V.G. Kolobrodov, *doc. techn. sciences, professor*
V.I. Mykytenko, *doc. techn. sciences, assistant professor*
G.S. Tymchyk, *doc. techn. sciences, professor*
Sokol B.V.

National Technical University of Ukraine
"Igor Sikorsky Kyiv Polytechnic Institute"
37 Peremohy Ave., Kyiv, 03056, Ukraine
e-mail: deanpb@kpi.ua

TEMPERATURE RESOLUTION OF COMPUTER-INTEGRATED POLARIZATION THERMAL IMAGER

The work is devoted to the development of a method for determining the energy (temperature) resolution of a polarization thermal imager, which contains a linear polarizer and a phase plate. For this purpose it is proposed to use the noise equivalent temperature difference (NETD). A physico-mathematical model of an optoelectronic system of the polarization thermal imager has been developed, which allows one to calculate its signal transmission function. Based on this function, a method for calculating NETD has been developed. The formula describing functional dependence of a polarization thermal imager temperature resolution on the angular orientation of the polarizer relative to the optical axis of the phase plate at a given degree of polarization is obtained. A study of the impact of a test object radiation degree of polarization on the polarization thermal imager temperature resolution was performed. Bibl. 8, Fig. 7, Tabl. 1.

Key words: polarization thermal imager, energy resolution, noise equivalent temperature difference, degree of polarization

Introduction

Polarization is one of the four parameters of the electromagnetic field of radiation, and the other three are intensity, wavelength and coherence [1,2]. Polarimetry measures the vector nature of the radiation and provides important information about the surface orientation of the object, its shape and surface quality. The polarization properties of radiation from objects of observation differ from the background radiation and are not correlated with their intensity and spectrum. As a rule, the radiation from the object is partially polarized, and from the background - natural [3, 4]. Thus, polarimetric images are very useful for magnifying the signal from an object and suppressing background noise.

The main characteristics of polarized radiation are intensity, degree of polarization, ellipticity and polarization angle [5,6]. To measure these characteristics in the infrared (IR) region of the spectrum, polarization thermal imagers (PT) are used [7, 8]. The main characteristics of any thermal imager used to study thermoelectric phenomena and devices are energy (temperature), spatial and temporal resolution, which depend on the transmittance of its optical system, the sensitivity of the radiation detector and the characteristics of the electronic video signal processing system [9 – 11]. There are a significant number of standards, monographs and articles devoted to modeling, calculation and measurement of the thermal resolution of thermal imagers, by which we mean the minimum radiation contrast between the object and the background that a thermal imager can detect [12 – 14]. At the same time, there is practically no scientific and technical information on methods for calculating the temperature resolution of a PT.

Formulation of the problem

The purpose of this paper is to develop and study a method for determining the temperature (energy) resolution of a polarization thermal imager.

Model of a polarization thermal imager

A polarization thermal imager can be viewed as a linear system that converts the brightness of the observation plane from the IR region of the spectrum to the brightness of the image of the object and background on the display screen in the visible region of the spectrum. The process of such a transformation can be investigated using the generalized scheme of the system "object of observation - atmosphere – thermal imager - observer" [12, 13].

Radiation (intrinsic or reflected) from the object of observation and the background passes through the atmosphere and enters the optical system of the thermal imager, which forms an image of the object and the background in the plane of the matrix radiation detector (MRD). The radiation detector converts the radiation stream, which forms an image, into an electrical video signal, which, after amplification, goes to analog and digital processing devices. After the necessary transformations, the video signal goes to the display, on the screen of which a visible analogue of the object and the background is formed, is perceived by the observer.

Consider the opto-electronic system of PT, which consists of an optical system and MRD (Fig. 1). The optical system, in turn, consists of an IR polarizer, a quarter-wave retarder, and an IR thermal imager lens arranged in series on the optical axis.

One of important characteristics of thermal imager is signal transfer function (*SiTF*) $u_s(L_t)$ – the dependence of the electrical signal at the output of the electronic unit of the thermal imager on the brightness of the object of observation. To obtain functional dependence $u_s(L_t)$, we will consider Fig. 1. Let the observation object have a spectral brightness uniform over the area $L_t(\lambda)$, and its angular dimensions $\zeta_{tx} \times \zeta_{ty}$ significantly exceed the instantaneous field of view of the thermal imager, which is located at a distance *R* from the observation object. We assume that the surface of the object and the background radiates according to Lambert's law.

Then the spectral brightness of the object surface is determined by the formula as

$$L_t(\lambda) = \frac{1}{\pi}\varepsilon_t(\lambda)M_\lambda(\lambda, T_t), \quad (1)$$

where $\varepsilon_t(\lambda)$ is the spectral coefficient of radiation of the object surface; $M_\lambda(\lambda,T_t)$ is Planck's function. If the normal to the surface of the object is placed at an angle φ to the optical axis of observation, then the input pupil of the lens receives a spectral flux of radiation

$$\Phi_\lambda(\lambda) = \tau_A(\lambda,R) L_{\lambda_t}(\lambda) \Omega_o A_t \cos\varphi, \tag{2}$$

where $\tau_A(\lambda)$ is spectral transmittance of the atmosphere; A_t is the area of the object within the instantaneous field of view of the thermal imager; $\Omega_0 = A_p/R^2$ is body angle within which the radiation from the object reaches the entrance pupil of the lens area A_p.

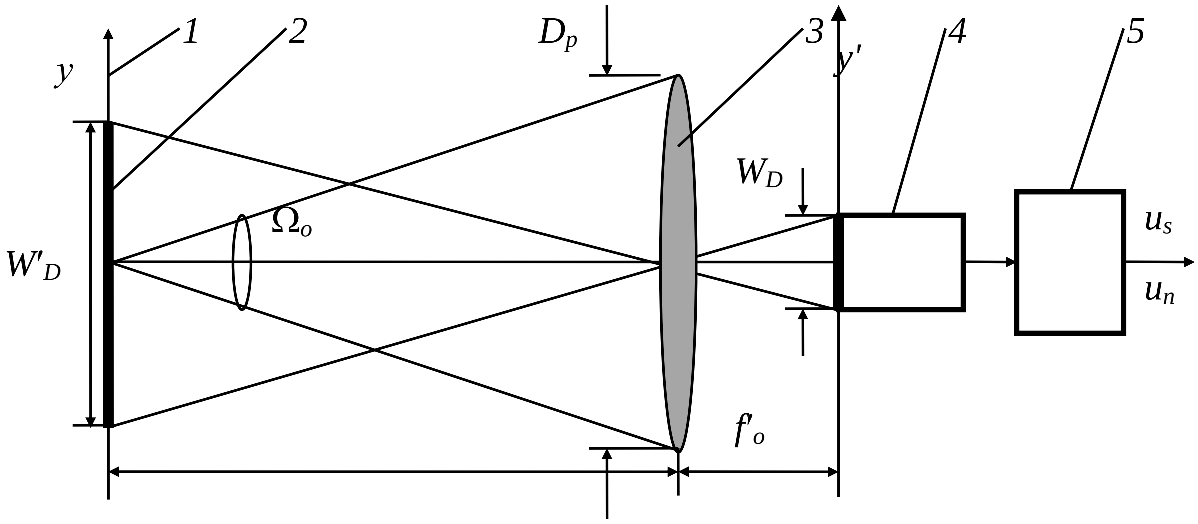

Fig. 1. To calculation of transmission function of thermal imager signal:
1 – the plane of the radiation object; 2 – instantaneous linear field of view;
3 – optical system; 4 – MRD; 5 – video amplifier

The signal at the output of MRD with spectral sensitivity $R_D(\lambda)$ will be equal to

$$u_s = \int_{\lambda}^{\lambda_2} \Phi_\lambda(\lambda)\tau_o(\lambda)R_D(\lambda)d\lambda = A_t \frac{A_p}{R^2}\cos\varphi \int_{\lambda}^{\lambda_2} \tau_A(\lambda)L_{\lambda t}(\lambda)\tau_o(\lambda)R_D(\lambda)d\lambda. \tag{3}$$

When measuring the SiTF function, it is assumed that the test object is located at a short distance from the thermal imager, i.e. $\tau_A(\lambda) \approx 1$, and the spectral transmittance of the optical system within the operating spectral range has an average value τ_0. Then the function *SiTF* (3) of the thermal imager taking into account the gain of the electronic unit C_{EI} and the relationships $A_p = \pi D_p^2/4$ i $A_t/R^2 = A_D/f'^2_o$, following from Fig.1, will be given by

$$u_s(L_t) = \frac{\pi}{4} C_{EI} A_D \left(\frac{D_p}{f_o'}\right)^2 \tau_o \cos\varphi \int_{\lambda_1}^{\lambda_2} L_t(\lambda) R_D(\lambda) d\lambda. \quad (4)$$

The function $u_s(L_t)$, has a complex form, which depends, first of all, on the working spectral range and spectral sensitivity of MRD, which makes it difficult to measure the true brightness of the object. Formula (4) does not take into account the spectral composition of the electrical signal, which is determined by the readout system. In addition, the magnitude of the signal u_s is influenced by the gain C_{EI} and noise of the system.

As can be seen from formulae (1) – (4), the value of thermal imager signal $u_s(x',y')$, at the output of MRD is a function of absolute temperature T_t of the object surface and its spectral radiation coefficient $E_t(\lambda,T)$. Moreover, video signal $u_s(x',y')$ depends on spectral transmittance of the atmosphere $\tau_A(\lambda,R)$, the characteristics of optimal system D_p, f_o', τ_o and MRD $R_D(\lambda)$, λ_1, … λ_2, A_D, as well as on the modulation transfer functions of separate elements of optoelectronic system of the thermal imager.

Determination of temperature resolution of PT

As the temperature resolution of PT, we will use classical parameter which is called *NETD* (Noise Equivalent Temperature Difference). The *NETD* parameter is understood as the temperature difference between the standard test object and the background, emitting as the absolutely black body, whereby the ratio of the peak signal value at the output of the standard reference filter of the thermal imager which considers the test object, to the noise is equal to unity [15,16]. The test must have angular dimensions that are several times the angular size of the sensitive area of the MRD pixel $\alpha_D \times \beta_D$, in order to eliminate the effect of spatial resolution on the measurement results.

To obtain formulae for the calculation of $NETD$, consider the signal transmission function of the thermal imager (4). Additionally, we make a number of assumptions:

1. The test object is located at a short distance from the thermal imager. Then we can assume that the radiation is little absorbed during passage through the atmosphere, i.e. in the operating spectral range $\tau_A(\lambda) \approx 1$.
2. The electronic system of the thermal imager has an effective noise bandwidth Δf.
3. A large test object is placed on a uniform background and has a temperature contrast ΔT. The test object and background emit as a blackbody.

Since the object is always in the background, a red (informative) signal appears when there is a temperature contrast between the object and the background, that is

$$u_s = u_{st} - u_{sb}, \quad (5)$$

where u_{st} and u_{sb} are signals formed by the object and background, respectively.

If the object and background radiate according to Lambert's law, then formula (5), taking into account (4), provided that the gain C_{El} = 1, can be represented as

$$u_s = \frac{1}{\pi} A_t \frac{A_p}{R^2} \tau_o \int_{\lambda_1}^{\lambda_2} R_D(\lambda)[M_\lambda(\lambda, T_b + \Delta T) - M_\lambda(\lambda, T_b)]d\lambda =$$

$$= \frac{1}{\pi} A_t \frac{A_p}{R^2} \tau_o \cdot \Delta T \int_{\lambda_1}^{\lambda_2} R_D(\lambda) \frac{\partial M_\lambda(\lambda, T_b)}{\partial T} d\lambda, \quad (6)$$

where τ_o is the average transmittance of the optical system.

The spectral sensitivity of MRD can be expressed in terms of the specific detective ability $D^*(\lambda)$ according to formula [13]

$$R_D(\lambda) = D^*(\lambda) \frac{u_n}{\sqrt{A_D \Delta f}}, \quad (7)$$

where A_D and u_n are area and noise signal of MRD pixel, respectively.

Substituting (7) into (6), we find the signal-noise ratio at the output of the reference filter

$$SNR = \frac{u_s}{u_n} = \frac{1}{\pi} A_t \tau_o \frac{A_0}{R^2} \frac{\Delta T}{\sqrt{A_D \Delta f}} \int_{\lambda_1}^{\lambda_2} D*(\lambda) \frac{\partial M_\lambda(\lambda, T_b)}{\partial T} d\lambda. \quad (8)$$

We find the formula for calculating *NETD* from (8), assuming that $SNR = 1$. Then

$$NETD = \Delta T = \frac{\pi R^2 \sqrt{A_D \Delta f}}{A_t \tau_o A_p \int_{\lambda_1}^{\lambda_2} D*(\lambda) \frac{\partial M_\lambda(\lambda, T_b)}{\partial T} d\lambda}. \quad (9)$$

The resulting formula is most general for calculating *NETD*. We present Eq.(9) in another form, using Fig. 1. It is obvious that $A_p = \pi D_p^2/4$ i $A_t/R^2 = A_D/f_o'^2$. Then

$$NETD = \frac{4k_o^2}{\tau_o \int_{\lambda_1}^{\lambda_2} D*(\lambda) \frac{\partial M_\lambda(\lambda, T_b)}{\partial T} d\lambda} \sqrt{\frac{\Delta f}{A_D}}, \quad (10)$$

where $k_o = f_o'/D_p$ is lens aperture number.

Using relation (10), we define the following ways to reduce the *NETD* parameter:

1. Use fast lenses with a small aperture number $k_o = f_o'/D_p$ and high transmittance τ_o. This is the most efficient way, because *NETD* ~ k_o^2.
2. Use MRD with a high specific detective ability $D^*(\lambda)$.

3. Reduction of effective noise band Δf of reference filter. However, to obtain a high spatial resolution, this band should be increased [15]. Therefore, Δf is chosen from a compromise between spatial and temperature resolutions.

The obtained formula (10) for energy resolution is valid for the case when the thermal imager converts the brightness of the object of observation from the IR region of the spectrum into its image on the display screen in the visible region of the spectrum. In other words, in a classical thermal imager there is a transformation of radiation intensity. A polarization thermal imager records the polarization characteristics of the object and background by changing the angular orientation of the polarizer and phase plate in the optical system. The transmittance τ_0 of the optical system of PT with such a change in the angular orientation will be different, which according to formula (10) will lead to different values of the energy resolution of the thermal imager.

The paper [16] investigates the method of calculating the energy transmittance of the optical system of polarization thermal imager for partially polarized radiation depending on the angular orientation of the polarizer and the phase plate. In the PT, the characteristics of the polarization image are determined using the Stokes parameters, which are measured for angles α between the transmission plane of the polarizer and the optical axis of a quarter-wave retarder equal to 0°, 90°, 45°, and 135°.

The results of these studies testify that the normalized transmittance of the optical system of PT $\tau_{os,n} = \tau_{os} / \tau_p \tau_{hp} \tau_o$, where τ_p, τ_{hp} and τ_o are transmittances caused by the Fresnel losses on the input and output surfaces of optical elements and the absorption in the optical medium of the polarizer and the phase plate, respectively; τ_o are transmittances of IR lens:

1. For natural radiation, the transmittance does not depend on the angular orientation of the phase plate and is equal to 0.5.

2. For partially polarized radiation, the transmittance depends on the angle α. For angles α equal to 0º, 90º, 45º and 135º, the normalized transmittance τ_ (os, n) for the degree of polarization 0.5 is equal to 0.75, 0.25, 0.5 and 0.5, respectively. This feature of the optical system of PT will be taken into account when calculating the temperature resolution of the thermal imager.

Method of calculating the temperature resolution of PT

An important step in determining is the selection of a test object that should be used in the calculations and measurements of the temperature resolution of the PT. In this case, one should take into account:

1. Polarization characteristics of the object of observation: intensity, degree of polarization and polarization angle.
2. Energy parameters of the object of observation (test object) and background, which are determined by temperature, radiation and reflection coefficients of the object and the background.
3. Orientation of the test object surface and background relative to the optical surface of the

thermal imager.

Taking these features into account requires a detailed study that goes beyond this article. The research will be based on NATO standard 4347 for ground forces "Determination of nominal characteristics of static range for infrared surveillance systems" [17].

Therefore, in this paper, in the formula of energy resolution of classical thermal imagers (10) we will additionally take into account the following:

1. Test object and background parameters:

   1.1. The surfaces of the object and background have a uniform distribution of temperature T_t and T_b, radiation coefficients ε_t and ε_b and reflection coefficients R_t and R_b. The background temperature T_b = 288 K.

   1.2. The degree of polarization of radiation from the test object is P_t, and from the background $P_b = 0$.

2. The transmittance of the optical system $\tau_{os}(\alpha) = \tau_{os,n}(\alpha)(\tau_p\tau_{hp}\tau_o)$ depends on the angular orientation α of the polarizer relative to the optical axis of the phase plate.
3. Radiation detector – microbolometric matrix (MBM), which has temperature sensitivity $NETD_D$, format $p_D \times q_D$, pixel size $V_D \times W_D$, frame frequency f_f.

The specific detective ability D^*_{th} of the thermal radiation detector, such as MBM, does not depend on the radiation wavelength, and, therefore, in formula (10) it can be factored outside the integral. To determine *NETD* as MBM parameter in formula (10), it is assumed that [18]:

– aperture number of the optical system $k_0 = 1$;

– effective noise band $\Delta f = 1/(2t_i)$, where t_i is matrix integration time, which may be equal to the pixel time constant t_D.

In the case of such assumptions, the MBM parameter $NETD_D$ is calculated by the formula

$$NETD_D = \frac{4}{\sqrt{2A_D t_i}\cdot D^*_{th}\int_{\lambda_1}^{\lambda_2}\frac{\partial M_\lambda(\lambda,T_{th})}{\partial T}d\lambda}, \tag{11}$$

where T_{th} is the temperature of the test object whereby the parameter $NETD_D$ is determined.

From formula (11) we find the specific detective ability D^*_{th} and substitute it to (10)

$$NETD = NETD_D\frac{k_0^2}{\tau_{os}(\alpha)\varepsilon_t}k_D(T_{th},T_b), \tag{12}$$

where $k_D(T_{th}, T_b)$ is a coefficient which takes into account the difference of the differential luminosity of the surface of the test object at temperature T_{th} whereby the specific detective ability of MBM was measured, from the real background temperature T_b when testing PT,

$$k_D(T_{th},T_b) = \frac{\int_{\lambda_1}^{\lambda_2}\frac{\partial M_\lambda(\lambda,T_{th})}{\partial T}d\lambda}{\int_{\lambda_1}^{\lambda_2}\frac{\partial M_\lambda(\lambda,T_b)}{\partial T}d\lambda}. \tag{13}$$

Formula (12) is valid, provided that radiation coefficients of the test object ε_t and background ε_b have close values, i.e. $\varepsilon_t \approx \varepsilon_b$. The effect of degree of polarization P of partially polarized light from the test object is taken into account in the transmittance $\tau_{os}(\alpha)$ of the optical system of PT. In [16], it was established that the transmittance $\tau_{os}(\alpha)$ is determined by the function:

$$\tau_{os}(\alpha) = \tau_p \tau_{hp} \tau_o \left[\frac{1}{2}(1-P) + P\cos^2\alpha\right]. \quad (14)$$

Thus, the resulting formula (12) allows calculating the energy resolution of the polarization thermal imager.

Example of calculating the temperature resolution of PT

Consider an example of calculating the temperature resolution of PT under the following conditions:

1. Test object parameters:
   - Background temperature T_b = 288 K.
   - Temperature contrast ΔT = 2 K .
   - Radiation coefficient of test object surface ε_t = 1.
   - Angular position of the normal to the surface relative to observation axis φ = 85 °
   - Degree of polarization P = 0.5.
   - Polarization angle Ψ = 0 °.
2. Integral transmittance of the atmosphere in the spectral range $\lambda_1 \ldots \lambda_2$ = 8 μm τ_A = 1.
3. Optical system parameters:
   - Input pupil diameter and infrared lens focal length – D_p = 50 mm and f_0 = 50 mm.

Input pupil diameter and IR lens focal length

- Integral transmittances of individual elements of optical system:
  - polarizer τ_p = 0.9;
  - phase plate τ_{hp} = 0.9;
  - IR lens τ_0 = 0.85.

4. Parameters of radiation detector – microbolometric matrix GWIR 0304X2A, which has parameters:
   - * Working spectral range $\lambda_1 \ldots \lambda_2$ = 8…14 μm.
   - Temperature sensitivity $NETD_D$ = 0.05 K
   - Matrix format $p_D \times q_D$ = 640×512 pixel.
   - Pixel size $V_D \times W_D$ = 17 × 17 μm.
   - Frame frequency f_f = 50 Hz.

To calculate the temperature separation of PT, we use formula (12), in which, according to the condition of the example, we know:

1. Noise equivalent temperature difference of MBM $NETD_D$ = 0.05 K.

- Radiation coefficient of test object surface $\varepsilon_t = 1$.

2. Aperture number of the optical system $k_0 = D_p / f_0 = 1$.

Coefficient of MBM $k_D(T_{th}, T_b)$ for the temperatures $T_{th} = 300$ K and $T_b = 288$ K will be calculated by the formula (13) [13]:

$$k_D(T_{th}, T_b) = \frac{\int_8^{14} \frac{\partial M_\lambda(\lambda,300)}{\partial T} d\lambda}{\int_8^{14} \frac{\partial M_\lambda(\lambda,288)}{\partial T} d\lambda} = \frac{232\ \frac{\text{мкВт}}{\text{см}^2 K}}{263\ \frac{\text{мкВт}}{\text{см}^2 K}} = 0{,}88\ \ \mu\text{W}$$

Determination of the transmittance of the optical system of PT depending on the angular orientation α of the polarizer relative to the optical axis of the phase plate is investigated in detail in [16]. For partially polarized radiation, the transmittance depends on the angle α. For angles α equal to 0°, 90°, 45° and 135°, the normalized transmittance $\tau_{os,n}$ for the degree of polarization $P = 0.5$ is equal to 0.75, 0.25, 0.5 and 0.5, respectively. This feature of the optical system of PT will be taken into account when calculating the temperature resolution of the thermal imager.

Let us substitute the above parameters of PT into formula (12) and calculate the temperature resolution for different values of angle α:

$$NETD(\alpha = 0^\circ) = 0{,}05 \cdot \frac{1}{0{,}9 \cdot 0{,}9 \cdot 0{,}85 \cdot 0{,}75 \cdot 1} 0{,}88 = 0{,}085\ K;$$

$$NETD(\alpha = 90^\circ) = 0{,}26\ K; NETD(\alpha = 45^\circ) = 0{,}13\ K; NETD(\alpha = 135^\circ) = 0{,}13\ K$$

Let us establish the dependence of the temperature resolution of PT on the degree of polarization P of partially polarized radiation, which affects the transmittance $\tau_{os}(P)$ of the optical system of the thermal imager. In [16], it was found that for angles α = 45◦ and 135◦ the normalized transmittance does not depend on the degree of polarization and is equal to $\tau_{os}(P) = 0.5$. For the angles α = 0◦ and 90◦ we have, respectively:

$$\tau_{os}(P, \alpha = 0^\circ) = \frac{1}{2} \tau_p \tau_{hp} \tau_o (1 + P); \tag{15}$$

$$\tau_{os}(P, \alpha = 90^\circ) = \frac{1}{2} \tau_p \tau_{hp} \tau_o (1 - P). \tag{16}$$

After substituting (15) and (16) into equation (12), we obtain the dependence of the temperature resolution of the PT on the degree of polarization of the radiation of the test object. The graph of this dependence for the previously selected parameters of the thermal imager is shown in Fig. 1.

$$NETD(P,\alpha=0^\circ)=NETD_D\frac{2k_0^2}{\tau_p\tau_{ph}\tau_o(1+P)\varepsilon_t}k_D(T_{th},T_b);\tag{17}$$

$$NETD(P,\alpha=90^\circ)=NETD_D\frac{2k_0^2}{\tau_p\tau_{ph}\tau_o(1-P)\varepsilon_t}k_D(T_{th},T_b).\tag{18}$$

It was also important to establish the dependence of the temperature resolution of the PT for an arbitrary angle α of orientation of the phase plate relative to the transmission plane of the polarizer. In [16], the dependence of the transmittance of the optical system on the angle α and degree of polarization *P* was obtained:

$$\tau_{os}(\alpha,P)=\tau_p\tau_{hp}\tau_o[0{,}5(1-P)+P\cos^2\alpha].\tag{19}$$

On substituting (19) into Eq. (12) we obtain a dependence of the temperature resolution of the PT on the angular orientation α of the polarizer with respect to the optical axis of the phase plate with a given degree of polarization *P*.

$$NETD(\alpha,P)=NETD_D\frac{1}{0{,}9\cdot 0{,}9\cdot 0{,}85\cdot[0{,}5(1-P)+P\cos^2\alpha]}0{,}88.\tag{20}$$

The plots of this dependence for the previously selected parameters of the thermal imager are given in Fig. 2 and 3.

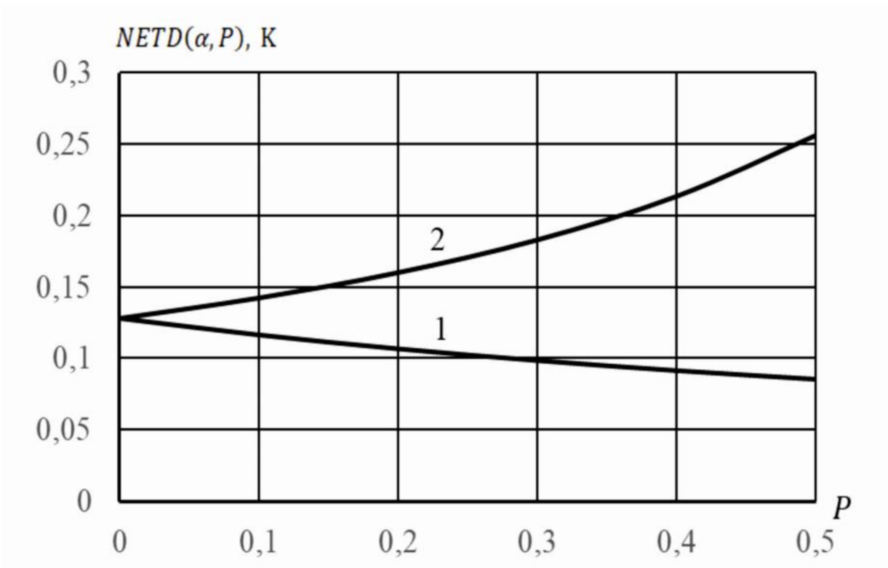

Fig. 2. Dependence of the temperature resolution of the polarization thermal imager on the degree of polarization P of test object radiation for the angular orientation α of the polarizer relative to the optical axis of the phase plate which is equal to: 1 – 0°; 2 – 90°

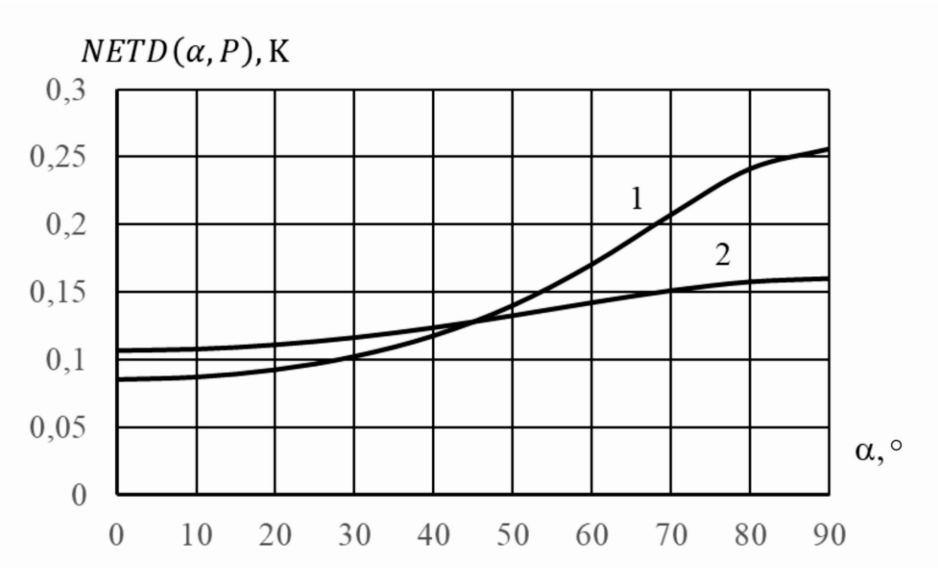

Fig. 3. Dependence of temperature resolution of the polarization thermal imager on the angular orientation α of the polarizer relative to optical axis of the phase plate for the degree of polarization: 1 – P = 0.5; 2 – P = 0.2.

Analysis of the obtained theoretical simulation results allows for the following conclusions:

1. As the degree of polarization P increases, the temperature resolution of the PT for the radiation component that is polarized in the observation plane ($\alpha = 0°$) decreases, and for the perpendicular component ($\alpha = 90°$) it increases.

2. For nonpolarized radiation ($P = 0$), the transmittance of the optical system does not depend on the angle α, so the temperature resolution remains unchanged at arbitrary orientation of the polarizer relative to the axis of the phase plate.

3. For fully polarized radiation ($P = 1$), the temperature resolution depends on the angle α and varies according to the law $NETD\ (\alpha,\ P = 1) \sim \cos^{-2}\alpha$. If $\alpha = 0°$, then the PT has the lowest temperature resolution.

4. If the optical axis of the phase plate forms an angle $\alpha = 45°$ with the plane of the polarizer, then the temperature resolution of the PT does not depend on the degree of polarization P and is equal to 0.13 K.

Conclusions

The proposed physics-mathematical model of the optoelectronic system of a polarization thermal imager, which consists of a polarizer, a quarter-wave retarder and a lens arranged in series on the optical axis, allowed developing a method for determining the temperature (energy) resolution of the thermal imager. The study of this method made it possible to:

1. Obtain an equation for the thermal imager signal transmission function which was used to determine the temperature resolution of the thermal imager.

2. As a temperature resolution of polarization thermal imager it is proposed to use a classical parameter – the noise equivalent temperature difference *NETD* and NATO standard 4347 [17-19].

3. Obtain an equation for calculating the *NETD* parameter, which takes into account the dependence of the transmittance of the optical system on the angular orientation of the polarizer and the phase plate. A study of this equation showed that

3.1. The polarization thermal imager records the polarization characteristics of the test object and the background by changing the angular orientation of the polarizer and the phase plate in the optical system. The transmittance τ_0 of the optical system of PT with such a change in angular orientation will be different, which leads to different values of the temperature resolution of the thermal imager [19].

3.2. The temperature resolution depends on the degree of polarization of the studied radiation. For unpolarized radiation the temperature resolution remains unchanged at an arbitrary orientation of the polarizer relative to the axis of the phase plate.

3.3. The lowest temperature resolution will be in the case when the optical axis of the phase plate forms and angle $\alpha = 0°$ with the plane of the polarizer.

The obtained results must be taken into account when developing an electronic system for processing video signals from a matrix radiation detector. In further research, it is also important to develop a model of a test object with specified polarization characteristics of IR radiation such as the degree, ellipticity and azimuth of polarization.

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Submitted 28.08.2020

Колобродов В.Г., *докт. техн. наук, професор*
Микитенко В.І., *докт. техн. наук, доцент*
Тимчик Г.С. *докт. техн. наук, професор*
Сокол Б.В.

Національний технічний університет України
«Київський політехнічний інститут імені Ігоря Сікорського»
проспект Перемоги, 37, Київ, 03056, Україна
e-mail: deanpb@kpi.ua

ТЕМПЕРАТУРНЕ РОЗДІЛЕННЯ КОМП'ЮТЕРНО-ІНТЕГРОВАНОГО ПОЛЯРИЗАЦІЙНОГО ТЕПЛОВІЗОРА

Робота присвячена розробці методу визначення енергетичного (температурного) розділення поляризаційного тепловізора. Запропоновано використовувати для цього величину еквівалентної шуму різниці температур NETD (Noise Equivalent Temperature Difference). Розроблено фізико-математичну модель оптико-електронної системи поляризаційного тепловізора, яка дозволяє обраховувати її функцію передачі сигналу. На основі цієї функції розроблено методику обчислення NETD. Отримано формулу, що описує функціональну залежність температурного розділення поляризаційного тепловізора від кутової орієнтації поляризатора відносно оптичної осі фазової пластини при заданому ступені поляризації. Виконано дослідження впливу ступеня поляризації випромінювання тест-об'єкта на температурне розділення поляризаційного тепловізора, який містить лінійний поляризатор і фазову пластину. Бібл. 8, рис. 7, табл. 1.

***Ключові слова**: поляризаційний тепловізор, енергетичне розділення, еквівалентна шуму різниця температур, ступень поляризації*

Колобродов В.Г., *докт. техн. наук, профессор*
Мыкытенко В.И., *докт. техн. наук, доцент*
Тымчык Г.С., *докт. техн. наук, профессор*
Сокол Б.В.

Национальный технический университет Украины
"Киевский политехнический
институт имени Игоря Сикорского», проспект Победы,
37, Киев, 03056, Украина, *e-mail: deanpb@kpi.ua*

ТЕМПЕРАТУРНОЕ РАЗДЕЛЕНИЕ КОМПЬЮТЕРНО-ИНТЕГРИРОВАННЫХ ПОЛЯРИЗАЦИОННЫХ ТЕПЛОВИЗОРОВ

В статье предложена поляризационная модель тепловизора с целью его применения при исследовании термоэлектрических явлений и устройств, позволяет повысить эффективность работы таких устройств. Для исследования и проектирования таких тепловизоров рассмотрена физико-математическая модель поляризации излучения от объектов наблюдения, которая учитывает поляризационные свойства собственного теплового излучения и отраженного внешнего излучения. Разработанная модель была применена для определения поляризационных свойств излучения плоской железной пластины. Анализ полученных результатов свидетельствует о том, что для теплового излучения при углах наблюдения $\psi < 40^o$, составляющие коэффициента излучения почти одинаковы $\varepsilon_{||} \approx \varepsilon_{\perp} \approx 0.16$, но $\varepsilon_{||} < \varepsilon_{\perp}$. С увеличением угла наблюдения $\psi > 40^o$ перпендикулярная поляризационная компонента $\varepsilon_{\perp}$ монотонно уменьшается до нуля, а параллельная компонента $\varepsilon_{||}$ увеличивается и достигает максимального значения при угле $\psi = 84^o$, а затем уменьшается до нуля. Степень поляризации излучения возрастает с увеличением угла ψ и при угле $\psi = 84^o$ равна 0.96. Полученные результаты исследований целесообразно использовать при разработке модели термоэлектриков, которая может использоваться при проектировании поляризационного тепловизора. Библ. 8, рис. 7, табл. 1.

Ключевые слова: Поляризационный тепловизор, температурное разделение, частично поляризованное излучение, степень поляризации.

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