2.1}$$

$$Q_h = A(\alpha T_c i + 0.5 i^2(\rho + 2r_c / L)L - \frac{\kappa}{L}(T_h - T_c)), \tag{2.2}$$

$$Q_c = Q_i + Q_T\,, \tag{2.3}$$

$$T_h - T_b = R_h Q_h\,, \tag{2.4}$$

$$T_b - T_a = R_{hs}(Q_h - Q_T)\,, \tag{2.5}$$

where A is the total cross-sectional area of all thermoelectric legs, L is the length of thermoelectric legs, α, ρ, κ are the Seebeck coefficient, resistivity and thermal conductivity of thermoelectric material, r_c is the value of contact resistance, i is density of TEC supply current, Q_c is cooling capacity of the cooler, Q_h is heat power on the heat-releasing surface of TEC, Q_i is heat generated by optical-electronic object, T_b is temperature of heat sink base, T_a is ambient temperature, R_h and R_{hs} are thermal resistances of the base and heat sink. Q_T is entering the cold surface of TEC from the environment which in the first approximation can be calculated by the formula

$$Q_T = K_c(T_b - T_c)\,, \tag{2.6}$$

where K_c is the coefficient of the combined effect of convection, radiation and thermal conductivity of the wires connected to the optical-electronic object. For a known Q_i and a given value of the current density i the system of equations (2.1) - (2.6) makes it possible to find the unknown temperatures T_c, T_h, T_b and heat capacities Q_c, Q_h, Q_T. However, the system is solved, if the thermal parameters of the case, namely K_c, R_h and R_{hs} are known values that can be determined experimentally.

Work [16] shows the influence of the thermal resistance R_h of the base on the characteristics of TECs with different lengths of thermoelectric legs. The maximum temperature drop loss is 2.4 K for a TEC with a leg length of 1.5 mm, and for a TEC with a leg length of 0.5 mm, the loss increases to 8 K. Thus, the intuitive desire to use a TEC with a larger cooling capacity to achieve better cooling may lead to the opposite result. On the other hand, it may turn out that the TEC with excessively long legs does not have sufficient cooling capacity to maintain the required value of the cooling temperature T_c. Therefore, the optimal TEC configuration should be based on the analysis of all system components taking into account their thermal connection, and the choice of the correct physical model of optical-electronic systems with TEC plays a significant role in the design of the cooler.

The physical model shown in Fig. 7, was used in [19] to develop and study the design of an IR detector with thermoelectric cooling for operation in the spectral range of 3 – 5 μm. A 3-stage cooler is used to col the $Cd_{1-x}Hg_xTe$ photosensitive element to 200 K. A photosensitive element on a leucosapphire substrate is glued to the heat-absorbing surface of the TEC. The cover, sealing the volume of the photodetector, is welded to the kovar base with sealed glass-metal terminals for the photocell and TEC. The cover includes an entrance window. To absorb the remaining gases after evacuation and sealing of the photodetector, a gas absorber (getter) is used in the design, which allows maintaining the pressure of residual gases in the working volume of the photodetector below 10^{-3} Pa throughout its entire service life. The photoelectric characteristics of the photodetector were measured. It was established that the value of the specific detectable power of the photodetector at a temperature of ~ 200 K at a wavelength of $\lambda = 4.5$ μm is equal to $D^*_{\lambda\max} \geq 1\cdot10^{10}$ cm $Hz^{1/2}W^{-1}$, the time to enter the operating mode is 70 s, the supply current of TEC is 1 A, TEC power consumption - 5.5 - 6.0 W, cooling capacity 120 - 100 mW, dimensions of the cooled area – 4 × 7 mm^2. It was also established that after conducting tests on vibration resistance, shock resistance, heat resistance and cold resistance, the photodetector maintained its main parameters within 3000 hours.

Screens in physical TEC models for IR detectors

To reduce the heat load on the coldest stage of the TEC, back in 1980 it was proposed in [20] to use a screen. An example of a physical model with a screen in a thermoelectric cooling system for an IR detector given in [20] is shown in Fig.8. Made of metal with high thermal conductivity, the screen is easily cooled by the TEC stage to which it is attached. Its main function is to shield the detector and the upper cold stages of TEC from the flow of heat coming due to convection and radiation from the inner walls of the IR device case, as well as from the hot surface of the TEC base. In addition to the screen, this physical model has another feature, namely, the wires from the detector before exiting the device case are first connected to the surface of one of the lower stages. This reduces the component of the thermal load on the upper TEC stage, caused by the thermal conductivity of the wires.

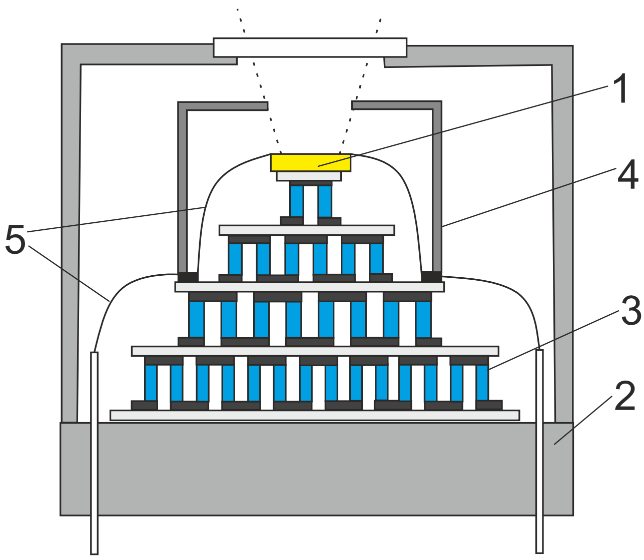

Fig. 8. Physical model of an optical-electronic device with a 4-stage TEC with a screen on the second stage [20].
1 – IR detector, 2 – device case, 3 – TEC, 4 – screen, 5 – IR detector wires

Physical models of thermoelectric cooling systems for IR detectors containing thermal screens are protected by patents [21, 22]. In [21], a system with screens on each TEC stage was proposed. The screens are cup-shaped, attached to the interstage plates and nested within each other, with each thermal screen covering all successive screens and stages. Each screen has an opening to provide an optical path for the optical radiation detector, which is installed on the coldest stage. Part of the thermal energy is absorbed by each screen and removed through the lower stage of the cooler. Screens are made of material with high thermal conductivity such as silver, copper, aluminum and polished to minimize heat absorption. It is noted that the use of screens on all stages provides maximum cooling. However, approximately 90 % of the maximum cooling capacity is achieved with only two screens mounted on the lower and upper interstage plates, eliminating all intermediate screens. This physical model also proposes installing an optical window on the outer screen, connected to the hottest surface, namely the base of the cooler. This arrangement eliminates the need for electrical window heating to minimize the formation of dew on the window.

Patent [22] describes the physical model of the cooling system of IR detectors with a screen that is installed in the base of the detector case and, accordingly, is not cooled. But it surrounds the TEC and the detector (Fig. 9).

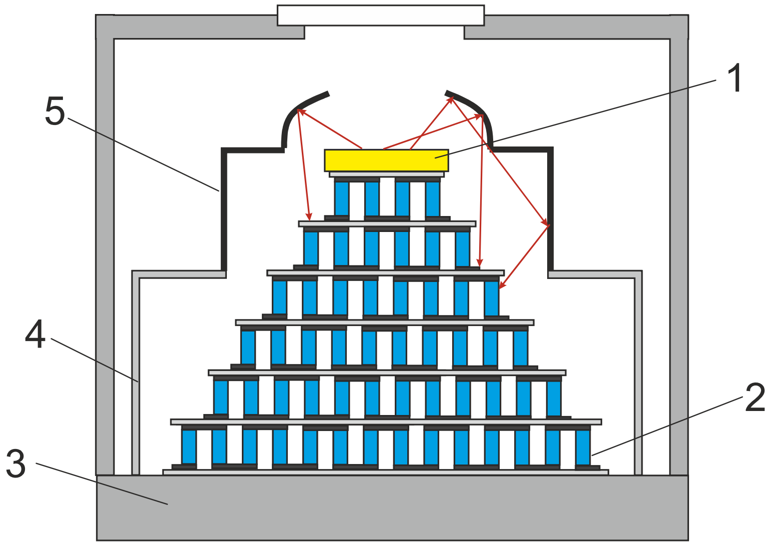

Fig. 9. Physical model of TEC with a screen for IR detectors [22].
1 – IR detector, 2 – cascade TEC, 3 – case, 4 – screen holder,
5 – screen with a curved surface

The screen has a curved reflective surface and reflective side walls that absorb and eliminate the thermal energy of radiation. This reduces the heat load on the coldest TEC stage.

Modern ideas in the physical models of optical-electronic systems with thermoelectric cooling

The introduction of modern advanced technologies for IR detectors allows a shift in the operating temperature of the IR detector from the cryogenic region to the range of 150 – 200 K [4, 23 – 25]. At the same time, its characteristics do not deteriorate. Such temperatures can be achieved by thermoelectric cooling by using new modern approaches in physical models of optical electronic devices with cascade thermoelectric coolers.

One of these approaches is the use of functionally graded thermoelectric materials (FGTM) for thermoelement legs [26]. These are heterogeneous materials with an optimal distribution of the main thermoelectric properties: thermoEMF, electrical conductivity and thermal conductivity along the height of the thermoelectric leg.

Another approach is the use of materials with increased efficiency in the low temperature region. An example of such materials are *Bi-Sb* alloys of n-type conductivity. These alloys have a high thermoelectric figure of merit at temperatures below 160 K, which also increases in a magnetic field. The use of an optimally non-uniform magnetic field further increases the cooling efficiency of modules made of such materials [26].

In [27], the results of calculating the energy parameters of low-temperature cascade thermoelectric modules that provide cooling to temperatures below 200 K at a heat-generating surface temperature of 300 K are presented (Table 1). The maximum coefficient of performance was calculated taking into account the above approaches.

Table 1

Estimated values of energy parameters of low-temperature TEC

Cooling temperature Tc, K	Number of stages	Coefficient of performance, ε_{max}	Power at thermal load Q_0 = 10 mW, W, W	TEC material
200	3	$4\cdot10^{-2}$	0.25	FGTM based on *Bi-Te*
190	3	$2.5\cdot10^{-2}$	0.4	FGTM based on *Bi-Te*
180	4	$1.2\cdot10^{-2}$	0.83	FGTM based on *Bi-Te*
170	4	$5\cdot10^{-3}$	2.0	FGTM based on *Bi-Te*
160	4	$2\cdot10^{-3}$	5.0	FGTM based on *Bi-Te*
150	5	$8\cdot10^{-4}$	12.0	4 stages – FGTM based on *Bi-Te*, 1 upper stage – *n-BiSb* in the inhomogeneous magnetic field, *p-BiTe* FGTM
140	6	$3\cdot10^{-4}$	33.5	4 stages – FGTM based on *Bi-Te*, 2 upper stages – *n-BiSb* in the inhomogeneous magnetic field, *p-BiTe* FGTM

It was established that to reach temperatures of 160 - 200 K it is enough to use three-, four-cascade modules, the thermoelements of which are made of FGTM on the basis of *Bi-Te*. Such FGTM can be formed by the formation of a corresponding inhomogeneous distribution of impurities in the material or by changing its composition. To cool to temperatures of 150 – 140 K, a four-stage module with a Bi-*Te*-based FGTM must be supplemented with low-temperature stages. In these stages, it is advisable to use alloys based on *Bi-Sb* for the n-type conductivity legs. At room temperature, the figure of merit Z in *n-BiSb* is approximately $0.8\cdot10^{-3}$ K^{-1}, at low temperatures, Z increases, reaching $5\cdot10^{-3}$ K^{-1} per 100 K. A magnetic field further increases this value to 8 – $9\cdot10^{-3}$ K^{-1} [26]. In this case, FGTM of *n*-type conductivity based on *Bi-Sb*, i.e. a material with variable basic thermoelectric characteristics α, σ, κ, can be obtained by optimally changing the induction of the magnetic field in which this material is placed. Until now, in the arsenal of thermoelectricity there are no materials of p-type conductivity with a similar dependence of the figure of merit on the magnetic field. Therefore, for *p*-type legs, it is possible to use FGTM based on the traditional *Bi-Te* composition.

The results of these studies indicate that the practical use of modern technologies in the manufacture of modules makes it possible to expand the temperature range of the thermoelectric method of cooling IR detectors and can ensure their operating temperatures up to 150 – 140 K with sufficient energy efficiency.

In [28] it is shown that the so-called SWaP-C (size, weight, power and cost) characteristics of thermoelectric deep cooling systems for IR sensors can be significantly improved by using FGTM thermoelements. Based on a comparison of the results of experimental studies of homogeneous and

FGTM thermoelements, an increase in the maximum temperature difference by 35 %, an increase in the coefficient of performance by 150 % and a cooling capacity by 200 % is predicted in a single-cascade TEC design, and in multi-cascade designs the maximum difference SWaP-C is expected.

An example of the development and manufacture of a prototype mid-wave IR sensor based on an *In*-doped *PbTe* photodiode with thermoelectric cooling is described in [29, 30]. The advantage of *PbTe* photodiodes is the ability to use them with cooling to temperatures significantly higher than the cryogenic level, namely up to 180 K. The optimal temperature range is 140 – 150 K. Therefore, multi-cascade coolers can be used for them. The physical model of the TEC photodiode system prototype is shown in Fig. 10. The TEC consists of two parts. The low-temperature part is a two-stage module that provides the operating temperature of cooling the photodiode to the level of 140 – 150 K from a temperature of 180 – 200 K. The high-temperature part is a 4-stage module with a cooling temperature of up to 180 K from 300 K.

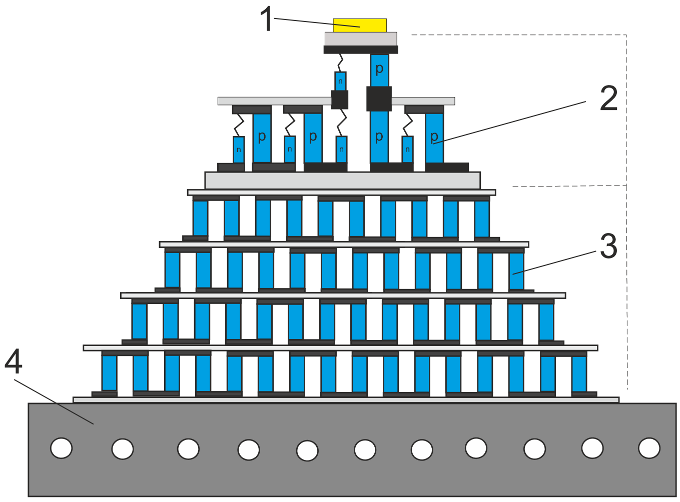

Fig.10. Physical model of the prototype photodiode system with a multi-stage TEC [30].
1- an IR range sensor based on a PbTe photodiode doped with In,
2 – low-temperature two-stage module, 3 – 4-stage module,
4 – heat-exchanger

For the low-temperature module, extruded $Bi_{0.91}Sb_{0.09}$ n-type crystals were used, which demonstrate a high figure of merit $Z \approx 3.5\ 10^{-3}\ K^{-1}$ in the temperature range of 80 – 200 K [31]. The figure of merit of *p*-type *Bi-Sb* alloys is much lower [32], and they cannot be used for thermoelectric coolers in this temperature range. Therefore, *p*-type $(Bi, Sb)_2Te_3$ solid solutions of optimized composition are used.

Due to the large difference in thermal expansion of the p- and n-legs, the rigid design of the two-stage low-temperature module would lead to destruction of the device. Large mechanical stresses of the n-legs are eliminated by their flexible connection with the p-legs. The thermocouple legs have different lengths and cross sections, optimized to achieve maximum figure of merit *Z* of thermocouples at the operating temperatures of each stage. Legs of both types of conductivity are hard soldered to the hot side of each module stage. The cold side of the *p*-type legs is also hard soldered, and the n-legs are connected to the base through a mechanical stress damper, made in the form of a flexible copper bus. The first stage of the TE module consists of four thermocouples with leg sizes: n-leg: 0.7 mm ×1. 4 mm × 2.7 mm; p-leg: 2.4 mm × 1.4 mm × 3.3 mm. The second stage consists of one thermocouple with leg sizes: n-leg: 0.7 mm × 1.4 mm × 2.7 mm; p-leg: 1.8 mm × 1.4 mm × 3.3 mm.

In this design, the length and cross-section of the legs were optimized to obtain thermal and electrical matching of the legs in the module and achieve the maximum coefficient of performance of the device. At the hot temperature of the low-temperature module T_{hot}=180 – 200 K the maximum temperature difference ΔT_{max} = 45 – 50 K and the maximum cooling capacity Q_{max} = 85 – 90 mW are achieved. The electrical power consumption of such a module is 1 – 1.3 W.

For the high-temperature part of the TEC, a standard 4-stage module made of Bi_2Te_3-based materials was used. The module is designed to provide cooling temperatures in the range of 180 – 200 K with a cooling capacity of 1 – 1.3 W. Under these conditions, the power consumption of the 4-stage module is 60 – 90 W.

Thus, in general, such a 6-stage TEC structure can provide cooling of a *PbTe*-based IR detector, the heat release of which does not exceed 10 mW, to a temperature of 140 – 150 K. In this case, the system must be equipped with a heat exchanger with a heat release power of 100 W. In [30], it is proposed to ensure the efficiency of the heat exchanger by using a heat pipe in the design.

Heat removal from TEC for optical-electronic devices plays an important role. Therefore, research is directed towards improving and developing new heat removal systems for cascade TEC. In particular, combined cooling systems for optical-electronic equipment, which include thermoelectric coolers and heat pipes, are common. Work [9] describes a version of such a system developed for aviation infrared technology. The physical model of the system is shown in Fig. 11.

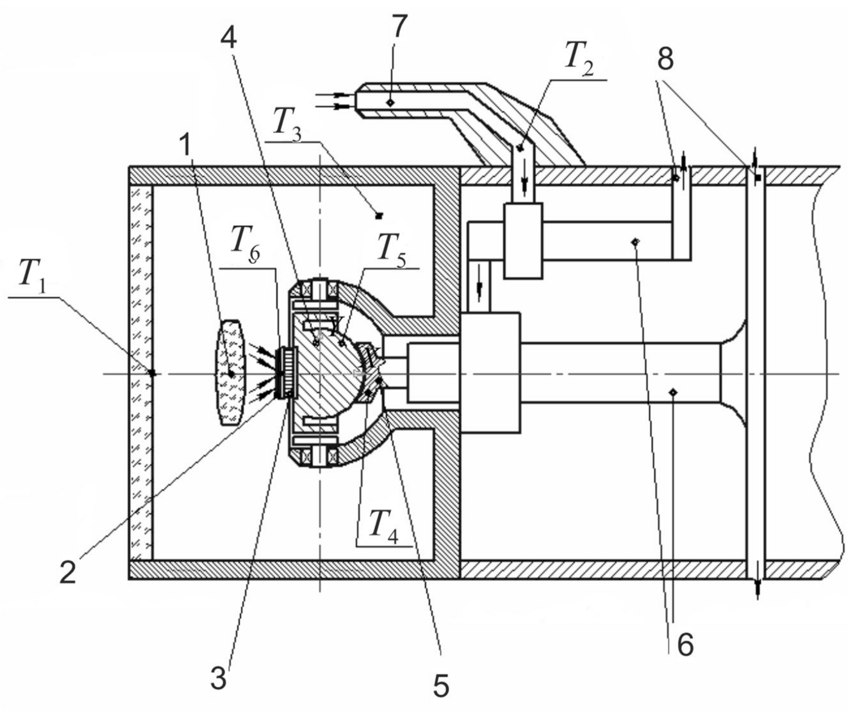

Fig.11. Physical model of the IR detector cooling system based on TEC and heat pipes [9].
1 – lens, 2 – IR detector, 3 – TEC, 4 –base, 5 – heat-dissipating rod,
6- system of vortex tubes, 7 -air intake,
8 – exhaust air outlets

The system includes a 4-stage TEC for the IR detector and vortex tubes. The optical system with an IR detector and a TEC is housed in a sealed case. Heat is transferred to the case base, which, using special thermal bridges, is connected to an unsealed block in which thermal bridge heat sinks are located, blown by atmospheric air cooled in a vortex tube. Such a system stabilizes the sensitive thermoelements of the IR detector at a level of 200 – 210 K. At the same time, the vortex tube maintains the base temperature at a level of 310 – 330 K.

One of the industrial manufacturers in Europe of IR detectors based on *HgCdTe* with thermoelectric cooling is the company VigoPhotonics[6]. For cooling, small-sized 2, 3 and 4-stage standard thermoelectric modules produced by many companies around the world are used. A traditional physical model is used, namely, the detectors, together with the TEC, are mounted in a special sealed metal case with a window for the entry of IR radiation. The case is filled with a dry mixture of krypton and xenon inert gases, which has low thermal conductivity. To prevent condensation of water vapor, a moisture absorber container is installed in the case. To reduce temperature fluctuations in a detector with a 3- or 4-stage TEC, a screen is installed on the surface between the two lower stages. The TEC parameters (maximum temperature difference Tmax, cooling capacity Qmax, voltage Umax, supply current Imax), which are equipped with IR detectors from VigoPhotonics, are given in Table 2 [6].

Table 2

Parameters of cascade TEC for cooling IR detectors [6]

Parameter	2-stage TEC	3-stage TEC	4-stage TEC
T_{detector}, K	~ 230 K	~ 210 K	~ 195 K
Q_{max}, W	0.36	0.27	0.28
$\Delta T_{\max}$, K	92	114	125
$U_{\max}$, V	1.3	3.6	8.3
$I_{\max}$, A	1.2	0.45	0.4

To remove the heat generated by a thermoelectric cooler, the use of metal case walls and a screw securing the case to the detector in an IR device is usually not enough. Therefore, the base of the case is fixed to a conventional heat sink. To improve the thermal contact of the base with the heat sink, layers of thermally conductive glue or silicone paste are used. For 2- and 3-stage TECs, it is recommended to use heat sinks with a thermal resistance of ~ 2 K/W; for 4-stage TECs, heat exchangers with a resistance of ~ 1 K/W are advised.

Conclusions

A review of scientific information regarding thermoelectric cooling of optical-electronic devices in the IR spectrum range has shown that despite the variety of physical models of such devices, the most common and used in industrial designs of IR detectors, is the simplest model of a TEC built into a sealed metal case with photosensitive elements that are cooled. 1-, 2-, 3-, and 4-stage TECs made of materials based on Bi_2Te_3, are used, which ensure the operating temperature level of IR devices up to 195 K. Screens can be used to reduce convective and radiative heat load in cascade TECs. Conventional heat sinks are usually used to remove the thermal power generated by the TEC.

The main disadvantage of TEC for optical-electronic devices in the IR range is their low coefficient of performance compared to mechanical cooling methods. Increasing the coefficient of performance and expanding the temperature range of the TEC is an urgent task, the implementation of which is possible with the development and use of new promising thermoelectric materials with increased figure of merit in the low temperature region (up to 140 K).

The energy efficiency of TECs, especially their miniature dimensions with the height of thermoelectric legs less than 0.5 mm, significantly depends on the optimization of its design, which should take into account the electrical and thermal resistances of the contacts, interconnect and insulation plates of the module. These resistances lead to electrical and thermal losses in the efficiency of thermoelectric energy conversion, reduce the coefficient of performance, and are one of the main reasons for the fact that in thermoelectric coolers the properties of materials are not fully realized.

Also, the energy efficiency of the TEC is influenced by the thermal resistance of the IR detector case, its connections to the TEC, heat sinks and heat exchangers, which are used in the system to remove the heat generated by the TEC.

Therefore, the design and optimization of the TEC configuration should be based on the analysis of all system components, taking into account their thermal connection, and the selection of the correct physical model of the optical-electronic system with the TEC is essential in the design of the cooler.

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ФІЗИЧНІ МОДЕЛІ ОПТИКО-ЕЛЕКТРОННИХ СИСТЕМ ІЧ ДІАПАЗОНУ СПЕКТРУ З ТЕРМОЕЛЕКТРИЧНИМ ОХОЛОДЖЕННЯМ
(Огляд)

В роботі розглянуті основні фізичні моделі оптико-електронних систем ІЧ діапазону спектру з термоелектричним охолодженням. Проаналізовані особливості і переваги цих моделей. Встановлено, що найпростішою і такою, що практично застосовується в промислових зразках ІЧ пристроїв, є модель вбудованого в металічний корпус термоелектричного модуля з фоточутливими елементами, які охолоджуються. Така модель з каскадними термоелектричними охолоджувачами (ТЕО) з матеріалів на основі Bi_2Te_3 забезпечує рівень робочих температур ІЧ пристроїв до 195 К. Показано, що розширення діапазону охолодження до температур 140 – 150 К можливе шляхом застосування для ТЕО функціонально-градієнтних матеріалів і додаткових каскадів з низькотемпературних термоелектричних матеріалів, наприклад, з матеріалів на основі BiSb. Встановлено, що енергетична ефективність ТЕО суттєво залежить від оптимізації його конструкції, яка повинна враховувати електричні і теплові опори контактів, комутаційних та ізоляційних пластин, а також вплив теплових опорів корпусу ІЧ приймача, його з'єднань з ТЕО, радіаторів і теплообмінників, які застосовуються в системі для відводу тепла від ТЕО. Отже проєктування ТЕО має враховувати всі компоненти системи і вибір фізичної моделі оптико-електронної системи з ТЕО має важливе значення. Бібл. 32, рис. 11, табл. 2.

Ключові слова: оптико-електронна система, ІЧ пристрій, термоелектричний охолоджувач, фізична модель.

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