Four-element fiber laser hydrophone array

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Abstract

A 4-element fiber optic hydrophone array based on distributed feedback fiber lasers (DFB FL) has been developed, constructed and tested. Acoustic sensitivity was enhanced by two diaphragms. The noise floor was tested to be 10^{-6} pm/√Hz @ 1 kHz and acoustic pressure sensitivity of about 10 nm/MPa was achieved.

Keywords: fiber optic hydrophone, fiber laser, array

1 Introduction

Since the late 1970's[1], a great deal of research has been devoted to high performance fiber-optic hydrophone system, aiming at lower cost and more sensitive acoustic detecting solution[2]. Due to their high sensitivity, interferometric sensors played a major role in fiber-optic hydrophone applications[3]. The development of the fiber laser sensors in the 1990's offered an competitor to interferometric fiber optic hydrophones. Extreme sensitivity coupled with comparatively simple structure and potential advantages in multiplexing has led to them being considered as an alternative to interferometric ones[4]. Over the past decade, fiber laser hydrophone technology has undergone a process from the basic lab demonstration to a sonar system approaching industrial applications.

This work presents a 4-element DFB FL hydrophone system. Theoretical and experimental investigation on the acoustic sensitivity is discussed. Interferometric interrogation technique is used employing phase generated carrier (PGC) method. An overview of the system as well as the main components and some test results are presented.

2 System description

The optical architecture of the 4-element DFB FL hydrophone array is shown in Fig. 1. The lasers are pumped by a semiconductor laser source of 980 nm. Each laser was designed to operate at a different center wavelength (1532.725 nm, 1537.489 nm, 1539.706 nm, and 1542.517 nm, respectively).

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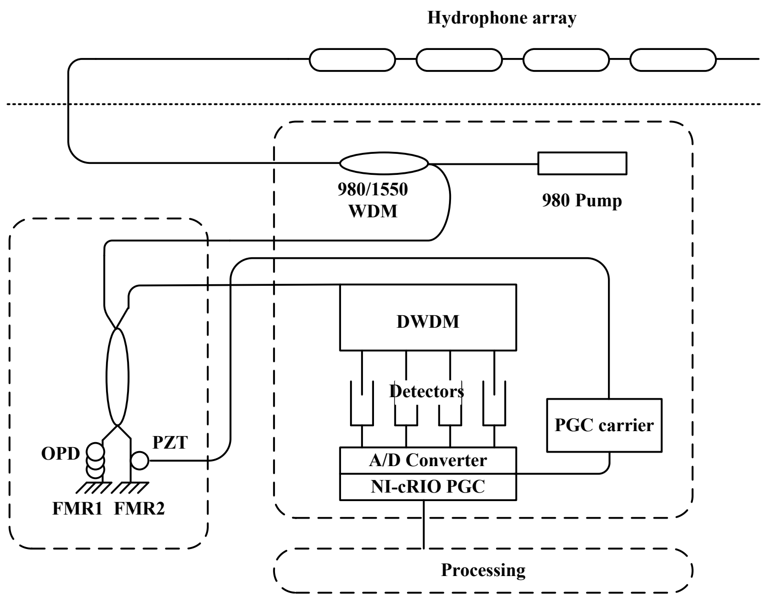

Fig.1 Optical architecture of the 4-element DFB FL hydrophone array

The interrogation of a fiber laser sensor can be achieved by using PGC demodulation[5]. A piezoelectric fiber stretcher in one of the unbalanced Mach-Zehnder interferometer (MZI) arms induces a phase-shift carrier signal on the sensor output signals that enables passive recovery of dynamic phase-shift information.

3 Hydrophone design

3.1 Fiber lasers

DFB fiber lasers are Bragg gating structures written into a section of Erbium-doped fiber with a gap that produces a phase step within the length of grating. Experiments are carried out to optimize the performance of the DFB fiber laser. The length of the DFB fiber laser used in the hydrophone is 44 mm, and the reflectivity of the grating is 99%.

3.2 Sensitivity enhancements

An ultrahigh sensitivity has been achieved by using two rubber diaphragms as the sensing element, as shown in Fig. 2.

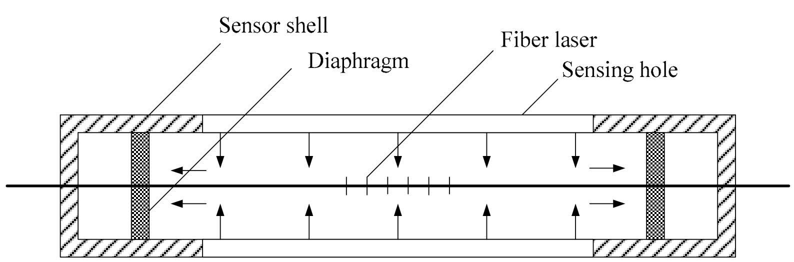

Fig. 2 Schematic of the sensor element

The sensitivity of the hydrophone, which is defined as the change in Bragg wavelength over acoustic pressure, is then enhanced to be [6]

$$M_p = \frac{\Delta\lambda_B}{p} = \frac{(1-p_e)\frac{R^4\lambda_B}{64D}}{\frac{L}{2}+\frac{AE_f R^2}{16\pi D}} \tag{1}$$

in which the following notation is used

$$D = \frac{Et^3}{12(1-\mu^2)} \tag{2}$$

Theoretical acoustic pressure sensitivity of about 9.8 nm/MPa is achieved by using parameters given in Table 1.

Table 1 parameters used in the configuration

Parameter	Value
L- fixed length of the fiber laser	45 mm
t- thickness of the diaphragm	1 mm
A- cross section area of the fiber	0.0123 mm^2
R-radius of the diaphragm	3 mm
μ- Poisson's ratio	0.3
E- Young's modulus of the diaphragm	72 GPa
λ- Bragg wavelength	1550 nm
p_e- effective photoelastic constant of the fiber	0.22
E_f- Young's modulus of the fiber	17 MPa

4 Experiments and results

4.1 Frequency response

Each fiber laser hydrophone was tested in a standing water tank, as shown in Fig. 3. A steady sound field was produced in the tank by using a loudspeaker at the bottom. A standard piezoelectric hydrophone, which is placed 5 cm apart from the fiber laser hydrophone, is used as a reference hydrophone to measure the acoustic pressure. The test was performed in the frequency range of 20-1000 Hz.

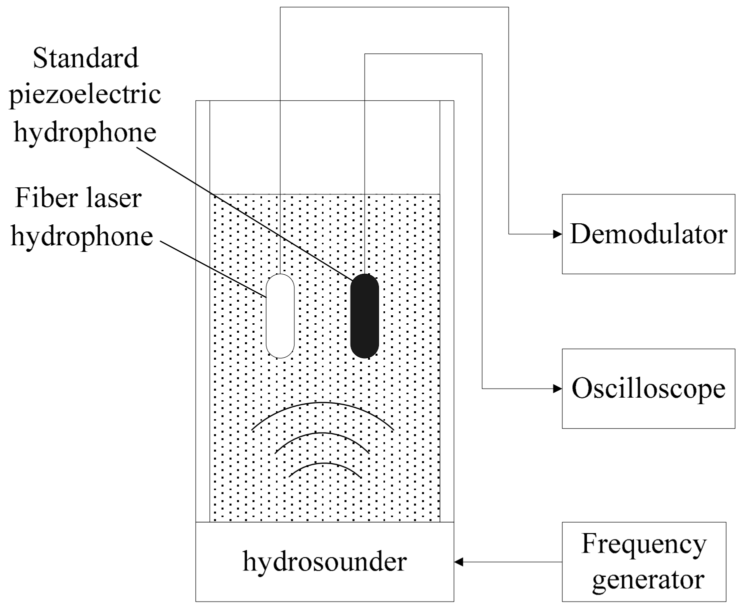

Fig. 3 Acoustic test setup

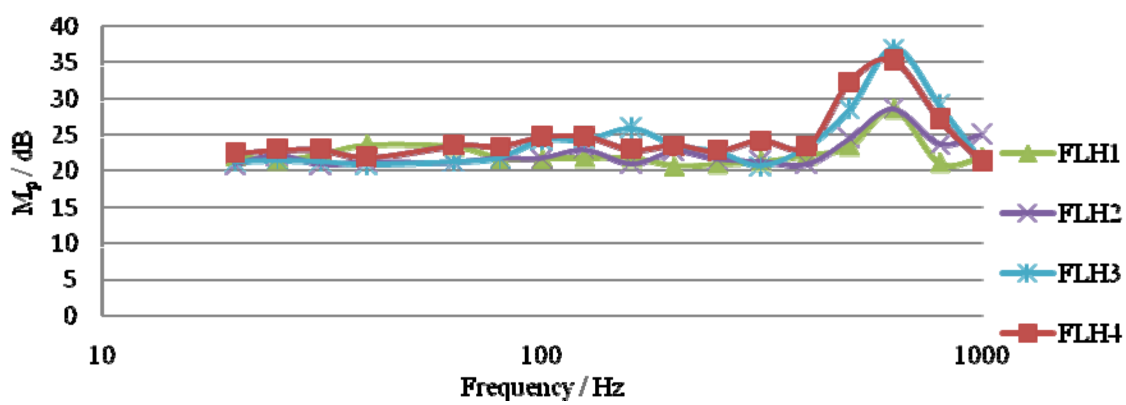

Fig. 4 In water frequency response of the fiber laser hydrophones

Fig. 4 shows that the frequency responses are flat in the bandwidth from 20 Hz to 400 Hz and meet their peaks at the frequency of about 600 Hz.

4.2 Array test

4.2.1 Noise floor test

The test was carried out in laboratory when the hydrophones were placed in a water tank in a quiet circumstance. The measured noise floor is shown in Fig. 5, which indicates good consistent to reported result[7].

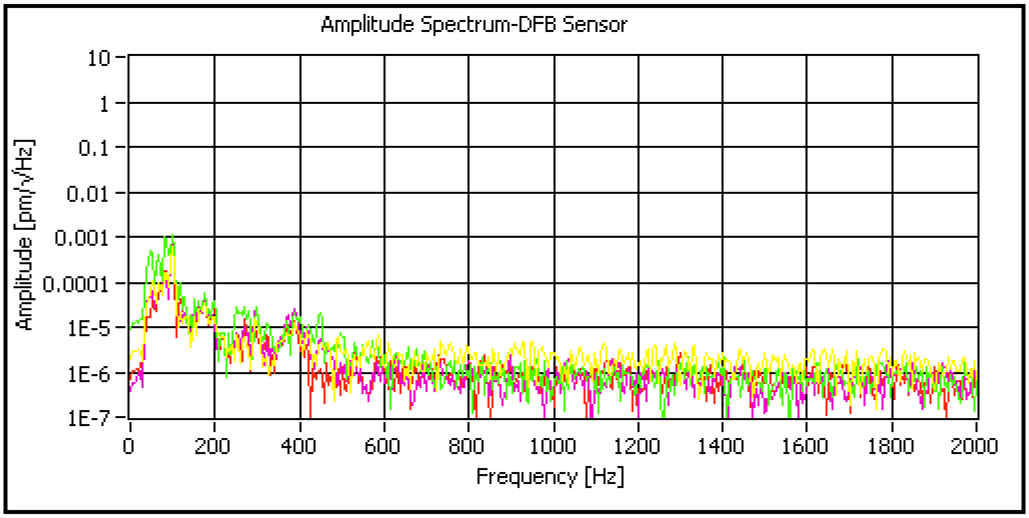

Fig. 5 Noise floor of the hydrophone array

From Fig. 5 it can be seen that the DFB fiber laser hydrophones give a noise floor of approximately 10^{-6} pm/√Hz @ 1 kHz. The noise is higher below 400 Hz because of the environmental noise.

4.2.2 Monochromatic signal test

A monochromatic signal of 400 Hz was stimulated in the water tank to test the response of the fiber laser hydrophones. The signal of each hydrophone is shown in Fig. 6.

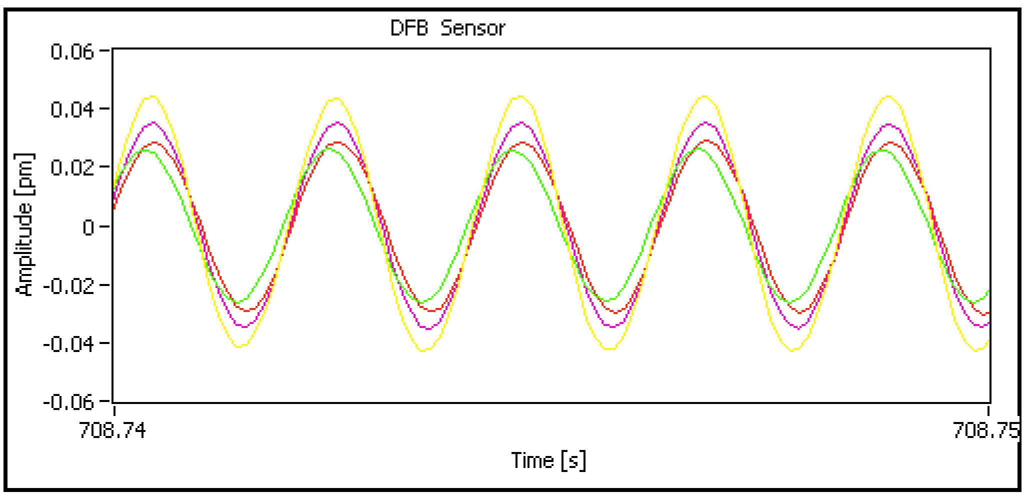

Fig. 6 Demodulated signals of 400 Hz

The signals are consistent both in amplitude and phase, which indicates that the hydrophones have good consistency.

4.2.3 Seismic signal test

The test was carried out in an outside field, where a steel tube was embedded into earth as a well. The hydrophone array was installed in the well with 20 cm apart. Seismic signals were stimulated by a shock of free fallen from 1 m high and 10 m far away from the well. The test result is shown in fig. 7

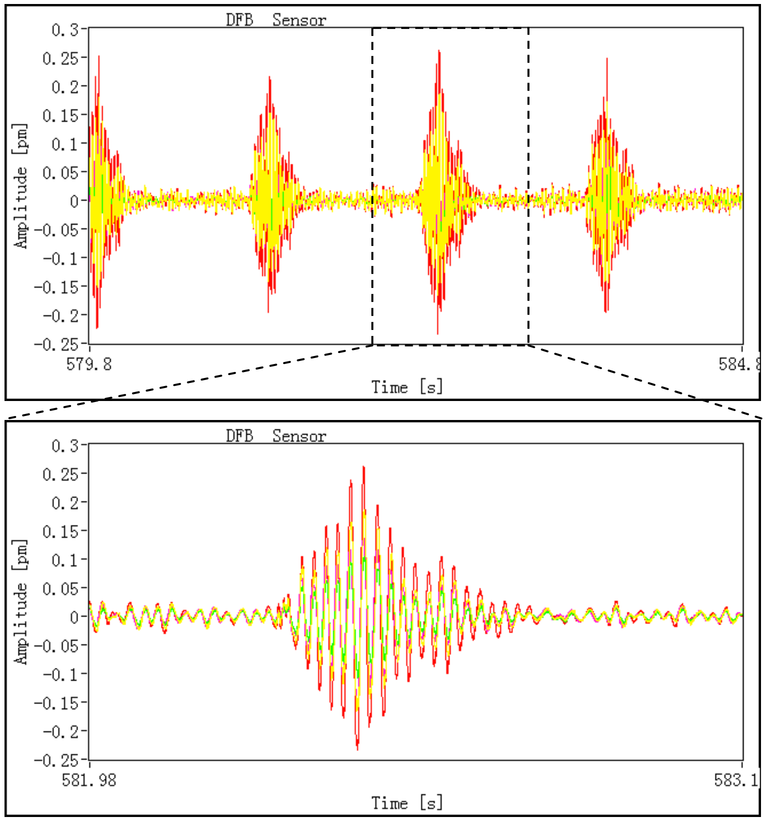

Fig. 7 Response to seismic signals

Fig.7 shows the hydrophones has good consistency. The signal-to-noise ratio, which would be better if there were lower noise floor, is deteriorated due to the environmental noise.

5 Conclusion

A 4-element fiber laser hydrophone array is demonstrated. Test result shows the hydrophone has a high sensitivity and good consistency, which provides promising prospect in down hole seismic detections and military underwater surveillance systems.

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