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An adaptive fibre-optic interferometer with low cutoff frequency

Oleg T. Kamenev [a, b], Vladislav A. Kolchinskiy [a, *], Yuri S. Petrov [a], Roman V. Romashko [a, b], Yuri N. Kulchin [a, b], Leonid P. Yatsenko [c], Vladimir M. Khodakovskyy [c]

[a] Department of Optoelectronics, Institute of Automation and Control Processes FEB RAS, Russia
[b] School of Natural Sciences, Far-Eastern Federal University, Vladivostok, Russia
[c] Institute of Physics of National Academy of Sciences of Ukraine, Kiev, Ukraine

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ABSTRACT

An adaptive fibre-optic interferomety system based on a dynamic hologram recorded in a bismuth titanium oxide crystal is developed and studied. The system possesses a low cutoff frequency (4 mHz), making possible the adaptive detection of ultra-slow physical signals with an amplitude equivalent to fibre elongation of 5 nm.

Introduction

The solution of a wide range of tasks related to the registration of ultra-weak seismoacoustic signals requires the further improvement of the sensitivity and noise immunity of geophones. The application of interferometric methods to measure deformations arising in the propagation of seismoacoustic waves combined with a fibre-optic element base will allow the indicated problem to be solved.

At the same time, the high sensitivity of fibre-optic interferometers, in particular, two-arm interferometers, makes them highly exposed to the influence of environmental conditions (drift of temperature and pressure).

To provide the maximal sensitivity of a two-arm interferometer (e.g., Mach–Zehnder interferometer), it is necessary to execute the so-called condition of balance of phases, which maintains the phases between the interfering beams at a difference of $\pi/2$. The interferometer's operation point is in the middle of the linear area of the transfer characteristic. However, the out-of-control changes of the terms of the environment result in the fading of the interferometer's operation point.

The sensitivity of the geophone at the displacement in the area of the maximum or minimum of the transmission description on the basis of the fibre-optic interferometer decreases to near zero. To solve this problem, a number of operation point stabilization methods of two-arm fibre-optic interferometers, which actually represent methods of the phase demodulation of the output signal of the interferometer, were worked out [1].

The two most widely used basic methods of demodulation are the method of active homodyne detection, which uses feedback for stabilizing the interferometer [2], and the method of passive homodyne detection, whereby a few output signals are formed in the interferometer. The combined processing eliminates the hit of the operating point to the zero response [3] and the hit of the operation point in the area of zero sensitivity, which are both formed in an interferometer [3]. However, the indicated methods of homodyne detection have a number of disadvantages.

Active homodyne demodulation is used mainly in the laboratory, as it has a limited dynamic range of feedback and is complexly realizable in multichannel measuring systems.

Passive demodulation methods are difficult to implement and often do not provide linearity of the measurement system transfer. Other methods associated with heterodyne demodulation are extremely difficult to implement [4]. In addition, most existing methods of demodulation associated with the use of electro-optic modulators negate the optical element base's immunity to electromagnetic noise.

Demodulation of the phase-modulated signal in the interferometer should be carried out in a simple, natural way, and it is necessary to satisfy the condition of phase balance, as well as ensure the adaptation to a slow change in the phase of the signal fading caused by the operating point. For this purpose, it is expedient to use the phase demodulation dynamic hologram formed in

* Corresponding author.
E-mail addresses: okamenev@dvo.ru (O.T. Kamenev), vladko.88@mail.ru (V.A. Kolchinskiy), romashko@iacp.dvo.ru (R.V. Romashko), director@iacp.dvo.ru (Y.N. Kulchin), khodak@iop.kiev.ua (V.M. Khodakovskyy).

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a photorefractive crystal (PRC), which imparts the property of adaptability to the interferometer [5].

The difference between an adaptive interferometer and a classical interferometer is that phase demodulation is accomplished by the interaction of the wave signal with a dynamic hologram formed by the interference of the signal and the reference waves in the PRC. If the phase of the signal wave is changed “quickly”, that is, less time during recording, the hologram has no time to be overwritten.

As a result, phase demodulation occurs. If the phase changes “slowly”, that is, longer than the recording time, the new crystal can be written by the hologram, and phase demodulation does not occur. This is the general principle of the adaptability of the measuring system based on the use of dynamic holograms. Thus, the dynamic hologram is a type of low-pass filter that compensates for the effects on the interferometer due to any slowly varying external influences. Under this condition, the phase balance is performed automatically.

To date, peculiarities of adaptive dynamic holograms in photorefractive crystals CdTe with a short recording time in the collinear and orthogonal geometry to create a high-speed optical signal processing systems have been sufficiently studied in detail [5,6]. However, for the construction of adaptive geophones, such crystals are not suitable because they will adapt not only with temperature fluctuations but also under low-frequency (0.01 … 1 Hz) seismic signals. To solve this problem, using PRC $Bi_{12}TiO_{20}$ (BTO), which, as CdTe, refers to crystals with cubic symmetry, is proposed, but this approach takes a long time to record the hologram. Further increasing the recording time is possible by reducing the radiation power of the interacting waves to values of the order of a few milliwatts or less, which is made possible by the higher diffraction efficiency of holograms formed in BTO. The aim of this work is to study the possibility of using photorefractive crystals BTO for building adaptive geophones.

Most promising is the use of the orthogonal geometry of the interaction of beams in a photorefractive crystal, which allows one to implement polarization-independent adaptive demodulation of the optical signal in the interferometer [6]. This is because the dynamic hologram that is formed in an orthogonal geometry has polarization selectivity, making it possible to use as the object wave completely depolarizes radiation and, consequently, eliminates the need for polarization filtering. In particular, it is possible to use a multimode optical fibre in the measuring arm of the interferometer, which allows for a larger amount of power in the measuring channel to increase the sensitivity of the measuring system and completely eliminates the problem of polarization noise.

Architecture of the measurement system

The experimental setup shown in Fig. 1 was created for the experimental verification of the possibility of applying the method of the adaptive demodulation of the optical radiation to stabilize the parameters of the fibre optic geophone.

The modified scheme of the fibre optic Mach–Zehnder interferometer is implemented in the experimental setup, where the output coupler is replaced by a photorefractive crystal, $Bi_{12}TiO_{20}$, which, as mentioned above, is characterized by a long recording time of the lattice, which allows for the demodulation of the phase changes caused by slow processes, such as seismic signals. In the BTO crystal, a two-wave interaction is carried out of the signal wave that is generated in the measuring arm of the interferometer and a reference wave that is generated in the reference arm of the interferometer in an orthogonal geometry.

The radiation of the He–Ne laser (1) through the polarizer (2) is directed to the micropositioner (3), where the radiation is input onto the optical fibre; the optical fibre is divided in a Y-coupler into two arms of the interferometer, the measuring and reference arms. The measuring arm is wound in the piezoceramic modulator (5), which is controlled by the generator (6). The modulator is designed to generate a phase modulation signal in the interferometer. Further, the signal beam passing through the spherical lens (8) and the polarizer (9) is directed to the PRC (12). The reference beam passing through the polarizer (2) and the half-wave plate (10) through the cylindrical lens (11) is directed to the PRC at 90° to the signal beam. Radiation transmitted through the PRC in the direction of the signal beam is modulated in intensity in accordance with the phase modulation of the signal wave that is registered by the photo detector (13). The selective voltmeter (14) registers the amount of signal demodulation.

As a result, the phase demodulation signal, which is defined as the ratio of the amplitude of the modulation signal to the constant component, is formed at the output of the photo detector. The phase demodulation signal corresponds to the signal of the phase modulation that is formed by the modulator (Fig. 2).

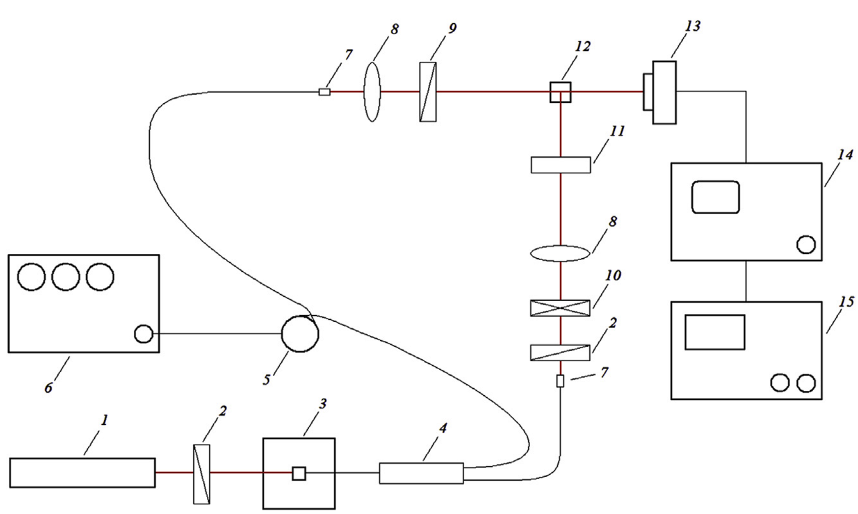

Fig. 1. Experimental setup: 1 – He–Ne laser, 2 – polarizer, 3 – an input device of the optical radiation into the optical fibre, 4 – Y-splitter, 5 – piezoceramic modulator, 6 – a frequency generator, 7 – optical collimator, 8 – spherical lens, 9 – optical filter, 10 – half-wave plate, 11 – cylindrical lens, 12 – photorefractive crystal, 13 – photo detector 14 – selective voltmeter, and 15 – an oscilloscope.