Vol. 34, No. 04, pp. 1461-1476/Septiembre 2021

ISSN-E 1995-9516
Universidad Nacional de Ingeniería

http://revistas.uni.edu.ni/index.php/Nexo
https://doi.org/10.5377/nexo.v34i04.12692

Developing and exploring the characteristics of optical-fibre vibration sensor

Desarrollo y estudio de características de sondas de vibraciones de fibra óptica

Vladimir S. Soloviev*, Sergey P. Timoshenkov, Andrey S. Timoshenkov

National Research University of Electronic Technology,Moscow, Russian Federation

*solov_06_v@mail.ru

(recibido/received: 26-mayo-2021; aceptado/accepted:05-agosto-2021)

ABSTRACT

Integration of optics into microelectronics is extremely attractive in terms of further microminiaturisation and information transmission rate. Hence, the article aims at opening up and studying all the opportunities that can be taken from a simple optical sensor that is based on reflection of light from an oscillating surface.To measure vibrations, a principle of determining the amplitude of a diverging cone of light has been employed depending on the distance to an oscillating surface. The most common optical fibre with the numerical aperture of 0.12 was used in the experiments. The wavelength of laser utilised in the sensor is 1310nm. A laser with 640nm wavelength was used in the control stand measurement path. The conducted studies resulted in creating a simple vibration sensor on the basis of optical fibre with the use of laser, photo-diode, and splitter. It has been experimentally shown that the amplitude of the reflected light changes exponentially depending on the distance to the oscillating surface. The accuracy of interferometric measurements was 22nm. The coherence length of lasers used in the interferometer amounted to 2mm, what well sufficed to obtain a contrast interference pattern. Vibrations of various surfaces from 500µm to 22nm were measured. A major plus of the sensor is its maximum ease and a rather high accuracy of measurements. Measured frequency of vibrations is limited only to the transfer characteristic of an electronic part of the sensor. The article materials are of practical value for using their principles in micro-accelerometers, angular velocity sensors, and many other sensors of physical values.

Key words: Optical fibre; Optical-fibre sensor, Sensor of physical values, Semiconductor laser, Vibration sensor.

RESUMEN

La integración de dispositivos ópticos en microelectrónica es muy atractiva para desarrollar subminiaturización continua y aumentar la velocidad de transmisión de datos. Por lo tanto aquí se tiene por objetivo presentar y explorar todas las oportunidades del uso de una sonda óptica simple basado en la reflexión de la luz de una superficie vibradora.Se miden las vibraciones por medir la amplituda de un cono de luz radiante en función de la distancia hasta la superficie vibradora. Se llevaron a cabo las pruebas usando la fibra óptica más popular con una apertura numérica de 0.12. La longitud de la onda láser en la sonda fue 1 310 nm. El láser usado en el canal de medida del banco de control tenía una onda de 640 nm. El resultado de las pruebas fue la construcción de una sonda de vibraciones simple basado en fibra óptica mediante el uso del láser, optodiodo y esplitter. Se mostró por experimentación que la amplitud de la luz reflejada cambiaba según la ley exponencial en función de la distancia hasta la superficie vibradora. La exactitud de las mediciones por el interferómetro fue 22 nm. El largo de coherencia de los láseres usados en este dispositivo fue 2 mm. Ese largo bien bastaba para derivar un patrón de franjas de contraste. Se midieron las vibraciones de varias superficies de 500 μm a 22 nm. Una ventaja de la sonda es su simplicidad máxima y una exactitud de mediciones bastante alta. La frecuencia medida de vibraciones se limita sólo a la característica transmisora de la parte electrónica de la sonda. Los materiales aquí presentados son de valor práctica para usar sus principios en medidores micro de acceleraciones, sondas de velocidad angular y muchas otras sondas de cantidades físicas.

Palabras claves: Láser semiconductor; Fibra óptica, Sonda de fibra óptica; Sonda de valores físicos; Sonda de vibraciones.

1. INTRODUCTION

An important advantage of optical-fibre sensors lies in their ability to measure, being immune to a wide range of physical fields. It means not only that no power supply in needed for a sensor head operation, but that the entire system, including input and output fibres, acting as telemetry communication channels, is also electrically passive and, hence, the whole system is characterised by low sensitivity to the effects of electromagnetic interferences (EMI) and electromagnetic pulses (EMP). Electric insensitivity and low susceptibility to EMI/EMP have acquired primary importance when a sensor needs to be used in a potentially explosive or electrically noisy environment. Since common input and output communication fibres can be employed to service many fibre sensors, a purely fibre network of sensors can be built with additional to the above-described advantages. First, telemetry systems based on fibre optics, are capable of transmitting output information from plenty of sensors, not requiring very high transmission capacity. E.g., for 1000 sensors with the 100кHz bandwidth required for each, merely about 100MHz transmission bandwidth is needed, which is relatively narrow as compared to the bandwidth, required for the systems offered and demonstrated in the area of fibre-optical communications systems, that transfer huge volumes of data. Second, a single fibre or a pair of fibres, servicing numerous sensors, afford an opportunity to decrease weight and ensure low cost of telemetric communications between an electric-optical processing module and a network or matrix of sensors. It is advantageous in those applications, where a decrease in weight plays an important role in designing, e.g., in aerospace industry. Third, fibre-optical communication lines allow for the extreme flexibility when configuring telemetry systems and the topology of systems.

In a general way, various methods can be used to design multi-sensor systems. The first one implies that numerous discrete sensors, developed to operate as point sensors, are combined into a network or an array; outputs of individual sensors therewith are multiplexed in the fibre system, employing the methods, widely applied in such high-frequency/microwave systems, as frequency division multiplexing (FDM) or time-division multiplexing (TDM), or using more special-purpose schemes, designed for multiplexing in optical communication systems and wavelength division multiplexing (WDM).

Employing distributed sensors with optical fibre as a sensing element is particularly attractive in those applications, where the only measured value needs to be monitored at numerous points or continuously throughout the entire fibre length. The following areas can be the examples of such potential uses: monitoring of tensions in such large structures, as buildings, bridges, dams, storage reservoirs, etc., as well as marine vessels, oil platforms, aeroplanes, spacecrafts, and so on; observing the temperature profile in electric power transformers, generators, reactor systems, furnaces, systems of controlling technology-related processes and just in fire detection systems; detection of leakage in pipelines, malfunction diagnosis and identification of anomalies of magnetic, and electric field in energy-distributing systems and security alarm systems; embedded sensors in composite materials, utilised on a real-time basis to estimate tension, vibrations, and temperatures in structures and housing assemblies, specifically in aerospace industry. The theory and description of operation principles of optical sensors are given in the literature

(Dmitriev & Slepov, 2010; Fraiden, 2006; Snider, 1987; Udd, 2008), specific structures and use are described in works (Amorebieta et al., 2019; Gao et al., 2013; Jena et al., 2020; Leandro & Lopez-Amo, 2017; Marie et al., 2019; Qin et al., 2009; Tohyama et al., 1996).

2. MATERIALS AND METHODS

To implement an optical vibration sensor, a simple circuit was chosen to measure the reflecting surface oscillation through bringing to it a cut of the optical fibre (see Fig.1).

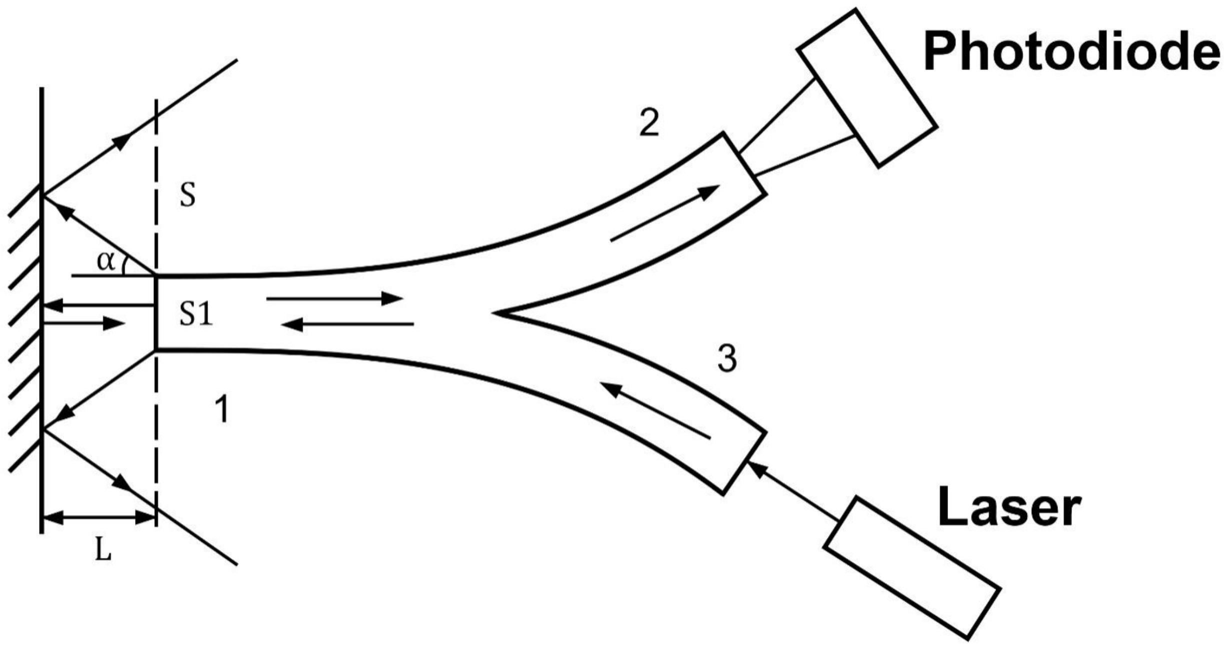


Figure 1. Optical circuit of splitter-based sensor

The light from a laser is brought to a splitter – an optical tee-connector made by welding optical fibres. The light going out of the splitter falls to the oscillating surface and, upon reflecting from it, goes back to the emitting end of the splitter fibre. Then, having passed through the splitter, the reflected light from the third end of the splitter falls on a photodiode, registering the intensity of the light, reflected from the oscillating surface.

The most common optical fibre with the numerical aperture of 0.12 was used in the experiments. A cone of outgoing light therewith will be about 14 degrees (angle α=7°). Diverging light flux passes spherically, therefore when the distance to the reflecting surface increases linearly, the area of spherical front will be proportional to the squared distance to the reflecting surface. As this takes place, the larger the numerical aperture or, to put it otherwise, the more oblique the angle of emission divergence and acceptance is, the higher the sensor sensitivity will be, since the area of spherical front will be proportional to the divergence angle. Or, in other words, the greater the divergence angle, the larger the area of the spherical light front changing at deviations of the oscillating surface to a specified value, and, respectively, the steeper the light intensity gradient will be as compared to a light waveguide with lower divergence. Hence, at deviations of the surface from the reference position, the light flux will change more drastically. Thus, opting for a fibre numerical aperture, the necessary sensor sensitivity can be chosen. For instance, the amount of returned light at the distance of 500μm from the reflecting surface to the splitter flat end at the numerical aperture of 0.12 will theoretically amount to 0.17%, whereas at the aperture of 0.2 it will be 0.056%. I.e., in section

S1 relative to section S (Fig.1) percent proportions of light will return. Hence, an amplification coefficient of the receiving system “photodiode – electronic amplifier” at large fibre apertures must be higher. In this case, the sensor differential sensitivity will also be higher, i.e., with equal deviations of the oscillating surface from the reference position, the signal amplitude will be higher.

The intensity of the light reflected from the surface depends on many parameters, which can change in this optical circuit. Here, of great importance is the polishing degree of the oscillating surface, the angle, at which the light goes out of the splitter fibre to the oscillating surface, transmission factor of splitter arms, mode content and wavelength of laser emission.

Hence, this work, where measurement capabilities of a sensor - optical sensing device were explored at oscillations of various types of membranes and when using different lasers, is purely experimental. In the experiments, the pieces of standard semiconductor wafer, which were glued onto oscillating surfaces, were taken as the reflecting surface.

At the first stage of studies, the sensor was implemented with a standard optical fibre, operating in the 1300–1550nm range. Red semiconductor laser with the 640nm wavelength and 10mW capacity was the light source here. Correspondingly, there was a photodiode, functioning in the visible range and not integrated into optical fibre. Since the wavelength was shorter than 1300nm, wave-propagation system had a multi-mode regime of light passage. Due to the interference of modes, minor beats emerged, which reduced the potential for carrying out accurate measurements. However, this design of the sensor was examined and had demonstrated rather high sensitivity indices. Sound reproductor was used as an oscillating surface.

At the second stage of work, the sensor was improved. Laser and photodiode, operating in the 1300nm range, were incorporated into the system. POM – 1305 laser of 30mW capacity made by the Russian company NOLATEKH, with regulation of capacity and internal temperature, built on a cold plate, the Peltier cooler. The project laboratory staff was in charge of the laser power supply and the Peltier cooler control. PIN InGaAs/InP DFD 300 – TO gallium-arsenide photodiode, made by the Russian DILAZ company, with 1.6-1.9nA dark current and 5pF capacitance, was integrated into the optical fibre. The diode photo-receiving pad has a 300µm diameter. Good photodiode characteristics allow the system frequency to reach 200 MHz. Laser wavelength is 1310nm, which conforms with wave-propagation system of optical fibre, hence, no interference beats occur in the system. It made it possible to reduce lower frequency range, down to a constant component. Both the laser and photodiode are produced in Russia.

To certify the optical sensor of vibrations, a stand was designed and produced with an interferometer based on ultrasonic emitter. Maximum oscillations of the ultrasonic emitter surface take place at the resonant frequency of 45кHz. Thanks to a high frequency, the amplitude of the US emitter surface oscillations proved to be low in the parasite harmonic cut-off mode. Amplitude of the US emitter surface oscillations, measured by the interferometer, was 226nm. Fabrication of this stand enabled certification of the sensor of vibrations to an accuracy of one tenth of the length of wave, falling at the angle of 45o. I.e., the accuracy of the stand measurements is 22nm.

The graphs were constructed of the dependence of the photodiode voltage amplitude on the distance, at which the optical sensor is located from the oscillating surface. It has been found that at oscillations of the emitter surface with the amplitude of 226nm, the sensor perfectly “sees” the oscillating surface at the distance of more than 100µm. In this case, when sensor moves away to the distance of 40µm, the signal amplitude changes very slightly.

Let the stand, where the vibration sensor was studied, be considered in greater detail. The general stand diagram is given in Fig.2.

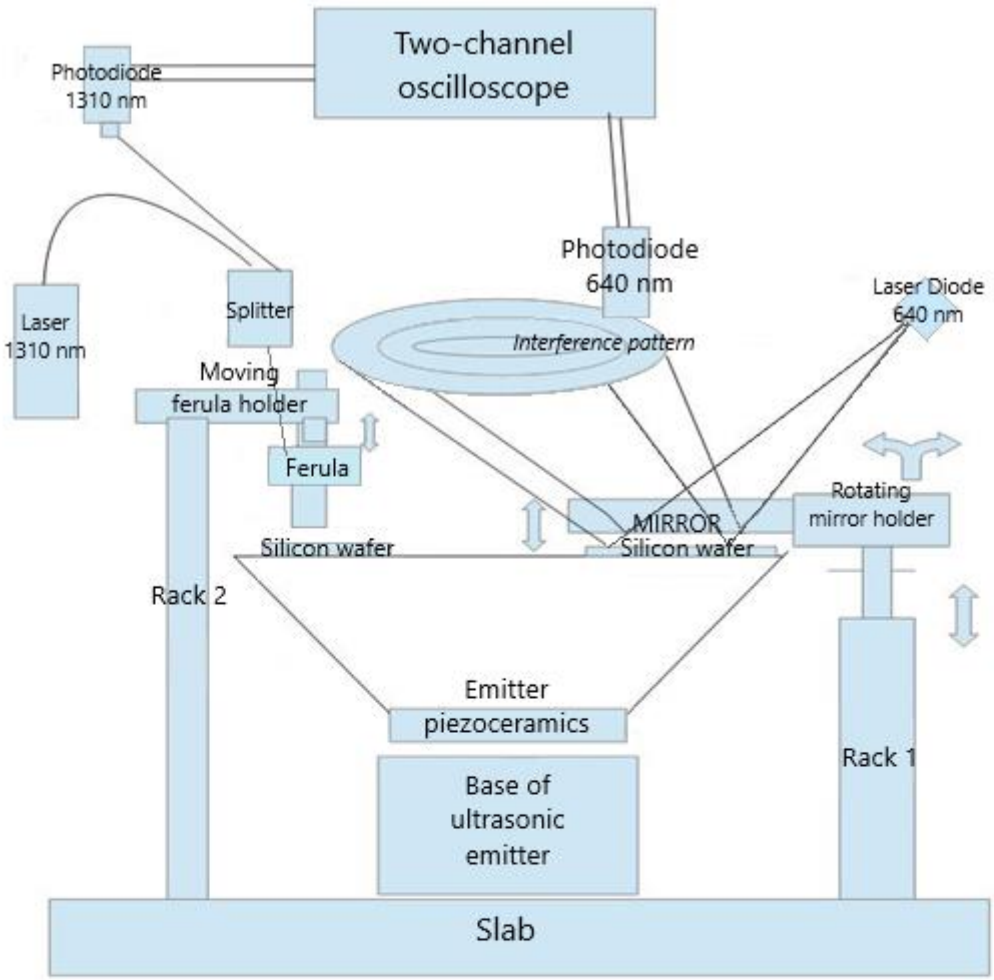
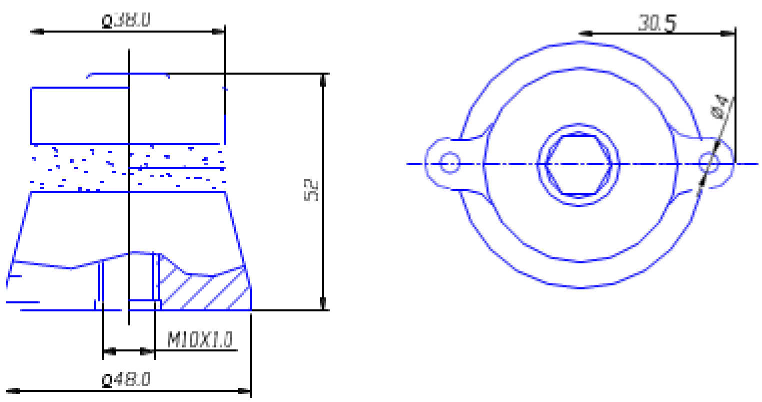


Figure 2. Optical circuit of controlling the amplitude of oscillations of the ultrasonic vibrator surface

The stand was assembled on the standard optical bench. Optical parts are fastened to racks 1 and 2. On rack 2, ferula of a connector with optical fibre is fixed, another end of the connector is linked to the 1st end of the splitter shown in Fig.1. A holder of ferula is fastened to a movable micro-pad with 1µm graduation. The second and third splitter ends are correspondingly connected with photodiode and laser. An interferometer mirror with a high reflection coefficient, at 640nm wavelength, is secured to rack 1. The second interferometer mirror is formed with a piece of the silicon wafer, fixed at the oscillating surface of the ultrasonic emitter. Above the mirror, there is a photodiode, which records the interference pattern intensity. The photodiode fronts onto oscilloscope.

An ultrasonic emitter is presented as an oscillating surface in this circuit. In the course of the experiment, instead of the ultrasonic emitter, a sound reproductor was also mounted with much larger membrane oscillations than in the ultrasonic emitter. For a dynamic build-up, a laboratory generator (Tektronix, AFG 3021, USA) was used, the signals were visualised and examined with an oscilloscope (Tektronix, TDS 2004B, USA). To build up the oscillations of the ultrasonic emitter (HNC-4SH-3840Y, Hainertec (Suzhou) Co., Ltd. China) a high-voltage generator (HNE-28100-SS Hainertec (Suzhou) Co., Ltd. China) was employed.

Figure 3. Photo of ultrasonic emitter HNC-4SH-3840Y



a b

Figure 4. Drawing of HNC-4SH-3840Y ultrasonic emitter in different planes: a – front view, b – top view

Ultrasonic vibrator (Fig. 3, Fig. 4) has an extensive flat surface, onto which two mirrors were glued, one mirror made of a silicon wafer is small – for vibration sensor, to directly register oscillations. Another mirror is big, having been located close to the small one. Opposite the big mirror, an optical mirror with a high reflection coefficient of about 90-98% and potential angle alignment is secured with a small clearance to a stationary slab. An interferometer, formed with movable and stationary mirrors, was lit by a semiconductor red laser with 640nm wavelength at 45o, with a certain selected divergence, so that a laser beam, upon reflecting from mirrors in an interference pattern, would form a pattern of black and white interference bands with an order greater field of view, than the photodiode aperture, within the photodiode view. A period of interference rings shall be pre-set using the inclination angle of mirrors, that form the interferometer. The period shall be set so that the PD-27 photodiode aperture of 2mm is accommodated with a small margin on the white band of the interference pattern. Then, upon normal displacement of mirrors to the distance of λ/2* cos 45 =(640nm/2) *0.707 = 226nm, the bands will shift to one period. I.e., a shift to 226nm provides a full scale of the measured value of the light amplitude from one maximum to another. In fact, the intensity of black and white interference bands varies sinusoidally from minimum to maximum. If this intensity scale is divided into 10, what causes no difficulties, this interferometer will allow for measuring normal displacements with an accuracy of 22.6nm. As we can see, the laser metrics, i.e., its wavelength defines the accuracy in our stand. If a laser with the wavelength of 405nm is employed, then with the same measurement diagram the accuracy will amount to 143nm/10 = 14.3nm.

The stand photo is presented in Fig. 5.

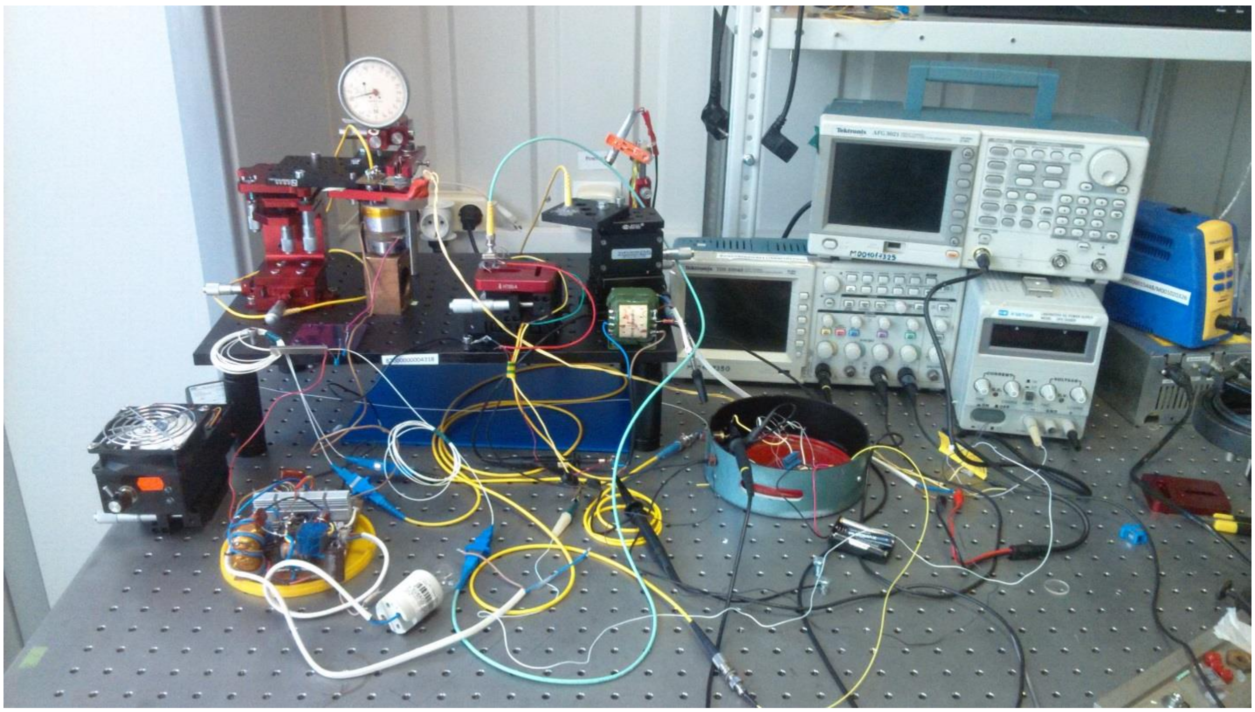


Figure 5. General photo of the stand with generator, oscilloscope, constant voltage source and optical circuit of interferometer and optical sensor

Interference measurement method is one of the most reliable measurement methods, hence, the conducted studies can be considered reliable.

To measure the amplitude of vibrations of the ultrasonic vibrator with a piezoceramic plate, the stand shown in Fig.2 was employed. After proper alignment of the circuit, it will suffice to merely touch the upper mirror to observe the displacement of interference bands. To align, it is required to relieve the upper mirror from clamps, holding it, and nail it down to the lower mirror, lying on the US vibrator. Flat mirrors pressed up together, with no dust particles that create non-flatness, when being pressed, will create a consistent visible pattern of concentric circular bands. Then, the upper mirror in this state must be very carefully fastened with clamps, so that the concentric bands can also be visible. The upper mirror must then be very carefully lifted, without changing the angle between mirrors, or to be more precise, retaining zero angle. When the angle is close to zero, there is a maximum possible period of the order of millimetres, and the bands are very clearly seen. Then, when everything has already been aligned, the mirrors are forced apart for a sufficient distance of about 300μm, the angle can be adjusted and a period of about 2mm between the bands can be made, as it is said above. Afterwards, it is necessary to manually verify how the interferometer circuit functions. To do it, one must gently press down over the upper mirror and make sure that, upon pressing in this way, at least 3-4 periods appear in the interference pattern view field. Photodiode PD-27 will further be connected with one channel of oscilloscope, and a probe – ferula of our vibration sensor will be brough to another small mirror, which is a piece of silicon wafer, glued onto the vibrator plane. Let's make sure that the vibration sensor functions, by having slightly tapped on the installation and seen an oscillatory process on the oscilloscope. The meaning of the assembled diagram for measuring distances is as follows. If the displacement of a movable mirror on a piezoceramic vibrator is greater than 22.6nm, for example, 45.2nm, on the oscilloscope we will observe the displacement over one period of vibrations, two passing bands. I.e., the frequency of sinusoid, registered by the PD-27 photo-receiver in the interferometric channel, will be twice higher than in the vibration sensor channel. If the amplitude of oscillations is 22.6* 3=67.8nm, the frequency will be 3 times higher, and so on.

An ultrasonic emitter will be connected with the electric excitation circuit, specifically designed for a build-up of the resonance piezoceramic circuit to the first harmonics of 45 KHz. To do this, there were selected high-voltage condensers with a certain capacitance to cut all high-order harmonics in the piezoceramic circuit. During the tests, resonance voltages in the piezoceramic circuit reached 5kV. When testing the sensor, we have restricted ourselves to the voltage of 1.1 kV.

From the measurements performed according to the above-described procedure, we have not seen that the frequency of oscillations in the interferometric channel is higher than the frequency in the vibration sensor channel. It means that the amplitude of the piezoceramic US vibrator surface oscillations does not exceed 22.6nm. At that, we have a very good output signal at the vibration sensor output.

Oscillogram of measurements is shown in Figure 6. It shows that the frequencies coincide, what indicates that the oscillation amplitude is not more than 22.6nm.

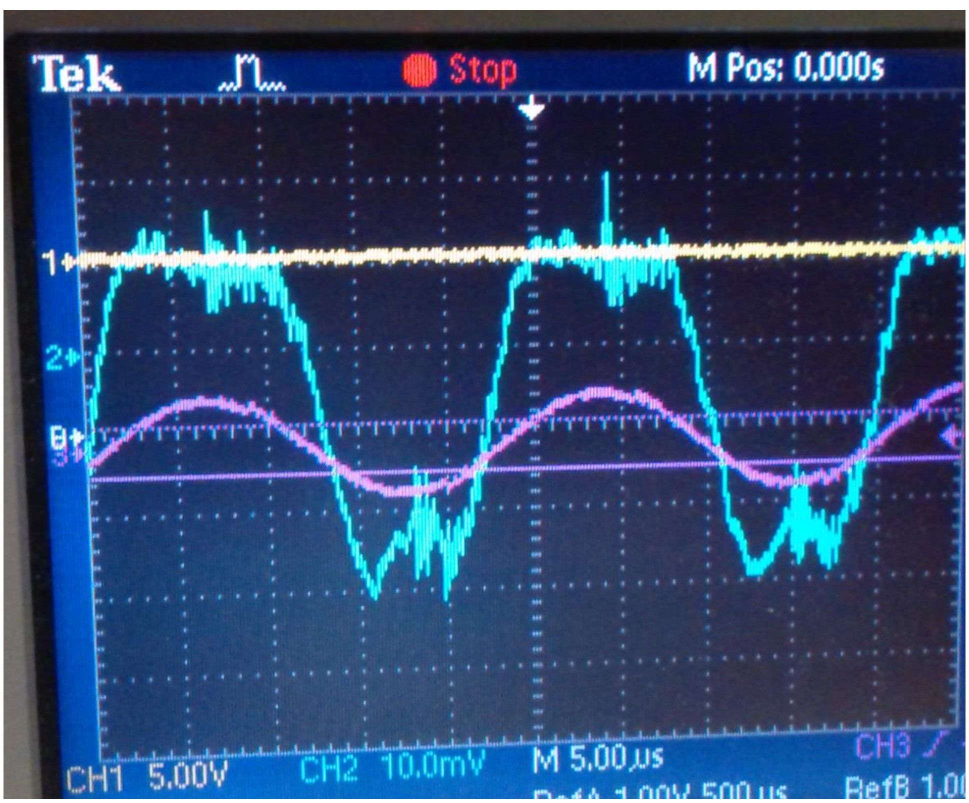


Figure 6. Oscillogram of measuring the amplitude of piezoceramic ultrasonic emitter oscillations. Sinusoid with small amplitude – signal from the vibration sensor, with large amplitude – signal from the interferometer diode

3. RESULTS AND DISCUSSION

3.1. Measurement of membrane oscillations with large amplitude

The first stage of studies was devoted to determining, with the use of an optical sensor, a maximum and minimum amplitude of fluctuations of the oscillating membrane, to which a small piece of thin silicon wafer was secured.

Of interest was also to know the maximum distance from the fibre light waveguide to the mirror, where the sensor reacts to the object fluctuations, as well as frequency characteristics, namely, minimum and maximum frequencies, that the sensor could register.

To avoid such steady-state errors as zero drift and midpoint drift of volt-ampere characteristic, a method of measurements was chosen on certain frequencies of the permissible range of electromagnetic diffuser operation, and two problems therewith were immediately solved: determination of characteristics of both optical-fibre sensor, and electromagnetic diffuser.

Measurements were done using oscilloscope functioning on frequencies within 60 MHz. Theoretically, the diffuser operates within the 0 to 20 KHz range.

To measure the amplitude of diffuser oscillations and define the distances from the optical-fibre sensor to the mirror, fastened to the diffuser, a microthermometer was used with 1 µm graduation interval.

A peculiarity of splitter operation in this application is that a certain portion of energy of laser emission (around 20%), even when there is no mirror, is brought to the light diode. Hence, something must be done so that this stray light caused no photodiode saturation. In this circuit, just pushing the photodiode outwards from the fibre output solves this problem. To avoid photodiode saturation, when the mirror approaches the main splitter channel to the maximum, the same procedure is carried out to regulate the distance between the photodiode and optical fibre.

This circuit employed a laser diode of 5mW capacity, and the distance from the photodiode to fibre was 45mm.

Thus, having set a midpoint of the transistor volt-ampere characteristic, and aligned the optical circuit so that the photodiode saturation is excluded, a diffuser was connected to the sinusoidal generator through an amplifier allowing for regulation of the signal amplitude. The frequency was set to be 4кHz. Mirror fixed to the diffuser, was moved away from the optical sensor to the maximum. The signal on the oscilloscope has started to emerge at the distance of 300 µm from the mirror to the sensor. As the sensor approached the diffuser, the signal increased (see Table 1).

Table 1. Dependence of the sensor signal amplitude on the distance at the 4 кHz frequency of diffuser oscillations

X µm	300	250	200	150	100	50	10	0
U mV	20	30	35	50	80	100	80	100

The table demonstrates that when the sensor approached to the distance of 10µm, the signal decreased, since the diffuser at the 4 KHz frequency oscillates with more than 10µm amplitude, and the diffuser was brought closer to the distance of 10µm, i.e., a mutual collision was caused between the sensor and oscillating diffuser. At that, the sensor was thrown away from the mirror, fastened to the diffuser, to the distance of 100µm, since (see Table 1) at the 100µm distance even prior to approaching the diffuser, the

signal was the same - 80µm, hence, the last 0 µm value in the table corresponds to the real distance of 50µm, what is also evident from Table 1 even when the sensor was just moving closer (column 6).
The graph constructed using the values from Table 1 is shown in Figure 3.

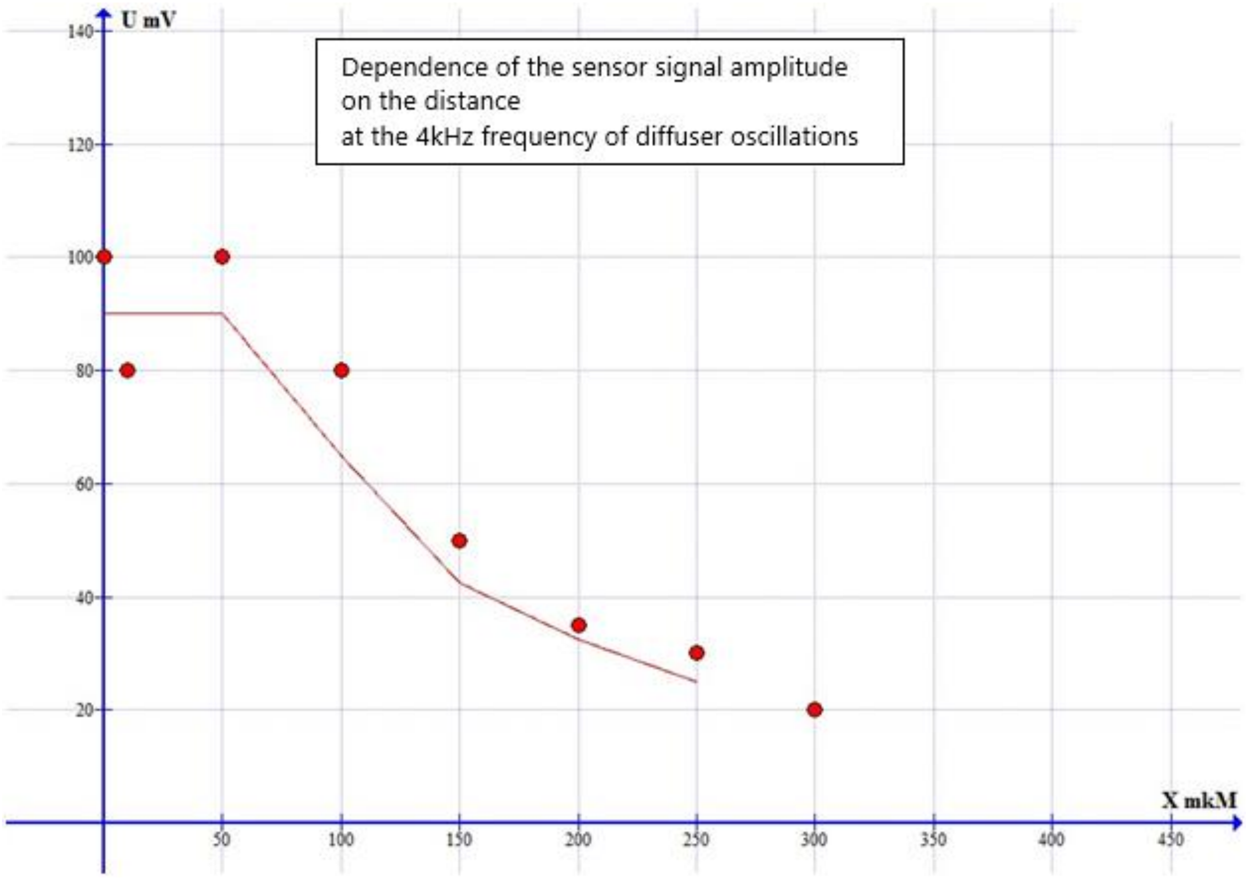


Figure 5. Graph of the dependence of the sensor signal amplitude on the distance from oscillating surface at the frequency of 4 кHz

Hence, it can be inferred from this experiment that the amplitude of diffuser oscillations is within 10-50 µm.

3.2. Determination of the amplitude of diffuser oscillations at the frequency of 100 Hz

On retaining the generator voltage amplitude, we have considerably reduced the frequency. 100Hz frequency of the diffuser oscillations was set. In this case, the amplitude of the diffuser oscillations greatly increased, and with the same experimental procedure as described above, the sensor signal came to appear even at the distance of 1000 µm (see Table 2).

Table 2. Dependence of the sensor signal amplitude on the distance at the 100Hz frequency of diffuser oscillations

Xµm	1000	900	850	800	775	750	725	700	650	600	500	400
UmV	2.5	7.5	10	40	60	100	150	200	250	275	250	250

The graph constructed using the values of Table 2 is shown in Figure 4.

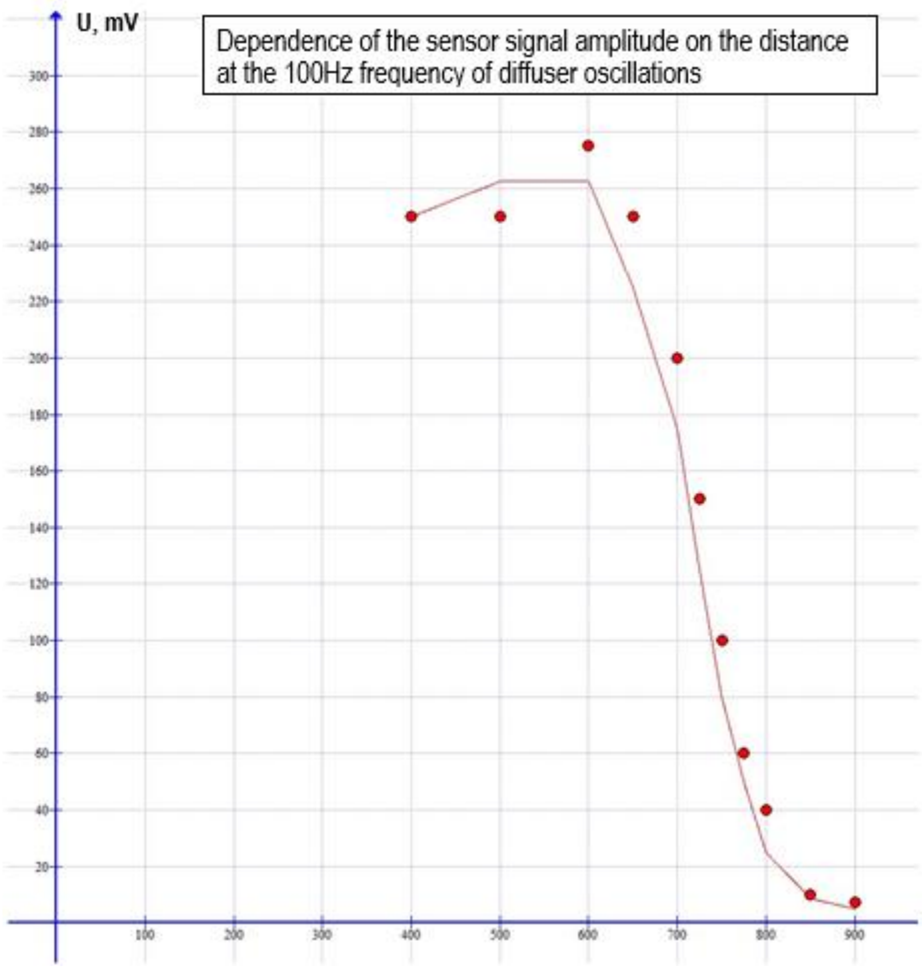


Figure 6. Graph of the dependence of the sensor signal amplitude on the distance from oscillating surface at the frequency of 100Hz

3.2 Frequency dependence of the amplitude of diffuser oscillations

As a follow-up to the Table 2 experiment, we have taken a distance of 650μm, at which the maximum signal was observed at the 100Hz frequency, and started to increase the frequency.

Table 3. Frequency dependence of sensor voltage at the distance of 650μm from diffuser

f Hz	100	200	250	300
U mV	250	200	50	48

The graph constructed using the values of Table 3 is shown in Figure 5.

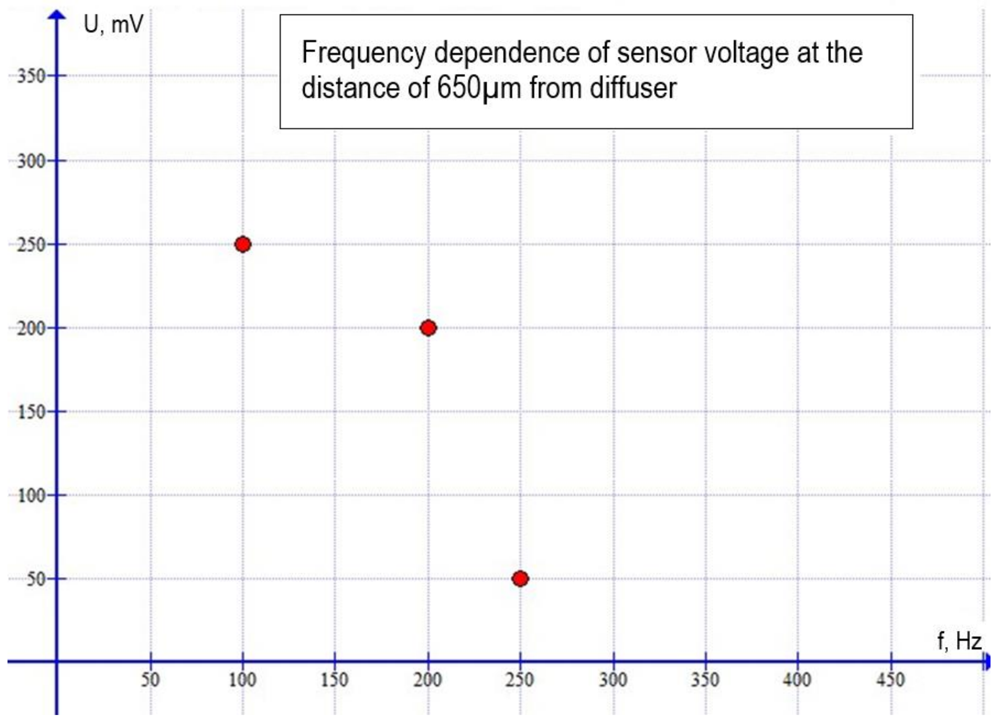


Figure 7. Frequency dependence of sensor voltage at the distance of 650μm from diffuser

Let the minimum amplitude of the membrane oscillations, which the sensor can register, be determined.

3.4 Determination of maximum sensitivity of sensor with red laser

Let the amplitude of membrane oscillations be defined at high frequencies, when the signal gets lost in the noises.

The frequency of membrane oscillations will be slightly reduced from 15KHz, when there is almost no detected signal, to 10 KHz.

The method for determining the amplitude of oscillations will be as follows. If the sensor is rigidly fixed, and oscillating membrane is considered as flexible, the amplitude of oscillations will be maximum when it will approach immediately adjacent to the light waveguide, built-in ferula (smoothly polished light-conductive cylinder with a light waveguide inside). If the distance from the light waveguide to the reflecting membrane is increased, the signal will decrease since the capacity of the reflected light will decrease (because at the output, there is a diverging cone with a certain fibre numerical aperture). If the oscillating membrane is brought to the distance, which is closer than the amplitude of membrane oscillations, the membrane will be butted up against ferula and restrict the amplitude. Thus, we have a strict criterion for measuring the amplitude of membrane oscillations. A mechanical micrometre, used to measure distances, has a scale accurate to 1μm/interval. I.e., we can measure the amplitude of oscillations to within 1 μm.

So, let the experiment be conducted. The sensor is brought right up to the membrane – there is no signal on the oscilloscope. The sensor is being brought away from the membrane; signal started to increase to

10μm. As the distance further increases, signal decreases. The amplitude of signal on 10KHz frequency amounted to 80mV at 10μm range of membrane oscillations. Hence, when membrane oscillates with 1μm amplitude, there will be obtained a sensitivity of 8 mV.

Let these conclusions be checked on the frequency, at which the amplitude of membrane oscillations merges with noises. The experiments were made on 12KHz, 13KHz, 14KHz, 15KHz frequencies. A whistle is heard on these frequencies, when the membrane approaches the sensor ferula. A loud whistle emerges, as the sensor ferula approaches the oscillating membrane or moves away from it to the distance of 1-2μm. When whistle appears (when the membrane touches the sensor ferula) at 15KHz frequency, the amplitude on oscilloscope was 8mV and it almost merged with noises by level. As the membrane recedes to more 1-2μm, the signal disappears completely. At such 1-2μm amplitude of oscillations, our sensor no longer reacts to them.

3.5 Measurements with the use of ultrasonic emitter

US emitter was fastened to an optical slab. A piece of silicon wafer was glued onto the emitter plane, above which a probe – ferula of vibration sensor was placed. Vertical displacements were made using a micro-screw and recorded with a pointer meter with a precision of 1μm. Measurements were made at two values of emitter voltages 216V – graph U1, and 1100V – graph U2. The frequency of voltage, applied to plates, was 45KHz. The graphs of the dependence of vibration sensor voltage on the distance to it are shown in Fig. 8.

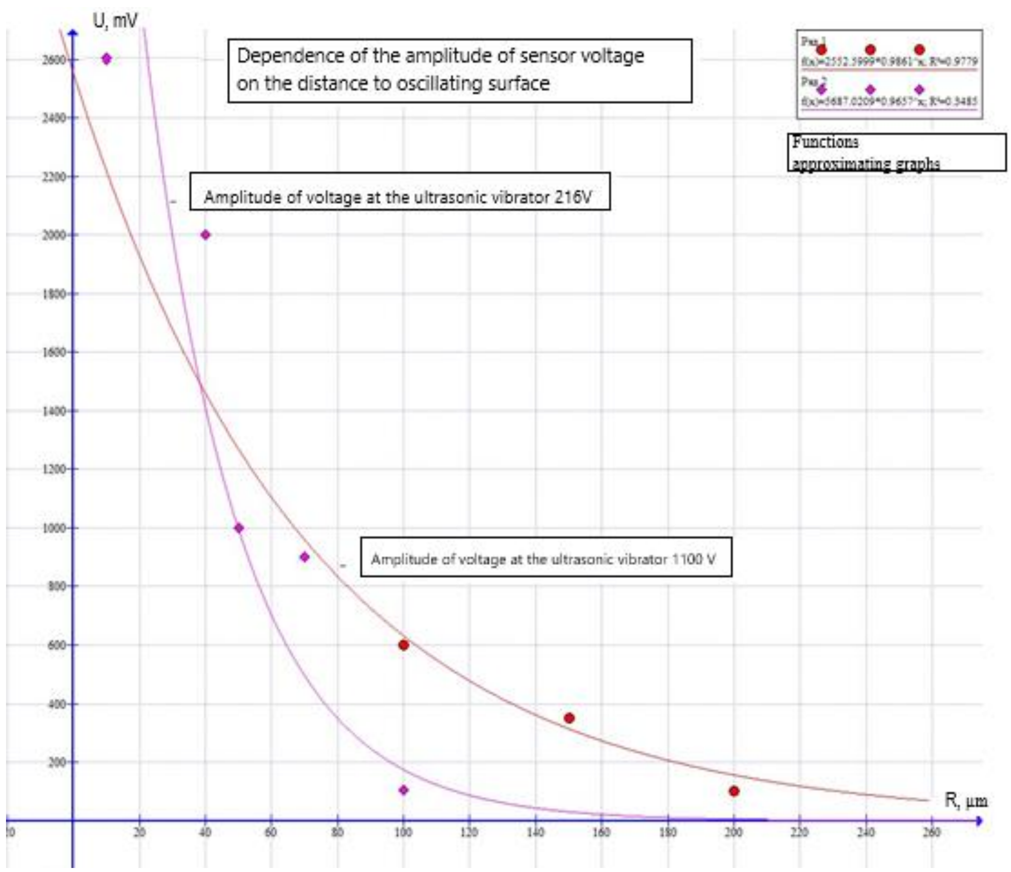


Figure 8. Dependence of the sensor voltage amplitude on the distance to ultrasonic vibrator, at various US vibrator build-up voltages

Graphs are approximated by exponential functions at high voltage 1100 V f(x)=2552.599877474152·0.986124081983^x, at low voltage 216 V f(x)=5687.02087851775·0.965744906361^x.

Table 5 shows that at the vibrator voltage of 216V, the sensor records vibrations with 226nm amplitude (see cl.2.2) at the distance of 100µm from sensor. At the 1100V vibrator voltage, the sensor has now recorded the vibrations at the distance of 300µm.

Table 5 shows that measurements can be made at the 10-40µm distance to the sensor probe, almost without losing sensitivity. This takes place at minor vibrations of about 30-300nm. At high-frequency vibrations the distance will increase greatly. It is indirectly evident from the graph (Figure 8), when at the vibrator voltage of 1100V, there is not yet the 2nd harmonic, i.e., the amplitude of oscillations was within 300nm, at the distance of 300µm to the probe, we can see a 50mV signal. In the first part of the report, it has been shown that at large amplitudes of oscillations, the signal from the sensor is visible at about 1mm distances, what was inherent in the first modification of the sensor, when its sensitivity was an order of magnitude lower.

Optical vibration sensor was tested in a wide range of amplitudes and distances from the oscillating surface. It can be inferred from the test results that the distance to the sensor, at which the surface oscillation is registered, corresponds to the amplitude of vibrations by the order of value. For example, when oscillations occur with the 10-50µm amplitude (Fig. 5), sensor can be positioned at the distance within 300µm.

When the surface oscillations are larger with the amplitude of about 400-500µm (Table 2, Fig. 6), the distance, at which measurements can be made, is 500-1000 µm. In this case, the amplitude of diffuser oscillations has increased greatly, and when carrying out the experiment in the above-described way (Table 1), the signal from sensor came to appear even at the distance of 1000µm. (see Table 2). As is obvious from comparing Tables 1 and 2, the amplitude of sensor voltage has increased almost threefold. Signal from the sensor reaches maximum 275mV at the distance of 600µm from the sensor to the mirror, glued to the diffuser. As the sensor moves to a closer distance, for example, 500 or 400µm (see Table 2), the oscillating membrane throws the sensor away to the distance of 650µm, what can be seen in Table 2: the amplitude of oscillations became even smaller than at 600µm. This suggests that the membrane is thrown away at the distances within 600-500µm. Hence, the amplitude of the diffuser oscillations is approximately 550µm. It can be inferred here from that the sensor should be used at the distances, which are definitely larger than the amplitude of fluctuations of the oscillating surface.

When the frequency of reproductor membrane oscillations increases, its amplitude declines sharply. The amplitude of the output signal from the sensor started to decline sharply from 250Hz frequency (see Table 3).

It can be related only to the fact that the amplitude of membrane oscillations declines considerably when frequency increases. When the frequency further increases, the signal amplitude declines substantially, and when the frequency becomes equal to 15KHz, the signal gets lost in the noise.

Hence, a conclusion is drawn that the sensitivity of our sensor is 1µm. I.e., if an object oscillates with the amplitude of 1µm, our sensor will notice it, whereas, at a smaller amplitude of oscillations of the object, for example, a membrane, our sensor will not be able to record it. The distance, to which the sensor ferula can be receded for normal operation, will depend on the amplitude of membrane oscillations, i.e., on the frequency of oscillations, the higher the frequency of oscillations, the smaller their amplitude. At high frequencies, where maximum sensitivity is needed, the chosen distance should be a little shorter than the amplitude of membrane oscillations.

At the reproductor cut-off frequencies of 13-15 κHz, as the membrane recedes to more 1-2μm, the signal disappears completely. At such 1-2 μm amplitude of oscillations our sensor no longer reacts to them.

Hence, it is inferred that the sensitivity of our sensor is 1μm. I.e., if the object oscillates with the amplitude of 1μm, our sensor will notice it, whereas at a smaller amplitude of oscillations of an object, e.g., a membrane, our sensor will not be capable of recording it. The distance, to which the sensor ferula can be carried away for normal operation, will depend on the amplitude of membrane oscillations, i.e., on the frequency of oscillations, the higher the frequency of oscillations, the smaller their amplitude. At high frequencies, where maximum sensitivity is needed, the chosen distance to a sensor should be a little larger than the amplitude of membrane oscillations.

To improve the sensor sensitivity, a numerical aperture of the utilisedfibre must be increased. The numerical aperture in the fibre used herein was 0.12. After the numerical aperture of optical fibre, passing from the splitter to the mirror, had been theoretically increased to 0.45, the sensitivity of red laser sensor will increase by two orders of magnitude, and the range of 0.01 μm membrane oscillations will be registered. It is attributed to the fact that, when numerical aperture increases, emission from optical fibre diverges more significantly, and the reflected light flux will greatly change upon every minor deviation of the mirror. In practice, it can be done through the use of lensed fibre, i.e., the fibre, at the end of which a lens is either etched, or integrated, which will collect the light that went out of it and the light reflected by the mirror.

4. CONCLUSIONS

To increase sensitivity, this work employed a laser with 1310nm wavelength and 30mW capacity, along with a photodiode integrated into optical fibre (see above). This system has already allowed for observing the ultrasonic emitter oscillations with the amplitude of about ten nanometres. Sensitivity in this case increased due to the two favourable factors: no interferential mode interaction in the light waveguide and increased sensitivity due to enhanced transmission capacity of optical and electronic path.

REFERENCIAS

Amorebieta, ., Durana, G., Ortega-Gomez, A., Fernández, R., Velasco, J., Sáez de Ocáriz, I., Zubia, J., Antonio-López, J. E., Schülzgen, A., Amezcua-Correa, R., & Villatoro, J. (2019). Packaged Multi-Core Fiber Interferometer for High-Temperature Sensing. *Journal of Lightwave Technology, 37*(10), 2328–2334.

Dmitriev, S. A. & Slepov, N. N. (eds.) (2010). *Optical-fibre technology: state-of-the-art and new prospects.* Moscow: Tekhnosfera.

Fraiden, J. (2006). *Modern sensors.* Moscow: Tekhnosfera.

Gao, X., Wang, Y., Yuan, B., Yuan, Y., Dai, Y., & Xu, G. (2013). Low-cost vibration sensor based on dual fiber Bragg gratings and light intensity measurement. *Applied Optics, 52*(27), 6782–6787.

Jena, J., Wassin, S., Bezuidenhout, L., Doucouré, M., & Gibbon, T. (2020). Polarization-based optical fiber acoustic sensor for geological applications. *Journal of the Optical Society of America, B37*(11), A147–A153.

Leandro, D., & Lopez-Amo, M. (2017). All-PM Fiber Loop Mirror Interferometer Analysis and Simultaneous Measurement of Temperature and Mechanical Vibration. *Journal of Lightwave Technology, 36*(4), 1105–1111.

Marie, B., Fouda, T., Dezhi, H,, & Bowen, A. (2019). Pattern recognition algorithm and software design of an optical fiber vibration signal based on Φ-optical time-domain reflectometry. *Applied Optics, 58*(31), 8423–8432.

Qin, F., Li, H., Fan, W., Sheng, & Qiuqin (2009). Experimental study on vibration frequency response of micro-bend optic-fiber sensor. *Chinese Optics Letters, 7*(7), 556–559.

Snider, A. L. (1987). *Theory of optic waveguides.* Moscow: Radio i svyaz.

Tohyama, M., Kohashi, K., & Yamamoto (1996). A fiber-optic silicon pressure sensor for ultra-thin catheters. *Sensors and actuators, 54*, 622–625.

Udd, E. (Ed.). (2008). *Fibre-optic sensors.* Moscow: Tekhnosfera.

SEMBLANCE OF THE AUTHORS

Vladimir S. Soloviev: Cand. Sc. Physics and Mathematics, Senior Researcher of National Research University of Electronic Technology, Moscow, Russian Federation.

Sergey P. Timoshenkov: Professor, Director of the Institute of Nano- and Microsystem Technology (INMT) as part of the Moscow National Research University of Electronic Technology (MIET), National Research University of Electronic Technology, Moscow, Russian Federation.

Andrey S. Timoshenkov: Head Researcher of MIET INMT Optical Laboratoryof National Research University of Electronic Technology, Moscow, Russian Federation.