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A method for detecting small oscillations based on homodyne demodulation with a tandem low-coherence interferometer

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The paper proposes a method for detecting small oscillations in the length of interference fiber-optic sensors, which makes it possible to compensate for the problem of slow drift of the working point with a remote sensor. The result is achieved by combining homodyne demodulation methods with a tandem low-coherence interferometer. Theoretically and experimentally, the possibility of detecting acoustic effects in the operating frequency band of 4 kHz with a sensitivity of up to 0.3 nm has been shown.

Keywords: Homodyne demodulation, tandem low-coherence interferometry, Michelson interferometer, fiber-optic sensors.

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Introduction

Fiber-optic sensors are becoming increasingly common nowadays in various monitoring tasks. Interference sensors have become quite widespread, in which an external impact leads to a change in the optical difference in the travel of interfering waves [1–4]. Accordingly, the issue of developing systems for detecting signals from such sensors with high sensitivity and stability is very relevant.

One of the widely used methods of recording signals from interference sensors is the processing of the spectrum of the reflected or transmitted signal [5–7], in which the shift of minima and maxima in the reflection spectrum is monitored. Despite the relative simplicity of implementation, it is difficult to multiplex sensors in this scheme, and there are also restrictions on the recorded frequencies.

Interference schemes are usually used to register high-frequency processes [8–10]. In the simplest case, with coherent illumination, a change in the length of the resonator leads to a change in the light intensity at the output of the device, which can be recorded with sufficiently high accuracy. The main problem of this approach is the adjustment of the operating point of the sensor interferometer to the position of maximum sensitivity and its retention in this state, which is complicated by random drift of the optical length of the resonator caused by parasitic deformations and temperature changes. There are various methods to combat this effect: laser wavelength tuning [11], homodyne demodulation methods [12–14] and various methods of low-coherence interferometry [15–19]. Currently, homodyne demodulation methods based on the introduction of additional modulation into the sensing element are well developed for coherent detection schemes. However, the need to modulate the sensor part leads to complexity in multiplexing sensors, as well as to the complexity of creating remote sensors. This paper proposes a method for detecting small optical delay oscillations in interference fiber-optic sensors, combining a homodyne demodulation algorithm and low-coherence interferometry, which allowed decoupling the sensor zone and the modulation zone, which, in turn, removed the restriction on the distance to the sensor from the source and the detection system.

1. Description of the scheme

Consider two series-connected interferometers (Fig. 1). Let both interferometers be a Michelson fiber interferometer, where a fiber splitter (FC) plays the role of a splitter, and the optical fiber in each arm is wound with some tension on a piezoceramic cylinder (PT). This allows changing the difference in the lengths of the arms by applying voltage to the cylinder, at which there is an increase or decrease in its diameter, which, in turn, leads to a change in the length of the wound fiber. An optical insulator was installed between the interferometers, which made it possible to exclude multiple interference of reflected waves. The Int1 interferometer acted as a reference, and the Int2 interferometer acted as a sensor. Obviously, a real sensor can have any other design, which is an interferometer, in particular Fabry–Perot intrafiber resonator or an optomicromechanical system [20], but within the framework of this work, the task was to test the method, which required the possibility of controlled exposure to a sensor with pre-known parameters. The proposed variant made it possible to set the oscillation of the difference in the arm lengths of the sensor interferometer with the required amplitude in a wide frequency range.

The scheme works as follows. First, light from a broadband source (superluminescent diode, $\lambda = 1310$ nm,

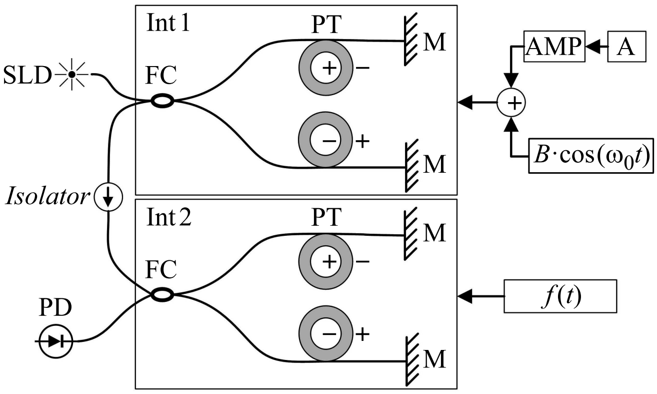

Figure 1. The scheme of the tandem interferometer (TI) assembled in the experiment. Notations: Int1 and Int2 — reference and sensor interferometer, respectively, SLD — superluminescent diode, FC — fiber optic splitter 2×2, PT — piezoceramic coils, M — Faraday mirror, Isolator — fiber-optic insulator, PD — photodetector, A — digital-to-analog converter, AMP — high-voltage amplifier, $B \cdot \cos(\omega_0 t)$ — reference modulation, $f(t)$ — measurable impact.

$\Delta\lambda = 40$ nm, $P = 1$mW) of optical radiation passes through the divider FC and enters the reference interferometer isolated from external influences, where high-frequency (relative to the measured effect) modulation of the difference in arm lengths, i.e. the delay between interfering waves. Then, through an optical insulator and a second divider, FC enters the sensor interferometer. The sensor interferometer is affected by some $f(t)$. This effect can be exerted both by applying voltage to the interferometer coils (for calibration of the circuit and testing of signal processing algorithms), and due to external influences in the form of a click, clap, etc. Then the signal reaches the photodetector and is entered into the computer using the ADC board, where it is subsequently processed.

It is known that when using a broadband source, interference is observed only if the difference in the optical paths of the interfering waves is less than the coherence length [15–19]. Accordingly, the signal on the photodetector when the condition

$$\Delta = |\Delta_1 - \Delta_2| < L_{coh},$$

is met,where $\Delta_{1,2}$ is the differences in optical paths in Int1 and Int2 interferometers, $L_{coh} = c/\Delta\omega$ is the coherence length, c is the speed of light in vacuum, $\Delta\omega$ is the width of the source spectrum, will have the form

$$I(\Delta) = a + b \cdot \gamma(\Delta)\cos(k\Delta),$$

where a, b is constants determined by the reflectances of mirrors, parameters splitters and losses in the circuit and determining the interference contrast, $k = 2\pi/\lambda$ is modulus of the wave vector, λ is the central wavelength of the source, $\gamma(\Delta)$ is the coherence function of the source. The form $\gamma(\Delta)$ is determined by the source spectrum, for a source with a Gaussian power spectral density distribution it has the form

$$\gamma(\Delta) = \exp\left(-\frac{\Delta^2}{2L_{coh}^2}\right)$$

Let some sinusoidal voltage be applied to the reference interferometer, leading to modulation of the optical difference of the arm lengths according to the law:

$$\Delta_1 = B\cos(\omega_0 t) + \Delta_{10},$$

where B is some modulation amplitude, ω_0 is the reference frequency, Δ_{10} is a constant difference in arm lengths, which can be controlled by applying an electric voltage to the coils of the interferometer. Suppose that some impact is exercised on the sensor interferometer, in which the difference in arm lengths changes according to the law

$$\Delta_2 = f(t) + \Delta_{20},$$

where $f(t)$ is the desired effect, Δ_{20} is the difference in shoulder lengths, slowly (compared to characteristic times of the measured processes) changing randomly over time as a result of temperature and deformation drifts. If, by adjusting the reference interferometer, the condition

$$|\Delta| = |\Delta_1 - \Delta_2| < L_{coh},$$

is met, then after processing the received signal using the standard homodyne demodulation algorithm with cross-multiplication [13], we get the output signal

$$S_{out}(t) = KJ_1(B)J_2(B)f(t)\gamma^2(\Delta(t)), \qquad (1)$$

where K — multiplier describing the total transmission coefficient of the system, $J_{1,2}$ — Bessel functions of the first and second kind.

It can be seen from (1) that the dependence of contrast on the average Δ can introduce quite strong distortions, nevertheless, for oscillations comparable and smaller than the wavelength, when the condition

$$|\Delta| = |\Delta_1 - \Delta_2| \ll L_{coh}$$

is met, these distortions turn out to be quite small. In this case, the reference modulation is carried out in the reference interferometer, and the sensor interferometer can be carried to almost any distance, limited only by losses in the optical fiber.

2. Simulation and experiment

Unlike the coherent scheme, where the contrast of the interference signal remains constant regardless of the difference in the optical paths of the interfering waves, in the tandem low-coherence scheme, the visibility of the interference fringes decreases when the interferometer mismatch. The condition of constancy of the amplitude of the interference signal is well fulfilled only near the zero stroke difference, i.e. in the region of maximum visibility of the interference pattern. Therefore, in mathematical modeling, two cases were considered corresponding to the exact adjustment of the wave delay in the reference interferometer to the sensor interferometer ($\Delta = 0$) and the adjustment with an offset of 4 interference bands. Figure 2 shows the simulation results. The registration system has a smooth amplitude-frequency response up to a certain frequency, which depends on the depth of modulation of the sensor interferometer, which is due to the overlap of the spectrum components 1 and 2 harmonics. The displacement of the working point from the optimal position does not lead to distortion of the frequency response, only reduces the amplitude of the output signal, since the cross-multiplication algorithm is sensitive to changes in the amount of light and the visibility of interference fringes.

A measuring unit was assembled in accordance with the scheme shown in Fig. 1 for experimental testing of the proposed method. The fine-tuning of the reference interferometer to the sensor was performed by applying high voltage to piezoceramic coils. To do this, the fine-tuning control signal was amplified by a high-voltage AMP amplifier. A low-voltage high-frequency modulation signal at the frequency $\omega_0 = 20$ kHz was mixed with high voltage.

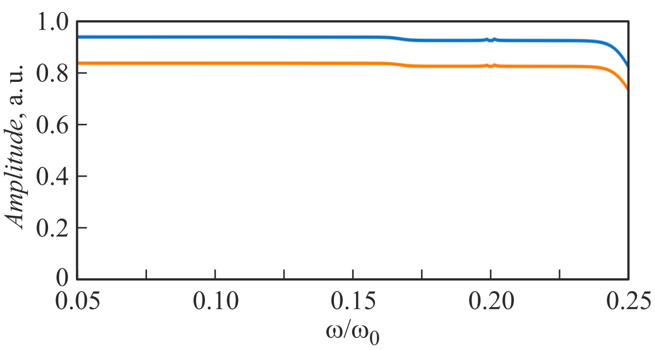

Figure 2. The calculated amplitude of the output signal of the proposed scheme at a constant input for precise adjustment of interferometers (blue curve (in the online version)) and for the case of a 4-band shift of the interference pattern (orange curve (in the online version)).

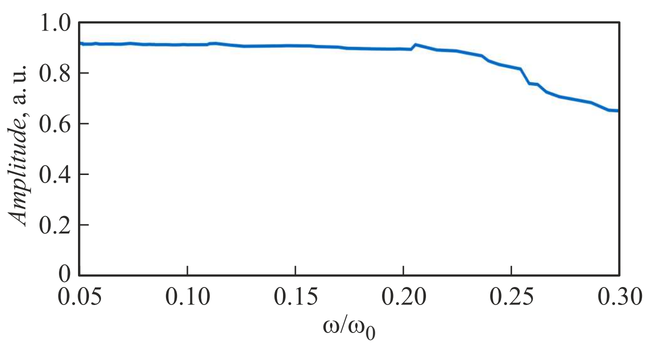

Figure 3. Experimentally measured amplitude of the output signal of the proposed circuit at a constant input.

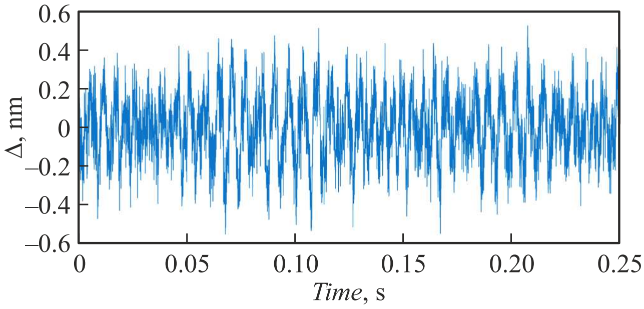

Figure 4. The noise track of the registration system, converted into nanometers.

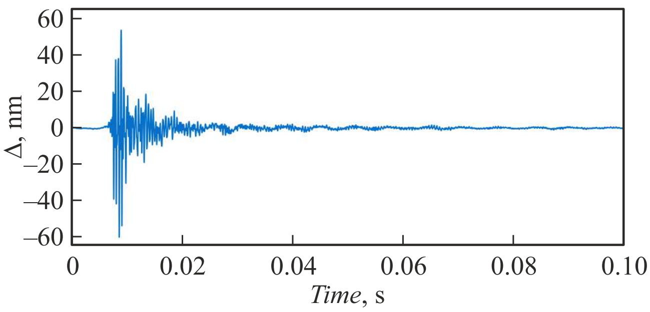

Figure 5. A finger-click signal next to the sensor interferometer.

The voltage amplitude was selected to ensure the optimal depth of phase modulation and amounted to units of volts.

Test signals were applied to the sensor interferometer, which were a sinusoidal signal with an amplitude of 0.1 V (modulation depth 92 nm), and a frequency of ω from 1 to 8 kHz, the sampling frequency of the ADC was 700 kHz.

The results are shown in Fig. 3. There is a qualitative coincidence with the simulation results.

Figure 4 shows the noise track recorded by the measuring circuit in the absence of external impact. It can be seen that it contains low-frequency components with peak amplitude values up to 0.5nm associated with the effect of external noise on interferometers. The noise floor minus low-frequency noise is 0.3 nm from peak to peak.

Acoustic impact measurements were also carried out to demonstrate the operation of the recording system. The same Michelson fiber interferometer was used as a sensor interferometer, but no voltage was applied to the piezoceramic coils. Figure 5 shows a record of a finger click at a distance of 10 cm from the interferometer.

Conclusion

This paper proposes a method that combines the advantages of homodyne demodulation algorithms (insensitivity to the drift of the interferometer operating point) and tandem low-coherence interferometry (the possibility of placing a sensitive interferometer at a great distance from the source and the registration system). The sensitivity was obtained at the level of 0.3−0.5 nm in the 4 kHz band. The possibility of using the proposed scheme for recording acoustic signals was demonstrated. The proposed scheme has good potential for development of systems for recording signals from interference fiber-optic sensors.

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Conflict of interest

The authors declare that they have no conflict of interest.

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