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Computer Modelling Technologies of Optical System of Polarizing Thermal Imager

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The energetic resolution is a main parameter of any thermal imager depending on the transmittance of its optical system. The optical system of a polarizing thermal imager (PTI) consists of a polarizer, a phase shifter and a lens arranged in series on the optical axis. This paper proposes a method for calculation of the energic transmittance of the PTI's optical system for partially polarized radiation as a function of angular orientation of the polarizer and the phase retarder. The physical-mathematical model of transformation of partially polarized radiation within the optical system which depends on parameters of optical elements and their orientation in space is investigated. This model allowed us to determine the transmittance of the system "polarizer - phase shifter" system depending on the angle α between the optical axes of the polarizer and the phase retarder. The analysis of this method has shown that, for the natural radiation, the normalized transmittance of the optical system does not depend on the angular orientation of the phase retarder and is equal to 0.5. For the partially polarized radiation, the transmittance depends on the angle α: the maximum transmittance value will be achieved in the case when the optical axis of the phase retarder lies in the transmittance plane of the polarizer ($\alpha = 0°$). For an arbitrary degree of polarization, the transmittance decreases with increasing angle α. At an angle ($\alpha = 45°$), the transmittance is equal to 0.5 and does not depend on the degree of polarization of the examined radiation. To calculate the characteristics of the partially polarized radiation using Stokes parameters, the intensity is to be measured at the output of the optical system for angles α equal to $0°, 90°, 45°$, and $135°$. For such angles, the normalized transmittance for the degree of polarization of 0.5 is equal to 0.75, 0.25, 0.5, and 0.5, respectively. This feature of the PTI's optical system must be taken into account when calculating the temperature resolution and the maximum range of the thermal imager.

Key words: polarizing thermal imager; polarizer; phase retarder; energetic transmittance; Stokes vector

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Introduction

Polarization is one of specific characteristics of the electromagnetic radiation field, besides its intensity, wavelength, and coherence [1–3]. Polarimetry measures the vector character of the radiation reflected or scattered from the object's surface and provides important information about the surface's orientation, shape and quality. The polarization properties of radiation detected from observation objects may differ properties of radiation obtained from backgrounds and are not correlated with the intensity and spectrum. As a rule, radiation from the target is partially polarized, while radiation from the background is natural [4, 5]. Thus, polarimetric images are very useful for increasing the signal from the target and suppressing background noise.

The main characteristics of polarized radiation are the intensity, the degree of polarization, the azimuth and ellipticity of polarization [6–8]. To measure these characteristics in the infrared (IR) region of the spectrum, polarizing thermal imagers (PTI) are applied [9–11]. The main characteristic of any thermal imager is energetic resolution, which depends on the transmittance of its optical system. There are many monographs and articles in whichthe calculation and measurement of the transmittance of thermal imager lenses are explored [12–14]. At the same time, there is almost no scientific and technical information on calculation of the transmittance of the PTI's optical system consisting of the polarizer, phase retarder and lens, which are sequentially located on the optical axis.

1 Problem formulation

The purpose of this article is to develop a method for calculating the energetic transmittance of the optical system of a polarizing thermal imager for partially polarized radiation depending on the angular orientation of the polarizer and the phase retarder.

2 Physical basics of the polarization of the thermal imager

We consider the optical system of PTI, which consists of the IR polarizer, quarter-wave retarder and IR lens of the thermal imager, sequentially located on the optical axis (Fig. 1). Let a parallel beam of natural or partially polarized radiation with amplitudes $\vec{E}_n$ or $\vec{E}_{pp}$ respectively is directed at the input of the optical system. At the output of the polarizer, the linearly polarized radiation is formed with the vector $\vec{E}_{lp}$, which is oriented at an angle α relative to the optical axis oo of the retarder (Fig. 2). After passing through a quarter-wave retarder, the optical axis of which is parallel to the surface of the retarder and makes an angle α with the vector $\vec{E}_{lp}$ (plane of polarization), as a result of birefringence, the ordinary and extraordinary rays with amplitudes E_o and E_e are formed in the retarder. They propagate in the same direction and have the following phase difference at the output from the retarder

$$\Delta\varphi = k \cdot \Delta d = \frac{2\pi}{\lambda}(n_o - n_e)d\,, \qquad (1)$$

where d is a thickness of the retarder, Δd is the optical path difference between the ordinary and extraordinary rays, n_o and n_e are refractive indices for ordinary and extraordinary rays, respectively.

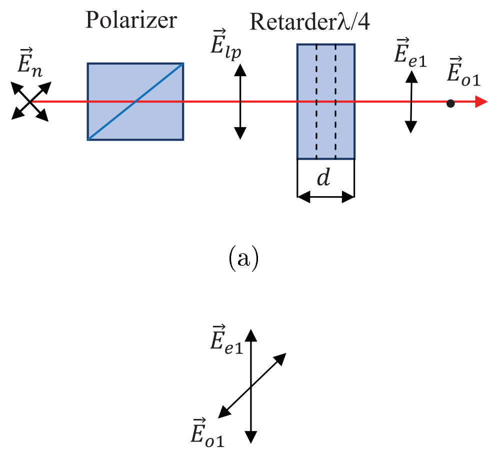

Fig. 1. Scheme for research of the polarization of radiation (a) and its vector model (b)

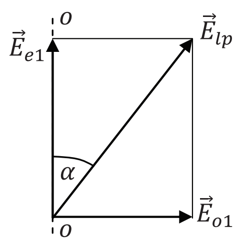

Fig. 2. Vector model of obtaining elliptically polarized light

First, let's consider the case when the optical system receives natural radiation with intensity $I_0 = I_{0o} + I_{0e}$, where $I_{0o} = |E_{0o}|^2$ and $I_{0e} = |E_{0e}|^2$ is the intensity of ordinary and extraordinary rays, respectively, and $I_{0o} = I_{0e} = 0,5 I_0$.

Let's determine the amplitudes of ordinary E_{o1} and extraordinary E_{e1} rays at the output of the retarder, if the plane of polarization of the ray E_{lp} incident on the retarder forms an angle α with the optical axis of the crystal. From Fig. 2, we have

$$E_{o1} = E_{lp}\sin\alpha; \quad E_{e1} = E_{lp}\cos\alpha.$$

The amplitudes (instantaneous values of field strengths) of ordinary and extraordinary rays change over time according to the law

$$E_e = E_{e1}\cos\omega t; \quad E_o = E_{o1}\cos(\omega t - \Delta\varphi). \qquad (2)$$

The system of equations (2) is represented as one equation, which does not depend on time t:

$$\frac{E_e}{E_{e1}} = \cos\omega t;$$

$$\frac{E_o}{E_{o1}} = \cos(\omega t - \Delta\varphi) = \cos\omega t\cos\Delta\varphi + \sin\omega t\sin\Delta\varphi =$$

$$= \frac{E_e}{E_{e1}}\cos\Delta\varphi + \sqrt{1 - \left(\frac{E_e}{E_{e1}}\right)^2}\sin\Delta\varphi;$$

$$\frac{E_o}{E_{o1}} - \frac{E_e}{E_{e1}}\cos\Delta\varphi = \sqrt{1 - \left(\frac{E_e}{E_{e1}}\right)^2}\sin\Delta\varphi.$$

Let us bring the right and left sides of the last relationship to the square

$$\left(\frac{E_o}{E_{o1}}\right)^2 - 2\frac{E_o}{E_{o1}}\frac{E_e}{E_{e1}}\cos\Delta\varphi + \left(\frac{E_e}{E_{e1}}\right)^2\cos^2\Delta\varphi =$$

$$= \sin^2\Delta\varphi - \sin^2\Delta\varphi\left(\frac{E_e}{E_{e1}}\right)^2,$$

or

$$\left(\frac{E_o}{E_{o1}}\right)^2 - 2\frac{E_o}{E_{o1}}\frac{E_e}{E_{e1}}\cos\Delta\varphi + \left(\frac{E_e}{E_{e1}}\right)^2 = \sin^2\Delta\varphi. \qquad (3)$$

The equation (3) is the equation of the ellipse, which is arbitrarily oriented relative to the optical axis oo of the retarder (Fig. 3). Therefore, the resulting field amplitude at the output of the retarder will form the elliptically polarized light, where $\vec{E}_r = \vec{E}_o + \vec{E}_e$. The semi-axes E_{o1} and E_{e1} of the ellipse, as well as its orientation depend on the angle α and the phase difference $\Delta\varphi$ (1). The obtained equation (3) is called a polarization ellipsoid, in which the ellipticity of the ellipse is a degree of polarization, the direction of the major axis of the ellipse is a direction of polarization θ_p of the ellipse, and the circle inscribed in the ellipse is a natural component of radiation. The linearly polarized component in the direction of the polarization angle θ_p

is the largest, while in the perpendicular direction it is zero.

By analysing the equation (3) for the case when the phase difference $\Delta\varphi$ between ordinary E_o and extraordinary E_e rays is equal to $\pi/2$, we can determine the thickness of the retarder that provides this case. From formula (1):

$$\Delta\varphi = \frac{2\pi}{\lambda}(n_o - n_e)d = \frac{\pi}{2}; \Rightarrow d = \frac{\lambda}{4(n_o - n_e)}. \quad (4)$$

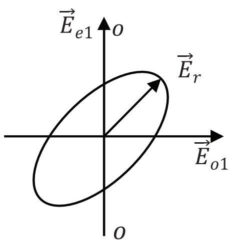

Fig. 3. Vector model of elliptically polarized light

In this case, the optical path difference Δd between the ordinary and extraordinary rays is equal to

$$\Delta d = (n_o - n_e)d = \frac{1}{4}\lambda\,.$$

Therefore, the uniaxial crystal retarder that provides the condition (4), is called a retarder thickness of $\lambda/4$ or a quarter wave retarder.

For such a retarder, equation (3) has the form

$$\frac{E_o^2}{E_{o1}^2} + \frac{E_e^2}{E_{e1}^2} = 1. \quad (5)$$

The expression (5) represents the equation of the ellipse having the semi-axes

$$a = E_{o1} = E_{lp}\sin\alpha; \;\; b = E_{e1} = E_{lp}\cos\alpha\,.$$

Here, we can consider four cases for the equation (5) with different values of the angle α between the plane of polarization of the radiation incident on the wave retarder and the optical axis of the retarder (2):

1. $\alpha = 0°$. Then $E_o = E_{o1} = 0$ and $E_{e1} = E_{lp}$, and the equation (5) will be presented as $E_e = E_{e1}$. This means that, in this case, the linearly polarized radiation with intensity $I_{0°} = I_{0e} = 0.5I_0$ is formed at the output of the retarder.

2. $\alpha = 90°$. Then $E_{o1} = E_{lp}$ and $E_e = E_{e1} = 0$, and the equation (5) will be presented as $E_o = E_{o1}$. This means that, in this case, the linearly polarized radiation with intensity $I_{90°} = I_{0o} = 0.5I_0$ is formed at the output of the retarder.

3. $\alpha = 45°$. Then $E_{o1} = E_{lp}/\sqrt{2}$ and $E_{e1} = E_{lp}/\sqrt{2}$, and the equation (5) will be presented as $E_o^2 + E_e^2 = E_{lp}^2/2$. This means that, in this case, the right-circular polarized radiation with intensity $I_{45°} = 0.5I_0$ is formed at the output of the retarder.

4. $\alpha = 135°$. Then $E_{o1} = E_{lp}/\sqrt{2}$ and $E_{e1} = -E_{lp}/\sqrt{2}$, and the equation (5) will be presented as $E_o^2 + E_e^2 = E_{lp}^2/2$. This means that, in this case, the left-circular polarized radiation with intensity $I_{135°} = 0.5I_0$ is formed at the output of the retarder.

Consider the case when partially polarized radiation is directed into the input of the optical system with the following parameters: the intensity I_0, the degree of polarization P, the direction of polarization θ_p. By using the model of partially polarized radiation, according to which such radiation is a superposition of linearly polarized I_p and unpolarized radiation (natural radiation) I_n, one can obtain the resulting intensity [2, 11, 15]

$$I_{pp} = I_0 = I_n + I_p. \quad (6)$$

After passing the polarizer (Fig. 1), the intensity will depend on the orientation angle θ_p of the partially polarized radiation relative to the vertical y axis and the observation (measurement) angle $\varphi = \alpha$. Then, according to Malus's law

$$I_{pp}(\varphi) = I_n(\varphi) + I_p(\varphi) = \frac{1}{2}I_n + I_p\cos^2(\varphi - \theta_p), \quad (7)$$

where $\frac{1}{2}I_n$ is a natural component; $I_p\cos^2(\varphi - \theta_p)$ is a linearly polarized component.

The degree of polarization is determined by the classical formula

$$P = \frac{I_\parallel - I_\perp}{I_\parallel + I_\perp}\,, \quad (8)$$

where $I_\parallel$ and $I_\perp$ are intensity components of two mutually perpendicular polarization components, which are obtained from formula (7):

$$I_\parallel(\varphi) = I(\theta_p) = I_n(\theta_p) + I_p(\theta_p) = \frac{1}{2}I_n + I_p\,, \quad (9)$$

$$I_\perp(\varphi) = I\left(\theta_p + \frac{\pi}{2}\right) = I_n\left(\theta_p + \frac{\pi}{2}\right) + I_p\left(\theta_p + \frac{\pi}{2}\right) = \frac{1}{2}I_n. \quad (10)$$

From equations (6) - (10) we can obtain the degree of polarization of the partially polarized radiation

$$P = \frac{I_p}{I_n + I_p} = \frac{I_p}{I_{pp}}\,,$$

where

$$I_p = PI_{pp} = PI_0; \;\; I_n = I_0 - I_p = I_0(1 - P). \quad (11)$$

Below we analyze four cases for the equation (7) with different values of the angle α between the plane of polarization of the radiation incident on the wave retarder and the optical axis of the retarder, when $\theta_p = 0$.

The characteristics of the polarization image are determined using Stokes parameters, which are measured for angles α equal to 0°, 90°, 45°, and 135°. For these angles, we have:

1. $\alpha = 0°$. Then $I_{0°} = \frac{1}{2}I_n + I_p = \frac{1}{2}I_0(1-P) + PI_0 = = \frac{1}{2}I_0(1+P)$.

2. $\alpha = 90°$. Then $I_{90°} = \frac{1}{2}I_n = \frac{1}{2}I_0(1-P)$.

3. $\alpha = 45°$. Then $I_{45°} = \frac{1}{2}I_n + I_p \cos^2 45° = \frac{1}{2}I_n + + \frac{1}{2}I_p = \frac{1}{2}[I_0(1-P) + PI_0] = \frac{1}{2}I_0$.

4. $\alpha = 135°$. Then $I_{135°} = \frac{1}{2}I_0$.

An energetic transmittance of the optical system of PTI is defined as

$$\tau_{os} = \tau_p \tau_{hp} \tau_o = \frac{I_\alpha}{I_0}, \tag{12}$$

where I_0 is the radiation intensity at the input of the optical system (polarizer); I_α is the radiation intensity at the output of the optical system (lens); τ_p , τ_{hp} , τ_o are transmittances of the polarizer, phase retarder and lens, respectively.

By using the formulas obtained above, we can determine the transmittance of the system "polarizer - phase retarder" depending on the angle α between the optical axes of the polarizer and the phase retarder.

For natural radiation, we have:

$$\tau_{p-hp} = \tau_p \tau_{hp}(\alpha) = \frac{1}{2}\tau_p \tau_{hp}, \tag{13}$$

where τ_p and τ_{hp} are transmittances due to Fresnel losses on the input and output surfaces of the optical elements and absorption in the optical medium of the polarizer and the phase retarder, respectively.

It is clear from the formula (13) that the transmittance of the optical system for natural radiation does not depend on the angle α.

For partially polarized radiation with different angles α:

1. $\tau_{os} = \tau_p \tau_{hp}(\alpha = 0°) = \tau_p \tau_{hp} \frac{1}{2}(1+P)$;

2. $\tau_{os} = \tau_{hp}(\alpha = 90°) = \tau_p \tau_{hp} \frac{1}{2}(1-P)$;

3. $\tau_{os} = \tau_{hp}(\alpha = 45°) = \tau_p \tau_{hp}$;

4. $\tau_{os} = \tau_{hp}(\alpha = 135°) = \tau_p \tau_{hp}$.

Let's determine the transmittance of the optical system for an arbitrary angle α. From the expressions (7), (11), and (12), we have

$$\begin{aligned} \tau_{os} &= \frac{I_\alpha}{I_0} = \frac{\tau_p \tau_{hp} \tau_o}{I_0}\left[\frac{1}{2}I_n + I_p \cos^2\alpha\right] = \\ &= \frac{\tau_p \tau_{hp} \tau_o}{I_0}\left[\frac{1}{2}I_0(1-P) + PI_0 \cos^2\alpha\right] = \\ &= \tau_p \tau_{hp} \tau_o \left[\frac{1}{2}(1-P) + P\cos^2\alpha\right]. \end{aligned} \tag{14}$$

The charts of the normalized transmittance of the PTI's optical system $\tau_{os,n} = \tau_{os}/\tau_p \tau_{hp} \tau_o$ in dependence on the angle α are shown in Fig. 4.

The analysis of the function (14) and its charts shows that:

1. For natural radiation, the normalized transmittance of the optical system $\tau_{os,n}$ of PT does not depend on the angle α and is equal to 0.5.

2. For partially polarized radiation, the transmittance of the optical system decreases as the angle α increases.

3. For partially polarized radiation, at an angle $\alpha = 45°$, the transmittance $\tau_{os,n}$ with an arbitrary degree of polarization is equal to 0.5. This occurs due to the fact the circularly polarized radiation is formed when the angle $\alpha = 45°$.

4. For partially polarized radiation, at observation angles $\alpha < 45°$, the transmittance $\tau_{os,n}$ is greater than for the natural radiation, while at angles $\alpha > 45°$ – vice versa.

5. For small values of the polarization degree $P < 0.1$, the normalized transmittance varies slightly within the range $0.45 < \tau_{os,n} < 0.55$.

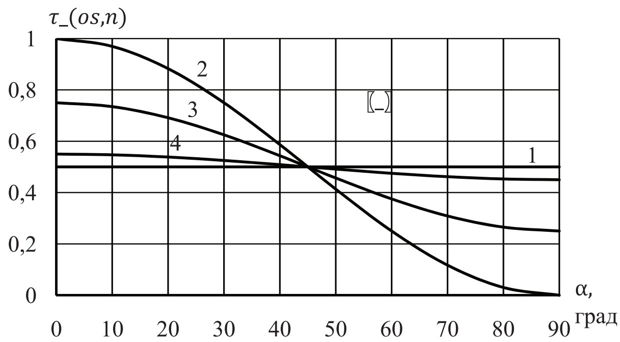

Fig. 4. Dependence of the energetic transmittance of the optical system of a polarizing thermal imager $\tau_{os,n}$ for the partially polarized radiation on the angle α between the plane of polarization of the radiation incident on the wave retarder and the optical axis of the retarder. Polarization degree value: 1 – P=0; 2 – P=1; 3 – P=0.5; 4 – P=0.1.

The increase the transmittance of the optical system of PTI, and hence the improvement the energetic resolution of PTI can be achieved by:

1. Reduction of Fresnel losses on reflection by using optical elements with low refractive index or applying antireflection coatings on surfaces.

2. Use a polarizer, phase retarder and IR lens with high transmittance.

Conclusions

The proposed physical-and-mathematical model of the optical system of a polarizing thermal imager enabled to develop a method of calculating the energetic transmittance of an optical system for the partially polarized radiation depending on the angular orientation of the polarizer and the phase retarder. The analysis of this method has shown that:

1. For natural radiation, the normalized transmittance $\tau_{os,n}$ of the optical system does not depend on

the angular orientation of the phase retarder and is equal to 0.5.

2. For partially polarized radiation, the transmittance $\tau_{os,n}$ depends on the angle α:

2.1. The maximum value of the transmittance will occur in the case when the optical axis of the phase retarder lies in the plane of transmission of the polarizer ($\alpha = 0°$). For an arbitrary degree of polarization, the transmittance decreases with increasing angle α.

2.2. At an angle $\alpha = 45°$ the transmittance is equal to 0.5 and does not depend on the degree of polarization of the examined radiation.

2.3. To calculate the characteristics of the partially polarized radiation using Stokes parameters, the intensity at the output of the optical system for angles α equal to 0°, 90°, 45° and 135° is measured. For these angles, the normalized transmittance $\tau_{os,n}$ with the degree of polarization of 0.5 is equal to $0.75, 0.25, 0.5$, and 0.5, respectively. This feature of the optical system of PTI must be taken into account when calculating the temperature resolution of the thermal imager.

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Комп'ютерні технології моделювання оптичної системи поляризаційного тепловізора

Колобродов В. Г.

У статті досліджується запропонований метод розрахунку енергетичного коефіцієнта пропускання оптичної системи поляризаційного тепловізора (ПТ) для частково поляризованого випромінювання в залежності від кутової орієнтації поляризатора і фазової пластинки.

Основною характеристикою будь-якого тепловізора є енергетичне розділення, яке залежить від коефіцієнта пропускання його оптичної системи. Оптична система ПТ складається із послідовно розташованих на оптичні осі поляризатора, фазової пластинки і об'єктива. Досліджена фізико-математична модель перетворення частково поляризованого випромінювання в такій оптичній системі в залежності від параметрів оптичних елементів та їх орієнтації у просторі. Така модель дозволила визначити коефіцієнт пропускання системи «поляризатор – фазова пластина» в залежності від кута між оптичними осями поляризатора і фазової пластини.

Дослідження цього методу показали, що нормований коефіцієнт пропускання оптичної системи для природнього випромінювання не залежить від кутової орієнтації фазової пластини і дорівнює 0,5. Для частково поляризованого випромінювання коефіцієнт пропускання залежить від кута α: максимальне значення коефіцієнта пропускання буде у випадку, коли оптична вісь фазової пластини лежить в площині пропускання поляризатора ($\alpha = 0°$). Для довільного ступеня поляризації із збільшенням кута α коефіцієнт пропускання зменшується. При куті $\alpha = 45°$ коефіцієнт пропускання дорівнює 0,5 і не залежить від ступеня поляризації досліджуваного випромінювання.

Для розрахунку характеристик частково поляризованого випромінювання з використанням параметрів Стокса вимірюється інтенсивність на виході оптичної системи для кутів α рівних 0°, 90°, 45° і 135°. Для таких кутів нормований коефіцієнт пропускання для ступеня поляризації 0,5 дорівнює $0{,}75, 0{,}25, 0{,}5$ і 0,5 відповідно. Таку особливість оптичної системи ПТ необхідно враховувати при розрахунках температурного розділення і максимальної дальності дії тепловізора.

Ключові слова: поляризаційний тепловізор; поляризатор; фазова пластина; енергетичний коефіцієнт пропускання; вектор Стокса

Компьютерные технологии моделирования оптической системы поляризационного тепловизора

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В статье исследуется предложенный метод расчета энергетического коэффициента пропускания оптической системы поляризационного тепловизора (ПТ) для частично поляризованного излучения в зависимости от угловой ориентации поляризатора и фазовой пластинки.

Основной характеристикой любого тепловизора является энергетическое разделение, которое зависит от коэффициента пропускания его оптической системы. Оптическая система ПТ состоит из последовательно расположенных на оптические оси поляризатора, фазовой пластинки и объектива. Исследована физико-математическая модель преобразования частично поляризованного излучения в такой оптической системе в зависимости от оптических элементов и их ориентации в пространстве. Такая модель позволила определить коэффициент пропускания системы «поляризатор - фазовая пластина» в зависимости от угла α между оптическими осями поляризатора и фазовой пластины.

Исследования этого метода показали, что нормированный коэффициент пропускания оптической системы для естественного излучения не зависит от угловой ориентации фазовой пластины и равен 0,5. Для частично поляризованного излучения коэффициент пропускания зависит от угла α: максимальное значение коэффициента пропускания будет в случае, когда оптическая ось фазовой пластины лежит в плоскости пропускания поляризатора ($\alpha=0^\circ$). Для произвольной степени поляризации с увеличением угла α коэффициент пропускания уменьшается. При угле $\alpha = 45^\circ$ коэффициент пропускания равен 0,5 и не зависит от степени поляризации исследуемого излучения.

Для расчета характеристик частично поляризованного излучения с использованием параметров Стокса измеряется интенсивность на выходе оптической системы для углов α равных 0°, 90°, 45° и 135°. Для таких углов нормированный коэффициент пропускания для степени поляризации 0,5 равен $0{,}75, 0{,}25, 0{,}5$ и 0,5 соответственно. Такую особенность оптической системы ПТ необходимо учитывать при расчетах температурного разделения и максимальной дальности действия тепловизора.

Ключевые слова: поляризационный тепловизор; поляризатор; фазовая пластина; энергетический коэффициент пропускания; вектор Стокса