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DEVELOPMENT OF AN OPTICAL TEMPERATURE SENSOR ON LIQUID CRYSTALS

Introduction. *High-tech production requires careful control of the technological process, the operation of factory equipment, as well as the parameters of work premises, which have to meet the criteria of safety and comfort of employees. For this, there are used sensors of physical parameters, including temperature.*

Problem Statement. *Inside industrial premises and near factory equipment, special temperature sensors that are not affected by various technological factors, such as high concentration of dust, aerosols of chemical substances, and high noise, shall be employed.*

Purpose. *The purpose of the research is to illustrate the possibility of creating an optical temperature sensor on liquid crystals, which reliably operates in the conditions of high-tech industrial production.*

Material and Methods. *Analytical review of scholarly research publications. Experiment, numerical analysis of experimental data.*

Results. *A design of optical threshold temperature sensor has been proposed. The sensor comprises an optical radiation source that is connected to the input optical pole of the optical switch. The sensor is capable of fixing a number of threshold temperatures that correspond to the phase transition temperatures of each temperature-sensitive element. Composites based on a liquid crystal 6CB doped with magnetic* Fe_3O_4 *nanoparticles have been used as heat-sensitive elements. The phase transition temperature of these composites varies from 22 to 29 °C depending on the concentration and size of the* Fe_3O_4 *nanoparticles. Due to it, the sensor is able to record threshold temperatures in the range of 22—29 °C with an accuracy of 0.05 °C.*

Conclusions. *The design of temperature sensor on liquid crystals, which can be used in manufacturing enterprises, in particular, in modern battery production for monitoring temperature conditions inside industrial premises and near technological equipment has been proposed.*

Keywords: industrial sensors, optical temperature sensors, liquid crystals, and phase transitions.

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Modern high-tech production is impossible unless the technological process, the operation of factory equipment, as well as the specified parameters of the working premises, which are necessary for the safety and comfort of employees are controlled carefully. In turn, it requires a variety of sensors of physical parameters, including the temperature sensors [1, 2]. Temperature control systems that use temperature sensors have been becoming increasingly popular in residential buildings [3].

Measuring the temperature of process equipment, industrial plants, as well as working and residential premises is possible both by the contact methods (for example, with the use of a thermometer or a thermocouple), and by the non-contact ones (for example, by the radiation analysis) [4].

One of the promising methods of temperature measurement is the use of optical temperature sensors on liquid crystals as a thermosensitive element. Therefore, such optical sensors that replace the mercury and alcohol thermometers, have already become widespread in the market of household services [5]. However, inside industrial premises and near factory equipment, special optical sensors that are not affected by various technological factors, such as high concentration of dust, aerosols of chemical substances, high noise level, and so on may be necessary. Often, such sensors shall act as logic devices that generate an output alarm signal if the measured parameter exceeds some threshold value. These are the so-called threshold optical temperature sensors [6].

Therefore, an urgent task is the development of such an optical temperature sensor on liquid crystals, which would operate reliably in the conditions of high-tech industrial production, in particular, at battery factories.

The purpose of the research is to illustrate the possibility of designing such a sensor.

GENERAL INFORMATION ABOUT LIQUID CRYSTALS AND COMPOSITE LIQUID-CRYSTAL MATERIALS

It should be emphasized that liquid crystals have many interesting physical properties, due to their complex crystal structure, more precisely, their liquid crystalline state of matter. Liquid crystal is a phase state that is taken by some substances are converted at a certain temperature or concentration in solution (so-called thermotropic or lyotropic systems). Liquid crystals simultaneously possess both the properties of liquids (fluidity) and crystals (characterized by anisotropy). Liquid crystals are viscous liquids consisting of elongated or disk-shaped molecules arranged in a certain way throughout the volume of the liquid [7—9].

The most famous structural types of liquid crystals are as follows: smectic, nematic, and cholesteric; the corresponding substances have the names: smectics, nematics, and cholesterics (Fig. 1). In smectics, the molecules are arranged in layers, but their centers of mass can move in the plane of the layer. The predominant direction of the molecule orientation is usually called the "director" that is denoted by the vector n (Fig. 1, *a*). In nematics, the molecules are oriented mainly along one axis, with their centers of mass located randomly. The molecules can be elongated (Fig. 1, *b*) or disk-shaped (Fig. 1, *d*). Cholesterics contain mirror-unsymmetrical molecules arranged in a periodic spiral structure (Fig. 1, *c*).

The thermotropic liquid crystals are characterized by the two temperature points: the melting temperature (T_m) and the clearing temperature

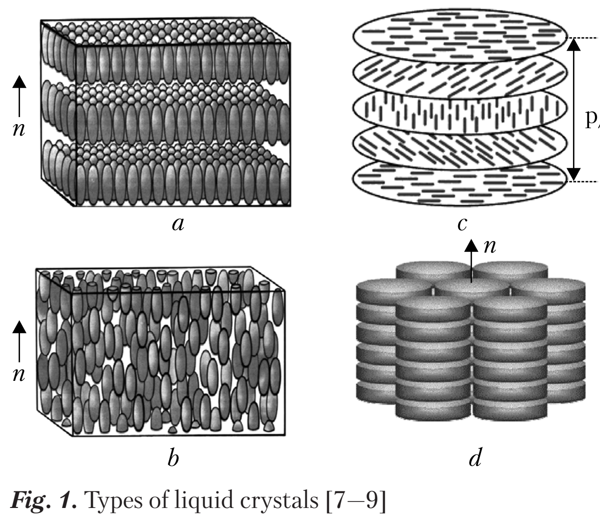

Fig. 1. Types of liquid crystals [7—9]

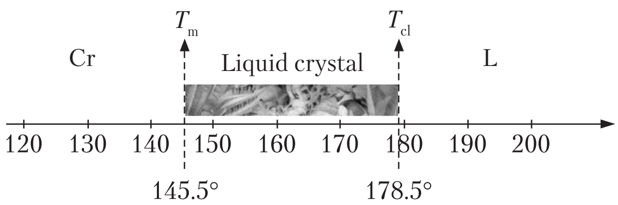

Fig. 2. Cholesteryl benzoate phases [10]

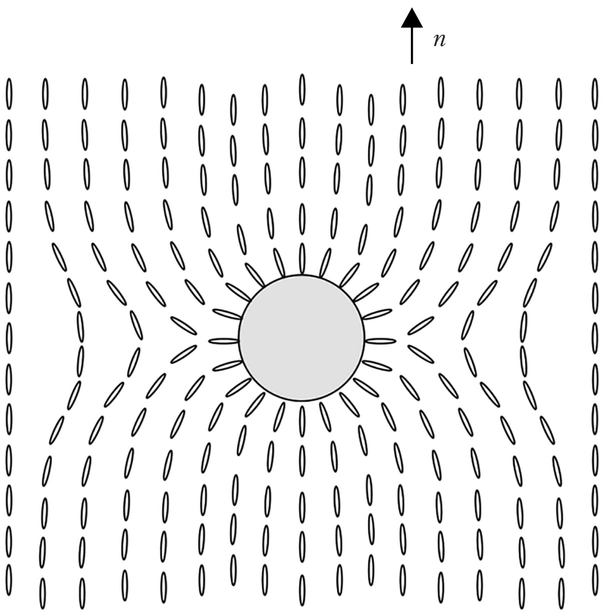

Fig. 3. Example of colloid suspension based on liquid crystals

(T_{cl}). Below T_m, the substance has a crystal structure (Cr), while above the T_{cl} the substance is a liquid (L), namely the liquid crystal phase exist between the melting and clearing points. This is illustrated by the example of cholesteryl benzoate (Fig. 2) [10].

Let us recall the history of liquid crystal discovery [10—16]. In 1861, during the synthesis of cholesteryl chloride, the professor of anatomy of the Lviv (at that time — Lemberg) University, Juliusz Planer, for the first time observed the unique optical properties of this substance that changed its color in incident and transmitted light upon melting. He published the results of his research in [14] (the English translation [15]), which became the first documentary observation of the physical properties of thermotropic cholesteric liquid crystals and phase transitions in these substances. In 1888, the Austrian botanist Friedrich Reinitzer observed how the crystalline substance cholesteryl benzoate, when heated to T_m, turned into a cloudy liquid that dispersed light a lot, and then upon further heating, at T_{cl}, the substance became transparent [10]. However, the physical reason for such optical properties was not clear to the researchers. Therefore, Reinitzer asked for an explanation to the German crystallographer Otto Lehmann who, in 1889, established that a cloudy liquid was anisotropic and had the properties of a crystal. Therefore, Otto Lehmann called this state of matter "liquid crystal" [16].

Since the 1960s, liquid crystals have been widely used in microelectronics, as they are able to easily change their structure and properties with little external influence, that is, they are able to display and transmit information with minimal energy consumption [7—9].

Let us consider another type of liquid crystal materials — colloidal suspensions or composites based on liquid crystals. They are liquid crystals with added nanoparticles having a size of 10—100 nm. These materials can be characterized by the properties that are even more interesting for science and useful for technical applications. Nanoparticles do not change the general orientation of molecules in the entire volume of liquid crystals, but they can significantly correct the orientation of molecules close to the particles (Fig. 3) and affect the effective properties of liquid crystals. For example, it is possible to change the point liquid crystal — liquid (T_{cl}) phase transition. It is possible to increase the sensitivity of composites to electric and magnetic fields. Figure 3 schematically shows the composite structure from which we can see that the spherical nanoparticles are able to turn the nearest liquid crystal molecules perpendicular to their surface.

The theoretical study of composites started in 1970 [17], and in the 1980s and 1990s they were synthesized experimentally [18—21]. Since the 1990s, there have appeared many publications on theoretical and experimental study of the internal structure and collective effects in composites, for example [22—31]. These studies, in particular, have shown that the points of phase transitions depend on the concentration and properties of nanoparticles, so engineering devices based on composite liquid crystals can serve as temperature indicators.

OPTICAL TEMPERATURE INDICATORS ON LIQUID CRYSTALS

Optical effects in liquid crystals have already used in information technology. Based on liquid crystals, the following devices have been designed: displays; microlasers; controlled optical diodes; light modulators; adaptive lenses; phase correctors; deformation detectors; detectors of electric, magnetic, and thermal fields; materials for recording holograms [7—9, 32, 33].

The effect of selective light scattering on the periodic structure of cholesteric liquid crystals (cholesterics) is widely known. In such substances, the molecules are arranged in layers, and within each layer the molecules are oriented parallel to the director. Since when moving from one layer to another, the director turns to a small angle, the liquid crystal looks like a layered spiral texture with some spiral pitch (Fig. 1, *c*). Under illumination with white light, such a liquid crystal selectively reflects light like a diffraction grating. With normal light incidence, light with a wavelength approximately equal to the pitch of the spiral is maximally reflected. Many cholesteric liquid crystals have a spiral pitch of 400—1000 nm. Therefore, they scatter in the region of visible light. Temperature variations and mechanical deformations affect the pitch of the helix in the texture of cholesterol. This leads to change in the color of the light scattered by them and allows displaying the deformation fields and the temperature fields [33].

Of course, temperature indicators on cholesterics are constructed in the form of a heat-sensitive film coating on the studied surface. In such liquid crystals, light splits into two waves, the transmitted and reflected ones. Black paint is applied to the studied surface to absorb the light wave passing through the liquid crystal. The second light wave is selectively reflected from the liquid crystal and characterizes the crystal color. This light wave gives information about the deformation or the temperature of the studied surface. This is how film thermosensors or deformation sensors work [33]. However, since high noise, vibration, and pressure drops, cause uncontrolled deformations, such sensors work unreliably, because these factors introduce errors into the process of temperature measurement. In addition, chemicals aerosols in the production conditions can damage film temperature sensors. An additional negative factor is that in many cases it is necessary to measure the temperature in some local places, and for this it is better to use a small liquid crystal rather than a film coating.

Therefore, let us consider fiber optic temperature sensors on liquid crystals [34]. The principle of operation of such sensors is based on the conversion of the temperature effect into a modulated light signal and its transmission over an optical fiber communication line. Usually, in such sensors, the light generated by the light source is transmitted to a heat-sensitive element via an optical fiber, the light signal is modulated on the heat-sensitive element and further fed to a detector via an optical fiber. There may be the sensors in which the optical fiber itself is a sensitive element and is capable of modulating the light signal. However, known fiber optic temperature sensors usually respond only to one temperature value that is set by the thermosensitive element properties and cannot react to several values in the temperature range [6, 34, 35].

Figure 4 illustrates the scheme of such a fiber optic temperature sensor. The temperature sensor has radiation source (*1*), such as a laser; lens (*2*); thermosensitive element (*3*); photodetector (*4*); fiber optic cable (*5*); dispersing lens (*6*); and focusing lens (*7*). A liquid crystal is used as thermosensitive element (*3*) that is capable of detecting one threshold temperature value. In this device, lens (*2*) allows improving the input of optical ra-

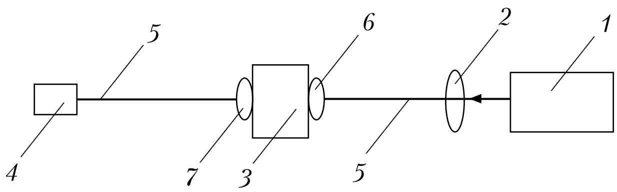

Fig. 4. Scheme of the fiber optical temperature sensor [35]

diation into optical fiber (*5*), and lenses (*6*) and (*7*) reduce the heating of liquid crystals (*3*) from radiation due to the redistribution of light over a larger plane, which reduces the error of environment temperature measurement. However, as already mentioned, such a sensor can record only the achievement of one threshold temperature. In order to carefully control the temperature conditions, it is necessary to use several similar sensors that react on different threshold temperature (due to, for example, special changes in the composition of liquid crystals) [34, 35].

Further, we demonstrate the results of our design of a fiber optical liquid crystal sensor of threshold temperature capable of detecting a range of threshold temperatures.

OPTICAL LIQUID CRYSTAL SENSOR OF TRESHOLD TEMPERATURE

We offer the following sensor design (Figs. 5, 6). The source of optical radiation (D) is connected to the input optical pole of the optical switch (OP), the output optical poles of which are connected to a group of optical fibers ($VS_1...VS_N$). A control signal (S_K) from an external monitoring system (not shown in Fig. 5) is connected to the input of the optical switch (OP). An optical switch is an optical device with one input optical pole and several output optical poles, which ensures the closure of an optical circuit with one of the output optical poles, and the switching process is controlled by an electric potential. With the help of the group of optical fibers ($VS_1...VS_N$), the output optical poles of the optical switch (OP) are connected to a group of thermosensitive elements ($T_1...T_N$) through the dispersing lenses ($LR_1...LR_N$) and through polarizers ($P_1...P_N$). Thus, the group of thermosensitive elements ($T_1...T_N$) is connected in parallel to the source of optical radiation (D) through the optical switch (OP). With the help of optical fibers ($VS_1...VS_N$), the group of thermosensitive elements through analyzers ($A_1...A_N$) and through the focusing lenses ($LF_1...LF_N$) is connected in parallel to the photodetector (F). The photodetector output (F) is connected (S_F signal) to the external monitoring system. In each thermosensitive element, a liquid crystal (RK) is fixed in an optically active structure that rotates the plane of light polarization by 90° (Fig. 6). To ensure this, the liquid crystal (RK) is placed between two parallel transparent plates with guiding layers (PV) and (PG), with the direction of the guiding layers on the second plate (PG) being perpendicular to that on the first plate (PV). This results in a 90° rotation of the liquid crystal optical axis: from the surface of the crystal in contact with the first transparent plate (PV) to the surface of the crystal in contact with the second transparent plate (PG). This leads to a 90° rotation of the light polarization plane. In principle, it is possible to simplify the sensor design by excluding the dispersing and the focusing lenses from it.

Such an optical threshold temperature sensor is capable of recording several threshold temperatures that correspond to the phase transition temperatures of each temperature sensitive element of the sensor. Due to the fact that the group of temperature-sensitive elements (T_1, T_2, ... T_N) is connected in parallel to the source of optical radiation by means of the optical switch and to the photodetector, the optical switch (OP) can close the optical circuit between the source of optical radiation (D) and one of the temperature-sensitive elements (T_i) and the photodetector (F). In this state, the sensor can record only the achievement of one threshold temperature that is equal to the temperature of the phase transition of the corresponding temperature-sensitive element (T_i). The optical switch is able to connect each temperature-sensitive element to the source of optical radiation, one after the other, depending on

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the control signal (S_K) from the external monitoring system, which is connected to the input of the optical switch. This allows the sensor to record the achievement of each threshold temperature that is equal to the temperature of the phase transition of the corresponding temperature-sensitive element, one after the other. Due to the fact that the output of the photodetector is connected (SF) to the external monitoring system, the external monitoring system has the ability to receive information about the achievement of each threshold temperature. It is possible to use a computer or other intelligent devices as an external monitoring system. Due to the fact that a dispersing lens and a focusing lens are placed in front and behind each temperature-sensitive element, respectively, the sensor is characterized by a small error in measuring the environment temperature.

Let us consider how an optical temperature sensor works. Unpolarized light from the optical radiation source (D) passes through the optical switch (OP). An external monitoring system (not shown in Fig. 5) controls the switching of the optical switch (OP) with the help of control signal (S_K) by sending successive commands that make the optical switch (OP) sequentially close the optical circuit with the thermosensitive element (T_i), one after the other. In parallel, the external monitoring system receives a signal (S_F) from the photodetector (F), which allows identification of another temperature-sensitive element (T_i), through which the optical radiation from the source (D) has to pass. After the optical switch (OP), the unpolarized light passes through the fiber optic guide (VC), the dispersing lens (LR), and through the polarizer (P_i). Further, the polarized light passes through the first transparent plate with a guiding layer (PV). For example, vertically polarized light passes through a transparent plate with a vertically oriented layer (PV). After that, the polarized light passes through the liquid crystal (RK), which leads to a light polarization plane rotation by 90°, provided the environment temperature and, accordingly, the temperature of the liquid crystal does not exceed the temperature of its pha-

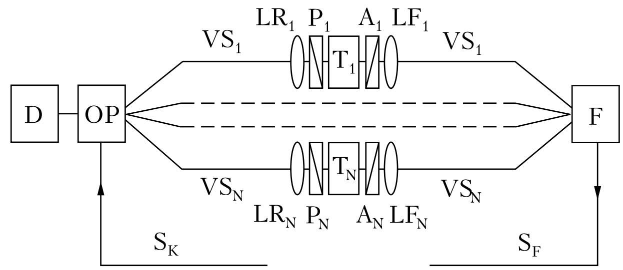

Fig. 5. Scheme of the proposed optical temperature sensor on liquid crystals

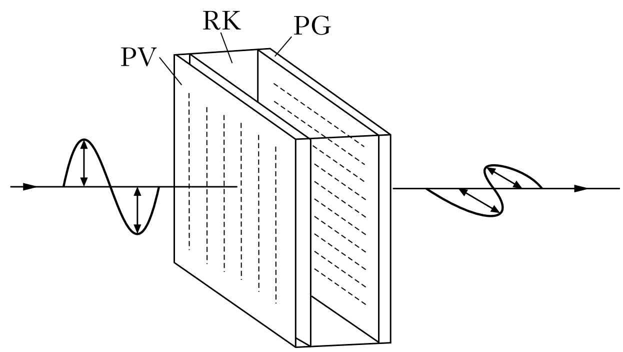

Fig. 6. Temperature sensitive element

se transition. After that, the polarized light passes through the analyzer (A) and through the focusing lens (LF). However, if the temperature of the environment and, accordingly, of the liquid crystal (RK) reaches or exceeds the temperature of its phase transition, the liquid crystal turns into an isotropic liquid that no longer rotates the plane of light polarization. In this case, the polarized light can no longer pass through (A_i), because it is crossed at 90° with the direction of light polarization. Thus, if the environment temperature reaches or exceeds the temperature (t_i) of the phase transition of the thermosensitive element (T_i), the photodetector records the absence of a signal, and thereby informs the external monitoring system that (t_i) has been reached. If we properly reduce the power of the optical radiation source (D) and accordingly increase the sensitivity of the photodetector (F), it is possible not to use lenses (LR_1...LR_N), (LF_1...LF_N), which simplifies the sensor design.

In this sensor, it is possible to use composites based on liquid crystal 6CB (4-cyano-4-hexylbiphenyl) with the addition of iron oxide (Fe_3O_4) magnetic nanoparticles as thermosensitive liquid crystals. The synthesis process of such composites and the results of experiments on determining the temperature T_{cl} of the liquid crystal — isotropic liquid phase transition have been described in [36]. The nanoparticles have a spherical shape, their diameter varies from 10 to 30 nm. The nanoparticles are pretreated with a surfactant (oleic acid) to prevent their magnetic coagulation. As a result, stable systems with a volume concentration of impurities from 10^{-4} to 10^{-3} are obtained. As shown by experimental studies [36], the phase transition temperature of such composite liquid crystals varies from 22 to 29 °C, depending on the concentration and size of Fe_3O_4 nanoparticles. For example, these liquid crystals can provide temperature-sensitive elements with threshold temperature of 22; 23; 24; 25; 26; 27; 28; and 29 °C with an accuracy of 0.05 °C. This means that sensors based on such composites can work near the battery forming plant in a battery factory, or near the lead paste coating plant, where the temperature rarely exceeds 28—29 °C.

The above analysis of the technical properties of the optical threshold temperature sensor on liquid crystals has shown that this device can be successfully used to monitor temperature conditions inside industrial premises, near process equipment, including in conditions of high concentration of dust in the air (at mines). For example, the proposed sensor can be used in battery production: in a paste preparation and paste spreading workshop, a molding workshop. The sensor is suitable for obtaining accurate information about changes in the temperature field both near the process equipment and inside the personnel premises. Our development has been protected by a Ukrainian utility model patent [37].

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РОЗРОБКА ОПТИЧНОГО ДАТЧИКА ТЕМПЕРАТУРИ НА РІДКИХ КРИСТАЛАХ

Вступ. Високотехнологічне виробництво потребує ретельного контролю технологічного процесу, роботи заводського устаткування, параметрів робочих приміщень, які задовольняють критеріям безпеки і комфорту працівників. Для цього використовують датчики фізичних параметрів, зокрема, й температури.

Проблематика. В умовах промислових приміщень і поблизу заводського устаткування необхідними є спеціальні датчики температури, які не пошкоджуються від дії різноманітних технологічних факторів: високої концентрації пилу, аерозолів хімічних речовин, високого рівня шуму.

Мета. Показати можливості конструювання оптичного датчика температури на рідких кристалах, який буде надійно працювати в умовах високотехнологічного промислового виробництва.

Матеріали й методи. Застосовано аналітичний огляд наукових публікацій, експеримент, чисельний аналіз експериментальних даних.

Результати. Запропоновано конструкцію оптичного порогового датчику температури, який містить джерело оптичного випромінювання, підключене до вхідного оптичного полюса оптичного перемикача. Датчик здатен фіксувати ряд порогових температур, які відповідають температурам фазового переходу кожного термочутливого елемента. Як термочутливі елементи використано композити на основі рідкого кристалу 6CB з додаванням магнітних наночастинок Fe_3O_4. Вони змінюють температуру фазового переходу від 22 до 29 °C залежно від концентрації та розмірів наночастинок. Завдяки цьому датчик може фіксувати порогові температури в діапазоні 22—29 °C з точністю 0,05 °C.

Висновки. Запропоновану розробку датчику температури на рідких кристалах може бути використано на промислових підприємствах, зокрема, на сучасному акумуляторному виробництві для контролю за температурними режимами у приміщеннях і поблизу технологічних установок.

Ключові слова: промислові датчики, оптичні датчики температури, рідкі кристали, фазові переходи.