Microoptomechanical sensor for intracranial pressure monitoring

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Abstract. The main idea of this research is the development of microoptomechanical sensor for intracranial pressure monitoring. Currently, the authors studied the scientific and technical knowledge in this field, as well as develop and test a prototype of microoptomechanical sensor for intracranial pressure (ICP) monitoring.

1. Introduction
Treatment of patients with acute cerebral injuries almost always represents a serious problem. The main of the problem is the location of the system features in a closed hermetic cavity of a skull with the fixed volume. Moreover, the quantitative assessment of pressure values in a skull cavity for patients with cerebral pathology is very important. The mankind passed a certain way in methodological aspect, having developed different methods of the intracranial pressure (ICP) measurement. These methods are implemented by means of a wide range of various ICP sensors. These sensors are characterized by high invasiveness that is connected to their overall dimensions and to a method of ICP determination. Also, modern sensors do not allow receiving information on ICP status in a dynamic mode and have rather high cost.

The purpose of this work was development of the microoptomechanical sensor for ICP control eliminating listed above defects of existing sensors. The developed microoptomechanical sensor for control of intra cranial pressure has the following advantages:

- safe way of information obtaining:
  - the measurement scheme without electric signals impact on a human brain;
  - sensor membrane of Si3N4;
  - the semiconductor diode with the optical radiation wave length of 850 nanometers;
- reduction of the sensor geometrical sizes in section to 3 mm;
- increase of a sensitivity threshold;
- possibility of obtaining information in a dynamic mode.

2. ICP sensors
In the modern medicine wide variety of sensors for ICP monitoring having different advantages and disadvantages are used [1]. They share on the following types:

- intraventricular catheter: or the so-called outside ventricular drainage (OVD) connected to the outside pressure sensor by a tube, filled with liquid. It is the standard for testing other sensors, principal advantages of this sensor are:
  - rather low cost;
except measurement of pressure it is possible to realize deduction of liquor with the medical purpose;
 it is possible to recalibrate for reducing a measurement error;
 • intraparenchymal sensor: similar to an intraventricular catheter, but more expensive. In certain cases the measurement error about several;
 • other less fine sensors:
   • the subarachnoidal screw ("bolt"), its main shortcoming is risk of infection 1% increasing after 3 days. In case of increase in ICP, the surface of a brain can superimpose a clearance that carries to the wrong indications;
   • epidural: it is possible to use a catheter filled with liquid.

Possible complications of ICP sensors installing (Table 1):
 • Infection;
 • hemorrhage: the overall incidence of 1.4% for all sensors. Risk of a large hematoma formation requiring removal ≈ 0.5%;
 • malfunction or blockage: for devices running on the fluid pressure transmission, a higher incidence of occlusion is observed with an increase in intracranial pressure> 50 mm Hg. Art.;
 • incorrect sensor position: intraventricular catheters in 3% of cases require prompt move to another position.

Table 1: The complication rate for different ICP sensors types.

| Sensor type                  | Bacterial colonization | Hemorrhage | Sensor malfunction or blockage |
|------------------------------|------------------------|------------|---------------------------------|
| Intraventricular catheter    | Average: 10-17%,       | 1,1%       | 6,3                             |
|                              | range: 0-40%           |            |                                 |
| Subarachnoidal screw         | Average: 5%,           | 0          | 16%                             |
| ("bolt")                    | range: 0-10%           |            |                                 |

Typical system of outside ventricular drainage, as most often used for measurement of intracranial pressure is shown on Figure 1. The right side of human head, if there are no special reasons for use left (for example, blood bunches in the right side ventricle which can lock a catheter), is usually used.

Figure 1. Typical system of outside ventricular drainage. 1 – The fixer, 2 - the air filter, 3 - a dropwise tip, 4 - the dropwise camera, 5 - the one-sided valve, 6 - port for the monitor, 7 - pressure scale, 8 - a bag for liquid collection [1].
The principle of operation of such ICP monitor is based on the intracranial pressure measurement transmitted by an air pole on a tube, which at the same time is a part of a measuring catheter located in a ventricle of a brain [1].

On the end of a catheter a latex barrel is located that is reporting on an air tube with a measuring pressure gage in the monitor. ICP is transmitted through a thin wall of a barrel, changing it volume and air pressure that register a pressure gage. After connecting a catheter to the monitor and switching on a power the compressor that built in monitor fills a barrel with air.

Example of this sensor type which is used in modern medicine, is the ICP measurement monitor Spiegelberg.

3. Amplitude sensors of pressure

To eliminate the disadvantages of existing ICP sensors the sensor based on the modern achievements of optoelectronics are developed.

The fiber-optic sensors (FOS) are now one of most dynamically developing areas of optoelectronics [2]. For the last 30 years there was a prompt transition from the simplest constructions of temperature and pressure fiber-optic sensors to creation of the wide nomenclature of physical quantities sensors. The important advantage of optical fiber sensors is introduction of new qualities into measuring systems, such as:

- small size;
- stability to uncontrollable and aggressive influences of environment and to electromagnetic interferences;
- high sensitivity;
- remoteness of measurements technological effectiveness of production.

Amplitude fiber-optic sensors are the simplest and convenient in maintenance constructions of FOS. The block-scheme of fiber-optic sensor is presented on Figure 2. Such sensors use the principle of intensity modulation of a laser light beam: the beam of light from laser source goes on an optical fiber and illuminates a diaphragm. In case of diaphragm oscillations the luminous flux is modulated (on intensity) and goes by the second optical fiber to the photodiode that transforms a signal to an alternating current, which value is shown on reader device.
According to such principle conversion of oscillations of a diaphragm directly in an electrical signal is not used. The diaphragm can be placed generally at distance of tens (hundreds) meters from a light source and the photodiode because of low transmission losses of a signal in an optical fiber (losses signal/noise make less than 3 dB on 1 km of an optical fiber). Such optical circuit does not cause any electromagnetic radiations. Also, it is insensitive to electromagnetic fields. The system can be placed in any hardly accessible place and can work in the strong magnetic or electrical fields because of its small sizes.

Figure 3. The block-scheme of fiber-optic sensor. 1 – light source, 2 – photodiode, 3 – reader device, 4 – optical fibers inside the sensor.

4. Diaphragm
One of the most important parts of construction of FOS is the diaphragm and many parameters of the sensor depend on its choice.

Hyperfine microsized diaphragms are a basis of many highly sensitive micromechanical, microheatphysical transformers, the active controlled microdevices and difficult analytics microsystems [3]. Physicomechanical properties of such diaphragms strongly depend on their composition, structure, properties of a surface and manufacturing techniques. Design of different transformers on the basis of hyperfine diaphragms requires the accounting of sized factors, and their manufacture assumes use of special technological operations.

Technological effectiveness and overall performance in composition with other constructional materials are the major criteria for choosing materials for implementation of constructions of membrane transformers. As a basic material of hyperfine diaphragms silicon nitride (Si₃N₄) – one of the main materials of microelectronics with well known technology of receiving and known properties is often used. Films of silicon nitride usually receive by silan amonolizing in the ammonia atmosphere at temperatures about 850 °C. The most important qualities of this material are mechanical and chemical stability, low porosity. It allows creating on its basis hyperfine, including nanosized films. Diaphragms can be made by technology of volume and surface micromechanics depending from construction of membrane transformers.
For the microoptomechanical sensor for monitoring of ICP implementation, we selected plane Si$_3$N$_4$ diaphragm. Photo of Si$_3$N$_4$ diaphragms is shown on Figure 4. This type of diaphragms possesses the following parameters:

- maximal withstood values of pressure up to 82 kPa;
- deflection at a pressure of 1 Pa is 0.9 nanometers;
- chemical inertness.

5. Construction and parameters of the ICP microoptomechanical sensor

Different options of the microoptomechanical sensor for ICP monitoring construction were developed. Figure 4 demonstrates the sensor with Si$_3$N$_4$ diaphragm fixed on a centralizer.

![Figure 4. Photo of Si$_3$N$_4$ diaphragm matrix.](image)

![Figure 5. The sensor with Si$_3$N$_4$ diaphragm fixed on a centralizer. 1 - the polycarbonate casing, intended for support of optical fibers safety from external mechanical influences; 2 - the ceramic casing, one of the construction elements, providing centering of optical fibers on surface of a diaphragm; 3 - glass tube in which the optical fibers ground from an external covering are located; 4 - the centralizer also provides centering of optical fibers on surface of a diaphragm. The centralizer with the diaphragm strengthened on it (7) can be disconnected from the general construction; 5 - the hollow tube providing alignment of pressure in submembrane volume with external atmospheric pressure; 6 - Si$_3$N$_4$ diaphragm is the reflecting element providing modulation of light on intensity, as a result of external influence; 7 - optical fibers: receiving, the transferring and two separate fibers providing as much as possible the close layout of the main fibers. Diameter of a core of fibers of 62,5 microns](image)
Construction of an end face of optical system is shown on Figure 6. This option of a design was built and investigated with use of two types of optical fibers with diameters of core 62.5 and 100 microns.

For the structure shown in Figures 5 and 6, transfer function shown in Figure 7 was obtained.

![Figure 7](image)

**Figure 7.** The output voltage as a function of distance between the ends of the optical fibers and a reflective surface for optical fibers of different types, 1 - 100/125 micron, 2 - 62.5 / 125 micron.

For obtaining the maximum sensitivity it is expedient to use optical fibers with a smaller diameter of a core. However on fibers with a larger diameter of a core it is possible to receive the maximum absolute value of output voltage. It is connected with fact that optical fiber with a 100 microns diameter of core possesses greater value of a numerical aperture. Larger range of measured pressure values at fibers by a 100 microns diameter is a result of wider initial quasilinear site of the transfer characteristic.
6. Conclusion
As a result of this work the level of scientific, technological and methodological knowledge in the field of human ICP measurement procedures was investigated as well as the existing ICP sensors, their advantages and disadvantages. Based on these studies microoptomechanical ICP monitoring sensor was developed, designed and investigated.

The analysis of the obtained data showed that the microoptomechanical sensor with a Si$_3$N$_4$ membrane that has been hermetically fixed on a centralizer, is the best solution for objectives. Also the dependence of the output signal and the sensor sensitivity from the optical fibers diameter was determined.

Results of this work can be used for further improvement of characteristics of sensors for control of intra cranial pressure, and also for development of the full-fledged medical system meeting all modern requirements.

References
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