Optical registration of nanoscale membrane deformation in optoacoustic infrared imager

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Abstract

The optical readout system for the membrane deformation detection for the matrix structure of the optoacoustic cells is developed in this work using the visible light of light-emitting diode (LED) and CMOS camera. Optical method based on Savart plate which splits the light from the LED on two mutually orthogonal polarized components. These two components reflected from the surface of the membrane, form the interference picture on the camera surface which varies at deformation of the membrane. The given readout system has sensitivity to the membrane displacement about 1 nm. On the basis of the given system the uncooled detector of infra-red radiation is created.

Keywords: Nanoscale membranes, optical registration of displacements, IR imager

1. Introduction

The sensitivity of many microsensors, such as accelerometers, microphones, and pressure sensors, ultimately depends on accurately detecting small displacements at a level of a few nanometers [1-3]. Most microscale devices use capacitance-based measurement methods, where the displacement-detection sensitivity increases with increase in the area and decrease of the gap. Optical sensing systems can potentially provide high-displacement sensitivity independent of the spot size and gap height. At use of the optical methods there is no necessity to integrate a sensitive element and readout system in one crystal. It essentially simplifies manufacturing technique and reduces the cost of the devices. It is the most actual for the devices representing multielement structure of microsensors, such as infrared imager based on a two-dimensional array of optoacoustic cells (OAC). The optoacoustic cell, or so-called Golay cell [4], represents the hollow cylinder, filled by a gas in which one end face is an absorber of radiation, and the opposite end face represents the flexible membrane with a mirror-image covering. Sorption of radiation leads to the heating of the absorber, and then the gas filling OAC volume which expands and deforms the membrane. In the present work the optical readout system for the membrane deformation detection for the OAC matrix structure is developed using the visible light of light-emitting diode (LED) and CMOS camera. In this system the signal reading is carried out by the well developed and low cost multiplex system of the CMOS camera. Use of the LED instead of the laser allows to lower dimensions, weight and power consumption of the detector.

2. Optoacoustic cell design

The scheme of the optoacoustic cell, realized in this work, is shown on Fig. 1a. The cell structure is formed at an input window made from ZnSe which is transparent in a range of wavelengths 0.5-20 microns. The diameter of the cell is varied from 100 up to 200 microns and the height has made 50 microns. The absorbing layer consisting of SiO₂ layer by thickness of 250 microns and a layer of aluminium by thickness of 0.01 microns settles down inside of the cell. SiO₂ have an absorption band over the range of wavelengths 8–14 microns.
The membrane consisted of polyimide and aluminium layers by the total thickness of 100 nanometers. The received structure of matrix optoacoustic cells on input window ZnSe was located in the closed gas volume of the IR matrix detector limited on the one side by the plate ZnSe, on the other side by the glass plate (Fig. 1b). The given design automatically provided a regime of equality of an intrinsic pressure in the optoacoustic cell and an intrinsic pressure in the volume at change of ambient pressure and temperature.

3. Optical readout system

The scheme of the optical readout system is shown on Fig. 2a. Light from a 650-nm-wavelength LED (1) passes through the condenser (2), the polarizer (3), the beam splitter (4), the objective (5) and Savart plate (6), and falls on the membrane surface of the optoacoustic cells (7). Further the membrane surface image is projected onto CMOS camera. The compensator (8) and the analyzer (9) are established before the camera (10).

The Savart plate consists of two identical plates (Fig. 3) made from the uniaxial crystal (crystalline quartz). The plates are cut out in such a manner that the normal to the plate surface makes with the optical axis of the crystal the angle 45°. From the position with identical orientation the second plate is rotated around of the normal on the angle 90° relatively the orientation of the first plate. At the arbitrary orientation of the input beam polarization, after the first plate there are two linearly polarized beams spatially displaced rather each other on size $d$ due to birefringence. The size $d$ is defined by a difference of refraction coefficients of quartz and by the thickness of a plate. After transition through the
second plate, the beams are displaced in addition on size $d$ in a direction, perpendicular to the displacement after the first plate. In the result, after the Savart plate the beams displaced rather each other on size $\sqrt{2}d$. Phase shift between the beams is equal to zero because the plates are made in uniform technology and have identical thickness. Therefore, these beams are coherent. The given condition allows using not coherent light sources, in our case the light-emitting diode with wavelength $\lambda = 650$ nm and emission line width $\Delta \lambda = 20$ nm was used.

Fig. 3. Scheme of the Savart plate.

The thickness of the Savart plate has been chosen so that one of the beams hits the central part of the movable membrane and the second one hits the immovable place between membranes. In other words $\sqrt{2}d$ is equaled to the membrane radius. The radiation which has been passed through the Savart plate, reflected from the membrane surface and again passed through the plate can be presented in the form of

$$
E_C = E_P \cdot \cos 45^\circ
$$
$$
E_f = E_P \cdot \sin 45^\circ \cdot e^{i\Delta
$$}

where $E_P$ is the amplitude of the polarized radiation falling on the Savart plate after the polarizer (see (3) in Fig. 2a) and the beam splitter (4), $E_C$ and $E_f$ are the amplitudes of the beams after the Savart plate, $45^\circ$ is the angle between the direction of the initial polarization and the beams polarization directions after the Savart plate, $\Delta$ is the phase shift due to the membrane deformation.

The radiation falling on the compensator ($\lambda/4$ plate) (see (8) in Fig. 2a) can be decomposed on to mutually perpendicular two vectors conterminous in a direction with fast and slow optical axes of the compensator. Considering that after compensator one of the component moves on a phase on $90^\circ$, we receive equations for amplitude of radiation after compensator:

$$
E_{kno} = E_P \left( \cos 45^\circ \cdot \cos \theta - \sin 45^\circ \cdot e^{i\Delta} \cdot \sin \theta \right)
$$
$$
E_{kne} = E_P \left( \cos 45^\circ \cdot \sin \theta + \sin 45^\circ \cdot e^{i\Delta} \cdot \cos \theta \right) \cdot e^{i90^\circ}
$$

where $\theta$ is the angle between beam polarization and compensator axis.

The radiation amplitude after analyzer (see (9) in Fig. 2a) will be defined by the equation:

$$
E_A = E_{kno} \cdot \cos \varphi + E_{kne} \cdot \sin \varphi
$$

where $\varphi$ is the angle of the analyzer orientation. The radiation intensity will be defined as:

$$
J = E_A^* E_A
$$

Substituting values from the equation (2) and believing $\theta = 45^\circ$, we shall receive

$$
J = \left[ E_P \frac{1}{2} \left( 1 - e^{i\Delta} \right) \cos \varphi + E_P \frac{1}{2} \left( 1 + e^{i\Delta} \right) e^{i90^\circ} \sin \varphi \right] \times
$$
$$
\times \left[ E_P \frac{1}{2} \left( 1 - e^{-i\Delta} \right) \cos \varphi + E_P \frac{1}{2} \left( 1 + e^{-i\Delta} \right) e^{-i90^\circ} \sin \varphi \right].
$$

In the result, the radiation intensity in the certain point will be equal to

$$
J = J_P \frac{1}{2} \left( 1 + \cos(\Delta + 2\varphi) \right)
$$
It can be seen from the equation that the intensity depends on the phase shift, which is defined by the deformation of the membrane, and analyzer orientation. The maximal membrane deformation sensitivity is reached by installation of the analyzer in position, when \( \Delta + 2\varphi = 90^\circ \).

The gas heating and expanding at IR radiation sorption shifts the membrane from the initial point that leads to the change of the interference picture. Software of CMOS camera displays on a monitor the change of the interference picture concerning the initial one which is accepted as the dark frame. The differential interference image of a fragment of the optoacoustic cells matrix, received by means of the described optical system, is presented on Fig. 2b.

4. Results

The displacement-sensitivity of the optical scheme, the membrane flexibility and own temperature sensitivity of the cell have been defined. The time dependence of the signal amplitude from the optoacoustic cell at smooth reduction, and then increasing in pressure in the gas volume of the IR matrix detector is shown on Fig. 4. It can be seen from the figure and the equation (6), the change of the signal amplitude from a maximum up to a minimum \( (J) \) corresponds to the displacement of the membrane on \( \frac{\lambda}{2} = 325 \) nanometers. The sensitivity of the optical scheme to the membrane displacement is defined as the amplitude of the membrane displacement producing a signal-to-noise ratio of 1 and is determined by dividing the \( \frac{\lambda}{2} \) displacement by the measured signal-to-noise ratio \( J/\Delta J \), where \( \Delta J \) is the noise level. The displacement equivalent to noise had amounted to 1 nanometer.

![Fig. 4. The time dependence of the signal amplitude from the optoacoustic cell at smooth reduction and then increase in pressure in gas volume.](image)

The membrane flexibility is determined as ratio \( \Delta x/\Delta P \), where \( \Delta x \) is the membrane displacement and \( \Delta P \) is the applied pressure. The time dependence of the optical signal at periodic change of pressure in the detector gas volume on various magnitudes is shown on Fig. 5. The minimal detected pressure had amounted to around \( \Delta P = 2 \) Pa that corresponds to the membrane displacement on 1 nm. Thus, the membrane flexibility had amounted to 0.5 nm/Pa.

The own temperature sensitivity of the cell can be evaluated from the minimal detected pressure change \( \Delta P \). Well-known, that the changes of temperature \( \Delta T \) and pressure \( \Delta P \) of gas at constant volume are connected among themselves according to Mendeleyev-Clapeyron’s equation:
Believing $P_0 = 100$ kPa and $T_0 = 300$ K, we get the own temperature sensitivity $\Delta T = 0.006$ K. Thus, the own sensitivity of the presented optoacoustic cell is close to a level of modern matrix thermal detectors.

![Fig. 4. The time dependence of the optical signal at periodic change of pressure in the detector gas volume on various magnitudes.](image)

Using the developed optical readout system the model of the IR imager with a matrix dimension $200 \times 200$ has been created and investigated. The results will be published later.

5. **Conclusion**

The optical readout system for the membrane displacement detection of the matrix structure of optoacoustic cells is developed. The system design with use of the Savart plate and the commercial CMOS camera allows make this system compact, light in weight, and with low power consumption. The sensitivity of the optical system to the membrane deformation had amounted to 1 nm. Using this system the membrane flexibility of the optoacoustic cell has been defined as 0.5 nm/Pa. The estimated own temperature sensitivity of the cell had amounted to 0.006 K. Thus, using the developed optical readout system, the inexpensive and compact thermal imager can be created as well as other devices, where the high-displacement sensitivity is required.

**References**

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