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Detection and research of solids emission properties using the modulation polarimetry technique

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The optical polarization technique (modulation polarimetry) was used to rapidly determine and analyze the emission properties of solids in which mechanical stresses arise during the contactless interaction of bodies with different emissivity coefficients at an identical system temperature. This method is a modern optical measurement approach that enables highly sensitive detection of anisotropic and polarization-dependent optical properties of materials. The materials investigated in this study (glass, silicon, aluminum, etc.) were selected due to their widespread use in thermal physics and materials science, as well as the significant differences in their emissivity and related parameters.Mechanical stresses and the characteristic heat-transfer time in solids were experimentally determined. It was further established that the characteristic heat-transfer time and the thermal conductivity coefficient are inversely related ($f=c(\tau)$), whereas mechanical stresses and emissivity are related by an exponential dependence ($f=\sigma(\varepsilon)$). Thus, this technique offers a rapid and effective method for determining the thermal conductivity and emissivity of solid materials. These capabilities are of considerable practical importance for technological and engineering calculations of radiative heat exchange between different materials (glass, metals, composites, synthetic and biological materials), including those containing internal defects and inclusions.

Keywords: optical polarization method, thermoelasticity, emissivity coefficient, thermal conductivity coefficient.

Детектування та дослідження емісійних властивостей твердих тіл методом модуляційної поляриметрії. *І. Матяш, І. Мінайлова, Б. Сердега, О. Міщук*

Оптико-поляризаційний метод (метод модуляційної поляриметрії) було використано для швидкого визначення і дослідження емісійних властивостей твердих тіл, в яких механічні напруження генерувались під час безконтактної взаємодії тіл з різними коефіцієнтами випромінювання при однаковій температурі системи тіл. Метод модуляційної поляриметрії, який використовується в роботі, це сучасний метод оптичних вимірювань, який дозволяє з високою чутливістю визначати анізотропні та поляризаційні оптичні властивості матеріалів. Матеріали, що досліджувались в роботі (скло, кремній, алюміній та ін.) вибирались за принципом поширеності в теплофізиці і матеріалознавстві та наявності суттєвої різниці між їх величинами коефіцієнтів. В роботі було експериментально визначено механічні напруження і характеристичний час теплопереносу в твердих тілах. Встановлено, що величина характеристичного часу теплопереносу і коефіцієнт теплопровідності в твердих тілах мають обернено пропорційну залежність $f=c(\tau)$, а величини механічних напружень і коефіцієнт випромінювання тіл – експоненційну залежність $f=\sigma(\varepsilon)$. Таким чином, даний метод швидко дозволяє визначити коефіцієнт теплопровідності та коефіцієнт випромінювання твердих тіл, які мають велике практичне значення для використання в технологічних і інженерних методах розрахунку емісійного теплообміну між різними матеріалами (склом, металом, композитом, синтетичним, біологічним, тощо) в тому числі із внутрішніми дефектами і включеннями.

1. Introduction

Thermal radiation is a form of electromagnetic radiation, the intensity and spectral distribution of which are determined by the temperature of the emitter [1]. It is a universal mechanism for energy transfer between all bodies with a temperature above absolute zero. Most technical solid materials, in particular glass, are opaque in the mid- and far-infrared range, so energy absorption and emission occur mainly at the surface of the body. Thus, the radiation characteristics depend not only on temperature but also on the physicochemical state of the surface, in particular, on roughness, degree of oxidation, and presence of coatings or films. The emissivity of the material also plays an important role, which can vary significantly depending on wavelength and temperature. Solids emit in a wide spectral range, forming a continuous spectrum that approaches the spectrum of a completely black body, unlike gases or plasma. This behavior is the result of the complex interaction of the electromagnetic field with the electronic and phononic subsystems of the material.

The amount of heat transferred or received is determined by the difference between the energy a body emits and the energy it absorbs. This energy exchange will always occur in the case of a temperature difference between bodies. Radiation heat exchange remains nonequilibrium even for bodies of the same temperature but different emissivity. A body with a lower emissivity loses less energy compared to an ideal emitter – a completely black body [2]. Under such conditions, the emissivity of the material becomes crucial. It determines the efficiency of a body's participation in radiation heat exchange, in particular in vacuum or rarefied environments, where other heat transfer mechanisms (thermal conductivity and convection) are absent or insignificant. Radiative energy losses can be estimated by considering the emissivity. This is critically important in the design of heat shields, thermal insulation coatings, optical systems, as well as in high-temperature technologies such as laser processing of materials, heating in vacuum furnaces, or thermal protection of spacecraft. Therefore, accurate determination and control of the emission characteristics of materials is a key aspect in calculating thermal regimes and ensuring the stability of the temperature field in complex physical systems.

Experimental data presented by the authors of [3] confirm this fact. These authors investigated the emission mechanisms of a number of crystalline materials under the same temperature conditions. According to the obtained results, thermal radiation largely depends on the presence of impurities and defects in the crystal lattice. The radiation intensity of single-crystal sapphire was found to be lower compared to polycrystalline corundum (polycor) and alumina-based ceramics (alundum) at the same body temperature. During cyclic thermal exposure (heating and cooling) to single-crystal sapphire, a gradual increase in radiation intensity was observed, which is associated with the accumulation of structural defects in the material. Theoretical and experimental studies of a similar nature are widely presented in the scientific literature [4–5]. They consider the radiation characteristics of solids participating in heat exchange at the same temperatures.

There are many ways to research the emission properties of bodies or the emissivity coefficient [6]. These methods are based on direct measurement of the body's radiation compared to the radiation of a black body at the same temperature (e.g., infrared thermography) or on measurement of the reflectance coefficients of these bodies. The main disadvantage of infrared thermography is the inability to measure materials with high reflective properties, since the actual radiation of such bodies is practically zero. An alternative option is a multispectral methodology, which involves quite complex signal processing.

In our work, the emission properties of two solids at the same temperature were investigated using the optical polarization method (modulation polarimetry method), which is characterized by high analytical and detection capabilities [7]. As we have shown in previous works, it can be used to record mechanical stresses when all mechanical and optical coefficients involved in the generation of mechanical stresses are practically independent of temperature. The objective of the work is to continue the study of the features of the emission (radiation) thermoelasticity of solids [8], in which mechanical stresses arose due to the contactless interaction of bodies with different radiation coefficients at their same temperature. This includes measuring and studying mechanical stresses in solids, calculating the characteristic time of heat transfer in the body, and determining their thermal conductivity and radiation coefficients.

2. Experimental methodology and samples

For the experimental study of the emission properties of solids, the optical scheme in Fig. 1 was used. Its main component is a photoelastic polarization modulator. The registration of linear birefringence is adjusted by the appropriate arrangement of elements (modulator with a linear polarizer after the sample) [7-8]. A periodic change in the polarization state occurs at a constant radiation intensity during polarization modulation. As a result, a variable signal component associated exclusively with polarized radiation arises, which is separated from the total signal by a selective recording device and can be amplified by orders of magnitude. This variable component (circular component of radiation) has a linear relationship with mechanical stress at small values σ:

$$I_V \approx \sin\Delta\varphi \sin(\omega t),$$

$$\Delta\varphi = \varphi_x - \varphi_y = \frac{2\pi}{\tilde{\lambda}} d(n_x - n_y) = \frac{2\pi}{\tilde{\lambda}} dC\sigma\ , \quad (1)$$

Ω is the modulation frequency; $\Delta\varphi$ is the phase difference between linear orthogonal radiation components; $\tilde{\lambda}$ is the wavelength of laser radiation; d is the sample thickness in the x-coordinate direction; n_x-n_y is the difference in refractive index of orthogonal linear components of radiation; C is the elasto-optic coefficient; σ is the mechanical stress.

The experiment used a detector sample 3 with dimensions (cm) of 1x2x3 made of optical glass of the heavy flint (HF) brand. All its surfaces were polished to reduce scattering of probe radiation and surface tension. Experimental samples 7 were in the form of disks with a diameter of 5 cm and a thickness of 1 cm.

The experiment was carried out at room temperature in an ambient air atmosphere as follows. Initially, a disk made of similar HF glass was installed above the y-surface of the sample-detector for the zero reference of the experimental curve. Then, the HF disc was quickly (t<1s) replaced with experimental sample 7, while the mechanical stress in sample-detector 3 was recorded as a function of time $\sigma(\tau)$ along the y coordinate at a distance of 1 mm from the irradiated surface of the detector sample. When $\sigma(\tau)\rightarrow$const, experimental body 7 was removed in one motion, and the HF disc was reinstalled for zero reference $\sigma(\tau)$=0 of the next experimental sample. A similar measurement algorithm was used for all six experimental samples.

Table 1. Emission and thermal conductivity coefficients of experimental samples

№		ε	c, W/m·K
Sample detector:			
1	Optical glass HF	0.93	1
Experimental samples:			
2	Aluminum	0.04	235
3	Graphite	0.8	200
4	Silicon	0.4	149
5	Fluorite	0.15	9.71
6	Window glass	0.9	1
7	Polytetrafluoroethylene (PTFE)	0.95	0.25

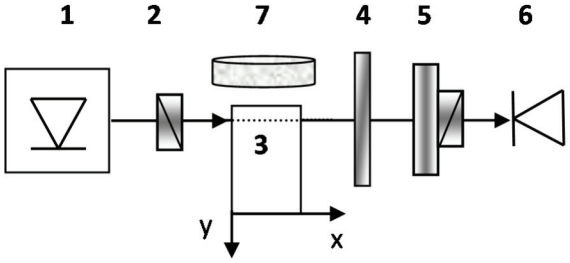

Fig. 1 Optical scheme: 1 – laser diode with wavelength λ=0.65 nm; 2 – linear polarizer; 3 – sample-detector; 4 – compensation phase plate λ/4; 5 – polarization modulator + linear polarizer; 6 – photodetector; 7– sample.

Experimental samples were selected based on their prevalence in thermophysics and materials science and the presence of a significant difference between their radiation coefficients ε. Table 1 shows the emission and thermal conductivity coefficients of all solids that participated in the experiment at a temperature of 300 K [9].

3. Results and discussion

The results of measurements of the time dependencies of mechanical stresses $\sigma(t)$ in the detector sample are shown in Fig. 2 for non-contact emission interaction of experimental samples at 300 K. It should be noted right away that the measurements of mechanical stresses in the sample-detector were performed and presented in the paper in relative units, since this is not essential in this experiment.

As can be seen, each curve of Fig. 2 (a, b, c, d, e, f) shows a certain trend in its shape, amplitude of mechanical stresses, time of observation of the maximum, and duration of measurement. All these differences in the curves can be explained primarily by the thermoelastic and optical properties of the samples. The curves

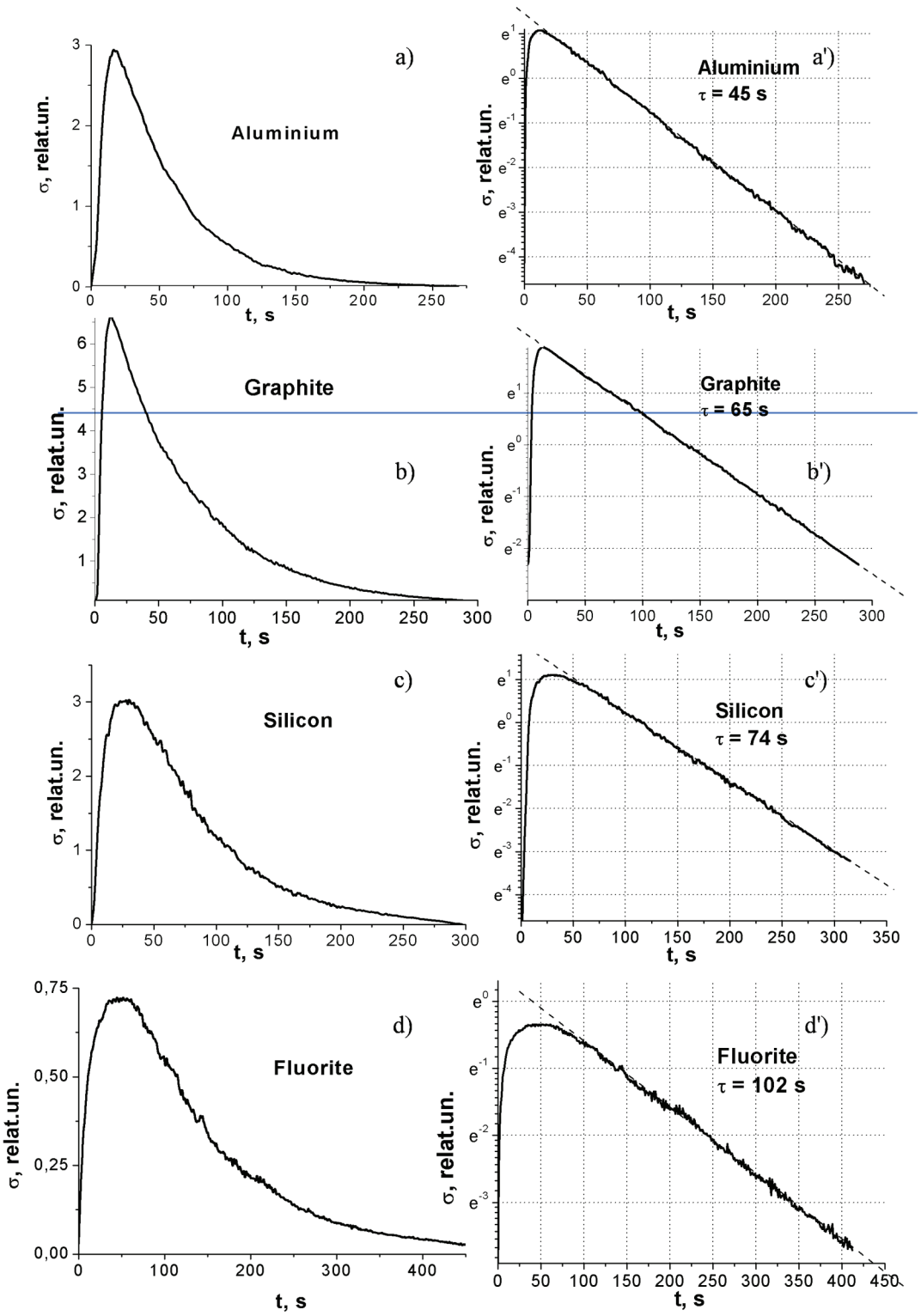

Fig. 2 Time dependencies of mechanical stresses σ(t) in the detector sample in linear coordinates (a, b, c, d, e, f); in semi-logarithmic coordinates (a', b', c', d', e', f').

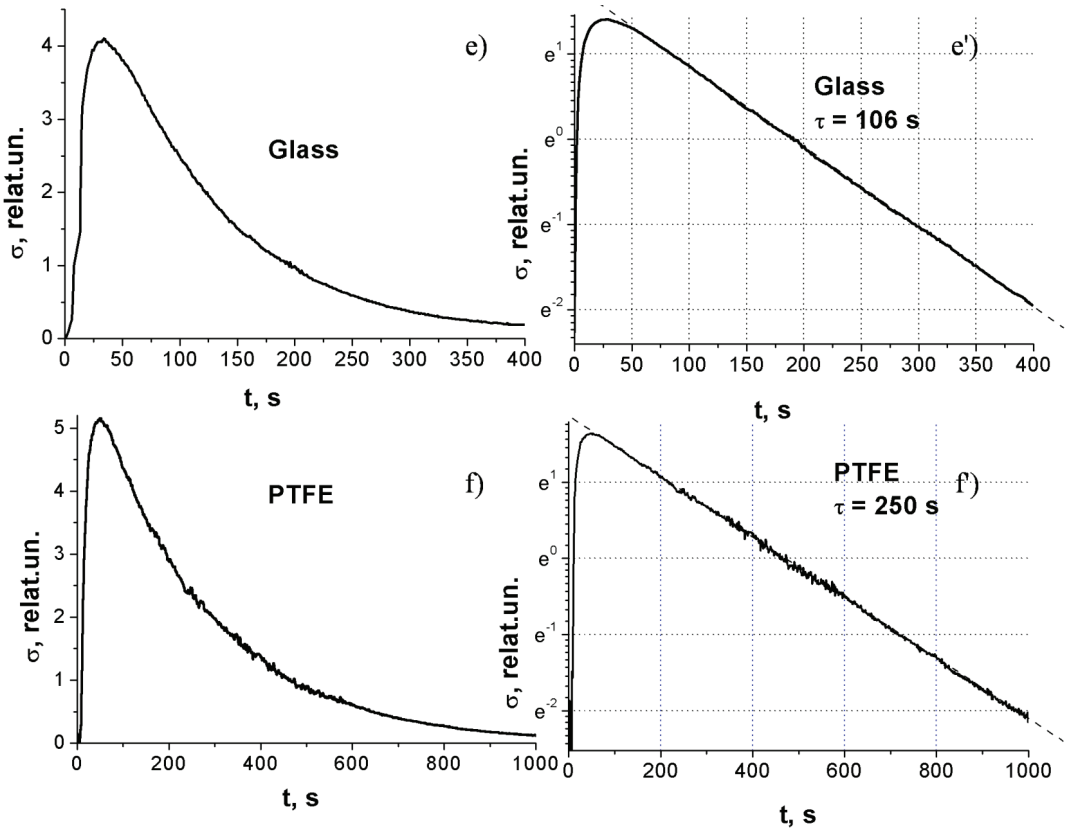

Fig. 2 Time dependencies of mechanical stresses σ(t) in the detector sample in linear coordinates (a, b, c, d, e, f); in semi-logarithmic coordinates (a', b', c', d', e', f').

show sections that are clearly distinguishable by origin (before and after the extreme point), since each break in the experimental curve corresponds to a specific change in the physical process or phenomenon. Indeed, experience in analyzing thermoelasticity arising from excessive radiation heating or cooling, allows us to establish that Fig. 2(a, b, c, d, e, f) shows two processes that differ significantly. The fact that these processes occur simultaneously is not disputed, because if necessary, they can be separated in the form of parallel kinetics [10].

It should be added that a test uniaxial force on a sample detector along the *y*-coordinate established a correspondence between the positive sign of the signal and compression in the laser beam coordinate. This fact is consistent with the geometry of thermodynamics, according to which the heat flux of radiative origin actually occurs in the *y*-direction and determines the geometric orientation of the generated optical indicatrix in the form of an ellipse constructed on the difference in refractive indices $\Delta n = n_x - n_y$.

To determine the characteristic parameters of the experimental curves, we will use an analysis method based on the linearization of exponential dependencies by presenting the data in semi-logarithmic coordinates (Fig. 2a', b', c', d', e', f'). From the slope of these linear dependencies, the characteristic heat transfer times in the sample detector were established under the emission action of experimental samples on it. These characteristic times compared to the thermal conductivity coefficients of experimental samples are presented in Table 2.

It is immediately apparent that these two thermophysical quantities have an inverse or hyperbolic relation. Indeed, if we plot them in

Table 2. Characteristic heat transfer times and thermal conductivity coefficients of experimental samples

№ п/п	Experimental samples:	τ, s	c, W/m·K
1	Aluminum	45	235
2	Graphite	65	200
3	Silicon	74	149
4	Fluorite	102	9.71
5	Window glass	106	1
6	Polytetrafluoroethylene (PTFE)	250	0.25

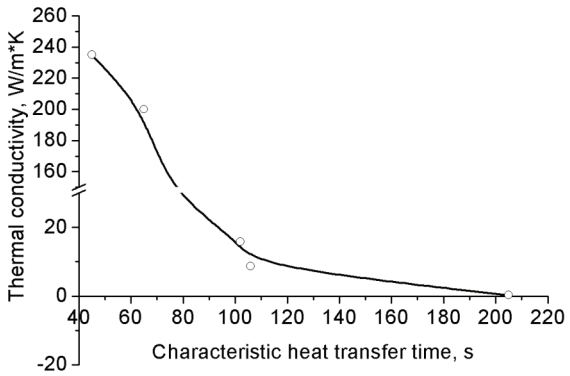

Fig. 3 Dependence of the thermal conductivity coefficient of experimental samples on the characteristic heat transfer time in the detector sample under the emission action of experimental samples.

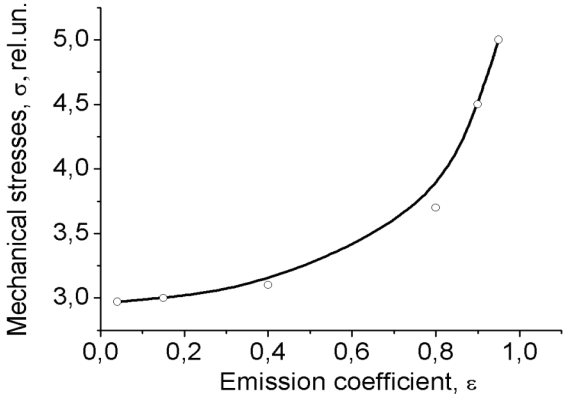

Fig. 4 Dependence of maximum mechanical stresses on emission coefficients in the sample detector.

the coordinates $f=c(\tau)$, we get Fig. 3. That is, we can say that the dependence of the thermal conductivity coefficient on the characteristic heat transfer time is described by the equation $f(\tau)=k/c$, where k is a constant.

Let's determine what other physical quantities can be inversely related to thermal conductivity. In general, these are thermal insulation capacity and thermal or temperature resistance. In non-metals (e.g., ceramics, dielectrics), thermal conductivity also decreases with increasing temperature, since phonon scattering increases. In addition, the more defects or impurities there are in the material, the lower the thermal conductivity.

Also, there is a clear inverse relationship between thermal conductivity and temperature gradient in the well-known Fourier's law of thermal conductivity $\frac{dT}{dx}$:

$$q = -\frac{cdT}{dx}, \quad (2)$$

$$c = -q\frac{dx}{dT}, \quad (3)$$

where q is the heat flux density, W/m².

It can be assumed that the temperature gradient and the characteristic time of heat transfer have a similar physical and mathematical basis. Essentially, a temperature gradient is a temperature difference within the body. In our experiment, such conditions are absent, so we can assume the following. During the contactless emission from the experimental sample, very small heat flows arise in the detector sample due to the absorption of energy by its surface. The energy then spreads further throughout the volume of the material through the mechanism of thermal conductivity. As a result, a very small temperature gradient still arises in the sample detector. On the other hand, the characteristic heat transfer time can be related not only to the temperature gradient, but also to other thermophysical quantities, such as thermal conductivity or the rate of temperature change in the body according to the Fourier-Kirchhoff heat equation. A more in-depth study of the physical nature of characteristic heat transfer time and its interrelationships will be the focus of further work in this area.

The dependence of the maximum values of the mechanical stress curves σ of experimental samples (Fig. 3a, b, c, d, e, f) on the radiation coefficients ε is shown in Fig. 4.

As can be seen, the dependence in Fig. 4 represents a typical exponential function with a formula: $y = a \cdot e^{bx}; \sigma = a \cdot e^{b\varepsilon}$, which allows extrapolating and determining the emissivity coefficient of new materials.

As can be seen, the dependencies in Fig. 3 and Fig. 4 are described by mathematical functions and formulas, i.e., they have an inversely proportional dependence $f = c(\tau)$ and an exponential dependence $f = \sigma(\varepsilon)$.

Therefore, it can be concluded that this method of detecting and studying the emission properties of solids allows determining the thermal conductivity and radiation coefficient of solids, including new materials with unique properties, functional materials, materials for extreme conditions, composites, materials for 3D printing and biomedicine, etc. Knowledge of thermal conductivity and radiation is fundamental to materials science and engineering, and their quantitative assessment allows for the design and selection of materials in those

application areas where temperature control is critical, such as electronics, construction, and energy.

4. Conclusions

The optical polarization method based on modulation polarimetry, which provides highly sensitive determination of anisotropic and polarization properties of solid materials, was used in the study. The method allowed for the rapid registration of mechanical stresses that arise during non-contact interaction of bodies with different radiation coefficients under the same temperature conditions. For the experiment, materials (glass, silicon, aluminum, etc.) were selected that are characteristic of thermophysics and materials science, and also have significant differences in the values of thermal radiation coefficients. The characteristic heat transfer time and thermal conductivity coefficient have an inverse proportional relationship during operation. At the same time, mechanical stresses correlate exponentially with the surface radiation coefficient. Based on optical measurements, this made it possible to quickly determine the specified parameters – the thermal conductivity coefficient and the radiation coefficient.

Thus, modulation polarimetry has demonstrated its effectiveness as an informative and sensitive method for diagnosing solid bodies. This is practically significant for engineering and technological calculations of emissive heat transfer between different materials, including objects containing internal defects or inhomogeneities.

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