# Phase Noise Suppression of Light Sources in Interferometric Fiber-Optic Hydrophone Systems Based on Linear Frequency Modulation


Ying Mao
*State Key Laboratory of Information Photonics and Optical Communications Beijing University of Posts and Telecommunications*
Beijing, China
1908115629@bupt.edu.cn

Mengyuan Zhao
*State Key Laboratory of Information Photonics and Optical Communications Beijing University of Posts and Telecommunications*
Beijing, China
zhaomy2020@bupt.edu.cn

Zexu Wang
*State Key Laboratory of Information Photonics and Optical Communications Beijing University of Posts and Telecommunications*
Beijing, China
2017213556@bupt.edu.cn

Feifei Yin
*State Key Laboratory of Information Photonics and Optical Communications Beijing University of Posts and Telecommunications*
Beijing, China
yinfeifei@bupt.edu.cn

Kun Xu
*State Key Laboratory of Information Photonics and Optical Communications Beijing University of Posts and Telecommunications*
Beijing, China
xukun@bupt.edu.cn

Yitang Dai
*State Key Laboratory of Information Photonics and Optical Communications Beijing University of Posts and Telecommunications*
Beijing, China
ytdai@bupt.edu.cn



***Abstract*—We introduced a reference interferometer in linear frequency modulation (LFM)-based heterodyne-type interferometric fiber-optic hydrophone system, and use an adaptive filtering technique to suppress the light source phase noise and improve system tolerance for laser linewidth.**



***Keywords*—phase noise of the light source, linear frequency modulation, fiber-optic hydrophone, laser linewidth, adaptive filters**


## I. INTRODUCTION

The fiber-optic hydrophone is a novel sensor that employs fiber-optics as the medium of information transmission to convert hydroacoustic signals into optical signals, thereby detecting underwater sound waves. It offers a host of advantages, including a large dynamic range, high sensitivity, compact size, ruggedness in harsh environments, high stability, long transmission distance, strong immunity to electromagnetic interference and crosstalk, and easy scalability into large-scale arrays[1]. Consequently, it finds extensive applications in both military and civilian domains, such as biomedical monitoring, military sonar, seismic surveys, oil and gas reservoir surveys, and hydroacoustic physics research[2-5].

In practical applications of fiber-optic hydrophones, the system background noise is a critical factor that affects detection performance, and several factors influence it. The interferometric fiber-optic hydrophone system based on linear frequency modulation (LFM) employs a nonequilibrium interferometer, which is a passive device that does not generate phase noise by itself. However, the phase noise of the light source is transformed into system noise after passing through the nonequilibrium interferometer, becoming one of the main factors that affect the detection sensitivity of the fiber-optic hydrophone. Therefore, it is necessary to suppress the phase noise of the light source. While some researchers attempt to suppress the phase noise of the light source by optimizing the laser's structure and parameters[6], it can be difficult and expensive to obtain such light sources. Alternatively, many researchers have combined the introduction of an auxiliary reference interferometer with direct phase subtraction or adaptive filtering techniques to suppress the phase noise of the light source[7-9]. Adaptive filters use adaptive algorithms to dynamically adjust the coefficients of the filters in signal processing, achieving an optimal estimation of system noise and providing excellent noise cancellation effects. These techniques have been successfully applied in various fields, including communication, radar, biomedical monitoring, fiber-optic sensing, and others[10]. However, most of the previous studies have used phase-generated carrier (PGC)-based signal detection methods.

In our previous work, we achieved improvement in the system's nonlinearity tolerance by applying LFM pulses in an interferometric fiber-optic hydrophone system[11]. Building on this, this paper proposes the introduction of a reference interferometer and the adoption of an adaptive filtering technique based on the recursive least squares (RLS) algorithm to suppress the phase noise of the light source. The experimental results demonstrate that this technique can reduce the phase noise level of a system with a laser linewidth on the order of MHz to the phase noise level of a system with a laser linewidth of 1.41 kHz. Specifically, when the laser linewidth is 338.06 MHz, the system phase noise is reduced by 18.5 dB and 26 dB at frequencies of 100 Hz and 1 kHz, respectively. Therefore, the work in this paper effectively reduces the phase noise introduced by the light source and improves the linewidth tolerance of the LFM-based heterodyne-type interferometric fiber-optic hydrophone system.

## II. OPERATION PRINCIPLES AND EXPERIMENTAL SETUP

The use of nonequilibrium interferometer is necessary for the LFM system, and the phase noise of the light source will become the main influence factor of the background noise of the system after passing through the nonequilibrium interferometer. To eliminate the phase noise of the light source, we first introduce a dumb probe with the same structure as the sensing probe in the LFM system, but insensitive to the sound pressure to obtain the phase noise of the light source that is homologous and highly correlated with the sensing probe, and then input the interference signal detected by the two probes into the adaptive filtering system after demodulation by the heterodyne demodulation method, and finally achieve the suppression of the phase

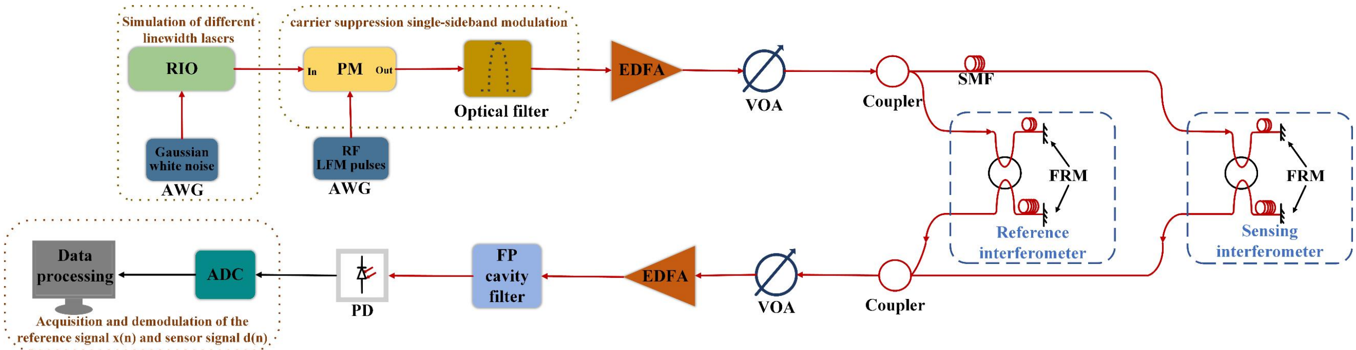


Fig. 1. Experimental setup. AWG: arbitrary waveform generator; RIO: Redfern Integrated Optics Inc; PM: phase modulator; EDFA: erbium-doped fiber amplifier; VOA: variable optical attenuator; SMF: single mode fiber; FRM: Faraday electromagnetic rotating mirrors; PD: photodetector; ADC: analog-to-digital converter.

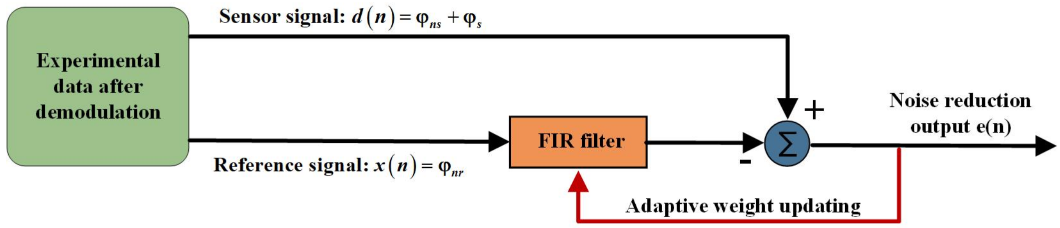


Fig. 2. Principle of adaptive filtering.

noise of the light source through the continuous iteration of the RLS algorithm to reduce the influence of the laser linewidth on the system.

The system of interferometric fiber-optic hydrophone based on high repetition rate LFM pulses after the introduction of reference interferometer is shown in Fig. 1. At the transmitter side, we use an RIO (Redfern Integrated Optics Inc) laser with a very narrow linewidth and high stability as the light source and add Gaussian white noise dither to it with an arbitrary waveform generator (AWG) to simulate lasers of different linewidths. Another AWG is used to generate radio frequency (RF) LFM pulses with a duration of 312.5 ns, bandwidth of 1.5 GHz, and repetition rate of about 195.31 kHz. The optical LFM pulses were first obtained by applying carrier suppression single-sideband modulation (CS-SSB) to the light source through a phase modulator (PM) and a narrowband optical filter aligned with the upper sideband of the modulation spectrum. The optical LFM pulse is then amplified by an erbium-doped fiber amplifier (EDFA) with adjustable gain and 4.5 dB noise factor and then linked to the long-distance fiber, and to eliminate the phase noise and nonlinear effects of fiber transmission, we simulate the fiber loss with a variable optical attenuator (VOA) and set the total loss of the fiber array to 44 dB. Each sensor in the sensor array consists of a Michelson interferometer, in which each interferometer uses a pair of Faraday electromagnetic rotating mirrors (FRMs) to cancel the polarization fading. The interferometric fringes formed by each sensor are independent and can therefore be sensed on a large scale in a time-division multiplexed (TDM) manner. The duty cycle is about 1/16 as indicated by the duration and repetition rate of the LFM pulses, thus, our system can achieve time-division multiplexing of 16 sensors. To simplify the system, we use a single Michelson interferometer with an arm-length difference of 0.247m to simulate the sensor array, and introduce a reference interferometer with the same structure as the sensing interferometer and an arm-length difference of 0.252m, but insensitive to acoustic pressure. The two interferometer signals each occupy a one-time division and form a TDM sequence for transmission. Another EDFA with adjustable gain and the same noise factor amplifies the echo signal, which is then filtered by a Fabry-Perot (FP) cavity filter and transformed into an electrical signal by a photodetector (PD). An analog-to-digital converter (ADC) with a sampling rate of 100 MHz and an effective number of bits (ENOB) of 10 is used for signal acquisition. Finally, the interferometric signal is demodulated by the heterodyne demodulation method.

In the LFM system, the nonequilibrium Michelson interferometer decomposes the LFM pulse into two equal LFM pulses through the two arms of the interferometer, the interferometer has a small difference in arm length between the two arms, and the two pulses will produce a delay in the time domain, the frequency of the LFM pulse changes with time, then the two pulse frequencies will be different, and then produce interference stripes in the time domain, the phase change of the stripes can be used to record the modulation of the sound signal[11]. The transmitter generates a sequence of optical LFM pulses as

$$x(t) = \sum_k q(t-kT)\cdot e^{-i\pi\alpha(t-kT)^2} \tag{1}$$

Where α is the chirp rate, $q(t)$ is the pulse envelope, and $T$ is the period of the LFM pulse. When considering the phase noise of the light source, the optical field entering the interferometer can be expressed as

$$E(t) = E_0 \cdot x(t) \cdot \exp\left\{ i\left[ 2\pi(v_0 + \Delta v)t + \phi_0 + \Delta\phi(t) \right] \right\} \tag{2}$$

$E_0$ is the amplitude of the optical field, $v_0$ is the initial center frequency of the laser and $\phi_0$ is the stable part of the optical field phase. The phase noise of the light source comes from the linewidth and center frequency jitter of the laser. Where $\Delta v$ is the center frequency jitter term and $\Delta\phi(t)$ is the phase undulation term which is closely related to the laser linewidth. The interference signal obtained after passing the interferometer with the arm length difference of $l$ is

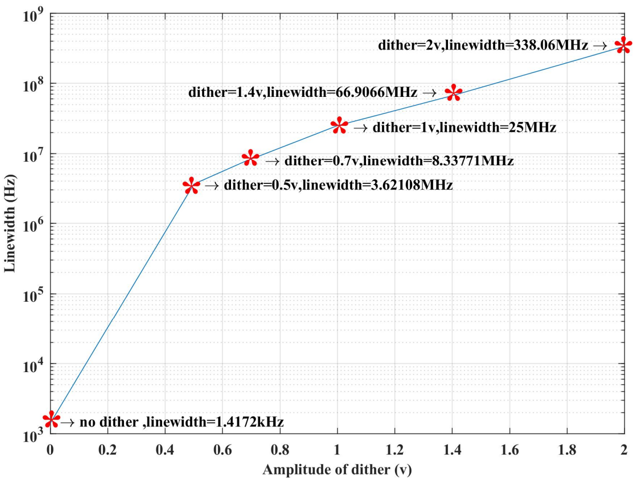


Fig. 3. Results of laser linewidth variation with different amplitudes of dither.

$$I = A + B\sum_k p(t-kT)\cdot \cos\begin{bmatrix} 2\pi\alpha\tau kT + \pi\alpha\tau^2 - 2\pi\alpha\tau t + \phi_s \\ +2\pi(v_0+\Delta v)\tau + \Delta\phi(t) - \Delta\phi(t-\tau) \end{bmatrix} \tag{3}$$

Where A and B are constants proportional to the input optical power and the visibility of the interferometric signal, $\tau=2nl/c$ is the difference in delay between the two arms of the interferometer, $p(t)=q(t)\cdot q^*(t\text{-}\tau)$ and $p(t)$ are the same for different time slots, and $\phi_s$ is the phase difference caused by the modulation of the acoustic signal. From equation (3), it can be seen that the phase shift $2\pi\alpha\tau kT$ in each cycle makes $\alpha\tau$ no longer one of the harmonics, and in order for the phase modulation to be carried on the carrier with frequency $\alpha\tau$, then $\alpha\tau T$ should be an integer. That is, the use of high repetition frequency LFM pulses makes the echo beat frequency no longer proportional to the arm length difference, but an integer multiple of the repetition frequency, so that accurate phase demodulation can be achieved[11]. Meanwhile, It can be seen that the phase noise of the light source is transformed into the system phase noise after passing through the nonequilibrium interferometer, and it is related to the interferometer arm length difference and the laser linewidth. The traditional heterodyne system uses the balanced interferometer, which can ignore the influence of light source phase noise on the system to a certain extent, while in the LFM system, it is necessary to suppress the phase noise of the light source.

As shown in Fig. 2. The reference signal detected by the reference interferometer $x(n)$ and the sensor signal detected by the sensing interferometer $d(n)$ are used as the two inputs of the adaptive filtering, respectively. $\varphi_{nr}$ and $\varphi_{ns}$ are the phase noise introduced by the light source in the reference interferometer and the sensing interferometer, respectively. $\varphi_s$ is the sensing signal detected by the sensing interferometer. Since the phase noise of the light source acquired by the reference and sensing interferometer comes from the same laser, and the system phase noise introduced by the light source is related to the interferometer arm length difference, the difference in arm length between the reference and sensing interferometer we use is only 5*mm*, so $\varphi_{nr}$ and $\varphi_{ns}$ are highly correlated. We use the RLS algorithm with fast convergence and high stability to control the FIR

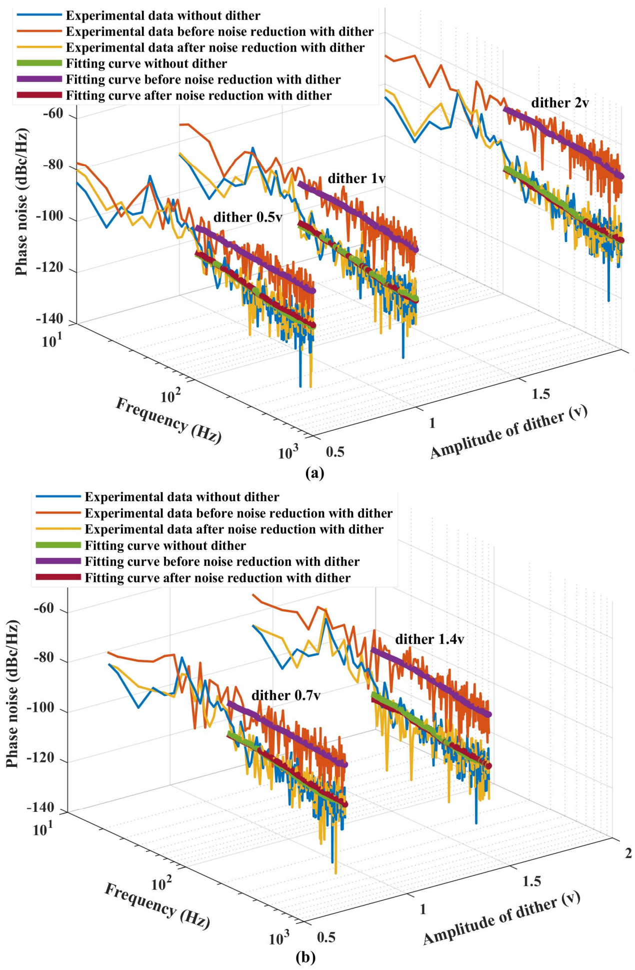


Fig. 4. Noise reduction results of sensing probe under different amplitude dither. (a) Dither for 0.5v, 1v , 2v ;(b) Dither for 0.7v, 1.4v.

filter weights by feedback and adjust them dynamically, which can make $\varphi_{nr}$ gradually approach $\varphi_{ns}$ and finally achieve the best estimate of $e(n)$ to $\varphi_s$ , effectively suppressing the phase noise of the light source. The cost function to be minimized in the RLS algorithm is

$$\varepsilon(n) = \sum_{i=1}^{n} \lambda^{n-i} \left|e(i)\right|^2 + \delta\lambda^n \left\|w(n)\right\|^2 \tag{4}$$

Where $i$=1,2,…,$n$ and $\lambda$ are a number close to 1 but less than 1, and $\lambda^{n-i}$ is the forgetting factor that ensures that long-ago data are forgotten so that the filter works in a nonsmooth environment. The second term on the right side of the equation is the regularization term that acts as a smoothing factor, and $\delta$ is the regularization parameter. The algorithm performs an iterative update of the weights according to the following procedure.

$$e(n) = d(n) - w^T(n-1)x(n) \tag{5}$$

$$k(n) = \frac{\lambda^{-1}P(n-1)x(n)}{1+\lambda^{-1}x^T(n)P(n-1)x(n)} \tag{6}$$

$$w(n) = w(n-1) + K(n)e^*(n) \tag{7}$$

$$P(n) = \lambda^{-1}P(n-1) - \lambda^{-1}K(n)x^T(n)P(n-1) \tag{8}$$

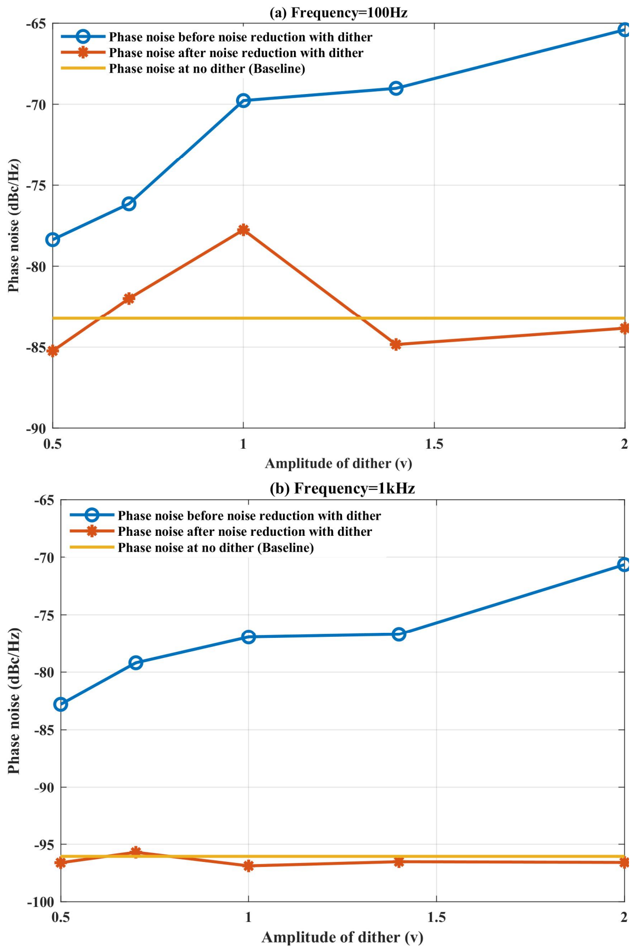


Fig. 5. Noise reduction results of sensing probe at different frequency points. (a) Frequency is 100 Hz ; (b) Frequency is 1 kHz.

Equation (5) is used for error signal estimation, Equation (6) is used to update the gain vector, Equation (7) is used for weight update, and Equation (8) is used to update the inverse correlation matrix of the input. Where n=1,2,3,..., T is the transpose, * is the conjugate transpose, and for initialization, let w(0)=0, P(0)=$\delta^{-1}$I, I be the unit matrix. Through several simulation tests, we set the filter order M=100, $\lambda$=0.9995, $\delta$=0.01.

In this paper, only single-wavelength systems are discussed. When multiple wavelengths are transmitted together, in the downlink, optical pulses of different wavelengths will occupy different time slots and not overlap with each other. In the uplink, the optical power is very low, so the nonlinear crosstalk between different wavelengths in the fiber can be neglected. So our conclusion can be extended to wavelength division multiplexing (WDM) systems.

## III. Experimental Results and Discussion

We simulate the laser with different linewidths by adding different amplitudes of white noise dither to the RIO laser. The laser linewidth variation under different dithers is shown in Fig. 3. As seen in the figure, we use the RIO laser linewidth of about 1.41 kHz, which belongs to a very narrow linewidth highly stable light source, and can to a certain extent ignore the phase noise of the light source. Frequencies of 100 kHz, and amplitudes of 0.5 V, 0.7 V, 1 V, 1.4 V, and 2 V Gaussian white noise dithers cause the RIO laser linewidth to gradually increase. For a dither of 2 V, the linewidth has increased to 338.06 MHz. At this point, the phase noise of the light source will also increase. Therefore, this simulation method is reasonable. Moreover, this method eliminates the effect of performance differences between different lasers, simplifies the experimental device, and reduces the experimental cost.

We acquire reference and sensor signals using the system shown in Fig. 1, and then pass them through an RLS-based adaptive filter for noise reduction. The suppression results of the light source phase noise are presented in Fig. 4. As shown in Fig. 4, the phase noise of the sensing probe after noise reduction is significantly reduced compared to that before noise reduction for dithers of 0.5 V, 1 V, 2 V, 0.7 V, and 1.4 V. Furthermore, the increase in dither amplitude does not affect the effectiveness of the noise reduction algorithm, and the phase noise level of the sensor signal acquired with lasers of different dithers after noise reduction is basically the same as that of the sensor signal acquired with the laser of no dither.

Figure 5 compares the phase noise values at different frequency points before and after noise reduction of the sensor signal acquired with the laser of different dithers, with the phase noise values at the frequency point of the sensor signal acquired with the laser of no dither given as the baseline. Both Fig. 5(a) and (b) show that when the amplitude of the dither loaded on the RIO laser increases, the phase noise also increases, which is consistent with the previous theoretical analysis. At the frequency point of 100 Hz, the phase noise after applying the algorithm is significantly reduced compared with that before noise reduction, and under different dithers, the phase noise can be reduced to the level of the phase noise without dither or even lower. At the 1 kHz frequency point, the phase noise value after noise reduction is basically 0.5 dB lower than the phase noise value when there is no dither.

The use of a very narrow linewidth highly stable RIO light source allows the influence of light source phase noise to be neglected. On this basis, the loading of different dithers can simulate the influence of phase noise from laser light sources with different linewidths. The scheme proposed in this paper can reduce the phase noise to the level of no dither under different dither conditions, and has a significant noise suppression effect.

## IV. Conclusions

The phase noise of the light source comes from the linewidth and center frequency jitter of the laser. In LFM systems, the use of highly stable light sources with very narrow linewidths can ignore the effect of light source phase noise to a certain extent, but this light source is quite expensive. In our experiments, we simulate lasers with different linewidths by adding different amplitude Gaussian white noise dither to this light source, while introducing a reference interferometer to obtain the highly correlated light source phase noise with the sensing interferometer, and passing it through an adaptive filter based on the RLS algorithm for noise reduction. The phase noise from the very large linewidth laser is suppressed so that the system phase noise level can be on par with that of the system using a very narrow linewidth highly stable laser with a linewidth of 1.4kHz. Therefore, our scheme effectively reduces the effect of increasing linewidth on the hydrophone phase noise, increases the linewidth tolerance, and reduces the system requirements for the light source.

## ACKNOWLEDGMENT

This work was supported in part by the National Key Research and Development Program of China (2018YFA0701902) and the National Natural Science Foundation of China (62135014, 62071055).

## REFERENCES

[1] Z. Meng, W. Chen, J. Wang, X. Hu, M. Chen and Y. Zhang, "Recent progress in fiber-optic hydrophones," Photonic Sens, vol. 11, pp. 109-122, January 2021.

[2] G. A. Cranch, P. J. Nash, and C. K. Kirkendall, "Large-scale remotely interrogated arrays of fiber-optic interferometric sensors for underwater acoustic applications," IEEE Sens. J., vol. 3, pp. 19-30, February 2003.

[3] J. Shi, X. Zhuo, C. Zhang, Y. Bian, and H. Shen, "Research on key technologies of underwater target detection," Seventh Symposium on Novel Photoelectronic Detection Technology and Applications, Vol. 11763, pp. 1128-1137, March 2021.

[4] K. Wang, Q. Shi, C. Tian, F. Duan, M. Zhang, and Y. Liao et al., "The design of integrated demodulation system of optical fiber hydrophone array for oceanic oil exploration," 2011 International Conference on Optical Instruments and Technology, vol. 8199, pp. 173-181, November 2011.

[5] W. Xia, et al., "In‐plane ultrasonic needle tracking using a fiber‐optic hydrophone," Med Phys, vol. 42, pp. 5983-5991, September 2015.

[6] A. Dandridge, "Noise properties of stabilized single-mode lasers in fiber interferometers," J. Light. Technol., vol. 1, pp. 517-518, September 1983.

[7] A. D. Kersey and T. A. Berkoff, "Passive laser phase noise suppression technique for fiber interferometers," Fiber Opt. Laser Sensors VIII, vol. 1367, pp. 310–318, February 1991.

[8] M. Y. Plotnikov and A. V. Volkov, "Adaptive phase noise cancellation technique for fiber-optic interferometric sensors," J. Light. Technol., vol. 39, pp. 4853-4860, April 2021.

[9] Q. Zhong, Z. Hu, C. Cao, and H. Dong, "Adaptive elimination of optical fiber transmission noise in fiber ocean bottom seismic system," In AOPC 2017: Fiber Optic Sensing and Optical Communications, vol. 10464, pp. 334-340, October 2017.

[10] S. S. Haykin, Adaptive filter theory. Pearson Education India, 2002.

[11] M. Zhao, Y. Mao, Z. Wang, F. Yin, K. Xu, and Y. Dai, "Interferometric fiber-optic hydrophone system based on linear frequency modulation," J. Light. Technol., vol. 40, pp. 6769-6777, July 2022.