MEMS-based Optic Fiber Fabry-Perot Sensor for Underwater Acoustic Measurement with A Wavelength-switched System

J Xia 1,2, F Y Wang 1, H Luo 1, Y M Hu 1 and S D Xiong 1*

1 Academy of Ocean Science and Engineering, National University of Defense Technology, Changsha 410073, P. R. China;
2 College of Optics Science and Engineering, National University of Defense Technology, Changsha 410073, P. R. China

*Corresponding Email: nudtxsd@163.com

Abstract. In this paper, a MEMS-based extrinsic Farby-Perot Interferometric (EFPI) acoustic pressure acoustic sensor is presented. The diaphragm structure is used as the second reflected surface, and the sensitive surface to acoustic pressure. A wavelength-switched phase demodulation system for EFPI sensors is used for acoustic signal recovery. The modified phase demodulation system has been demonstrated to recover the signal to a stable intensity fluctuation level of ±0.5 dB at the test frequency of 2000 Hz. In the test depth of 50cm, the sensor has a resonant frequency of 3.7 kHz, a flat frequency range of 10-800Hz, and a corresponding acoustic pressure sensitivity of -159 dB re. 1/μPa.

1. Introduction
The miniaturization of the traditional long-arm fiber interferometers is in the state of bottleneck at present, whereas new generation of the micro electro-mechanical system (MEMS) technique brings a light path to the sensor miniaturization. MEMS-based miniaturized fiber optic acoustic sensor reduces the size of sensing element greatly, and its precise processing control fabrication and mass production capacity are far beyond traditional fiber acoustic sensor. At present, the structure types of MEMS-based miniaturized fiber optic acoustic sensors are classified as below. (1) Capillary structure[1-3]: in order to enhance the sensitivity of capillary structure fiber acoustic sensor, the feasible way is to increase the radius of the capillary tube and reduce its wall thickness. However, the sensor with a thin capillary wall has a weak strength, which is easy to damage and limited to use. (2) Diaphragm structure: MEMS-based diaphragm structure can be classified into two types: fiber-end structure[4-5] and fiber-tip structure[6-8]. The most obvious difference between these two types is the size of sensor. Fiber-tip structure is characterized in compact structure and small bulk, and the sensor size is close to the diameter of the fiber. The key point of fiber-tip structure is located at fabricating the sensor diaphragm in a small scale. The common method to solve that problem is to utilize MEMS fabrication technology or coating technology, and the corresponding diaphragm thickness can reach at ~μm and ~10nm respectively.

Compared with the conventional acoustic sensors, fiber optic acoustic sensors have been illustrated and researched for decades for their characteristics, such as immunity to electromagnetic interference, electrically passive, resistance to corrosion, remote sensing operation, light weight and small size.
Extrinsic Fabry-Perot interferometric (EFPI) fiber optic sensor has attracted the interests of researchers in the acoustic signal detection due to its high sensitivity and wide frequency response. Various kinds of diaphragm-based EFPI fiber optic sensors, such as the structure based on a silica diaphragm spliced with a silica capillary, a glass/silicon diaphragm bonded to a silicon base, and a dipped polymer membrane on a hollow fiber tip have been developed, and some of these sensors are applied in the detection of marine hydro-acoustic waves. But most types of these sensors are not suitable for acoustic detection due to the mismatch of the acoustic impedance with the sensors diaphragm. As the effective diameter of the diaphragm, limited by the fiber itself, is small, the diaphragm must be thin if it is to have considerable sensitivity, which presents a great challenge in sensor fabrication. And it is difficult to adjust and control the F-P cavity length during fabrication. In addition, some EFPI fiber optic sensors based on MEMS diaphragm [9] may encounter high stress in the deep underwater because of the mismatches in coefficients of thermal expansion among the sensing elements with different materials, which may even lead to a failure.

In this paper, we focus on the structure design and production, packaging technology of MEMS-based optical fiber EFPI acoustic sensor. Based on the deficiency of EFPI fiber optic acoustic sensors and the demodulation methods, an optimized wavelength-switched phase demodulation system can be achieved completely in one optical path to track the underwater acoustic signal. MEMS-based optical fiber EFPI acoustic sensor has the characteristics of low noise, high sensitivity and reliability, large dynamic range, and low cost, which can be applied in the miniaturized optical fiber MEMS underwater acoustic detection system.

2. Sensor fabrication and apparatus

2.1. MEMS-based EFPI acoustic pressure sensor

In the schematic diagram of EFPI acoustic pressure acoustic sensor, the diaphragm structure is used as the second reflected surface, and the sensitive surface to acoustic pressure. The sensor is constituted with fiber end, clamp, diaphragm, and sleeve, as shown in Fig. 1. Considering the gas permeability, pressure resistance and assembly process specification, the center of sensitive diaphragm is composed of transition part and connection part. The innermost/centermost part is sensing diaphragm. There are two small holes in the part of diaphragm transition area for the achievement of acoustic pressure, which has the characteristics of temperature compensation and buffering hydrostatic pressure.

![Figure 1. Schematic diagram of EFPI acoustic pressure acoustic sensor](image)

Here, the silicon-on-insulator (SOI) material is used for fabrication of the acoustic pressure sensitive structure. The technological process is detailed as below, as shown in Fig. 2, which includes four lithographic steps and one wet corrosion step. Step 1: Etching the convex diaphragm structure. A circular arrangement is etched on the top silicon using the lithography and reactive ion etching (RIE) etching techniques. In order to obtain the convex diaphragm structure, etching time manipulation is used to reach the pre-set diaphragm thickness. Step 2: Etching holes at the transition zone. Due to the
large depth-to-width ratio of holes, the etching of the silicon and the depositing of the sidewall protective materials are carried out alternatively using the deep reactive ion etching (DRIE) method. At this point, the etching operation on the top silicon has been completed. Step 3: Etching on the bottom silicon at the transition zone using the lithography and RIE etching techniques. Step 4: Etching the frontal area of the diaphragm to SiO₂ layer. This processing technology is carried out on a thicker bottom silicon, and it is not necessary to control the processing time accurately. Step 5: Removing the exposed SiO₂ layer. Step 6: Clean the diaphragm structure.

Figure 2. Flow chart of acoustic pressure structure fabrication
The local microscopic images of diaphragm structure is observed with the optical microscope and scanning electron microscope (SEM), as shown in Fig. 3.

In Fig.3(a), it can be seen that the diameter of diaphragm sensitive area is about 1 mm and the diameter of the convex platform is about 0.36 mm. The thickness of diaphragm and convex platform are measured about 2.73 mm and 1.87 mm in Fig.3(b) respectively. It can be calculated that the acoustics pressure sensitivity of diaphragm is 2.19 nm/Pa and the corresponding deflection angle is 1.22° at 50m depth of water, and its underwater operation resonant frequency can reach at 4.1 kHz.

2.2. Configuration

The proposed configuration is presented in Fig. 4. The optical output from the broad-band source (BBS, with a maximum power of 42.5 mW) injects into a single-mode fiber optical circulator (OC). As explained, the back reflected optical signal from PMFBG has two orthogonal reflection peaks with different central wavelengths and transmits into an electro-optic modulator. Two natural wavelengths of PMFBG are chosen to present the spectral separation, which are set into a manual polarization controller (PC) first for wavelength switching. For the back-reflected bandwidths of PMFBG are narrow, the optical intensity via the OC attenuates to 14.75 μW. To acquire sufficient optical intensity, a polarization-maintaining Erbium-doped fiber amplifier (PM-EDFA) is added into the successive system. The signal generator applies continuous square waves (with a high-level V1 and a low level V2) to EOM. Aim to achieve the separation of two natural wavelengths at different electrical level status, a polarizer (P) is inserted after EOM and only one linearly polarized beam in certain special direction can pass through the polarizer. Two separated optical signals with different Bragg wavelengths are guided into the EFPI sensor probe via another optical circulator (OC). Then, their back reflected signals from the EFPI sensor are detected using the photoelectric detector (PD2) and recorded with another data acquisition device. To verify the dynamic measurement characteristic of the system, all tests are implemented based on the underwater acoustic signal measurement. To detect the underwater acoustic signal, the EFPI sensor probe is hanged in a water tank. The position under the EFPI sensor probe locates an acoustic emission (AE) device. The continuous sine wave in Fig.1 is sent to drive the AE device to modulate the EFPI sensor, and the given frequency of AE device acts as the compared reference with the frequency of detected signal. The polarization control unit is added to realize the operation point of EOM immune to external disturbance.
3. Experiments and results
To verify the features of the optimized wavelength-switched phase demodulation system, the output of the wavelength-switched structure at different voltage level status are obtained in Fig. 6. The continuous DC voltage levels are set as $V_1=1.2V$ and $V_2=-5.4V$ respectively. It is concluded that the wavelength-switched structure can achieve the separation of two orthogonal reflection peaks with different central wavelengths, which can be taken as two signal lights for EFPI sensor phase recovery. The demodulated phase signal is shown in Fig. 5(a), and the frequency-domain of the phase signal is shown in Fig. 5(b). It can be found that the frequency of the demodulated phase variation is consistent with the 2000 Hz sinusoidal driving signal, and the intensity of the 2000Hz phase signal reaches a stable state and the signal to noise ratio (SNR) level of ~37 dB. In Fig. 5(b), the first harmonic slightly emerges out of the noise at its double frequency, which is due to the self-resonance of the EFPI sensor and the crosstalk between two output channels. In addition, the power spectral density variation of the target signal is measured to be a fluctuation level of ±0.5 dB at the test frequency of 2000 Hz.

![Figure 5](image_url)

**Figure 5.** The demodulated phase signal (a) Demodulated phase time-domain signal; (b) Demodulated phase frequency-domain signal
Adjusting the location depth of the acoustic pressure sensor, the acoustic pressure sensitivity of the sensor at different depths are measured and analyzed, as shown in Fig. 6. In the test depth of 50cm, the sensor has a resonant frequency of 3.7 kHz, a flat frequency range of 10-800Hz, and a corresponding acoustic pressure sensitivity of -159 dB re. 1/μPa. When the location depth increases from 50cm to 12.5cm, the acoustic pressure sensitivity at 12.5cm decreases about 10dB, and the resonant frequency decreases from 4000Hz to 2600Hz, which illustrates that diaphragm has been warped due to the hydrostatic pressure when the depth changes. When the location depth of sensor returns back to 12.5cm, however, the resonant frequency of sensitivity curve changes due to the water weeping in the FP cavity. As the added mass effect of sensor increases, the resonant frequency of sensor reduces.

Figure 6. The acoustic pressure sensitivity of the sensor at different depths

4. Conclusions

In this paper, a stability-enhanced wavelength-switched phase demodulation system based on the polarization control unit is presented and demonstrated. A diaphragm-based EFPI sensor is presented for the underwater acoustic measurement. The experiment result shows that the system with polarization control can enhance the stability of power spectral density variation with a fluctuation level of ±0.5 dB. In addition, the demodulation system can operate in a wide frequency range under different water depths. Preliminary experimental results have shown that the wavelength-switched with polarization control could find potential applications in marine acoustic, medical science measurements, etc.

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