Optical fiber accelerometer based on the single-mode fiber waveguide with low normalized frequency

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The present paper is devoted to the development of a fiber-optic accelerometer based on single mode optical fibers with low normalized frequency. It was shown that for registration of vibration with small amplitudes it is expedient to use an optical fiber working in a singlemode waveguide regime with a low normalized frequency. A fabrication technology was developed for producing localized sensitive elements based on singlemode optical fibers characterized by extremely low normalized frequency. It was shown that the sensitivity of such fibers to vibration impacts can reach $6*10^{-5}g$. This enables the development of fiber optic sensors on their basis with the following specifications: linear frequency response in the range 2 – 50 Hz, dynamic range 50 dB. Temperature dependent drift of the output signal 0,2%/ºC, long term stability 0,1%/24h. Such specifications make it possible to use fiber optic sensors of this type in a wide range of geophysical and other applications.

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NOMENCLATURE

V = normalized frequency
ρ = fiber core radius
$h(\omega)$ = amplitude-frequency characteristic
ω_0 = natural frequency
γ = damping constant

1. Introduction

Further improvement of seismic sounding methods, prediction of global processes in Earth crust as well as detection of new fields of oil, gas and other minerals require the enhancing of accuracy, reliability and stability of measurement devices, which are used for these purposes. Apparently, one of the more perspective ways to solve this problem is the conversion to the element basis of fiber optics and optoelectronics. In contrast to conventional electric measuring devices, optical fiber sensors possess considerable immunity to electromagnetic interference and corrosive environmental influences, very small weight and size in aggregate with high sensitivity. Practically these sensors are the only type of sensors, which are able to overcome the seven years survival threshold in field conditions of operation without maintenance with preservation of measuring performance. This fact is very important in multi-year monitoring of physical processes [1,2].

To detect the parameters of seismic processes, one of the most promising are intensity-based optical fiber sensors, since they are characterized by extreme simplicity of design, resistance to thermal shocks, as well as the option to transfer measurement data to a remote terminal directly without additional encoding on high-speed noise-free fiber-optic communication lines or wireless link. Because of the optical fiber in the standard mode of excitation does not have sufficient sensitivity to the parameters of seismic processes, the schemes of fiber-optic sensors with the optical fiber rupture and the light beam blocking at the site of the rupture by the use of moving mechanical elements, whose adjustment is a formidable challenge, are generally used [3,4].

In [5] it was shown that high amplitude sensitivity to weak bending deformation can be achieved with excitation of single-mode optical fibers in the modes with low normalized frequency. This preserves the integrity of the optical fiber that does not involve the use of mechanical choppers. It offers the prospect of using such fibers as sensitive elements of seismic accelerometers.

Therefore, the purpose of this work is to develop the optical fiber accelerometer based on the single-mode optical fiber waveguide with low normalized frequency.

2. Experimental Investigation

In this paper it is assumed that seismic effects are transmitted to the sensitive segment of optical fiber due to the movement of the attached inertial mass of a spring pendulum (Fig. 1). The direction of movement of the mass is chosen in a such way as to maximize the

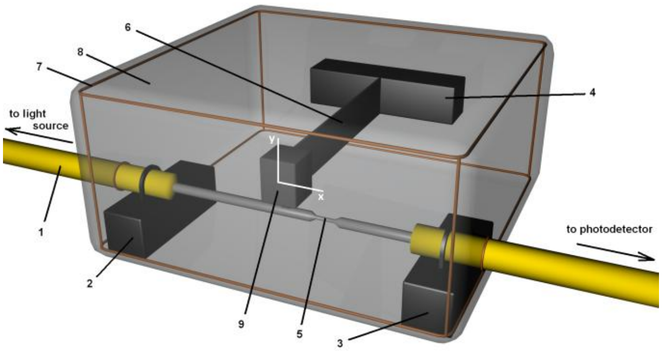


Fig. 1 Experimental setup. 1 - optical fiber. 2,3,4 - still supports. 5 - bottleneck on the area of fiber. 6 - pendulum. 7 - hermetic enclosure. 8 - viscous liquid. 9 - inertial mass.

bending of the sensitive segment of the optical fiber and therefore to maximize an amplitude modulation of a light wave directed to it. The regime with low normalized frequency on the segment of single-mode optical fiber is achieved by building a sensitive bottleneck (Fig3). This is carrying out by calibrated stretching of the section of an optical fiber, heated to the melting temperature (Fig. 2). Normalized frequency decreases in the bottleneck region from 2,4 to 0,6 due to reducing of an optical fibers core radius ($V=(2\pi/\lambda)\rho(n_1^2-n_2^2)^{1/2}$ - normalized frequency, λ – wavelength of guided light, n_1, n_2 – refractive index of the fiber cor e and cladding, respectively, ρ – fiber core radius). According to

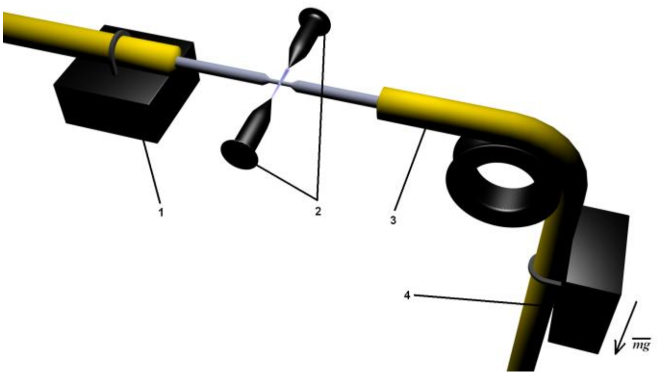


Fig. 2 Scheme of creation of the sensing element. 1 - holder. 2 - electrodes. 3 – optical fiber. 4 – calibrated load.

[5], it provides the increase of the amplitude sensitivity of the optical fiber in the bottleneck region to bending at least 2 orders of magnitude compared to other sections of the fiber. Bending the fiber in the bottleneck can be achieved both in the transverse and the longitudinal displacement of the fiber section. To study the amplitude sensitivity of the sensitive element based on the bottleneck to such displacements we used experimental setup, shown in Figure 1. A superluminescent LED with a central wavelength of 1550 nm was used. A single-mode fiber (1) with a formed sensitive element on it (5) was mounted on two supports (2,3), as shown in Figure 1. Offset of the pendulums inertial mass (6) attached to the bottleneck area of the optical fiber relative to the equilibrium position was carried out along the X and Y axes using a system of linear nanopositioners (not shown in figure). The output signal is received by a photodetector and measured by digital oscilloscope. The obtained dependences of the intensity of output signal from both types of displacement are presented in figure 4. As one can see, both dependences are linear, but slope of the curve is substantially higher in the case of displacement of the optical fiber bottleneck along the X axis. This is so due to the fact that the longitudinal displacement results in a greater deformation of the sensitive element. On this basis, as the elastic element of a pendulum in the accelerometer it seems appropriate to use a flat spring located so as to enable movement of the inertial mass with

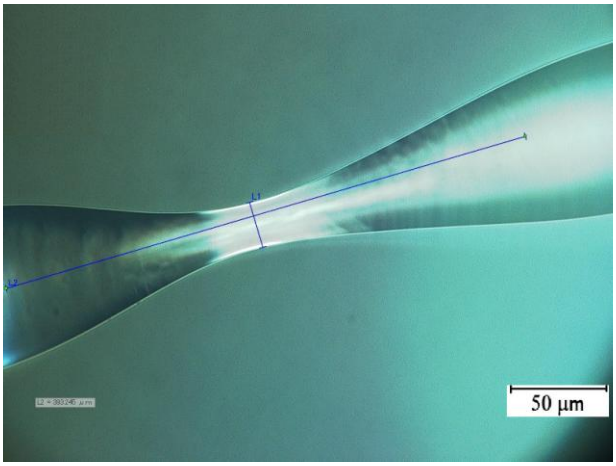


Fig. 3 Photo of the sensitive element of the accelerometer.

attached sensitive element only along the axis X. The threshold sensitivity to the magnitude of such displacement, as shown by the results of measurements reaches 90 nm at the noise level of the measurement system we use 0,2 mV. Shift of the inertial mass in the sensor under seismic influence on the housing is described by the well known expression $x=h(\omega)a_{ext}$, [6,7] where x – the longitudinal displacement of the free end of the pendulum, a_{ext} – acceleration of environment, ω – frequency of the external seismic field, $h(\omega)=((\omega_0^2-\omega^2)^2+\omega^2\gamma^2)^{-1/2}$ - amplitude-frequency

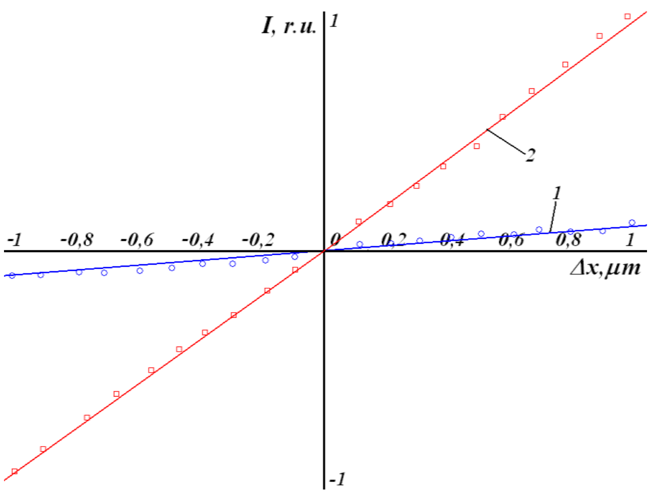


Fig. 4 Static characteristic of the sensitive element of the accelerometer. Curve 1 - the dependence of the light intensity at the output of the sensitive area from the transverse displacement of free end of the pendulum along the axis y. Curve 2 - from the longitudinal displacement of the free end of the pendulum along the axis x.

characteristic of the sensor, in which γ – damping constant, which is determined by the viscosity of the medium filling the sensors housing, $\omega_0 = (k/m_{eff})^{1/2}$ – natural frequency of the pendulum. Figure 5 shows the calculated frequency response of the transmitter for different ratios of γ and ω_0. It is seen that at low frequencies, this characteristic has a linear section, the range of which is determined by the ratio between γ and ω_0.

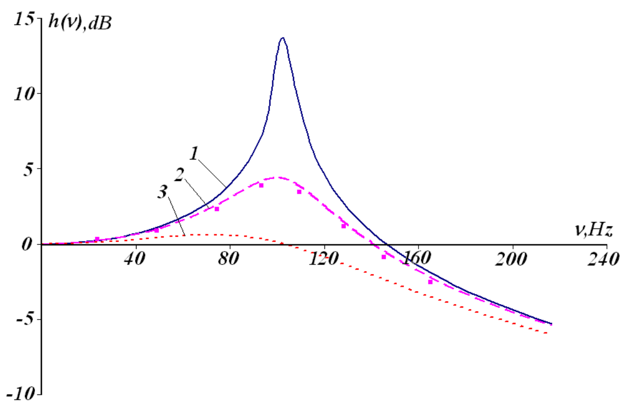


Fig. 5 Amplitude-frequency response of the transmitter. Curves - the result of calculation for the cases with γ = 0,1ω_0 (curve 1), γ = 0,5ω_0 (curve 2), γ=ω_0 (curve 3). Points represent experimental dependence in the case of filling the shell with glycerol (marker ■).

When creating an accelerometer prototype, mass and stiffness of the spring pendulum is chosen so that its frequency of natural oscillations was 95 Hz. In this paper we selected the proper viscosity of the liquid to satisfy condition γ=ω_0 based on the measurement of free vibration decay time of the pendulum. Filling the body of the sensor with the glycerol provided $\gamma \approx 0,5\omega_0$.

Test the durability of prototype showed that mechanical disruption of the fiber in the bottleneck occurs at the shock effects on the body of sensor with peak acceleration about $a_p \approx 6$g. It was also found that multiple (about 100 cycles) short-term shock with peak acceleration of 2g did not affect the integrity of the fiber in the

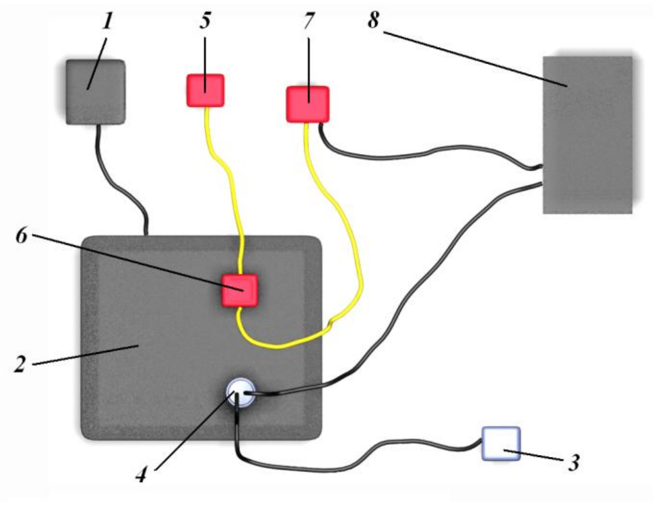
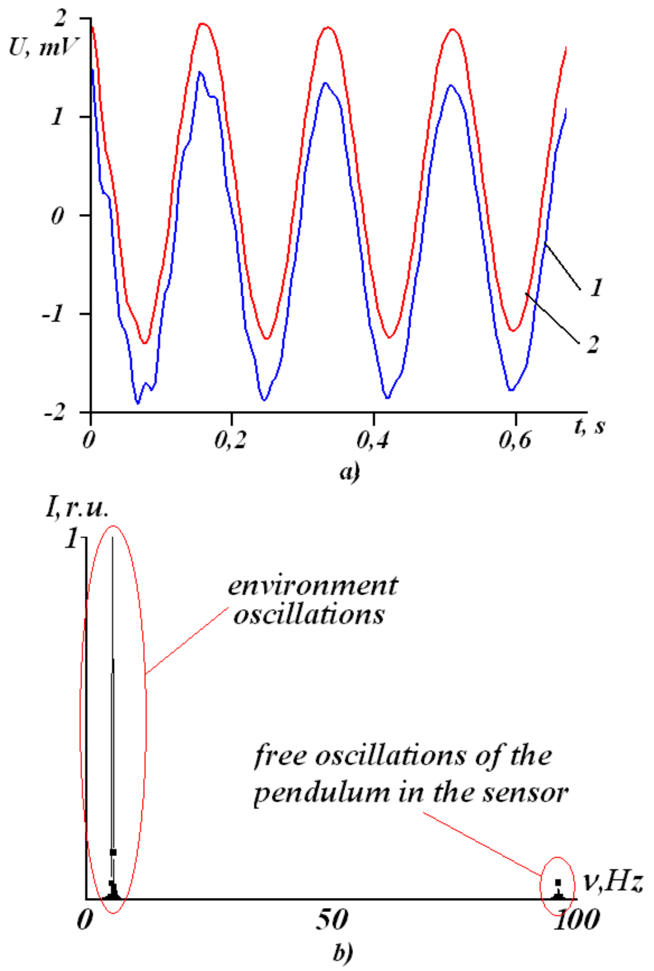


Fig. 6 The experimental setup for the study of amplitude-frequency characteristics of the sensor. 1 - generator of sinusoidal voltage. 2 - calibrated shake table. 3 – power supply. 4 - calibrated seismic sensor. 5 – light source. 6 - fiber-optic accelerometer prototype. 7 - photodetector. 8 - oscilloscope.

prototype and do not lead to a change in metrological characteristics. Experimental studies of the sensor were performed on a calibrated shake table (Fig. 6) to simulate different types of seismic vibrations. Figure 7,a shows the result of registration harmonic sinusoidal oscillations of vibrostand by the designed fiber-optic accelerometer prototype (curve 1). For comparison, Fig. 7,a shows the signal of the calibrated seismic sensor (curve 2). It is seen that the seismic signal



perceived by our prototype is partially distorted over the time of decay of the pendulums natural oscillations, which is also illustrated in Fig. 6,b. It is obvious that to eliminate these distortions

Fig. 7 a) Result of registration harmonic sinusoidal oscillations of vibrostand by the designed fiber-optic accelerometer prototype (curve 1) and by the calibrated seismic sensor (curve 2) b) Spectrum of sinusoidal oscillations registered by prototype.

requires the use of damping liquid, which provides the condition γ=ω_0.

The results of measurements of amplitude-frequency characteristics of the prototype are shown in Fig. 5. It is seen that they correspond to the calculated dependence for the accelerometers chosen value of γ. We reached the threshold sensitivity of the prototype to acceleration the $6 \cdot 10^{-5}$g on a linear plot of amplitude-frequency characteristic in the frequency range 2 ÷ 50 Hz, the dynamic range of at least 50 dB, the drift of the output signal is not more than 0,1%/day, temperature drift - not more than 0,2%/℃.

3. Conclusions

In conclusion, optical fiber accelerometer based on the single-mode optical fiber waveguide with low normalized frequency was developed. It was shown that the sensitivity of such fibers to seismic impacts can reach $6*10^{-5}$g. This enables the development of fiber optic accelerometers on their basis with the following specifications: linear amplitude-frequency characteristic in the range 2 ÷ 50 Hz, dynamic range 50 dB. Temperature dependent drift of the output signal 0,2%/℃, long term stability 0,1%/24h. Obtained sensitivity of the developed fiber-optic accelerometer prototype is comparable to the sensitivity of commercially available at present electric accelerometers with the same frequency range, but they significantly inferior to them in the the dynamic range of measurements. However, it should be borne in mind that unlike conventional electrical sensors, the proposed prototype, as well as fiber-optic communication lines used to transmit the data to remote data-processing devices, is insensitive to electromagnetic interference.

This makes it perspective technology to create noise-immune acceleration sensors for a wide range of problems in geophysics, seismology, and monitoring of seismic processes and fields in objects that represent an increased potential risk to the human community and the environment.

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