Directions for the development of modern sensor equipment. Fiber-optic sensors.

At the present time, according to the literature data, in the technologically developed countries the intensive scientific researchers are being conducted in the sphere of development of new types of optic and fiber-optic sensors (FOS) of various physical quantities.

The priority ranking and competitive ability of that direction is determined by the advantages of FOS as compared to other functionally similar sensors:

- Protection from the impact of electromagnetic fields;
- Wide dynamic measurement range;
- High corrosion and radiation resistance;
- Ability to multiplex many sensors on one communication line;
- Small size and weight;
- Electrical insulating resistance;
- High sensitivity;
- Durability;
- Fire-explosion safety;
- Fast response time.

Such unique properties of FOS allow controlling multiple parameters of the automated systems like:

- pressure, temperature in pneumatic / hydraulic systems and in their actuating mechanisms, working environment (of the carrier)
- absolute pressure, humidity, ambient temperature in industrial premises
- level of working fluid in hydraulic systems
- fluid flow / gas rate of the carrier
- mass, grain size, component of the dosed material (for example, after grinding in a ball mill)
- quantity of the transported elements, units, products, containers
- condition of the important units of technological installations (for example, ball mill bearings)
- three-dimentional state (condition) of the actuating elements of technological equipment (rotational speed, distance of the linear / angular movement of actuating elements etc.)
- temperature, pressure, concentration of harmful gases in the air
- electrostatic voltage magnitude in the explosion-hazardous premises
- voltage and supply current magnitudes of conducting and actuating elements of technological installations and automation systems etc.

There is a big variety of FOS, the main types of which are given in the classification scheme of the figure 2.

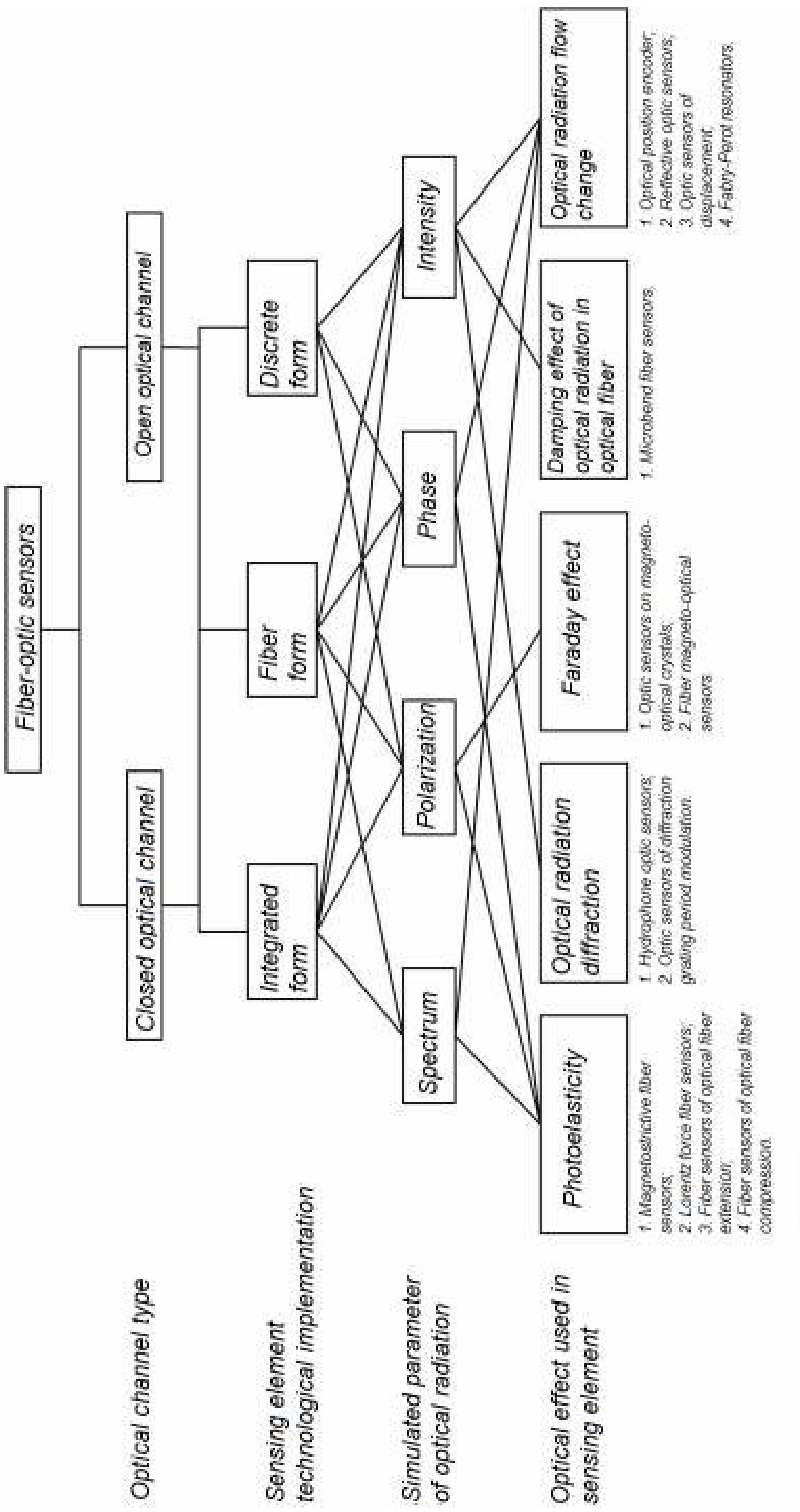


Figure 2- Classification of fiber-optic sensors

FOS on photoelastic effect. This effect takes place in optic waveguide under the influence of external applied voltage that stretches and compresses optical fiber. At the same time there is a change of the refractive index:

$$\delta n = -\frac{n^3}{2}(p_{11}\varepsilon_x + p_{12}\varepsilon_y + p_{12}\varepsilon_z),$$

where ε_x, ε_y is a relative deformation in cross-section area;

$\varepsilon_z = \frac{\Delta l}{l}$ – deformation along the fiber axis.

At the present time there is a large number of FOS using the photoelastic effect. Magnetostrictive fiber sensors have been found very useful. For example, FOS described in patent, FIBER-OPTIC POSITION SENSOR RU N°2413178 (application form 2006116928/28, 17.05.2006) is shown in figure 3.

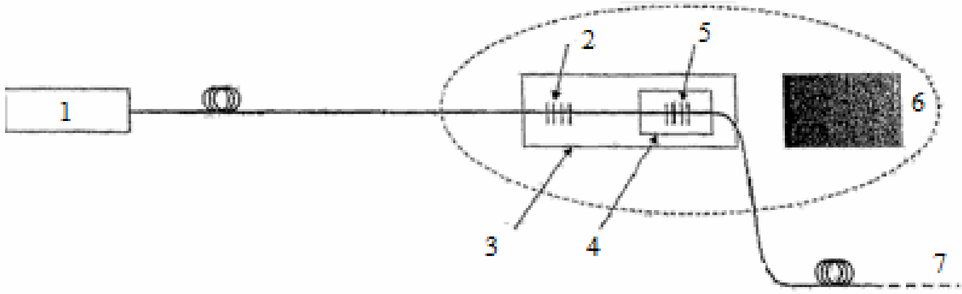


Figure 3 - Magnetostrictive fiber sensor
(1– broadband light source, 2 and 5 – fiber-optic Bragg gratings, 3 – shank, 4 – magnetostrictive material segment, 6– magnetic component)

FOS contains a magnetic element 6, broadband light source 1, optical fiber, two fiber-optic Bragg gratings 2 and 5 made of optical fiber, one magnetostrictive material segment 4, shank 3 made of the material impervious to magnetic fields. One Bragg grating is attached to the magnetostrictive material segment and that segment is attached to the shank. The magnetic component and the shank are connected in a manner that they can experience relative shift only along the shank axis. The pointed shift provokes size changes of the magnetostrictive material segment which leads to the changes of wave-length reflected by the Bragg grating.

Lorentz force FOS. Lorentz force FOS scheme is shown in figure 4. In such sensors optical fiber is covered with current-conducting coating through with the current i in flowing in the presence of the magnetic field B . In this case the optical fiber of length L will be influenced by the force F equal to:

$$F = i * L * B,$$

If we consider the point x of the optical fiber (it is assumed that the optical fiber is fixed at the ends with such straining force that some static sag arises), then the strain amplitude ε on a frequency ω of the magnetic field:

$$\varepsilon(x) = \frac{f_0 L^2}{A\rho\omega^2 EI} K i B_0,$$

where K =0,307 is a numerical coefficient;

A – The cross sectional area of the current-conducting coating;

ρ – density of the current-conducting coating;

I – the projection of the inertia moment;

E – Young's modulus of optical fiber;

f_0 – optical fiber straining.

The given sensor can be used for the movement registration of a magnetic object, however, in order to obtain the reasonable deformations of optical fiber it is necessary to use the fiber's extended section.

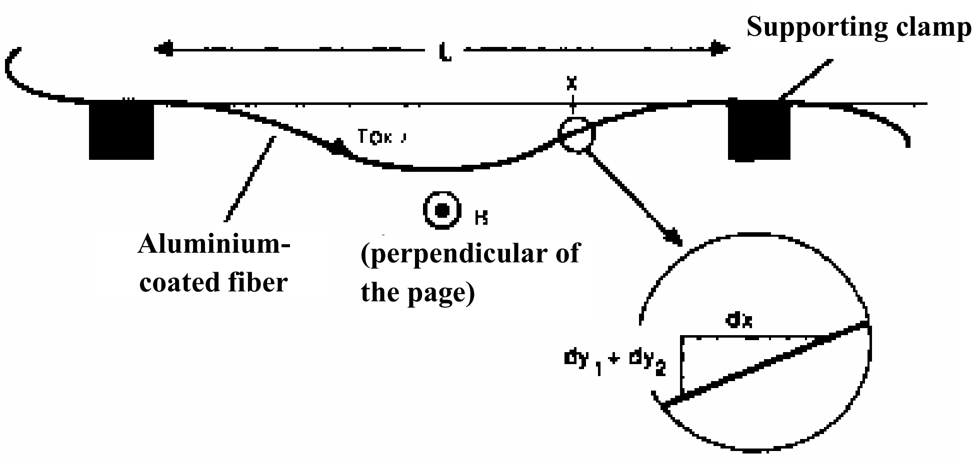
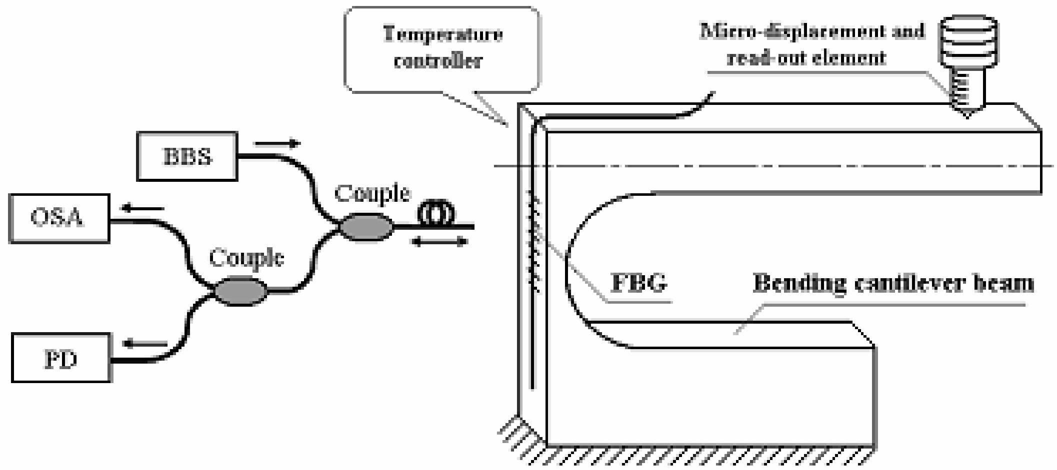


Figure 4 – Operating principle of Lorenz force FOS

Optic fiber deformation FOS. Operating principle of this FOS is that the movement of an object affects the cantilever arm, which transmits deformation to optical fiber with Bragg gratings connected to this cantilever (figure 5). As a result, affected by the movement of the cantilever, the optical fiber gets deformed, and consequently the wavelength of light reflected from the Bragg gratings changes.



Fiber 5 – Fiber sensor of fiber stretching

The advantages of Fiber Bragg Gratings in comparison to alternative technologies (for instance, interference mirrors and volume gratings) are as follows: vast variety of obtained spectral and dispersive characteristics, most of which can be implemented only on the basis of fiber gratings; all-fiber structure; low optical losses; relative simplicity of fabrication and many others.

The principle of measurement is based on the dependence of resonant wavelength λ_{BG} on the applied mechanical tension or compression stress.

$$\lambda_{BG} = 2n\Lambda\left(\left\{1-\left(\frac{n^2}{2}\right)[P_{12}-\nu(P_{11}+P_{12})]\right\}\varepsilon+\left[\alpha+\frac{1}{n}\frac{dn}{dT}\Delta T\right]\right), \qquad (2.4)$$

where ΔT – temperature change;

ε – applied mechanical stress;

P_{11}, P_{12} – elastic coefficients of optical tensor;

ν – Poisson ratio;

α – thermal expansion coefficient of quartz glass;

n – effective rate of dominant mode;

Λ – period of grating.

This formula is the basis for using Bragg gratings as sensory elements of physical quantities sensors.

This FOS measures movements of up to 20 mm within the limits from 20 to 100 C^0 and has the inaccuracy of 0.5 mm. It should be noted, that structuring of tension FOS is also possible according to phase as the modeling parameter. Then the following formula determines the phase movement resulting from the deformation caused by stretching:

$$\psi = \frac{2\pi n\xi}{\lambda} * L * \eta * \varepsilon_z,$$

where L – length of fiber exposed to deformation ε_z,;

η – deformation transmission efficiency, n – core refractive index;

ξ – optic deformation correction factor, allowing to take into account the changing of propagation coefficient in the fiber core under longitudinal deformation.

$$\xi = 1 - \frac{1}{2} n^2 * [(1-\mu)P_{12} - \mu P_{11}],$$

where μ – Poisson ratio for fiber material;

P_{ij} – coefficient tensor elements of optical sensitivity to deformations;

$\xi = 0{,}78$ and (for silica fibre).

The example of FOS of this type is fiber-optic deformation sensor SOFO (figure 6).

Basic technical specifications:

– length of active part: from 0.25 m to 20 m;

– length of passive part: from 1 m to 2000 m;

– measuring range: 0.5% of the active part at compression, 1% of active part at stretching;

– measurement accuracy: 0,2% of the measured deformation or more;

– measurement resolution: 2 microns;

– operating temperature: active part from - 50 °C to 170 °C, passive part from - 40 °C to 80 °C;

– water resistance: 5 bar.

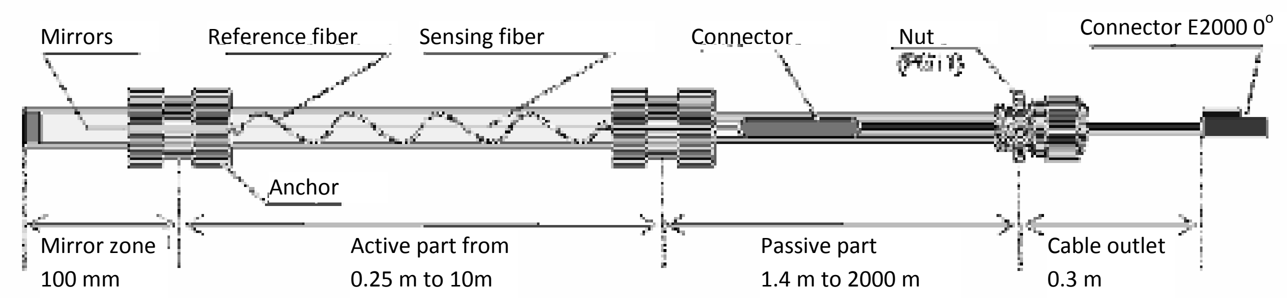


Figure 6 – FOS of SOFO deformation

Advantages:

– compensation for extraneous environmental effects, due to the introduction of the reference channel;

– an extremely high accuracy.

Disadvantages:

– sensitivity to fluctuations of the input radiation;

– only relative measurements are possible;

– necessity of using phase compensating elements;

– complexity in manufacturing.

FOS of optical fiber compression is used as strain sensors. In the patent US4904863, there is the description of the device based on the compression of the fiber coil (figure 7). Optical converter built on a retroreflective scheme, is shown in figure 8.

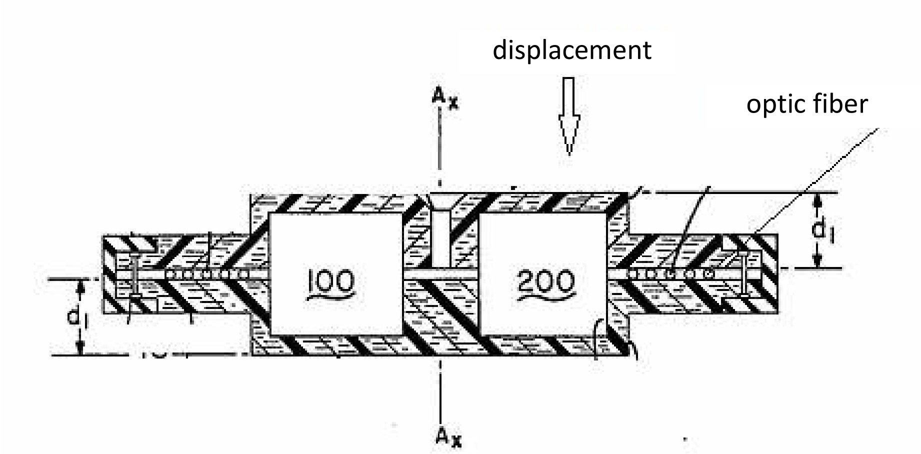


Figure 7 - Sensing element of the FOS of the optic fiber compression

The phase shift of the optical signal for the given design is determined by the following formula:

$$\frac{\Delta\psi}{\psi} = \left(\left\{1 - \left(\frac{n^2}{2}\right)[p_{12} - \nu(p_{11} + p_{12})]\right\}\varepsilon + \left[\alpha + \frac{1}{n}\frac{\Delta n}{\Delta T}\right]\Delta T\right),$$

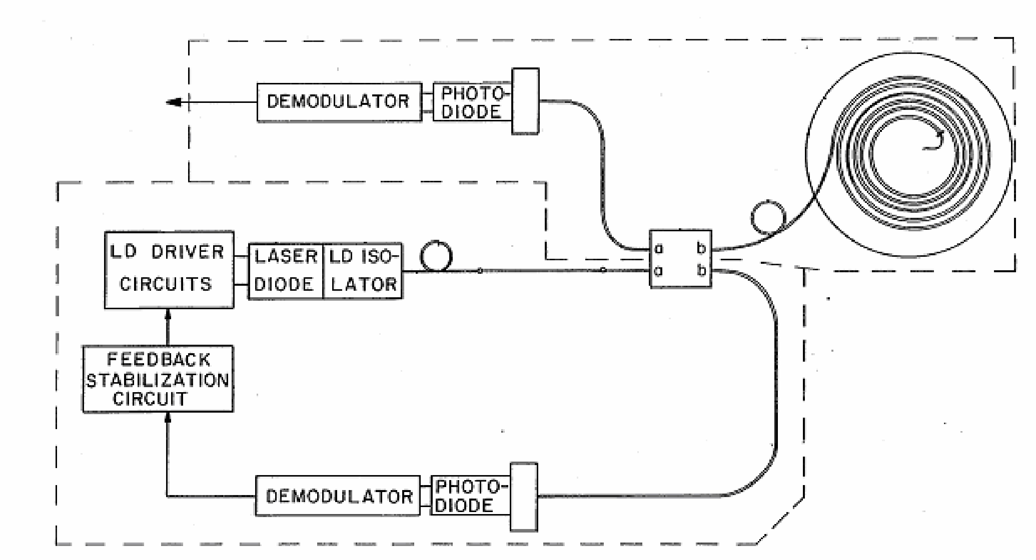


Figure 8 – FOS of the optic fiber compression

FOS on the diffraction lattices. In multimode FOS using diffraction lattices, sensitive elements are applied on the basis of two adjacent identical gratings, one is fixed and the other one can move, as shown in figure 9. If lattices are located close enough to one another, relative to the incident light, they reveal themselves as one lattice, the period of which is constant, but the proportion of the leaking area may be changed from 0.5 to 0 depending on the position of the movable lattice.

Maximum measurable displacement is determined by the value of the opaque and empty sectors of the lattices. It is always necessary to choose a compromise between the dynamic range of the modulator and its sensitivity, because the larger the lattice spacing, the lower the sensitivity, but wider the measurement interval. To improve sensitivity, it is desirable to make the lattice spacing as little as possible so the smallest displacement of the lattice leads to a significant change of the output signal.

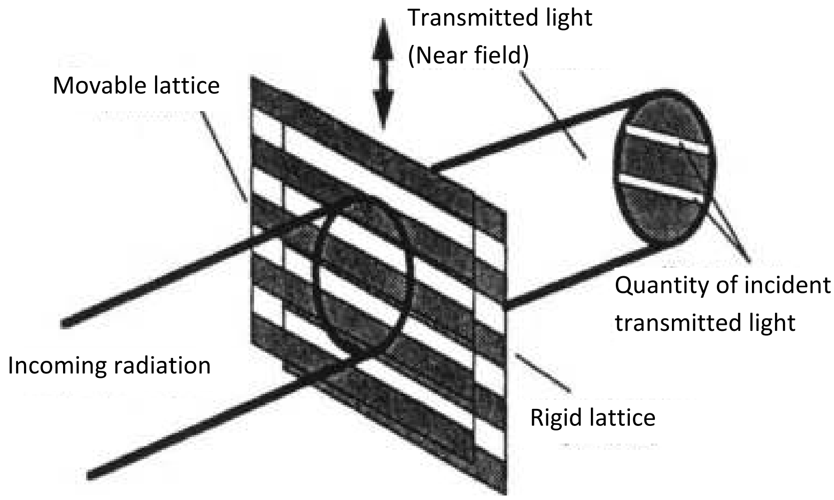


Figure 9 - Intensity modulation by a pair of gratings

This measurement method is used in optical hydrophone sensors to determine the displacement of the diaphragm, as shown in figure 10. When the lattice spacing is 10 μm, the measured maximum displacement is 5 μm. The testing showed that the sensitivity of this hydrophone is 1 μPa in a dynamic range of 125 dB, and operating frequency range is about 1 kHz.

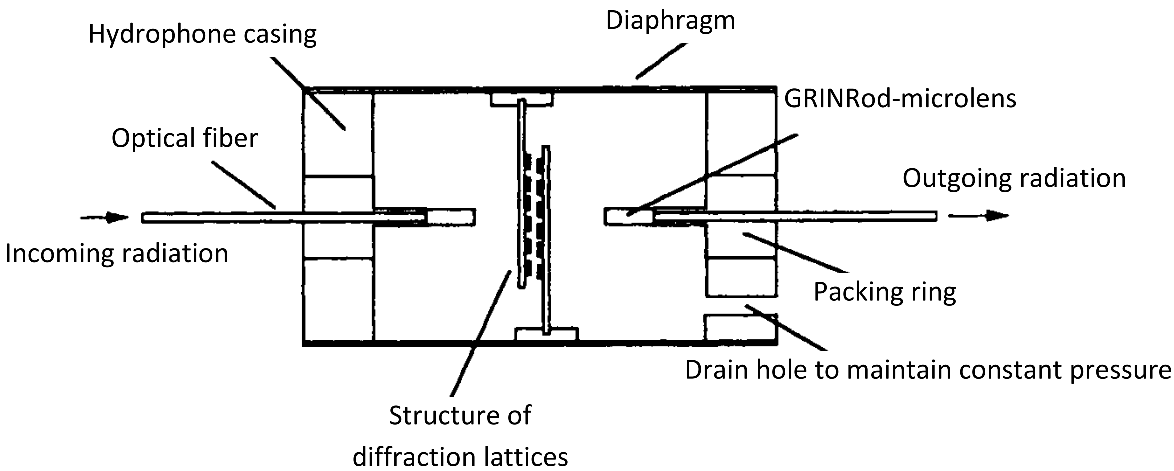


Figure 10 - Schematic representation of FOS - hydrophone based on the structure of diffraction lattices

Sensor type: open channel.
The range of recorded displacement: up to 5 μm.
Resolution: 0.01 μm.
Sensitivity: 1 μPa in a dynamic range of 125 dB.
Advantages:
- high resolution;
- insensitivity to fluctuations of the input radiation;
- high sensitivity to pressure;
- contactless measurement method.

Disadvantages:
- small range of measured displacements;
- an open channel.