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Fiber-optic interferometric accelerometer of horizontal type for seismoacoustic monitoring

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The possibility of constructing a horizontal type fiber-optic accelerometer based on a multi-turn sensing element, an optical scheme of the Mach–Zender interferometer and passive phase demodulation is shown. Laboratory tests of the accelerometer prototype were carried out. The sensitivity of the presented fiber-optic accelerometer is 1770 rad/g.

Keywords: accelerometer, interferometer, optical fiber.

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The problem of construction of seismoacoustic monitoring systems for natural and man-made facilities is of great relevance to geophysical, health and safety, environmental management, and various other applications. Seismic acceleration is considered to be the most informative parameter [1], since it is directly proportional to the intensity of a seismic event source. Inertial accelerometers with the amplitude of vibrations of an inertial mass at low frequencies being directly proportional to the amplitude of seismic acceleration are typically used to detect this acceleration. The requirements as to the threshold sensitivity of inertial accelerometers are rather strict. Specifically, a threshold sensitivity on the order of $10^{-8}g$, which corresponds to inertial mass displacements on the order of 10^{-12} m [2], is required from accelerometers targeted at the detection of weak low-frequency seismic signals. If the designed seismoacoustic measurement instrument is to be made portable, only fiber-optic interferometers provide the indicated sensitivity levels [3].

Various designs of sensing elements (SEs) are used in fiber-optic interferometric accelerometers. Multi-turn SEs, which provide a threshold sensitivity on the order of $10^{-8}g$ [4,5], stand out from the competing types of elements. However, active phase demodulation methods applied in them have a negative effect on the resistance to interference and limit the dynamic range, while passive methods have no such drawbacks.

In the present study, a novel design of a horizontal-type fiber-optic interferometric accelerometer with a multi-turn SE and passive phase demodulation based on a 3×3 coupler [6] is reported.

Figure 1 shows the diagram of the accelerometer. Emission of a semiconductor DFB laser is fed along a single-mode fiber guide (FG) to a fiber-optic Mach–Zender interferometer formed by a Y-coupler, a reference arm FG, a measurement arm FG, and a 3×3 coupler. A NOLATECH DFB-1550-AX InGaAsP distributed-feedback laser with a wavelength of 1549.94 nm, a spectral line width of 5 MHz, and an optical power up to 1 mW is used in the accelerometer. The FG of the measurement arm of the interferometer is wound round cylinders of moving and stationary parts of a mechanical linear translator of the multi-turn SE. The translator features a spring and ball bearings. A single-mode ITU-T 657. A fiber guide 80 cm in length with reduced bending losses is used in the sensing element. The length difference between the interferometer arms is 5 mm.

The moving part (inertial mass) is at equilibrium under the influence of elastic forces from the spring of the mechanical linear translator and the measurement arm guide. If the accelerometer body vibrates with vibratory acceleration amplitude a_0, the inertial mass undergoes induced vibrations. These lead to fluctuations of the length of straight sections of the measurement arm guide and, consequently, to oscillations of the phase difference between optical waves propagating in the interferometer arms with amplitude φ_0. Three optical signals shifted by $2\pi/3$ in phase relative to each other form at the 3×3 coupler outputs as a result of interference of these waves. These signals are detected by a unit of three photodetectors (NOLATECH FDM-14-2K photodiode modules with an operating wavelength of 1100–1600 nm and a sensitivity of 0.9 A/W). Electrical signals formed by them are fed via a Zetlab ZET230 (24 bits, 25 kHz per channel) four-channel analog-to-digital converter (ADC) to a personal computer and processed there in accordance with the procedure outlined in [6]. The variation of the phase difference of optical waves propagating in the interferometer arms is reconstructed as a result.

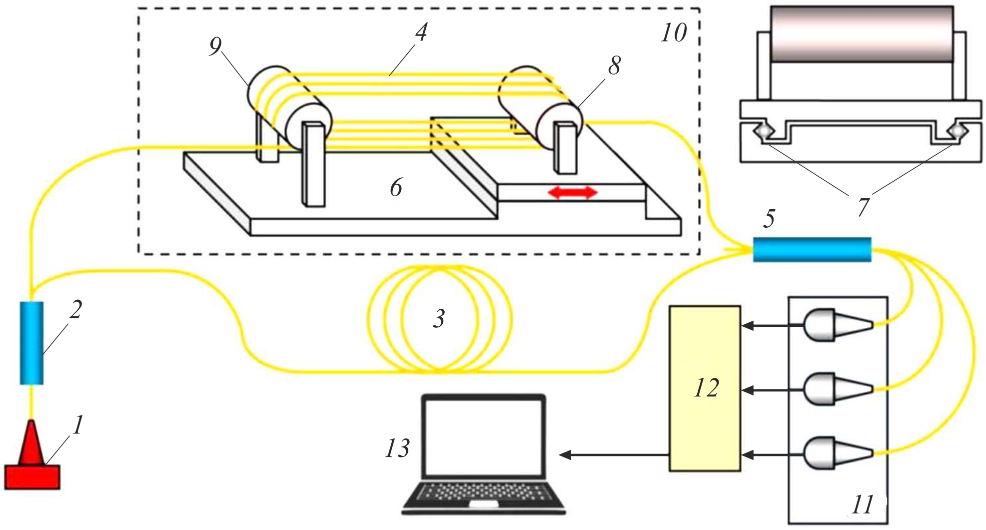

Figure 1. Diagram of the horizontal-type fiber-optic interferometric accelerometer. *1* — DFB laser, *2* — *Y*-coupler, *3* — FG of the reference arm of the interferometer, *4* — FG of the measurement arm of the interferometer, *5* — 3 × 3 coupler, *6* — mechanical linear translator with a spring and ball bearings, *7* — ball bearings, *8* — cylinder of the moving translator part, *9* — cylinder of the stationary translator part, *10* — multi-turn SE, *11* — photodetector unit, *12* — ADC, and *13* — notebook.

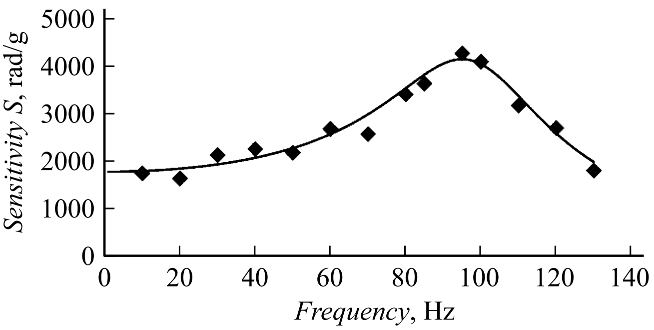

Figure 2. Amplitude-frequency response of the fiber-optic accelerometer.

The sensitivity of the accelerometer to vibrational acceleration is written as [2]

$$S=\varphi_0/a_0=(Nn/\pi f_0^2\lambda)/\sqrt{\left(1-(f/f_0)^2\right)+\left(2\varepsilon(f/f_0)\right)^2}, \tag{1}$$

where λ is the optical radiation wavelength, n is the refraction index of the fiber core, ε is the friction coefficient, N is the number of straight sections of the fiber guide of the multi-turn SE with their length varying in the course of acceleration measurements, f is the vibration frequency, and f_0 is the natural frequency of the vibration system, which is given by

$$f_0=\sqrt{Nk_c/4\pi^2m}, \tag{2}$$

where k_c is the elastic coefficient of one section of the fiber guide and m is the inertial mass.

Figure 2 presents the amplitude-frequency response of the horizontal-type fiber-optic interferometric accelerometer calculated using formula (1). The following accelerometer parameters were used in calculations: $n = 1.47$, $\lambda = 1.55\,\mu$m, $m = 0.31$ kg, $N = 6$, $k_c = 20$ kN/m, and $\varepsilon = 0.22$. Symbols denote the experimental data obtained under excitation of horizontal vibrations with an amplitude of $5\cdot 10^{-4}g$ by a VSV-133 electrodynamic vibration shaker. The shaker parameters are as follows: the frequency range is 10–1000 Hz, the nominal load in a horizontal position is 2.5 kg, and the nonlinear distortion factor does not exceed 3%. It can be seen from Fig. 2 that the sensitivity of the fiber-optic accelerometer to vibrational acceleration within the horizontal section of the amplitude-frequency response (low-frequency region) is 1770 rad/g.

The results of experimental examination of the test accelerometer model revealed that the sensitivity to transverse vibrations did not exceed 9%.

Figure 3 shows the spectra of output signals of the fiber-optic accelerometer and a BC1313 piezoelectric accelerometer measured in the course of detection of vibrational acceleration with an amplitude of $1.6\cdot 10^{-7}g$ and a frequency of 55 Hz. It can be seen that the intrinsic noise level of the fiber-optic accelerometer is lower than the one of the piezoelectric accelerometer and provides an opportunity to detect accelerations down to $5\cdot 10^{-8}g$.

Thus, the design concept of a high-sensitivity horizontal-type fiber-optic accelerometer utilizing a multi-turn sensing element, a Mach–Zender interferometer arrangement, and passive phase demodulation was demonstrated. The obtained results open up new opportunities for production of high-sensitivity seismoacoustic monitoring systems resistant to interference.

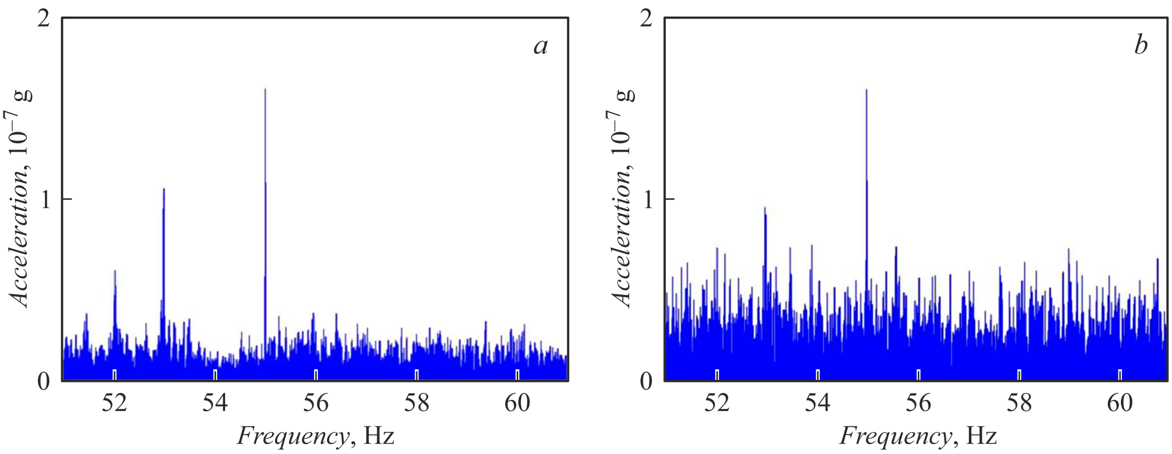

Figure 3. Spectrum of the output signal of the fiber-optic accelerometer (*a*) and a BC1313 piezoelectric accelerometer (*b*).

Conflict of interest

The authors declare that they have no conflict of interest.

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