FOS (fiber-optic sensor) on the Faraday effect. FOS, using the Faraday effect, have been applied to measure the magnetic field and electric current, displacement, vibration, motor shaft speed sensors, etc.

The operating principle of such FOS is based on the polarization of the optical radiation propagating through the optical medium. In general, there are such optical media in the propagation, through which the polarization state is changed, such substances are called birefringent. Such materials have a strong influence on the polarization state of the linearly polarized radiation, as shown in figure 24, where the plane of polarization of linearly polarized radiation rotates through an angle after passing through the circular birefringent medium. Generally, a complete change of the polarization state depends on the distances traversed by the radiation in birefringent substance, magnitude and form of birefringence and the polarization state at the input.

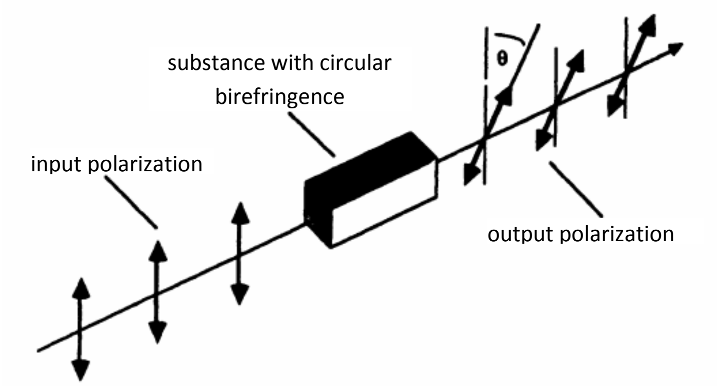

Figure 24 - The rotation of the polarization plane of linearly polarized light by the circular birefringent medium

In the presence of a magnetic field H, circular birefringence that occurred in the fiber will rotate the polarization plane of linearly polarized radiation by an angle of:

$$\varphi_F = V_v \int H d\, L,$$

– where the Verdet constant V is an intensity measure of the Faraday effect in the fiber and the integration is performed along the length of the fiber subjected to the H field action. The value of V depends on the composition of the fiber material and the optical wavelength; it is much weaker dependent on the temperature of the dielectric substance.

Today, there are two types of optical sensors using the Faraday effect. The first type is fiber-optic sensors in which the optical fiber is a transmission medium and a sensing element. The second type is optical sensors with magneto-optical crystals; in these sensors, the optical fiber is a transmission medium, and the sensing element is a magneto-optical crystal.

An example of FOS on the Faraday effect is the invention: FIBER-OPTIC CURRENT SENSOR RU 2437106, order 2009148729/28, 29.12.2009 (figure 25).

FOS works as follows. The light source sends light via optical waveguide to the linear polarizer, then to the polarization splitter, which generates two linearly polarized fluxes, and then to the optical phase modulator. The light streams are fed via optical fiber to the measuring unit, where they pass through the quarter-wave circular polarizer, which gives them the right- and left-hand polarization, and then through the current-sensing loop around the conductor; they are reflected from the fiber end and return the same way to the processing unit. During the passage of the light through the loop, the magnetic field induced by the current flowing through a conductor creates phase shift proportional to current between polarized light streams due to the Faraday effect. In the processing unit, light streams enter the optical detector which determines the phase shift and converts it into an analog or digital signal. The described system provides a measurement accuracy of 0.15% in the range of currents from 1 to 3000 A, laboratory samples have an error of 0.03%.

Advantages:

- high accuracy;
- insensitivity to fluctuations of the input radiation;
- no need for repeated adjustment;

– fast response time (up to 100 khz).
Disadvantages:
need to use expensive optical fiber.

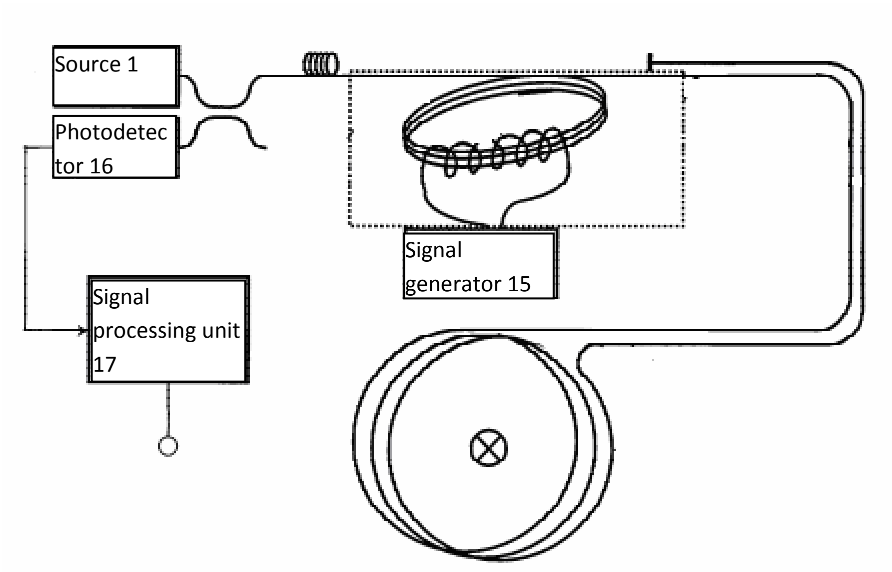

Figure 25 – FOS of the current on the Faraday effect

The other example of implementation of FOS of the first type is the implementation of fiber-optic linear displacement sensor (FOLDS). This FOLDS may not have mechanical contact with the test object and monitor its movement across an impermeable wall (for example, control the position of a valve plate through its non-magnetic metal wall).

An example of the FOLDS construction on the Faraday effect is given in figure 26. Magnetic field is generated by two solenoids. Depending on the movement of the movable plunger 4, the angle between the fiber length section and the density of the field changes, acting on the fiber, and the magnitude of the field density in this section of the fiber also changes.

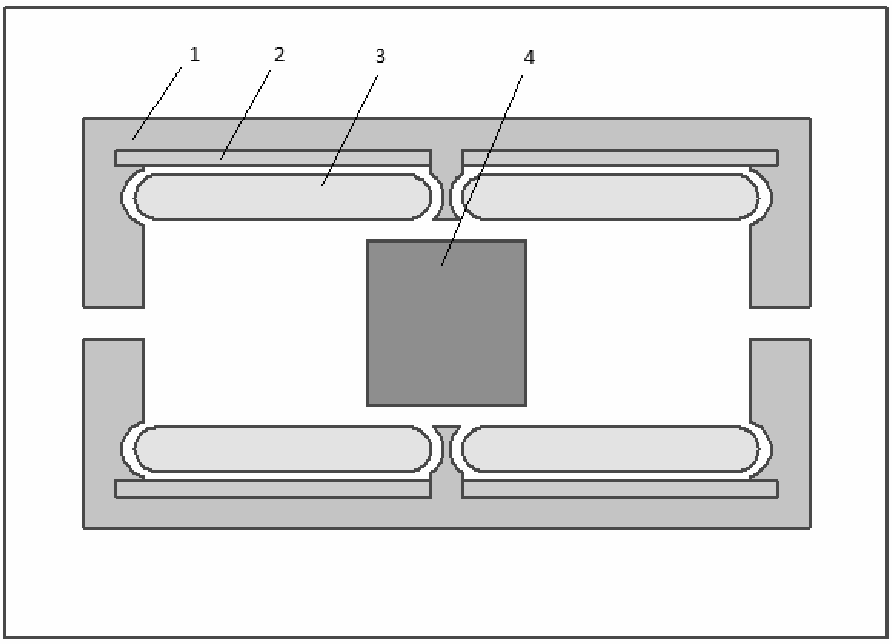

Figure 26 – FOLDS.

(1 – body, 2 – one of the 2 windings of the solenoid, 3 – coil of non-magnetic material, on which fiber is wound, 4 – movable plunger)

The direction of the lines of magnetic flux and light in the fiber is shown in figure 27. When the plunger is moving, the magnitude and the direction of the magnetic field change. The patterns of the magnetic field are shown in figures 28 and 29.

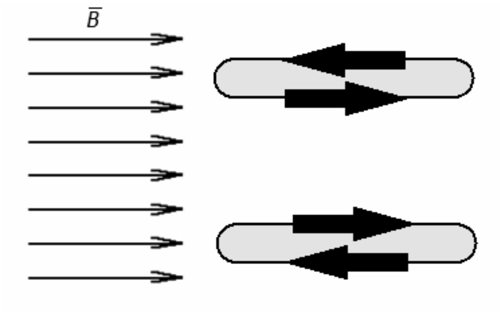

Figure 27 – Optical coil in a magnetic field. Black arrows indicate the direction of the light

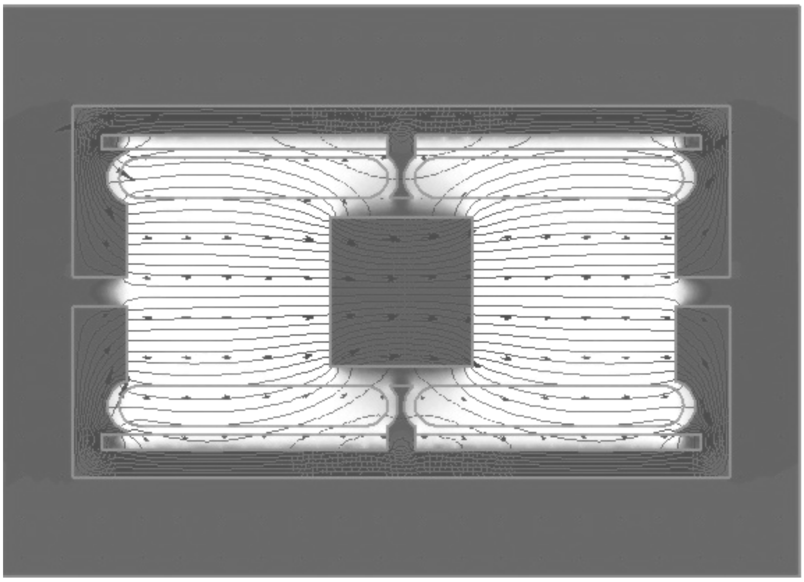

Figure 28 – Field pattern for the zero position of the plunger

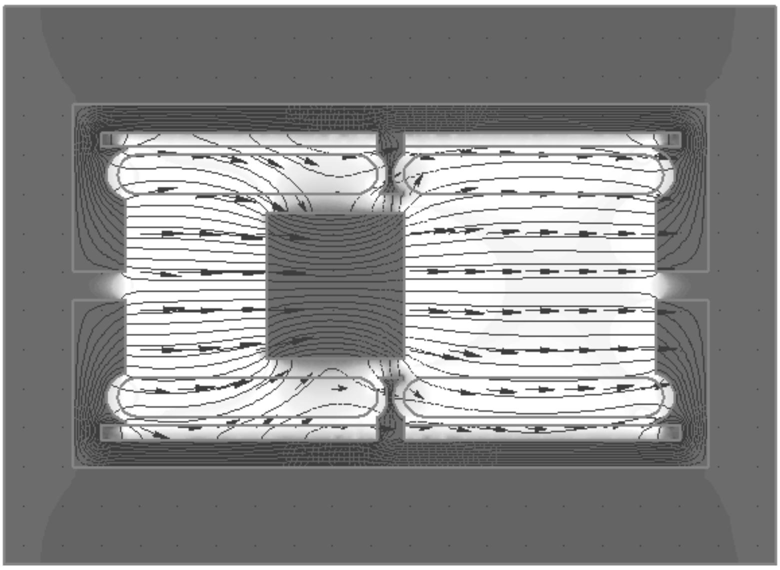

Figure 29 – Field pattern for the end position of the plunger

Disadvantages of the FOLDS mechanism:

– the lack of autonomy due to the power supply of bias windings.

Advantages:

– the possibility of correction through the bias windings;

– smaller in size than the sensing element with magnet.

In the second variant, the magnetic field is generated by a permanent magnet. The FOLDS designs are presented in figures 30 and 31.

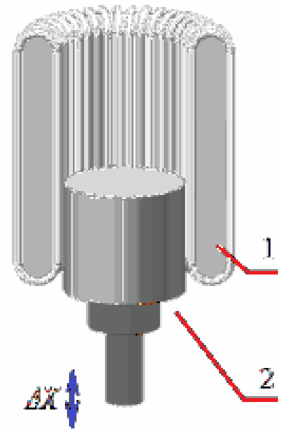

Figure 30 – FOLDS design

FOLDS consists of a fiber optic coil 1 wound from fibers with magneto-optical effect (SPUM fiber), rotary magnet 2 connected to the monitor object. When you move the magnet inside the coil, the magnitude of the magnetic field changes, penetrating the turns of the coil and, as a consequence, the angle of rotation of the polarization plane of optical radiation transmitted through the coil.

The other FOLDS design with a fixed magnet and a movable magnetic plunger is shown in figure 31.

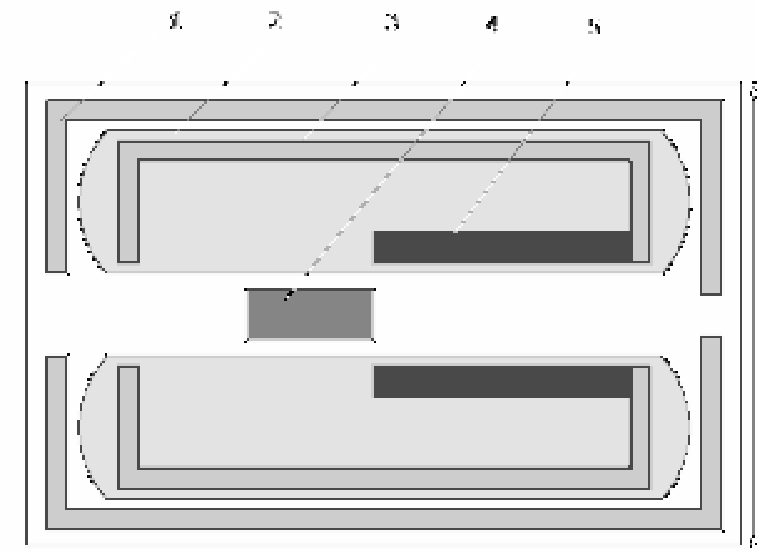

Figure 31 – FOLDS with a magnetic screen.

(1 – external protective housing, 2 – optical coil, 3 - inner housing, 4 – movable core, 5 – magnet)

When the movable core is moving, the pattern of the magnetic field changes (figures 32, 33).

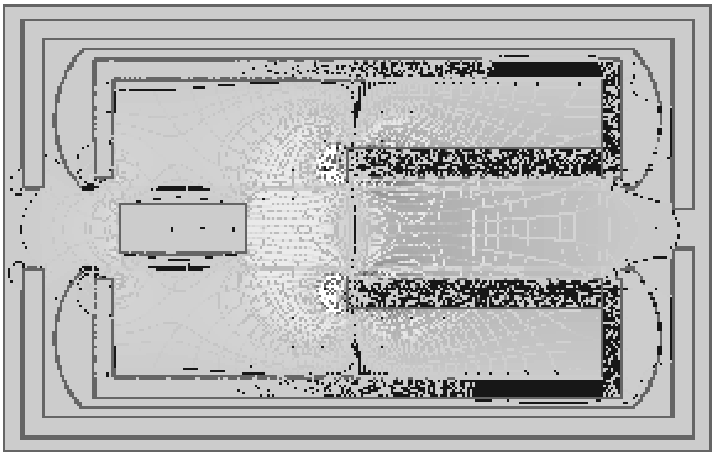

Figure 32 – The pattern of a magnetic field for the leftmost position of the plunger

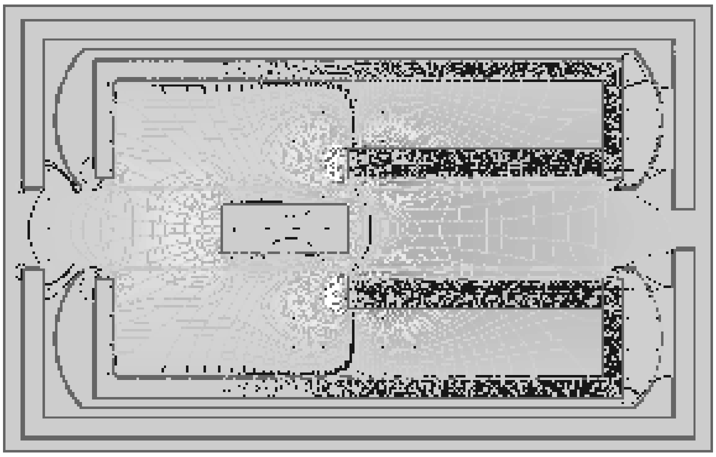

Figure 33 – The field pattern for the rightmost position of the plunger

Disadvantages of the FOLDS mechanism:

– the absence of the possibility of external correction, as in the case with the solenoid;

– large dimensions when compared to the sensing element with the bias coils.

Advantages:

– autonomy, the field is generated by a permanent magnet, and as a result does not require power supply.

For the registration of the Faraday effect, various interferometric schemes are used created on the basis of fiber interferometers of Mach-Zehnder, Michelson, Sagnac, etc. There are various options for implementation of the scheme of the secondary optical converter.

The scheme of the linear polarimeter is the simplest (figure 34). Optical radiation from the laser source enters the linear polarizer. At the input to the fiber optic coil, the polarizer generates linearly polarized optical radiation. Under the change of the magnetic field in the sensing element, the polarization plane of optical radiation is turned. At the output of the fiber-optic coil for reception, polarization state changes set the polarizer at ±45 degrees with respect to the input polarizer. As a result at the output of this scheme, the intensity of optical radiation on the photodetector will be determined by the formula 1.

$$J = \frac{J_0}{2} * (1 \pm Sin2\theta),$$

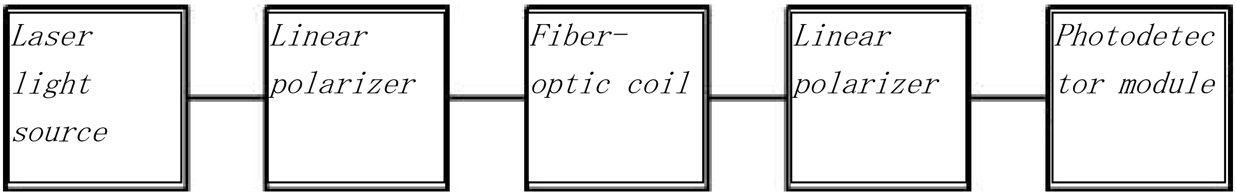

Figure 34– Structural scheme of the optical converter, made in the form of a linear polarimeter

This scheme has the following advantages:

– a simple scheme for constructing the optical converter, using the minimum number of optical components that allows to make a study of different types of sensory fibers and the magneto-optical crystals at the initial stage;

– the implementation of this optical converter is available in discontinuous and fiber performance.

The optical converter made according to this scheme has the following disadvantages:

– optical converter made according to the scheme of the linear polarimeter is sensitive to temperature changes and vibrations;

– in this scheme, there is no possibility of hardware correction of the optical signal, depending on the external destabilizing factors;

– for manufacturing of a sensitive element of the converter, it is necessary to use a large number of expensive magneto-optical fiber.

A more complex scheme is the scheme of the linear polarimeter with a polarization resolver. The polarization resolver is a fiber-optic polarizer or a prism of Wollaston, which splits the optical radiation into two orthogonal flows, the linear polarizations of which are perpendicular. The principle of operation of this scheme is similar to the previous scheme with the difference that the optical radiation is decomposed using a polarization beam splitter, tilted 45 degrees relative to the input polarizer, into two orthogonal polarizations, each of which is routed to a separate photodetector.

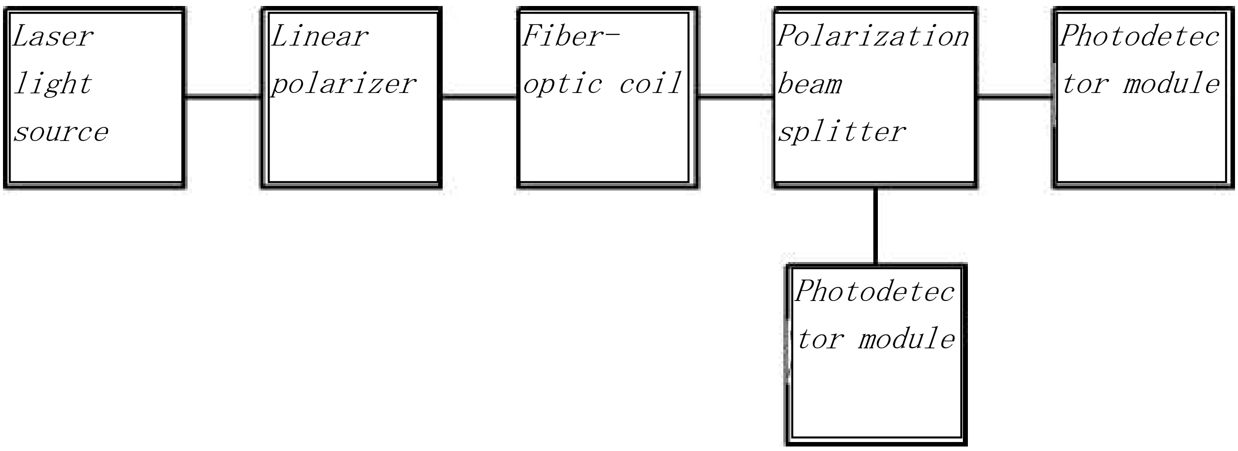

Figure 35 – Structural scheme of the optical converter, made in the form of a linear polarimeter with a polarization beam splitter

The use of this scheme allows to obtain two measuring channels, and thus producing a correction of the output signal, removing the multiplicative and additive components.

$$J = \frac{J_1 - J_2}{J_1 + J_2} = Sin2\theta \approx 2\theta$$

This scheme has the following advantages:

- the scheme of the optical converter made according to the scheme with a polarization resolver, allows to obtain greater stability to external destabilizing factors due to the correction of the output signal.

The optical converter made according to this scheme, has the following disadvantages:

- optical converter made according to the scheme of the linear polarimeter with a polarization resolver is sensitive to temperature changes and vibrations;
- for manufacturing of a sensitive element of the converter, it is necessary to use a large number of expensive magneto-optical fiber.

Figure 36 shows the appearance and table 4 – main characteristics of FOLDS on the Faraday effect.

Figure 36 – Appearance of FOLDS.

Table 4 – Main characteristics of FOLDS on the Faraday effect

N°	Characteristics	Value
1	Size, mm	85x60x26
2	Length of fiber optic cable, m	up to 10
3	Moistureproof reinforced with kevlar fiber optic cable Ø3 mm MM (62.5/125), terminated with FC/PC fiber optic connectors	

4	In a protective aluminum housing	
5	Movable valve rod travel, mm	from 0 to 25 mm
6	Operating temperature, °C	from 0 to +50
7	Storage temperature, °C	from - 40 to +85

Despite the fact that the use of SPUM fibers in FOS on the Faraday effect allows to achieve good technical characteristics, however, such FOS tend to have large dimension and mass parameters, due to the size of the fiber coil.

Using of materials on the basis of bismuthiferous single-crystal garnet ferrite films (Bi:GF films) as magneto-optical material for the visible range of wavelengths allows to eliminate this drawback [1-6].

Bismuthiferous single-crystal garnet ferrite films are transparent monocrystalline layers grown by liquid-phase epitaxy method on a nonmagnetic substrate. Magnetic and magneto-optical properties of Bi:GF films can be adjusted within wide limits by changing the production conditions, composition and post-processing. The best material is bismuthiferous garnet ferrite $R_{3-x}Bi_xFe_{5-y}M_yO_{12}$, where R_{3-x} is a combination of rare earth elements; M-Ga, Al and microadditives of elements with unfilled d-shell. The working layer of Bi:GF thickness of 1-100 μm is grown by liquid-phase epitaxy method on a rigid flat transparent plate (substrate) of non-magnetic gadolinium-gallium garnet $Gd_3Ga_5O_{12}$ with thickness about 0.5 mm.

Bi:IG films have abnormally large specific rotation of polarization plane of light and high transparency. Magneto-optical properties of Bi:IG depend basically on the content of bismuth.

Figure 37 shows the experimental dependence of the output signal of fiber-optic vibration sensor (FOVS) on the magnetic field strength.

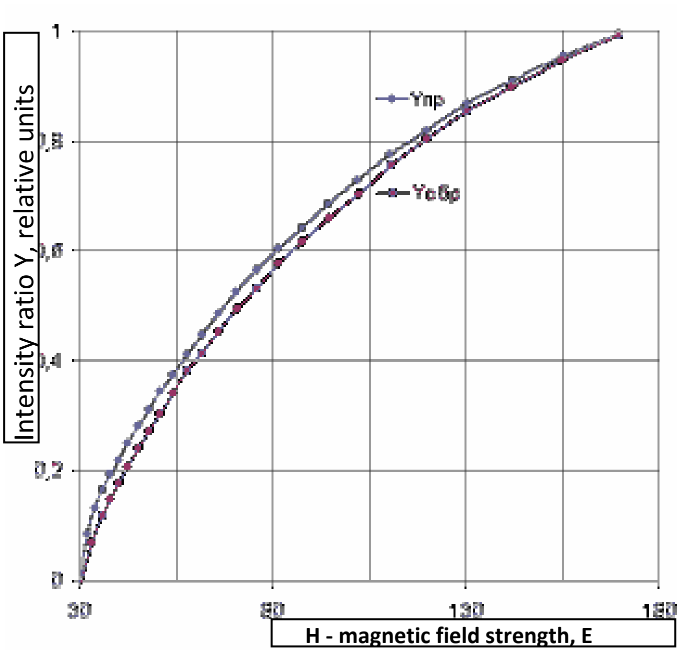

Figure 37 - Experimental dependence of the FOVS signal on the magnetic field strength

The vibration of the monitored objects leads to modulation of the magnetic field strength in time. It is obvious that the monitored objects need to be made or to be coated with ferromagnetic materials. The cobalt magnet was used as the source of the magnetic field.

It is clear that the losses in the ferromagnetic materials of the sensor and monitored object by eddy currents and remagnetization limit the range of controlled vibrations. In the engineered sensors, high-frequency ferrites were used as materials of the magnetic cores. It made it possible to increase the working frequency range of the sensor to 1000 Hz.

Figure 38 shows the frequency and positional response of the sensor, and figure 39 - its photos.

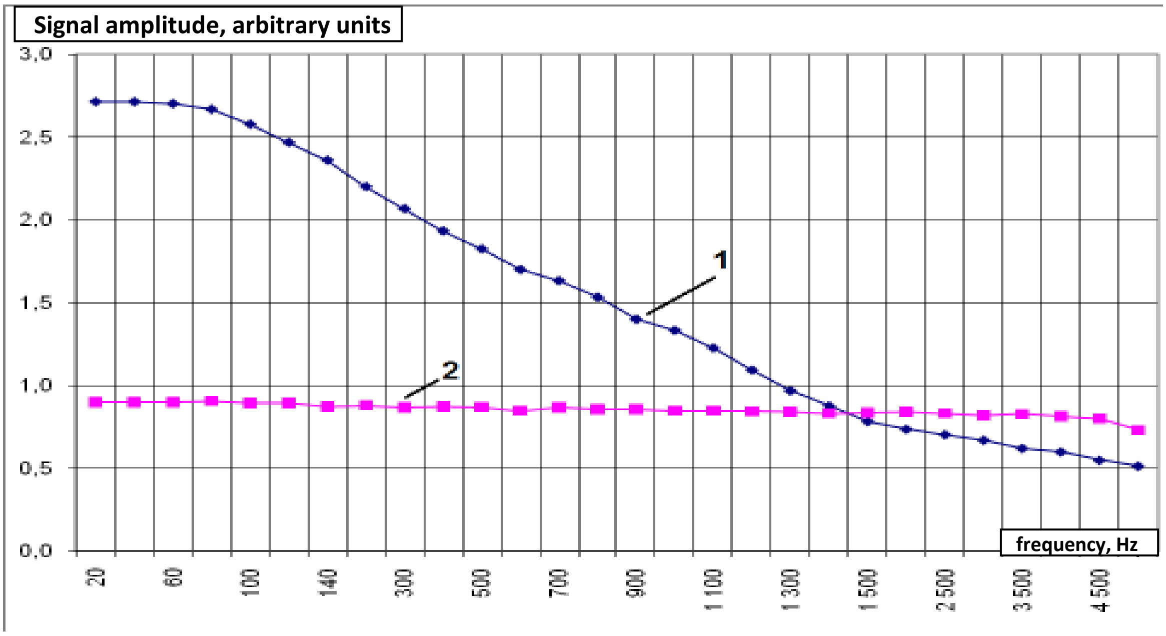

Figure 38 - Frequency response of the sensor: 1 – the sensor with a magnetic core, 2 – the sensor without a magnetic core.

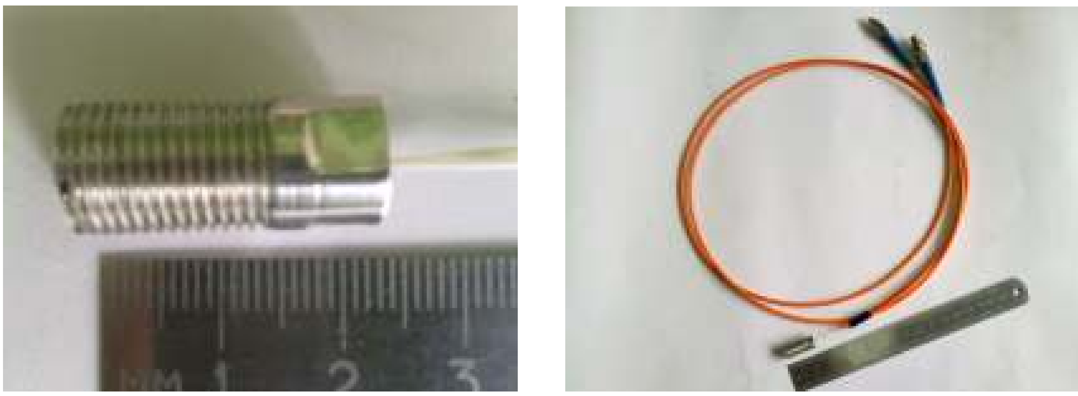

Figure 39 – The photo of a sensor

Table 5 shows the main characteristics of the FOVS.

Table 5 - The main characteristics of the vibration sensor.

N°	Characteristics	Value
1	Overall size, мм	8x20
2	Length of fiber optic cable, m	from 0,5 to

		100
3	Moistureproof reinforced with kevlar fiber optic cable, terminated with FC/PC fiber optic connectors	Ø3 mm
4	Gap between the sensor and the vibration object, mm	from 0 to 30
5	Frequency of vibration, Hz	up to 1000
6	vibration amplitude, mm	up to 10
7	amplitude measurement error, %	1,0
8	error of frequency measurement, %	0,1
9	operating temperature, °C	from - 30 to + 60
10	storage temperature, °C	from - 60 to + 85