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Optical polarimetric temperature sensor

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ABSTRACT

The paper covers an issue of optical polarimetric method for temperature measurement based on the use of a laser autocollimation polarimeter and a sensitive birefringent plate. The sensor works in the following manner. The linear polarized probe beam of the polarimeter illuminates the sensitive element which reflects the radiation backward. The sensitive element results in a phase shift between the beam polarization components which value is proportional to the element temperature. The autocollimation polarimeter determines this phase shift and enables to calculate the temperature value. The distance between the polarimeter and the sensitive element may change from 0 to 100m. The use precisely of the polarization properties of light makes it possible to decrease substantially the effect of beam attenuation on the measurement errors in case where the radiation passes through smoked or dusty space. Small size of the sensitive crystal plate provides rather fast reaction of the sensor to temperature variation in the medium. The basic expression that describes the operation of the system are presented. It is shown that with the use of a quartz plate 1.912mm thick the device makes possible to determine values of temperature in the range of 0 to +180 deg.C.

Keywords: Temperature sensor, polarimetry, birefringence.

1.INTRODUCTION

On numerous occasions temperature monitoring must be performed under conditions where the direct connection of the object under investigation and measuring device is either impossible or difficult to arrange. In these cases optical methods based on pyrometry and use of color change in liquid crystals or thermopaints are crucial importance[1]. It is well known that the magnitude of birefringence in crystals is strongly depend on temperature[2].This property makes it possible to design a quick-response remote-indicating temperature sensor. For this purpose a plane-parallel birefringent crystal plate is set in the medium under investigation and illuminated with a polarized light beam. The plate birefringence can be determined from the change in the polarization parameters of the radiation, and then one can determine the temperature value of the medium. The back-reflection design with the compensation method of registration[3] is convenient for practical implementation of measuring instrument.

2.DESCRIPTION OF THE SENSOR

The measuring device consists of the source of polarized collimated light ***I***, polarimetric block ***II***, modulator ***III***, and control unit ***IV*** (see Fig.1). The sensor is indicated as ***V***. An He-Ne laser can be used as a radiation source. The elements of the polarimetric unit are as follows: the fixed attachment 1, the first rotating body 2, the first goniometric limb 3, the second rotating body 4, the second goniometric limb 5, the first $\lambda/4$ plate 6, the first polarizer 7, the polarization beamsplitter 8, the second polarizer 9, the photodiode 10, and the second $\lambda/4$ plate 11. The modulator should not affect the polarization of the beam, and therefore a disc with slits 12 is used in the system, which is driven by the motor 13. The sensor consists of the plane-parallel crystal plate 14 and mirror 15. The control unit consists of the narrow-band amplifier 16, amplitude detector 17, and indicator device 18.

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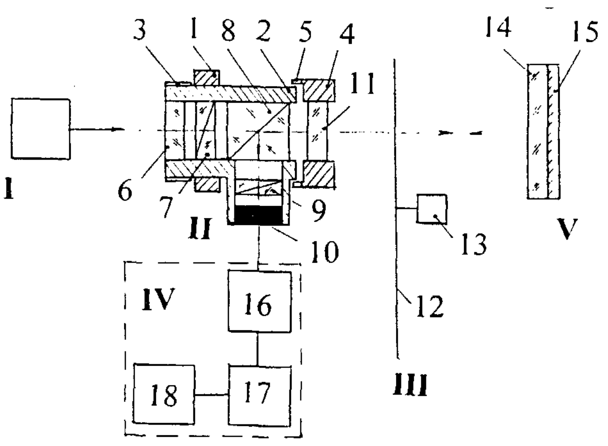

Fig.1. Configuration of the device measuring temperature: Laser I, polarimetric block II, modulator III, control unit IV, sensor V. 1 - fixed attachment, 2 and 4 first and second rotating bodies, 3 and 5 - first and second goniometric limbs, 6 and 11- first and second λ/4 plates, 7 and 9- first and second polarizers, 8- polarization beamsplitter, 10- photodiode, 12- disk with slits, 13- motor, 14- plane-parallel crystal plate, 15-mirror, 16 - narrow-band amplifier, 17 - amplitude detector and 18 - indicator device.

The original laser beam with linear polarization with fixed azimuth is incident on polarimetric block. Using a system that consists of the first λ/4 plate, the first polarizer, and polarization beamsplitter, the azimuth of the linearly polarized light is turned through the desired angle. In this case the output beam intensity is kept constant. Then the linearly polarized probe beam illuminates the sensor, which reflects the radiation backward. If the polarization plane of the probe beam is parallel to the principal planes of the crystal plate then the reflected beam retains its polarization. In the case where the polarization plane of the probe beam does not coincide with the principal planes of the plate the polarization state of reflected beam is changed. As a consequence, a component perpendicular to the polarization plane of probe beam appears in the reflected beam. The orthogonal component of the reflected beam is directed to the photodiode 10 by beamsplitter 8. Since a beamsplitter with an interference coating is utilized in the block, the additional polarizer 9 is employed. It makes it possible to eliminate the small portion of the collinear polarization component that remains after reflection from the beamsplitter. The presence of an orthogonal component in the radiation incident on the photodiode 10 is determined by the control unit.

The intensity of the radiation flux of the orthogonal component I' in the reflected beam is described by following expression:

$$I' = \{\sin(\Delta/2)\cos 2(\varphi-\theta)\sin 2(\varphi-\psi) - \cos(\Delta/2)\sin 2(\varphi-\theta)\}^2 R^2 I, \qquad (1)$$

where I is the probe beam intensity, R is the amplitude reflectivity of the mirror surface of the sensor, Δ is the phase difference introduced into the beam by the crystal plate upon double passage of the radiation, φ, ψ and θ are the angular positions of the fast axes of the second λ/4 plate and the crystal plate, as well as of the principal plane of the polarization beamsplitter which specifies the polarization plane of the probe beam with respect to the zero direction of the device.

When the principal planes of the polarization beamsplitter and the second λ/4 plate coincide (i.e., $\varphi = \theta$) Eq.(1) can be put in the following form:

$$I' = \sin^2(\Delta/2)\ \sin^2 2(\psi - \theta)\, R^2 I, \qquad (2)$$

In this case compensation of the intensity I' is achieved by simultaneous rotation of the polarization beamsplitter and the second λ/4 plate. In the position found, the orientation of the principal planes of the crystal plate corresponds to the orientation of the principal planes of the polarization beamsplitter.

Furthermore, we install the second λ/4 plate in such a way that its fast axis makes an angle of 45° with the fast axis of the specimen, i.e. $\varphi-\psi = 45^\circ$. In this case

$$I' = \sin^2 [\frac{\Delta}{2} - 2(\varphi-\theta)]\ R^2 I, \qquad (3)$$

By rotation the polarization beamsplitter with the second λ/4 plate fixed, one can attain compensation of the flux I' of the orthogonal component. The difference in the azimuths of the beamsplitter an the second λ/4 plate, latter being in the position found, makes it possible to determine the value of the phase shift of the crystal plate:

$$\Delta = 4(\varphi - \theta) + 360^\circ m, \qquad (4)$$

where m is an integer.

3.MEASUREMENT OF TEMPERATURE

Let us use a sensitive crystal quartz plate cut parallel to the optical axis to illustrate the operation of the device. In the temperature range of -200°C up to the phase transition point at +573°C quartz possesses good optical quality and stable characteristics[4]. The phase shift $\Delta(t)$ introduced by the plate at normal incidence and double passage of the beam is defined by the expression

$$\Delta(t) = \frac{720^\circ}{\lambda} l(t)[n_e(\lambda,t) - n_o(\lambda,t)], \qquad (5)$$

where λ is the wavelength of the radiation in the vacuum; $l(t)$ is the thickness of the plate; $n_e(\lambda,t)$ and $n_o(\lambda,t)$ are the refractive indices for extraordinary and ordinary rays, respectively.

The temperature change in the thickness of the quartz plate in the temperature range of -200° to +500°C is approximated adequately by the linear function[5]

$$l(t)=l_o(1+At), \qquad (6)$$

where l_o is the thickness of the plate at t=0°C; A is the linear coefficient of the thermal expansion of the quartz in the direction perpendicular to the crystallophysical axis with A=13.24 10^{-6} deg^{-1}.

The relationship between the magnitude of the birefringence and the value of the temperature is usually given by the linear approximation:

$$n_e(\lambda,t) - n_o(\lambda,t) = n_e(\lambda) - n_o(\lambda) + [\frac{dn_e(\lambda,t)}{dt} - \frac{dn_o(\lambda,t)}{dt}]t, \qquad (7)$$

where $n_e(\lambda)$- $n_o(\lambda)$ is the magnitude of the birefringence at t=0°C. In the case where an He-Ne laser with λ=632.8 nm is used as excitation source we obtain

$$n_e(\lambda) - n_o(\lambda) = 9.1\cdot 10^{-3}, \qquad \frac{dn_e(\lambda,t)}{dt} - \frac{dn_o(\lambda,t)}{dt} = -1.04\cdot 10^{-6}\,\mathrm{deg}^{-1}.$$

Substituting expressions (5) and (6) into expression (7), one can obtain an equation for the temperature dependence of the increase in the phase shift of the plate:

$$\Delta(t) - \Delta_0 = (\mu + A)\Delta_0 t. \tag{8}$$

Here

$$\Delta_0 = \frac{720^o}{\lambda} l_0[n_e(\lambda) - n_o(\lambda)], \qquad \mu = \frac{\frac{dn_e(\lambda,t)}{dt} - \frac{dn_o(\lambda,t)}{dt}}{n_e(\lambda) - n_o(\lambda)}. \tag{9}$$

Equation (8) makes it possible to estimate the temperature range t_{max}- t_{min} within which the phase shift $\Delta(t)$ changes within the limits of one period:

$$t_{\max} - t_{\min} = \left| \frac{360^o}{(\mu + \mathrm{A})\Delta_0} \right| \tag{10}$$

If it is necessary to ensure the temperature range then the crystal plate thickness is calculated by the formula:

$$l_0 = \frac{\lambda}{2(\mu + \mathrm{A})[n_e(\lambda) - n_o(\lambda)](t_{\max} - t_{\min})}. \tag{11}$$

In the case where a quartz plate with l_0 =1.912 mm is used the value of t_{max}- t_{min} equals 180^0 C. Figure 2 shows the temperature dependence of the $\Delta(t)$- Δ_0 for a quartz plate 1.912 mm thick, with the results obtained using Eqs.(8). As is seen from Fig.2, the phase shift of the plate changes linearly with temperature within the limits of one period from 360 to 0 deg in the temperature range of 0 to +180° C.

The measuring device can also determine the value of the phase shift Δ with an accuracy of one period (see Eq.(4)). Therefore, having determined the azimuth difference φ-θ at which the flux of the orthogonal polarization component is compensated, one can determine the temperature of the quartz plate under consideration in the range 0 to +180°C. Using the of the expression (8) we obtain

$$t = \frac{\Delta(t) - \Delta_0}{(\mu + \mathrm{A})\Delta_0}. \tag{12}$$

In principle, if the parameters Δ_0 and μ (see Eq.(9)) were calculated previously, then just one measurement of value of Δ is required (see Eq.(4)) to obtain the desired temperature value according to formula (12). However, in this case $\Delta(t)$- $\Delta_0 << \Delta_0$. Therefore, even a minor relative error in the parameter Δ_0 caused by the inaccuracy in the fabrication or installation of the sensitive plate can lead to a substantial error in the temperature measurement.

This can be avoided if one first determines the position of compensation at a known temperature t'. Taking into account that $\psi(t)$=const and, correspondingly, $\varphi(t)=\psi(t)+45^0$ =const, one can derive from Eq.(4) the system of equations

$$\Delta(t) = 4(\varphi - \theta(t)) + 360^\circ m, \qquad \Delta(t') = 4(\varphi - \theta(t')) + 360^\circ m, \tag{13}$$

where m is an integer.

On the other hand, dependence (11) can be written in the form

$$t = t' + \frac{\Delta(t) - \Delta(t')}{(\mu + \mathrm{A})\Delta_0}. \tag{14}$$

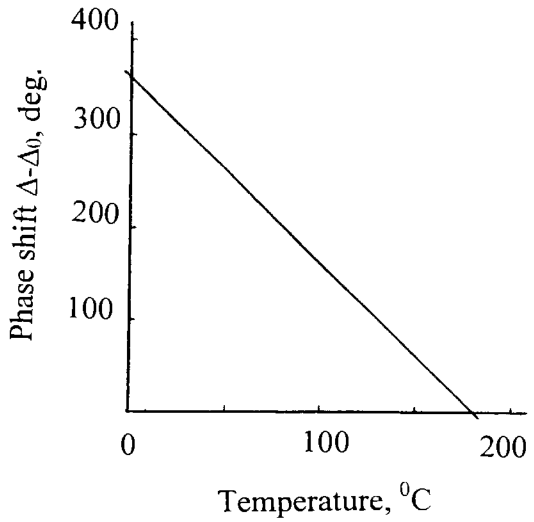

Fig.2. Dependence of the increase in the phase shift on the temperature for a quartz plate 1.912 mm thick.

Having determined the phase shift difference $\Delta(t)$-$\Delta(t')$ using system (12), we finally arrive at

$$t = t' + k[q(t) - q(t')], \tag{15}$$

where $k=-4/(\mu+A)\Delta_o$. In particular, for the 1.912-mm-thick quartz plate under consideration $k=2^0$C/deg.

Thus, in order to find the temperature of the plate one needs to find the value of the difference in the azimuths of the polarization beam splitter $\theta(t)$-$\theta(t')$ for the known temperature and the temperature being measured for compensation of the orthogonal polarization component in the reflected beam. Thereafter, one can easily obtain the desired quantity using Eq.(15).

In a particular device one needs to find the position $\theta(t')$ only once and take it thereafter as a reference point. The scale of the first goniometric limb is conveniently calibrated in ^{0}C in the corresponding scale. This makes it possible to obtain directly the temperature values in the course of measurements.

4.CONCLUSIONS

An error in measurement of crystal plate shift for our device is 0.1deg. It enables to get a temperature measurement sensitivity of 0.05^0 C. This sensitivity can be raised by use of thicker plate or plate made from crystal with longer slope for dependence of birefrigence upon temperature.

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