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LASER HYDROPHONES

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Laser adaptive holographic hydrophone

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Abstract. **A new type of a laser hydrophone based on dynamic holograms, formed in a photorefractive crystal, is proposed and studied. It is shown that the use of dynamic holograms makes it unnecessary to use complex optical schemes and systems for electronic stabilisation of the interferometer operating point. This essentially simplifies the scheme of the laser hydrophone preserving its high sensitivity, which offers the possibility to use it under a strong variation of the environment parameters. The laser adaptive holographic hydrophone implemented at present possesses the sensitivity at a level of 3.3 mV Pa^{-1} in the frequency range from 1 to 30 kHz.**

Keywords: *laser hydrophone, adaptive interferometer, dynamic hologram.*

The development of systems for monitoring water areas and the World Ocean is inseparably linked with the design of technical means for the detection of hydroacoustic signals. Until recently, they were based on piezoelectric transducers [1]. Recently optical receivers of acoustic signals attracted the attention of researchers, since they possess a number of advantages as compared to their electric analogues, e.g., the insensitivity to electromagnetic noises and corrosion, low specific weight, small dimensions, etc. Among the optical sensors a specific class of instruments is presented by laser interferometer hydrophones, which are potentially able to measure extremely weak hydroacoustic perturbations with the acoustic pressure smaller than 1 Pa in the wide band of frequencies and smaller than 0.1 Pa in the narrow band [2–6]. The sensitive elements in such hydrophones are usually fibre-optical sensors [2–8] or resonance elements in the form of elastic membranes [9–11]. However, in the course of exploitation of laser hydrophones under real conditions, random mechanical impacts, temperature drift, variations of the static pressure of the environment and a number of other factors lead to the drift of the operating point of the interferometer and, as a consequence, to the reduction of the signal-to-noise ratio and a decrease in the sensitivity of the measurement system. This makes it necessary to use special means of stabilising the operating point in laser hydrophones. As such means they often use additional compensation interferometers [12], active and passive phase control methods [9–11, 13, 14], methods of optical feedback by intensity [15] or laser oscillation frequency [16, 17], methods based on tunable diffraction gratings [18] and multi-wavelength radiation with subsequent spectral analysis [19], etc. Unfortunately, the use of all these means of stabilising the interferometer operating point unavoidably complicates the construction, which negatively affects their reliability and stability of operation of the entire measurement system.

As shown in Ref. [20], the use of dynamic holographic gratings formed in photorefractive crystals (PRCs) allows sufficiently simple and efficient solution of the problem of operating point stabilisation in the measuring laser interferometers. The adaptivity to uncontrollable external perturbations in such systems is based on the fact that the permanent rewriting of dynamic holograms in the PRC enables the interferometer to adapt automatically to the change in the external conditions, thus providing the stability of its characteristics.

The aim of the present paper is to study the possibility of using an adaptive holographic interferometer based on dynamic holograms, formed in a photorefractive crystal, for the stabilisation of the operating characteristics of a laser hydrophone.

The schematic of the laser adaptive holographic hydrophone (LAHH) is presented in Fig. 1. The sensor part of the LAHH has a robust hermetic case. A thin (50 μm) round (∅40 mm) brass membrane, playing the role of a hydrophone sensitive element, is embedded in one of the walls. The optical part of the sensor is implemented as follows. The radiation from the Nd:YAG laser (λ = 1.06 μm, the output power 0.5 W) passes through the beam splitter and is launched into the multimode optical fibre (the core diameter 62.5 μm, the numerical aperture NA = 0.22), from the output of which the light is incident on the membrane. The separation between the output face of the optical fibre and the membrane is 0.5 mm. The radiation reflected from the membrane returns back into the waveguide, forming a signal wave. The mechanical vibrations of the membrane caused by the action of the acoustic wave, lead to the phase modulation of the signal wave. The radiation of the signal wave, diverted by the Y-coupler (intensity I = 0.8 mW mm^{-2}), is directed into the PRC along its [001] crystallographic axis. The reference wave (I = 50 mW mm^{-2}), elliptically polarised after passing through a quarter-wave plate, enters the crystal in the perpendicular direction along the [100] crystallographic axis. Due to the photorefractive effect, the interference of the signal wave with the reference one leads to the dynamic hologram recording in

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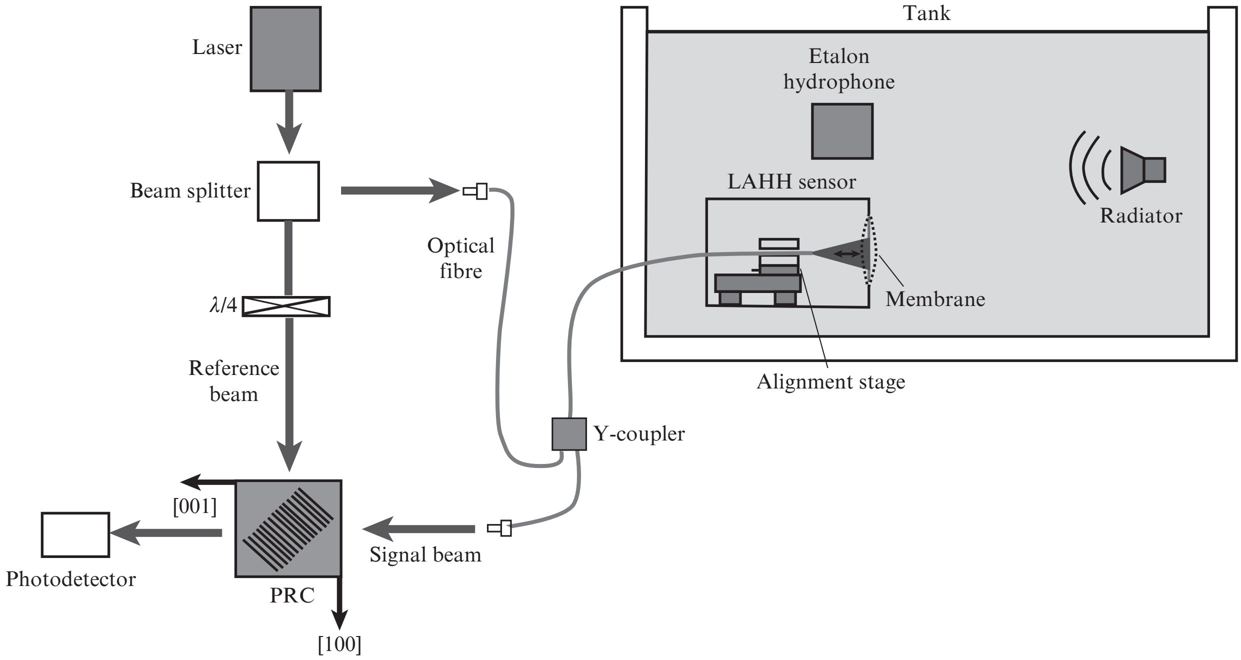

Figure 1. Schematic of the adaptive holographic hydrophone.

the crystal with the lattice vector directed along the [101] crystallographic axis. The vectorial mixing of the elliptically polarised reference wave with the depolarised (after the transmission through the multimode fibre-optical waveguide) signal wave in such orthogonal geometry in the PRC with cubic symmetry provides the fulfilment of quadrature conditions for the interferometer, due to which its high sensitivity is achieved [21, 22]. The interaction of waves at the dynamic hologram produced by them provides the precise conjugation of wave fronts and maximally efficient conversion of the signal wave phase modulation, caused by the vibrations of the membrane, into the variations of intensity, recorded by the photodetector.

It is worth noting that the optimal intensity ratio of the interfering beams is such that the contrast of the interference pattern does not exceed 0.5. For higher contrasts (e.g., when the intensities of the beams are equal) the holographic grating becomes distorted, and its profile becomes different from the sinusoidal one, which leads to the reduction of the beam interaction efficiency due to the diffraction of their radiation at the gratings of higher spatial order [23]. As the contrast of the interference pattern decreases, the phase demodulation signal passes its maximum and smoothly decreases due to the reduction of the efficiency of the hologram recording [24, 25]. With the intensities used in the present paper, the contrast of the interference pattern was 0.25. Despite a relatively low diffraction efficiency of the dynamic hologram (smaller than 0.1 %), the adaptive interferometer provided a high sensitivity to the detection of phase modulation, as will be shown below.

One should also note that the time of recording the dynamic hologram in the crystal is finite, as well as the lifetime of the recorded hologram after switching off or changing the interference field [23]. When the change of the interference field is slow, e.g., when the drift of the environment parameters causes it and its time is greater than the time of the hologram recording, the hologram is completely rewritten, which determines the adaptive properties of the interferometer and, therefore, the hydrophone. In the CdTe crystal for the intensity ~50 mW mm^{-2} the time of hologram recording amounted to 1.2 ms, which makes the LAHH capable of automatic adaptation to all noise perturbations with characteristic frequencies smaller than 800 Hz.

The experimental studies of the LAHH were carried out in the tank with sound-absorbing walls. To control the acoustic pressure a ZETLab BC311 calibrated etalon piezoelectric hydrophone was placed in the vicinity of the LAHH membrane. The acoustic pressure in the tank was produced by means of a LUZ.837.9 piezoelectric radiator placed at the same depth as the laser hydrophone and the etalon one at the equal distance from them (20 cm).

We experimentally measured the amplitude–frequency characteristic of the LAHH. For this aim, an electric pulse with a duration 5 μs and an amplitude 2 V was applied to the acoustic radiator. Figure 2a presents the shapes of acoustic pulses, recorded using the LAHH and the etalon hydrophone. The Fourier analysis of these signals with the sensitivity of the etalon hydrophone (56 μV Pa^{-1}) taken into account allowed us to determine the amplitude–frequency characteristic of the LAHH (Fig. 2b). One can see that the LAHH sensitivity is uniform in a sufficiently wide range of frequencies (1–30 kHz). At higher frequencies (0.1–1 MHz) the LAHH sensitivity is reduced by an order of magnitude. Figure 3 presents the transient characteristic of the LAHH, measured at a frequency of 10.5 kHz, i.e., in the region of its maximal sensitivity. The experimentally measured sensitivity of the LAHH at the linear fragment of the transient characteristic amounts to 3.3 mV Pa^{-1}.

Note that the total sensitivity of the LAHH to the acoustic pressure (V Pa^{-1}) is determined by the characteristics of all transforming elements and can be presented by the expression:

$$S_\Sigma = S_1 S_2 S_2, \tag{1}$$

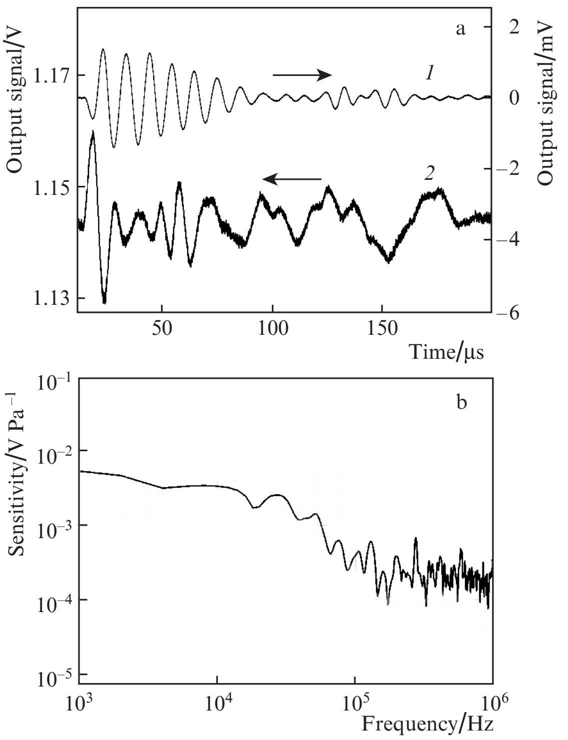

Figure 2. (a) Acoustic pulse recorded by means of the etalon hydrophone (*1*) and LAHH (*2*) and (b) the amplitude–frequency characteristic of the laser adaptive hydrophone.

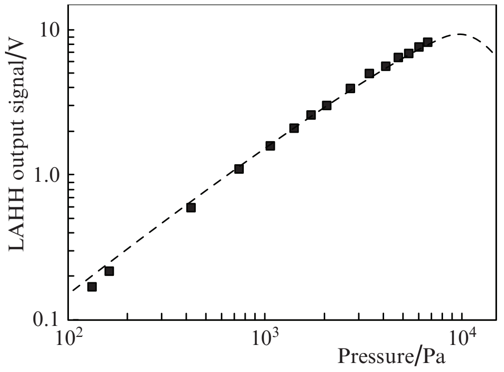

Figure 3. Transient characteristic of the laser adaptive hydrophone at the frequency 10.5 kHz (points show the experiment, dashed line–calculation).

where S_1 (rad Pa^{-1}) is the membrane sensitivity; S_2 (W rad^{-1}) is the sensitivity of the adaptive interferometer; and S_3 (V W^{-1}) is the sensitivity of the photodetector. The sensitivity S_3 of the Thorlabs PDA10CS photodetector used in the present work amounted to 5×10^5 V W^{-1}. The sensitivity S_2 of the adaptive interferometer was determined using the technique of Ref. [26] and amounted to 0.18 mW rad^{-1}.

The LAHH calibrating dependence calculated using expression (1) is shown in Fig. 3 by the dashed curve. It is seen that at a large acoustic pressure the transient characteristic of the LAHH has a nonlinear fragment, limiting the dynamic range. With the data presented in Fig. 3 and the level of intrinsic noise of the measurement system taken into account, it was found that the LAHH provides the measurement of the acoustic pressure in the dynamic range of 36 dB, the minimal detected acoustic pressure being 130 Pa.

The acoustic wave receiving membrane is the element of the LAHH design of primary importance. Since the membrane is a primary acoustic receiver, it mainly determines the sensitivity of the laser hydrophone. Using Eqn (1) and the transmission characteristic presented in Fig 3, it was found that the sensitivity S_1 of the membrane used in the LAHH is 0.37 mrad Pa^{-1}.

The parameters of the LAHH developed by us and the existing analogues are presented in Table 1. It is seen that the sensitivity S_1 of the primary receiver of the LAHH – the membrane – is not extremely high. It is possible to increase S_1 and, therefore, the sensitivity of the entire LAHH, by the appropriate choice of the material, area and thickness of the membrane that determine its hardness. An alternative way is to use a primary acoustic receiver, similar to that presented in Ref. [7] providing the acoustic sensitivity at the level of 0.5 rad Pa^{-1}. The total LAHH sensitivity S_Σ will amount to 4.4 V Pa^{-1}, which is much higher than the sensitivity of the hydrophone proposed in Ref. [7], as well as that of most other analogues. It is important that, in contrast to other hydrophones, the LAHH has a simple optical scheme that provides its operation including the adaptivity.

In addition, note that the sensitivity S_2 of the adaptive interferometer that enters expression (2) is determined by the diffraction efficiency of the holographic grating, which is not maximal in the orthogonal geometry of the interaction between the reference wave and the signal one in the PRC. The maximal diffraction efficiency of the dynamic hologram will be achieved in the reflection geometry, i.e., in the case of counterpropagation of the interacting waves [21]. The use of the reflection geometry will allow an additional increase in the sensitivity of the adaptive interferometer and, as a consequence, the total sensitivity of the LAHH by $\sqrt{2}$ times [28].

Table 1. Parameters of hydrophones.

Hydrophones	Sensitivity of the primary transducer S^1/mrad Pa^{-1}	Total sensitivity S_Σ/mV Pa^{-1}	Minimal detected pressure/Pa	Frequency range/kHz
[5]	1.1	11.0	1.3	100–300
[6]	143	0.1	–	5–20
[7]	500	–	5	5–300
[8]	7.5×10^{-5}	5.8×10^{-4}	1.5×10^4	20000
[9]	–	–	0.013	0.3
[27]	20	–	–	3–8
Piezoelectric ZETLab BC311	–	0.056	100	0.003–100
LAHH (present work)	0.37	3.3	130	1–30
LAHH (perspective)	500	4400	0.09	5–300

We also studied the stability of the operating characteristics of the LAHH under the conditions of varying temperature, one of the most critical parameters for the systems based on interferometry schemes. With this aim during 24 hours we measured the amplitude of the LAHH output signal keeping the acoustic pressure constant at a room temperature with daily variation ±5 °C. The measurements have shown that the fluctuations of the amplitude of the LAHH output signal did not exceed 1 %.

As shown in Refs [24, 29–31], photorefractive media allow efficient multiplexing of dynamic holograms in one crystal. It was found that the formation of up to 70 holograms leads to the reduction of the sensitivity by no more than 10 % [29]. In practice, an adaptive interferometric system with 26 holographic channels was implemented [32]. Therefore, the use of dynamic holograms in the scheme of a laser hydrophone can provide not only the stability of its characteristics and the high sensitivity, but also opens perspectives for creating a multichannel adaptive hydroacoustic complex.

Thus, in the present paper a new type of a laser hydrophone based on the formation of dynamic holograms in a photorefractive crystal is proposed and studied. It is shown that the use of dynamic holograms in the interferometric hydrophones allows one to avoid the necessity of using complex optical schemes and systems of electronic stabilisation of the operating point of the interferometer. This essentially simplifies the scheme of the laser hydrophone, keeping high its sensitivity, and makes it promising for the use under the conditions of strongly changing environmental parameters. The LAHH implemented in the present work has the sensitivity at the level of 3.3 mV Pa^{-1} that provides the detection threshold of the acoustic pressure 130 Pa in the frequency range 1–30 kHz. The design of the laser hydrophone based on the principles of adaptive holographic interferometry opens the possibilities of reducing the threshold of broadband detection to the level smaller than 0.1 Pa without modifying the optical scheme. Moreover, due to the multiplexing of many dynamic holograms in one photorefractive crystal one can build a multichannel laser high-sensitivity hydroacoustic complex with the number of channels greater than 30.

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