

Article

Low-Frequency Optical Hydrophone Based on Active Optical Path Compensation and Low-Coherence Interference

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Abstract

Traditional interferometric optical hydrophones typically employ narrow-linewidth lasers. Although their long coherence length facilitates interference, it also makes the system highly susceptible to spurious interference and phase noise. Low-coherence sources can effectively suppress such parasitic noise; however, their extremely short coherence length imposes stringent stability requirements on the optical path difference (OPD). In underwater environments, ambient disturbances easily cause OPD drift beyond the coherence length, resulting in loss of interference. To address this issue, we propose and experimentally demonstrate a closed-loop hydrophone system that combines low-coherence interferometry with dynamic OPD compensation using a programmable fiber delay line (FDL). Numerical simulations and experiments confirm that the closed-loop compensation algorithm maintains the OPD within the coherence length under environmental perturbations, thereby ensuring long-term stable interference. The prototype achieves a sensitivity of -117.82 dB re rad/ μPa at 171 Hz, a noise-equivalent sound pressure spectral density of 8.69 dB re 1 $\mu\text{Pa}/\sqrt{\text{Hz}}$, a measured peak phase amplitude of 130 rad, a minimum detectable phase of 14 μrad , and a corresponding logarithmic dynamic range of 139 dB. These results verify the feasibility of integrating low-coherence interferometry with active OPD compensation for low-frequency underwater acoustic detection, under laboratory quasi-static environmental conditions, the proposed closed-loop compensation maintained stable interference throughout a continuous 1.5-h experiment, presenting a differentiated and worthy-of-further-engineering-exploration technical path for high-sensitivity and low-noise optical hydrophones.

Keywords: fiber optic hydrophone; low-coherence interferometry; active optical path compensation; low-frequency



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1. Introduction

Fiber-optic hydrophones (FOHs) offer high sensitivity and strong immunity to electromagnetic interference, making them indispensable in underwater target detection and marine resource exploration [1–4]. Since the attenuation coefficient of acoustic waves in seawater is approximately proportional to the square of the frequency, low-frequency signals (from a few Hz to several hundred Hz) are critical for long-range detection of submerged targets, such as quiet submarines [5–7]. Therefore, FOHs must possess excellent low-frequency weak-signal detection capability.

Conventional interferometric FOHs use lasers as the light source. While their long coherence length facilitates stable interference, it also renders the system excessively sensitive to backscattering, Rayleigh scattering, and nonlinear effects, which introduce additional

phase noise [8–10]. For low-frequency weak acoustic signals, the induced phase changes are small and can easily be overwhelmed by such parasitic noise. Studies have shown that Rayleigh spurious interference can increase the background noise of phase demodulation by approximately 10 dB [11]. Although reducing the laser coherence length can suppress this parasitic noise, it concurrently raises the noise floor due to decreased fringe visibility, creating a trade-off [12]. Low-coherence sources, such as amplified spontaneous emission (ASE), inherently suppress spurious interference via their ultra-short coherence length [13,14]. However, this same property makes the system extremely sensitive to OPD variations. In dynamic underwater environments, even minor temperature and pressure fluctuations can cause the OPD to drift beyond the coherence length, leading to system lock-out and severely hindering practical deployment [15].

Recent efforts have explored various approaches to improve low-frequency FOH performance. Sensitization structures, such as ultra-weak fiber Bragg grating (UWFBG) coils, have achieved an average sensitivity of 144.8 dB in the 1–100 Hz range [16]. Sagnac-based arrays and EFPI-based designs have also demonstrated high sensitivity and low equivalent noise [17–20]. In terms of noise suppression, Wang et al. proposed PRBS phase modulation to achieve 84.5 dB background noise suppression [21]. Despite these advances, a significant trade-off remains among sensitivity, noise-equivalent pressure, and long-term stability. Critically, the ability of low-coherence interferometric systems to maintain stable interference over extended periods in low-frequency bands has not yet been systematically validated.

To address these bottlenecks, we propose and implement a closed-loop system based on low-coherence interference and active OPD compensation via a programmable FDL. The system employs an ASE source to fundamentally suppress parasitic noise, integrates a Y-branch phase modulator, and incorporates a real-time feedback algorithm that drives the FDL to compensate for environmentally induced OPD drift. This design maintains the low-noise advantage while ensuring long-term interference stability, thereby demonstrating the feasibility of this alternative technical route for high-sensitivity, low-frequency underwater acoustic detection.

2. Configuration and Simulation of Fiber Hydrophone Based on Low-Coherence Optical Interferometry

The proposed high-performance fiber-optic hydrophone employs a Michelson interferometer architecture, with its optical path configuration shown in Figure 1. A broadband amplified spontaneous emission (ASE) source serves as the low-coherence light source, operating at a center wavelength of 1550 nm with spectral width of 6 nm. The measured coherence spectrum is presented in the figure, yielding a coherence length of 0.2 mm, which is adopted throughout this work. A two-hour source stability test revealed a center-wavelength drift of only 0.005 nm and power fluctuation within 1.2%, with negligible spectral bandwidth change. The resulting coherence length variation was estimated below 1%, confirming that a fixed coherence length is a valid approximation.

As shown in Figure 2, The ASE source used in this system provides an output power of 10 mW, corresponding to a measured coherence length of 0.2 mm. The optical signal is routed through a three-port circulator (insertion loss: 0.8 dB; isolation: ≥ 50 dB) into a Y-waveguide phase modulator, which exhibits an insertion loss of 3.5 dB, a polarization extinction ratio of ≥ 20 dB, and a half-wave voltage of 3.5 V. The interference signal is detected by a photodetector featuring a responsivity of 0.85 A/W at 1550 nm, a bandwidth of 10 MHz, and a dark current of 1 nA. This Y waveguide divides the incident light into two paths and feeds them into the sensing arm and the reference arm. At the same time, push-pull phase modulation is implemented on the two arms by applying stepped wave

voltages, generating a phase carrier in the optical domain. Stepped wave voltages with opposite polarities are applied to the two output arms of the Y waveguide, resulting in phase changes of $+\phi_m \cos(2\pi f_m t)$ and $-\phi_m \cos(2\pi f_m t)$ respectively. When the acoustic pressure acts on the sensing arm, the introduced acoustic-induced phase difference is $\phi_s(t)$.

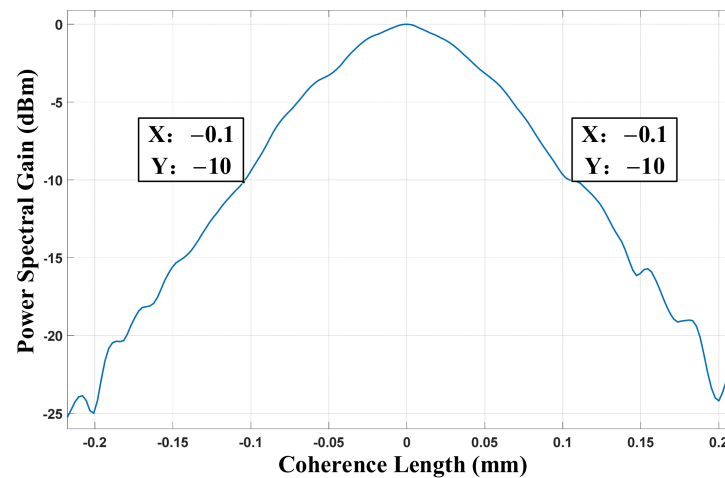


Figure 1. ASE light source coherence spectrum diagram.

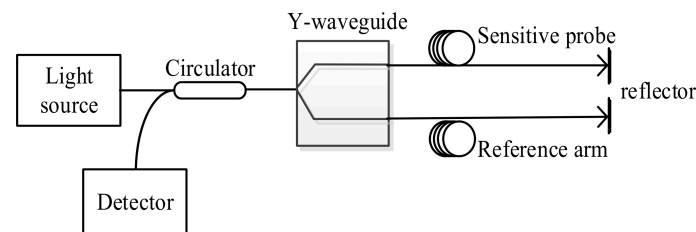


Figure 2. Optical path scheme for optical fiber hydrophones based on low-coherent optical interference.

Therefore, the phase difference of the two returning beams at the output end of the interferometer is:

$$\Delta\phi(t) = \phi_s(t) + 2\phi_m \cos(2\pi f_m t) \quad (1)$$

Among them, $\phi_s(t)$ represents the phase change of the measured object caused by the sound pressure. This phase difference is encoded in the interference light intensity. The photocurrent output by the photodetector is:

$$I(t) = I_0 \{1 + V \cos[\phi_s(t) + 2\phi_m \cos(2\pi f_m t)]\} \quad (2)$$

In order to linearly extract $\phi_s(t)$ from this nonlinear function, the system employs the phase generation carrier (PGC) demodulation technique. The $I(t)$ is multiplied respectively with the reference signals of frequencies f_m and $2f_m$, and the high-frequency components are filtered out through a low-pass filter to obtain two orthogonal signals:

$$P(t) = -I_0 V J_1(\phi_m) \sin[\phi_s(t)] \quad (3)$$

$$Q(t) = -I_0 V J_2(\phi_m) \cos[\phi_s(t)] \quad (4)$$

J_1 and J_2 are Bessel functions. By differentiating and cross-multiplying (DCM) these two signals or performing the arctangent operation directly, $\phi_s(t)$ can be demodulated:

$$\phi_s(t) = \arctan\left(\frac{P(t)}{Q(t)} \cdot \frac{J_2(\phi_m)}{J_1(\phi_m)}\right) \quad (5)$$

This demodulation process restores the tiny phase changes caused by sound waves from the high-frequency carrier, achieving high linearity, large dynamic range and high-precision phase detection.

The shot noise level of the high-precision optical hydrophone determines the lower limit for detecting weak sound wave signals. Based on low-coherence optical interference, the noise of the optical hydrophone mainly comes from optical path noise, including: shot noise, relative intensity noise, detector thermal noise, etc.

According to theoretical derivation, the system signal-to-noise ratio is:

$$\Delta\Omega = \left(\frac{e}{2P_d R t} \frac{1}{\sin^2(\Phi_m/2)} + \frac{\lambda_0^2}{4c\Delta\lambda t} \frac{1}{\tan^2(\Phi_m/2)} + \frac{4KT}{R_L R^2 P_d^2 t} \frac{1}{\sin^2\Phi_m} \right)^{1/2} \quad (6)$$

In the formula, the first term represents random noise, the second term represents relative intensity noise, and the third term represents detector thermal noise. The size and physical meaning of the parameters in the formula are shown in Table 1. By substituting the parameters of the optical fiber hydrophone into the formula, when the sound wave is input, the minimum detection of the sound wave phase change can be calculated to be 0.3 μrad . This value characterizes the lower limit of phase detection of the optical fiber hydrophone based on low-coherence optical interference under ideal conditions, providing a theoretical benchmark for subsequent experimental evaluation. The gap between this ideal lower bound and the experimentally measured value is attributable to quantifiable noise sources in the experimental environment, including power-line harmonics and mechanical vibration, as discussed in Section 3.

Table 1. Calculation parameters.

	Physical Quantity	Value	Unit
e	Electron charge	1.60207×10^{-19}	C
K	Boltzmann constant	1.381×10^{-23}	J/K
c	Speed of light in vacuum	2.99793×10^8	m/s
t	Output integration time	10	s
T	Absolute temperature	298	K
R	Detector responsivity	0.85	A/W
λ	Mean wavelength	1531	nm
Φ	Modulation amplitude	$\pi/2$	rad

The sensitive arm and the reference arm of the Michelson interferometer are separated from each other. After actual assembly, the static OPD of the two arms is usually in the centimeter range, much larger than the coherence length of the light source. To enable the system to enter the interference state, the total OPD (the sum of the static OPD and the OPD introduced by the delay line) needs to be reduced to within the coherence length through dynamic compensation. For this purpose, an optical fiber delay line (FDL) is introduced into the system [17]. The FDL with an adjustment range of ± 5 cm, a step resolution of 0.1 μm , and a maximum slewing rate of 500 $\mu\text{m/s}$ is incorporated into the reference arm for active optical path compensation.

When the system is started, the FDL scans continuously within the ± 5 cm range and changes the OPD it introduces. If the static OPD is denoted as L_s , then the total OPD is $L_s + L_{\text{FDL}}$. When L_{FDL} scans to near $-L_s$, the total OPD approaches zero, and the system can enter the coherence length range (< 200 μm) and generate an interference signal. To ensure that this zero point is within the scanning range of the FDL, it is necessary to satisfy $|L_s| \leq 5$ cm. In practical engineering, the initial OPD is controlled within 2 cm, accommodating the normal assembly errors, and a sufficient margin is reserved for the

± 5 cm regulation range of the FDL to ensure that the interference zero point can still be reliably searched for under assembly deviations and environmental disturbances. Once the interference peak is located, the system records the position of the FDL at this time as the initial zero point L_0 . The closed-loop control system will lock the total OPD within the coherence length and real-time compensate for the optical path drift caused by subsequent environmental disturbances, thereby maintaining a long-term stable interference state. To achieve this, two key thresholds are defined in the control algorithm. Choosing a smaller L_1 would trigger compensation more frequently and increase actuator wear, whereas a larger threshold would allow the interference visibility to decrease significantly before compensation starts. The selection of L_1 and L_2 is a compromise between the interference visibility and the working frequency of the actuator. When L_1 is set to 100 μm , the corresponding interference visibility is still above 0.7, which can ensure the linearity of PGC demodulation; at this threshold, the compensation trigger frequency caused by typical environmental disturbances is within the reasonable working range of the actuator. L_2 is set to 10 μm , which is one order of magnitude smaller than the coherence length to ensure compensation accuracy, and is much larger than the bottom of the OPD measurement noise (about 1 μm), which can effectively avoid limit cycle oscillation. The assembled physical object is shown in Figure 3.

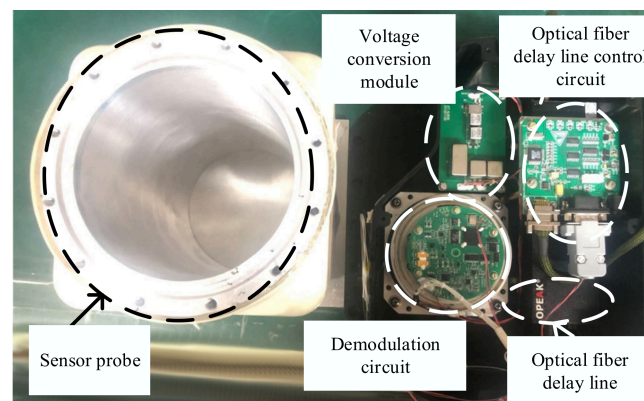


Figure 3. Physical diagram of the optical fiber hydrophone configuration.

The algorithm flowchart is shown in Figure 4. The specific steps are as follows:

Initialization and zero-point calibration: After the system starts, FDL scans within the range of ± 5 cm, searches for the peak of the interference signal, and defines the position corresponding to the maximum interference visibility as the system zero point L_0 . Since the initial static OPD is ≤ 2 cm, the FDL scanning range covers the interval where the zero point is located, ensuring that the zero point position can be successfully scanned.

Real-time monitoring and judgment: The demodulation circuit samples the current OPD at fixed time intervals Δt and calculates its moving average OPD. The system continuously judges whether the absolute value of $|\text{AverageOPD} - L_0|$ exceeds the startup threshold L_1 . If not, it indicates that the OPD drift is still within the acceptable range and no compensation is required.

Execute compensation: Once it is detected that $|\text{AverageOPD} - L_0| > L_1$, the demodulation circuit immediately sends a start command and direction signal (the movement direction is opposite to the trend of OPD drift) to the delay line motor, and begins to perform optical path compensation.



Figure 4. Flowchart of the optical fiber delay line control program.

Precise locking and stopping: During the motor movement, the system continuously monitors the OPD. When the compensation reduces the difference to the stop threshold L_2 , that is, $|\text{OPD}-L_0| < L_2$, it indicates that the OPD has returned to the interference center area, and the system issues a stop command, stopping the motor, until the next drift triggers.

To verify the effectiveness of the proposed dynamic compensation mechanism for optical path difference, this paper uses MATLAB (v2019) to establish a numerical simulation model for a low-coherence interferometer system. The simulation content includes: the relationship between the interference visibility and the OPD, as well as the stability analysis after closed-loop compensation.

The low-coherence light source adopts a Gaussian spectrum, with a central wavelength $\lambda_0 = 1550$ nm and a spectral width $\Delta\lambda = 6$ nm. According to the Wiener–Sinc theorem, the envelope (visibility) of the interference signal is determined by the Fourier transform of the light source spectrum. For a Gaussian spectrum, the interference light intensity can be expressed as:

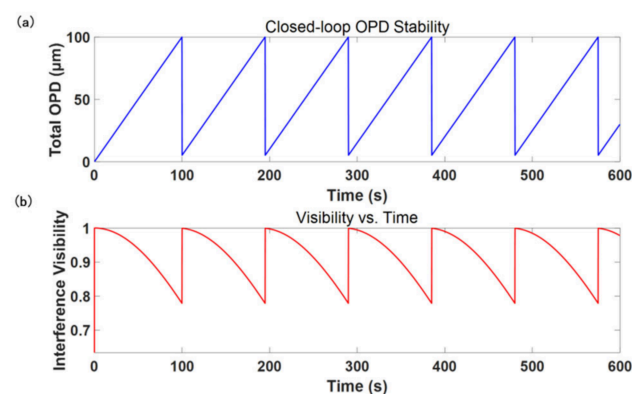
$$I(\Delta z) = I_0 \left[1 + \exp \left(- \left(\frac{\Delta z}{L_c} \right)^2 \right) \cos(2\pi \Delta z / \lambda_0) \right] \quad (7)$$

In the simulation, the initial static optical path difference of the two arms of the Michelson interferometer was set to $L_s = 2$ cm. The adjustable optical path L_{FDL} introduced by the programmable FDL ranges from -5 cm to $+5$ cm, with a step accuracy of $0.1 \mu\text{m}$. The environmental disturbance simulation is as follows: the linear OPD drift rate caused by temperature change is $1 \mu\text{m/s}$, and the standard deviation of the superimposed random noise is $0.1 \mu\text{m}$. The key parameters used for simulating the dynamic compensation of optical path differences are shown in Table 2.

Table 2. The key parameters used in the simulation of dynamic compensation for optical path difference.

Parameter Symbol	Description	Value	Unit
λ_0	ASE source center wavelength	1550	nm
$\Delta\lambda$	Spectral width	6	nm
L_c	Coherence length	200	μm
L_s	Static optical path difference	2	cm
L_{FDL}	Programmable delay line adjustment range	± 5	cm
L_1	Compensation start threshold	100	μm
L_2	Compensation stop threshold	10	μm
v	FDL motor moving speed	500	$\mu\text{m/s}$
T_{sim}	Total simulation time	600	s
dr/dt (env.)	Environmental disturbance-induced optical path drift rate	1	$\mu\text{m/s}$
σ_{noise}	Random OPD noise standard deviation	0.1	μm

After enabling the closed-loop compensation algorithm, the system continuously monitors the total OPD and controls the FDL motor for compensation. Figure 5a presents the total OPD timing curve after the closed-loop locking. In the initial stage (0–10 s), the system quickly searches and locks the zero point. When the simulated environmental temperature disturbance causes the OPD to drift, the compensation motor starts approximately every 80 s, and each compensation lasts for about 0.2 s, pulling the OPD back to near the zero point. Under the continuous 600-s environmental drift, the total OPD is always limited within the range of 100 μm . Figure 5b shows that the interference visibility remains above 0.7. During the compensation process, there is no interruption of the interference signal, and the phase modulation frequency caused by the motor movement is much lower than the high-frequency carrier of demodulation. This can be eliminated through subsequent filtering. This simulation result provides a theoretical basis for the subsequent experimental system design and parameter selection, and verifies the feasibility of low-coherence interference combined with active OPD compensation.

**Figure 5.** Simulation results: (a) Curve showing the variation in total optical path difference over time. (b) Curve showing the variation in interference visibility over time.

3. Experiment of Optical Fiber Hydrophone Based on Low-Coherent Light Interference

During the research process of this paper, experiments were mainly conducted on sound wave signals ranging from 10 to 300 Hz. The testing work would follow a logical progression from standard to practical: Firstly, the core performance parameters of the prototype, namely phase sensitivity and threshold, would be precisely calibrated in an acoustic water tank to quantify its static performance; then, in a laboratory vibration-isolation environment, its ability to detect large signals and weak signals would be tested to verify its dynamic performance.

The sensitivity of the optical hydrophone refers to the efficiency of converting the input sound pressure signal into an optical signal change. It represents the phase change of the optical fiber caused by a 1 μPa change in sound pressure, which is also the core principle of the interferometric optical hydrophone. The sensitivity is measured in dB re $\text{rad}/\mu\text{Pa}$ and is typically quantified using an exponential scale, i.e., $M = 20\lg(\text{MP}/\text{Mr})$, where $\text{Mr} = 1 \text{ rad}/\mu\text{Pa}$ is the reference sensitivity. The threshold refers to the minimum sound pressure that can be detected, that is, the input sound pressure when the output signal equals the system noise, which is the background noise in the sound pressure level, and it is a quantitative indicator of the system's detection capability limit. The threshold is measured in dB re $1 \mu\text{Pa}/\sqrt{\text{Hz}}$ and can intuitively reflect the performance of frequency band normalization. The testing process follows the "comparison method"; that is, the tested optical hydrophone is calibrated using a standard piezoelectric hydrophone. In the experimental process of this paper, a standard reference hydrophone, a standard transmitting transducer, a signal generator, and a data acquisition system need to be prepared. The standard reference hydrophone selected in this paper is the B&K 8103 piezoelectric hydrophone (with a frequency range of 0.1 Hz to 180 kHz and a sensitivity of $-211 \text{ dB re } 1 \text{ V}/\mu\text{Pa}$). The test results are as follows:

The test was conducted on the intermediate value of the low-frequency sound wave signal at 171 Hz. The sound pressure level test result of the standard piezoelectric hydrophone is shown in Figure 6. The sound pressure value is 91.23 dB, and the threshold is 27.13 dB.

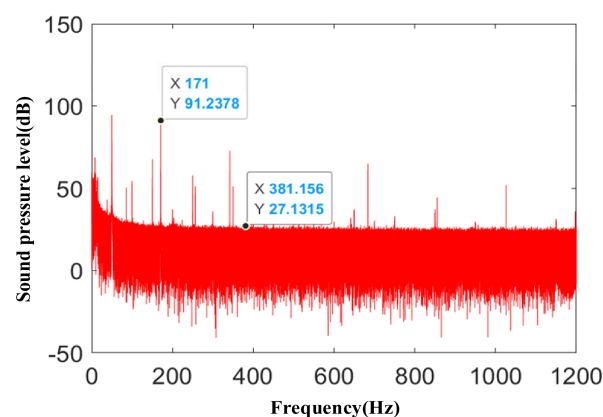


Figure 6. Sound pressure level of standard piezoelectric hydrophone at 171 Hz.

The demodulation phase test results of the corresponding optical fiber hydrophone prototype are shown in Figure 7. The acoustic signal is 91.23 dB, and the threshold is 8.69 dB. Based on the known sensitivity of the standard piezoelectric hydrophone at the corresponding frequency point, the actual sound pressure value is calculated, and finally, the sensitivity of the optical fiber hydrophone prototype at the frequency point 171 Hz is determined to be $-117.82 \text{ dB re rad}/\mu\text{Pa}$.

In addition to the dominant 171 Hz tone, several discrete spurious lines are observable in Figures 6 and 7. Based on their frequency characteristics, these lines are quantitatively identified as follows:

- (1) 50 Hz and its integer harmonics (150 Hz, 250 Hz, 350 Hz, etc.): these coincide with the power-line fundamental and harmonics, attributed to electrical coupling through the power supply and spatial radiation to the photodetection circuit.
- (2) 200 Hz and its mechanical harmonics: these match the stepping frequency of the fiber delay line motor, attributed to vibration coupling into the optical fiber.

- (3) Non-integer spurs: these are characteristic of clock feedthrough from the digital signal processing circuitry [22].

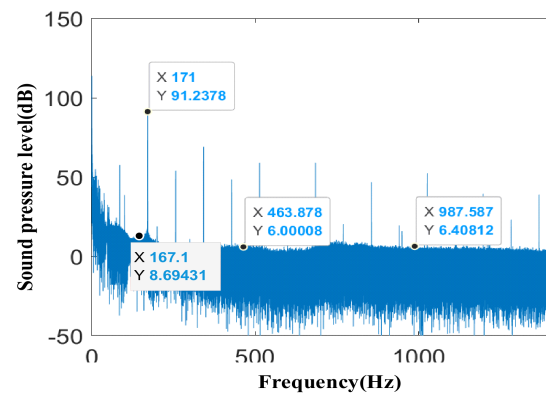


Figure 7. Sound pressure level of the optical fiber hydrophone prototype at 171 Hz.

More importantly, we deliberately did not employ power-line filtering, electromagnetic shielding, electrical isolation, or acoustic encapsulation in this proof-of-concept prototype, specifically to assess the inherent immunity of the low-coherence interferometric scheme under harsh electromagnetic and vibrational conditions. Despite the presence of these spurious lines, the system still achieved the threshold of 8.69 dB re 1 $\mu\text{Pa}/\sqrt{\text{Hz}}$ at 171 Hz.

The prototype was then placed on the isolation platform. After the optical path stabilized and worked in the interference state, a loud wave signal of 171 Hz was emitted from the standard emission transducer in the environment. The sound wave signal caused a phase shift in the sensitive arm fiber, and through acquisition and analysis, the time-domain graph is shown in Figure 8. The maximum peak amplitude of the true position measured in this experiment can reach 130 rad.

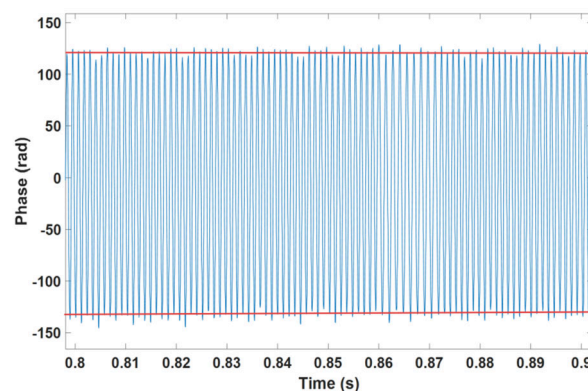


Figure 8. Time-domain phase response of the fiber-optic hydrophone prototype under high-amplitude acoustic excitation at 171 Hz.

The system noise level determines the weakest signal that the system can detect. The lower the value, the smaller the background noise of the system, and the stronger the system's ability to detect weak signals. As shown in Figure 9, which is the frequency domain analysis of the low-frequency part, the phase noise can detect as low as -107.5 dB re rad, the average background noise is approximately -98 dB re rad, and the corresponding phase difference change caused by the weak signal that can be detected is 14 μrad . The maximum detection phase amplitude and the minimum detection phase conversion to the logarithmic dynamic range: $20 \times \lg(130 \text{ rad}/14 \mu\text{rad}) \approx 139$ dB.

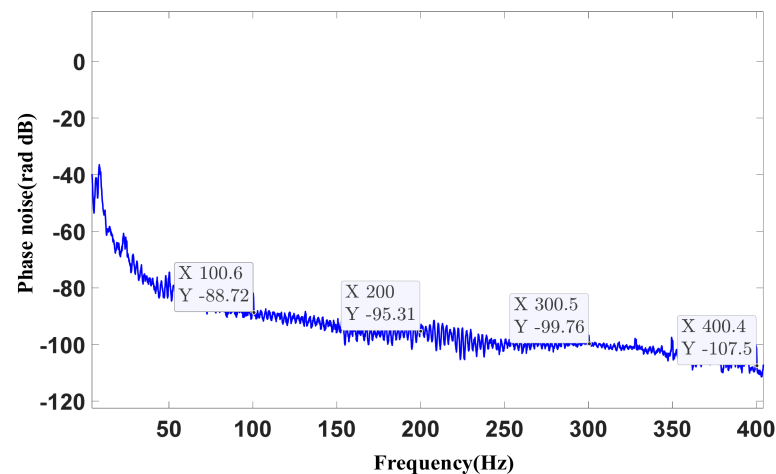


Figure 9. Phase noise power spectral density of the fiber-optic hydrophone prototype in a quiet environment.

To verify the long-term stability of the closed-loop system under environmental drift in real conditions, this system underwent a continuous 1.5 h stability experiment. The system was normally powered on and operated on an optical platform, with the laboratory temperature fluctuating within the range of 22 ± 2 °C. The closed-loop compensation algorithm was continuously in operation. As shown in Figure 10, throughout the 1.5 h observation period, the closed-loop system maintained the optical path within the set range using FDL and no interference loss event occurred. This experimental result further confirmed the effectiveness of the closed-loop active compensation mechanism in resisting quasi-static environmental disturbances.

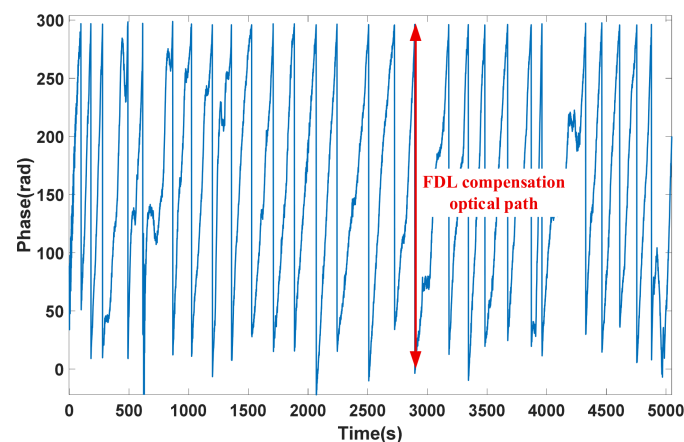


Figure 10. The stability test results of the closed-loop system operating continuously for 1.5 h.

To better position this work, we compare our system with several recently reported representative fiber-optic hydrophones [16–20]. Their reported sensitivities typically range from approximately -140 to -130 dB re rad/ μ Pa. In comparison, our system achieves a sensitivity of -117.82 dB re rad/ μ Pa at 171 Hz and a noise-equivalent pressure of 8.69 dB re 1 μ Pa/ $\sqrt{\text{Hz}}$.

Unlike previous studies that primarily enhance performance through sensing element optimization or interferometric configuration design, the present work addresses parasitic interference at its source by employing a low-coherence light source. However, the ultra-short coherence length makes the interference state highly susceptible to OPD drift. To overcome this, we introduce an active closed-loop OPD compensation strategy to maintain stable interference. This combination—low-coherence light source for noise

suppression plus active compensation for stability—offers a differentiated technical route from previously reported interferometric fiber-optic hydrophones.

4. Conclusions

To address the key issue of being susceptible to parasitic interference noise in the detection of weak acoustic signals by low-frequency optical hydrophones, this paper proposes and validates a technical solution based on the combination of low-coherence optical interference and active optical path compensation. Through programmable optical delay lines and closed-loop active compensation algorithms, real-time tracking and optical path correction for quasi-static disturbances such as temperature and pressure are achieved, effectively mitigating the core bottleneck of low-coherence sources—their difficulty in maintaining stable operation in dynamic underwater acoustic environments due to short coherence length. Experimental results show that the sensitivity of this prototype at 171 Hz is -117.82 dB re rad/ μ Pa, the noise-equivalent threshold is as low as 8.69 dB re 1 μ Pa/ $\sqrt{\text{Hz}}$, the maximum phase amplitude peak can reach 130 rad, the minimum detectable phase is 14 μ rad, and the calculated logarithmic dynamic range is 139 dB. Taken together, the present results demonstrate, at a proof-of-concept level, the feasibility of integrating low-coherence interferometry with active OPD compensation for low-frequency underwater acoustic sensing. The closed-loop method proposed and validated here effectively maintains interference stability under laboratory-scale quasi-static disturbances.

Although encouraging results have been obtained, the present validation is limited to laboratory quasi-static conditions and a prototype-level implementation. Future work will include long-duration operation, dynamic underwater environmental testing, and engineering optimization of electromagnetic shielding and vibration isolation.

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