Noname manuscript No.
(will be inserted by the editor)

A High-Frequency Sound based PGC Demodulation Scheme for Fiber Optics Hydrophone

Yunjie Shi [1,4] · **Mengke Yin** [1] · **Zijue Zhu** [1] · **Shun Wang** [2] · **Panting Niu** [3] · **Yuming Dong** [1] · **Liang Zhang** [1]

Received: date / Accepted: date

Abstract In the research field of fiber-optic hydrophone, the performance of demodulation scheme is crucial. In this work, a phase-generated-carrier (PGC) demodulation scheme based on high-frequency sound source is proposed. High-frequency acoustic signal from the external sound source is applied to the fiber-optic hydrophone to achieve phase modulation of the interference signal instead of the piezo-electrical transducer (PZT) or frequency-modulated laser. It possesses the merits of low system complexity and low cost. Through the acoustic detection experiment, we achieve demodulation of acoustic signal at frequency varying from 300 Hz to 800 Hz, and the signal-to-noise ratio (SNR) is higher than 45 dB. Furthermore, the proposed scheme is successfully applied to time division multiplexing (TDM) experiment.

Keywords Fiber-optic hydrophone · PGC demodulation scheme · High-frequency sound · Phase modulation

---

* Yuming Dong
E-mail: ym.dong@siat.ac.cn

* Liang Zhang
E-mail: liang.zhang@siat.ac.cn

1
Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences, Shenzhen 518055, China

2
School of Civil and Environmental Engineering, Nanyang Technological University, 50 Nanyang Avenue, 639798, Singapore

3
Hubei Key Laboratory of Optical Information and Pattern Recognition, Wuhan Institute of Technology, Wuhan 430205, China

4
Schools of Science, Changchun University of Science and Technology, Changchun, 130022, China

1 Introduction

Recent decades, due to the advantages of immunity to electromagnetic interference, high sensitivity, large dynamic range, ease of forming an array, etc., fiber-optic hydrophone have become an important "ear" for exploring the sound of ocean, and it has attracted the attention of researchers in the acoustic detection field[1–4]. Then, how to accurately demodulate the sounds explored by the fiber-optic hydrophone is crucial. Phase-generated-carrier (PGC) technique and 3×3 coupler-based technique are two traditional demodulation methods, of which PGC technique is preferred due to its advantages of large dynamic range and good linearity [5–8]. It plays an important role in anti-submarine warfare, marine seismic detection, subsea oil exploration, and underwater navigation.

A. Dandridge et al. achieved a dynamic range of 107rad in 1982 [9]. A high-frequency carrier is necessary which can be generated by 1) employing a piezo-electrical transducer (PZT) or 2) utilizing a frequency-modulated laser [10–13]. Since the use of a balanced interferometer, the first modulation method is immune to the phase noise caused by laser frequency jitter [9]. However, the hysteresis nonlinearity of PZT influences the demodulation performance [14]. In addition, the dimension of fiber-optic hydrophone array greatly increases as a PZT is necessary in each single hydrophone element. The second modulation method can realize all-fiber in the interferometer part [15]. However, the frequency modulated laser increases the system cost. Besides, the current induced frequency (CIF) modulation in laser may cause the amplitude modulation and broaden laser linewidth, which will increase total harmonic distortion (THD) and reduce the signal to noise ratio (SNR) [16,17]. At the same signal frequency, the noise floor of PZT modulation drops by a factor of 5 than CIF modulation [9]. In other words, the SNR of CIF modulation is 14 dB lower than PZT modulation. Improved demodulation algorithm or modulation method can suppress the impact of laser intensity modulation [18, 19]. Specific system design is capable of suppressing the signal distortion and improving the system stability (e.g. using a balanced photoreceiver [13] or an analog divider [20]). In order to achieve a higher level of performance, a phase carrier generation method of all-fiber and low phase noise is urgently needed.

In this work, we propose a PGC demodulation scheme based on high-frequency sound source which obviates the problem discussed above. Phase modulation is achieved by high-frequency sound instead of PZT, which means that all fiber is implemented in the interferometer without using a modulated light source. Besides, the proposed scheme allows us to use an ultra-narrow band laser as a light source, and thus, furtherly weaken the phase noise. Experimental results demonstrate the feasibility of the proposed method. When the frequency modulated signal is under 10 kHz, acoustic signal from 300 Hz to 800 Hz can be detected. The proposed modulation method provides an alternative way to producing high-frequency carrier. Moreover, it is promising to realize phase modulation of all sensing elements in the hydrophone array using only one high-frequency sound source.

2 Principle and experimental results

In the proposed scheme, phase modulation is realized by applying a high-frequency acoustic signal to the fiber-optic hydrophone, therefore, the interference output signal can be expressed as:

$$I = A + B\cos\left[C\cos\omega_c t + D\cos\omega_s t + \varphi(t)\right] . \tag{1}$$

where A, B, C, D are constants. ω_c and C are the frequency and the phase modulation depth of the applied acoustic signal, respectively. ω_s is the frequency of the detected signal, and $\varphi(t)$ is the environmental noise term. The output signal based on cosine function is obtained via mixing, a sequence of calculation and filtering. The value of ω_s can be eventually obtained through further processing.

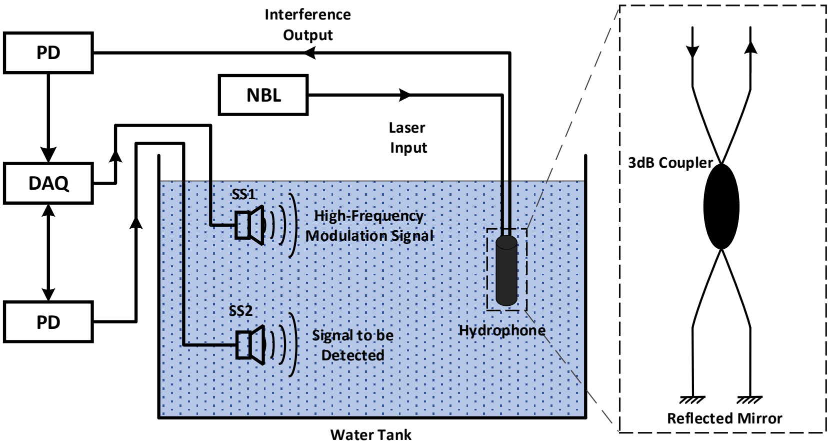

Fig. 1 Experimental configuration of PGC demodulation scheme based on high-frequency sound source.

The schematic of experimental configuration is shown in Figure 1.A high-frequency cosine wave voltage signal, produced by the data acquisition (DAQ) system, is imposed on sound source 1 (SS1) to generate modulation signal. Light beam from narrow band laser (NBL) is injected into the fiber-optic hydrophone and generating. The high-frequency modulation signal from SS1 and the acoustic signal from SS2 interacts with the fiber-optic hydrophone (see Fig.3), and then the interference output is detected by photodetector (PD). After analog-to-digital(A/D) conversion at the DAQ system, data processing is performed in the personal computer (PC). The construction of the PGC demodulation system is based on LabVIEW.

The key parameters of the sensing system are as follows. The frequency of the modulation signal is 10 kHz. For the stability of demodulation system, is limited to 2.37 rad by adjusting the output voltage of the DAQ system.

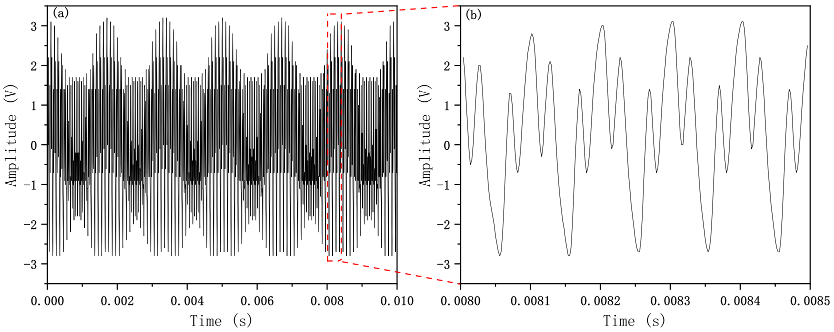

Fig. 2 Interference output obtained by PD.

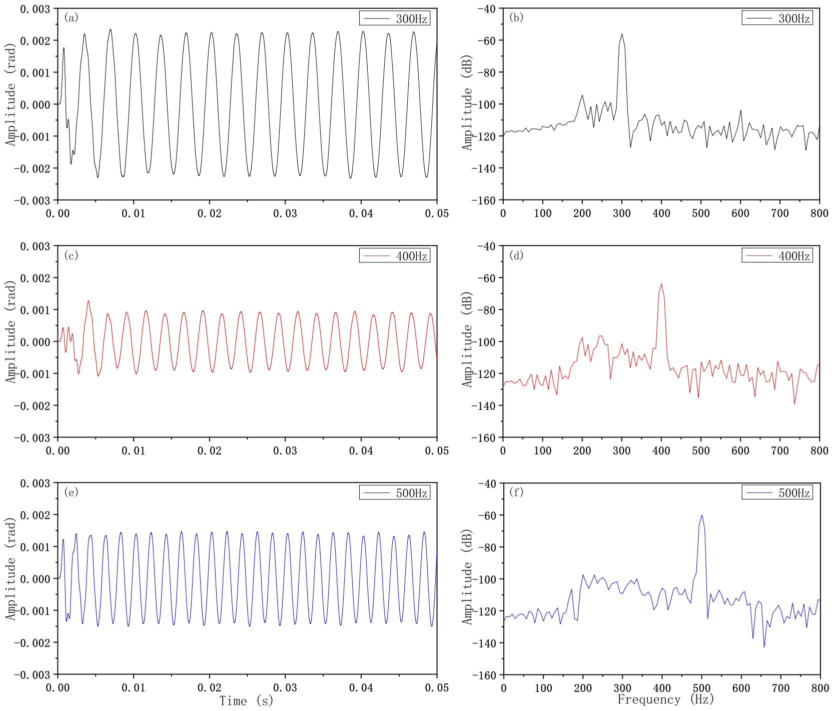

Fig. 3 (Color online) Demodulation results of acoustic signal at different frequencies: (a) (c) and (e) are the output waveform at 300 Hz, 400 Hz, 500 Hz; (b) (d) and (f) are the output spectrum at 300 Hz, 400 Hz and 500 Hz.

The sampling frequency and the sampling point are set to be 500 kHz and 50000, respectively. The passband of the filtering process is set from 250 Hz to 2000 Hz.

In the acoustic signal detection experiment, the signal to be detected is generated by SS2 and its frequency is controlled by the PC. The interference output with phase modulated obtained by PD is presented in Fig.2. As we can

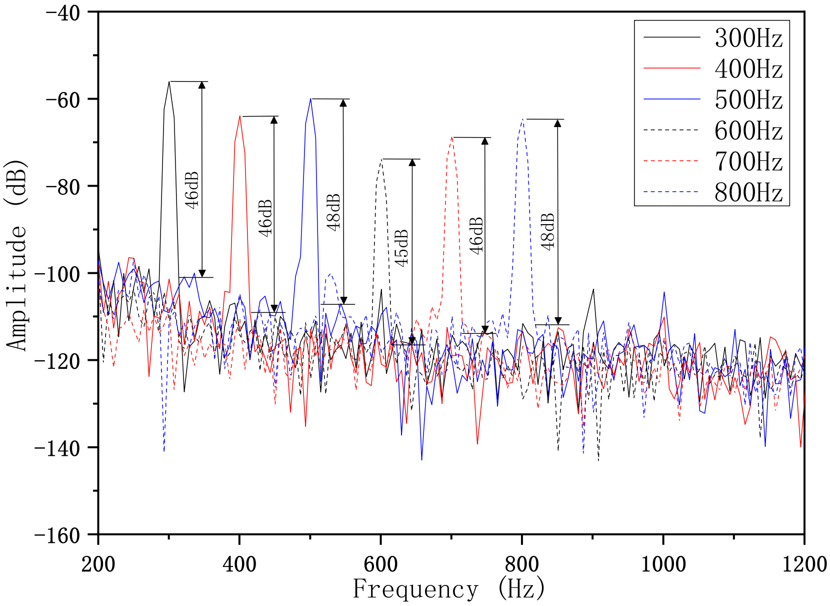

Fig. 4 (Color online) Spectrum of acoustic signal at different frequencies.

see from Fig.2 (b), the phase of the interference output comprises components of the carrier and detected acoustic signal.

Fig.3 depicts the demodulation results of the detected acoustic signal of 300 Hz, 400 Hz and 500 Hz. The acoustic signals have been successfully demodulated with the SNR greater than 50 dB, which indicates the feasibility of our proposed demodulation scheme. Subsequently, we gradually increase the frequency of the acoustic signal up to 800 Hz, and the demodulation results in frequency domain are shown in Fig.4. According to the figure, the detection of acoustic signals with in the frequency range from 300 Hz to 800 Hz with all SNRs higher than 45 dB can be realized.

Then, we apply the proposed scheme to the time-division multiplexing (TDM) experiment, whose configuration is shown in Fig.5. Behind the output of the NBL, an acousto-optic modulator (AOM) is utilized to generate a 100 kHz (corresponding to a 10 μs period) light pulse train with 3 μs pulse width. The light pulse is divided by the coupler into two parts and respectively enter the two hydrophones, between which a 1 km long fiber delay (corresponding to about 5 μs time delay) is set to ensure light pulse from two hydrophones can be distinguished. Similar to the previous experiment, SS1 generates a 10 kHz modulation signal and the 500 Hz acoustic signal to be detected is generated by SS2.

Fig.6 illustrates the interference output obtained by PD and DAQ. Channel 1 refers to hydrophone 1 and channel 2 refers to hydrophone 2. We can see two light pulse can be easily distinguished. After data processing, they can be

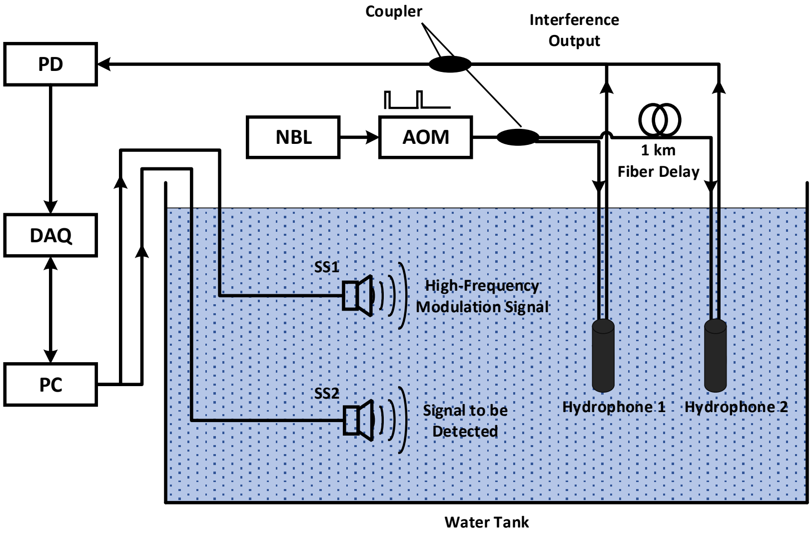

Fig. 5 Experimental configuration of TDM experiment.

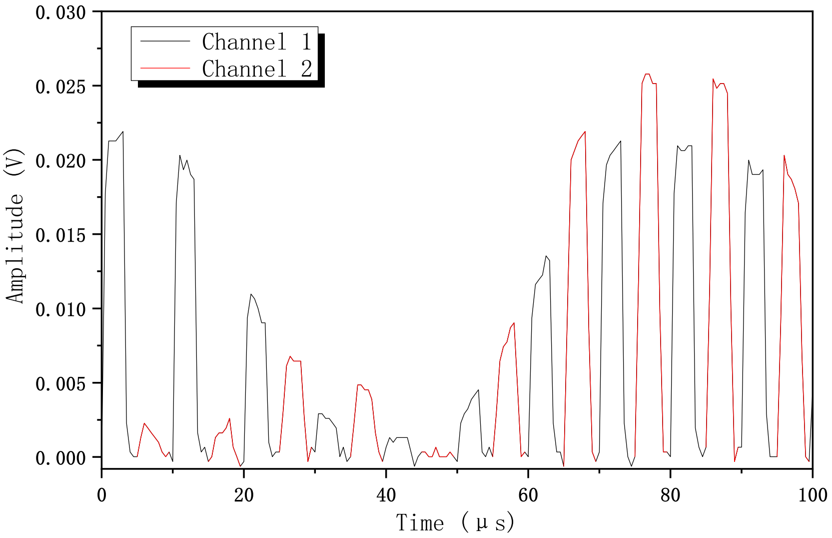

Fig. 6 (Color online) The light pulse train received by PD.

separated and finally demodulated via PGC algorithm processing as shown in Fig.7.

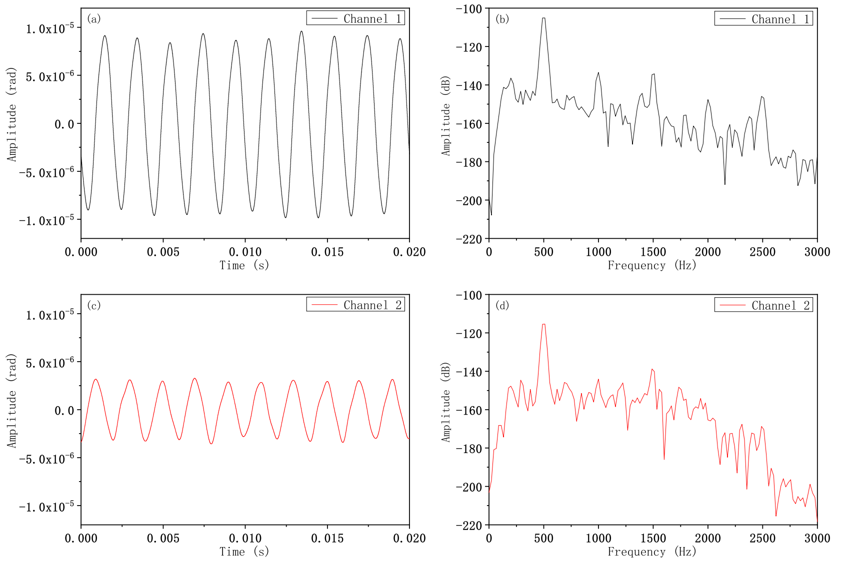

Fig. 7 (Color online) Demodulation results of TDM experiment: (a) Waveform and (b) spectrum from hydrophone 1. (c) Waveform and (d) spectrum from hydrophone 2.

3 Discussion

Apart from the design of hydrophone, the frequency of modulation signal determines the detectable frequency of acoustic signal. The detectable frequency range of the acoustic signal in this work ranges from 300 Hz to 1 kHz, because the frequency response of SS1 is decreased at 10 kHz. In other words, the employment of a sound source emitting with higher frequency modulation signal will help break through this limitation.

On the other hand, we can apply the proposed scheme on the demodulation of a fiber-optic hydrophone array. The whole system utilizing neither PZT nor frequency-modulated laser will significantly decrease the dimension and cost of the sensing system.

However, some issues remain unresolved. The response to acoustic modulation signal of each hydrophone is different. On one hand, the different position of each hydrophone yields a delay difference, so phase matching between modulation signal and mixing signal should be implemented for the PGC demodulation. On the other hand, the transmission loss of acoustic wave in water brings a modulation depth difference for different hydrophones. Further investigation for the solution is in progress.

4 Conclusion

In summary, we have experimentally demonstrated the feasibility of a PGC demodulation scheme based on high-frequency sound source. During the acoustic detection experiment of fiber-optic hydrophone, the acoustic signal at frequency ranging from 300 Hz to 800 Hz can be demodulated with a SNR higher than 45 dB. A TDM experiment is implemented, and a 500 Hz acoustic signal detected by two hydrophones can be simultaneously demodulated. To the best of our knowledge, the employment of high-frequency sound source for phase modulation has not been reported in the PGC technique. Since neither PZT nor frequency-modulated laser is needed, thus the interferometer part is all-fiber and the system complexity significantly decreases. Besides, ultra-narrow band laser can be utilized as light source to reduce phase noise. Furthermore, the proposed scheme is regarded as a promising candidate to realize phase modulation of all sensing elements in the hydrophone array using only one high-frequency sound source.

Acknowledgements This work was supported by National Key R-D Program Funding project(No.2016YFB1200401), Shenzhen Research Foundation (JCYJ20170413152328742, JCYJ20160608153308846).

References

1. J.A. Bucaro, H.D. Dardy, E.F. Carome, J. Acoust. Soc. Am **62**, 1302 (1977)
2. D.J. Hill, P.J. Nash, D.A. Jackson, D.J. Webb, S.F. O'neill, I. Bennion, L. Zhang, Int. Soc. Opt. Photonics **3860**, 55 (1999)
3. C.G. Fox, H. Matsumoto, T.K.A. Lau, J. Geophys. Res-Sol. Ea **106**, 4183 (2001)
4. V.S. Lavrov, M.Y. Plotnikov, S.M. Aksarin, M.E. Efimov, V.A. Shulepov, A.V. Kulikov, .A.U. Kireenkov, Opt. Fiber Technol **34**, 47 (2017)
5. D.A. Brown, Int. Soc. Opt. Photonics **1584**, 32 (1991)
6. L. Wang, M. Zhang, X. Mao, Y. Liao, Int. Soc. Opt. Photonics **6292**, 62921E (2006)
7. Y. Liu, L. Wang, C. Tian, M. Zhang, Y. Liao, J. Lightwave Technol **26**, 3225 (2008)
8. G. Wang, T. Xu, F. Li, IEEE Photonic. Tech. L **24**, 2093 (2012)
9. A. Dandridge, A.B. Tveten, T.G. Giallorenzi, IEEE T. microw. theory **30**, 1635 (1982)
10. J.Y. Wang, Q.M. Sui, J. Chang, T.Y. Liu, L.Z. Ma, J.S. Ni, Optoelectron. Lett **3**, 264 (2007)
11. C. Li, S. Xu, X. Huang, Z. Feng, C. Yang, K. Zhou, J. Gan, Z. Yang, IEEE Photonic. Tech. L **28**, 1692 (2016)
12. D. Chen, X. Huang, H. Wang, L. Jiang, Symposium on Piezoelectricity, Acoustic Waves, and Device Applications (SPAWDA) pp. pp. 148–150t (2012)
13. S.C. Huang, Y.F. Huang, F.H. Hwang, Sensor Actuat. A-Phys **191**, 1 (2013)
14. M. Rakotondrabe, IEEE T. Autom. Sci. Eng **8**, 428 (2010)
15. Z. Meng, Y. Hu, M. Ni, S. Xiong, R. Zhang, X. Li, G. Stewart, F. Dong, B. Culshaw, Int. Soc. Opt. Photonics **5589**, 114 (2004)
16. A. Dandridge, A.B. Tveten, Appl. Phys. Lett **39**, 530 (1981)
17. Z. Meng, Y. Hu, S. Xiong, G. Stewart, G. Whitenett, B. Culshaw, Appl. Optics **44**, 3425 (2005)
18. H. Zhang, M. Zhang, L. Wang, Y. Liao, D.N. Wang, Int. Soc. Opt. Photonics **8199**, 81990Q8 (2011)
19. L. Yan, Z. Chen, B. Chen, J. Xie, S. Zhang, Y. Lou, E. Zhang, Opt. Express **26**, 4818 (2018)
20. X. Wu, R. Tao, Q. Zhang, G. Zhang, L. Li, J. Peng, B. Yu, Opt. Commun **285**, 738 (2012)