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Underwater acoustic signal acquisition based on optical interferometry in shallow water

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ABSTRACT: Here, it is investigated the results of the implementation of an interferometric optical fiber acoustic sensor based on fiber Bragg grating (FBG). It is investigated the importance of different types of interferometer configurations as Michelson or Mach-Zehnder interferometers on the signal to noise ratio. It is also considered the role of polymer coating on the increasing of signal to noise ratio. The results show the Michelson interferometer setup using polymer packaging causes an increasing signal to noise ratio. This latter configuration is used in a field set up in shallow water for acoustic signal detection in the range of 0.5-5 kHz. The goal of this paper is to extract acoustical signals using optical signals via optical sensors and demodulation methods.

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1- Introduction

Fiber optics sensors are devices in which, different measurands interact with light transmitted into an optical fiber to generate a modulated signal that has data according to measurement parameters [1-3]. Acoustic sensors are very interesting field that utilize in nowadays lives and communities, with broad applications ranging from submarine to medicine applications. These sensors benefit advantages in submarines, and exhibit already performance capable of competing with the electronic sensors [4]. nowadays, many investigations in optical fiber acoustic sensors have been reported as [5-12]. Recently, FBG based sensors have been applied in a growing range of sensing applications, since their response to measurands as acoustic waves, is encoded as a linear or near-linear function of wavelength [13]. The operating principle of the FBG based acoustic sensor is based on the intensity modulation of the laser light due to the shift of the transmission power spectrum curve of the sensing element under the influence of the acoustic field [14]. Some articles have been reported about optical fiber acoustic sensors based on FBG [15-17].

In this paper, it is proposed a new FBG based interferometric optical fiber acoustic sensor. Actually, the proposed sensor measures an optical phase change defined as a variation of displacement or refractive index of FBG in the sensing arm of the interferometer. The optical phase shift is the basis of the sensing utilization of the phase generated carrier (PGC) demodulation method.

The results show it is detected the acoustical demodulated signal with PGC demodulation method based on the arctangent function with coordinate rotation digital computer (CORDIC) algorithm and the utilization of Michelson interferometer with mandrel package caused obtaining maximum signal to noise ratio. Signal amplitude in oscilloscope is considered as a measure of signal to noise ratio. In this paper, the acoustical wave in a frequency range of 500Hz to 5000Hz is detected. The main innovation of this research is the integration of optical interferometry methods with technique one.

2- Theory

FBG is a spectrally reflective element into the core of an optical fiber The FBG is made up of alternating regions of different refractive indices. The difference in refractive indices results in Fresnel reflection at each interface. The regular period of the grating, Λ, results in constructive interference in the reflection at a specific wavelength called the Bragg wavelength, The Bragg wavelength is given as:

$$\lambda_B = 2n\Lambda \tag{1}$$

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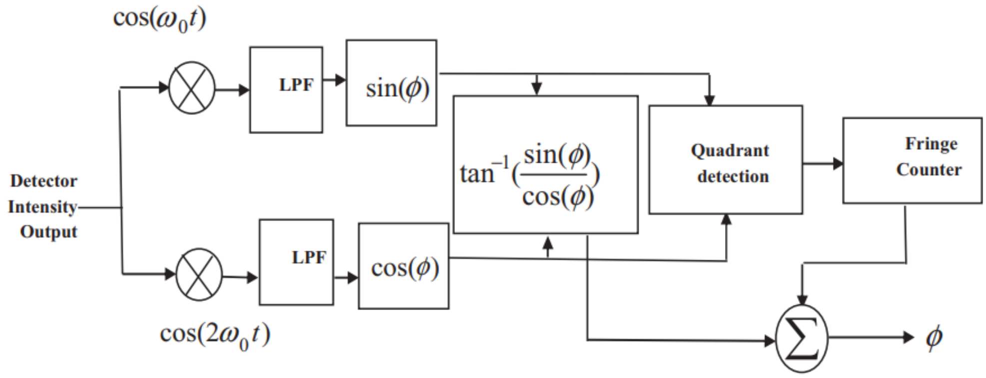


Fig. 1. Schematic of PGC arctangent algorithm [19].

where n is the average refractive index of the grating [1]:

In reality, any measurement that causes a change in the refractive index or period of FBG can be detected.

The change in Bragg wavelength is calculated as [14]:

$$\Delta\lambda_B = \varepsilon\lambda_B - \frac{\varepsilon\lambda_B n^2}{2}[p_{12} - v(p_{12} + p_{11})] = \varepsilon\lambda_B \left(1 - \frac{n^2}{2}[p_{12} - v(p_{12} + p_{11})]\right) \quad (2)$$

In equation 2, ε is applied longitudinal strain, V is Poisson's ratio, and P_{ij} is the strain optic tensor.

Phase Generated Carrier method is a method to detect a sharp small signal without fading effects due to ambient noises. The output intensity of the interferometer is written as [18]:

$$I = A + B\cos(C\cos(\omega_0 t) + \varphi(t)) \quad (3)$$

that, A and B are the constants representing the average intensity and the visibility of the interferometer.

C cos(ω_0 *t)* is modulation with a frequency ω_0 and amplitude C. The carrier signal is produced by a piezo-electrically stretched fiber coil. $\varphi(t)$ includes signal of interest, and noise effects are written as:

$$\varphi(t) = D\cos\omega t + \psi(t) \quad (4)$$

If in relation (4), $\psi(t) = \frac{\pm(2n+1)\pi}{2}$ low phase change causes a high current change in the photodiode. This condition is called the quadrature condition. Fringe counting is a method for correcting the large phase signal outside of $-\pi \le \varphi(t) \le \pi$

ω is interested in acoustic frequency. With expanding (1) versus Bessel functions, the light intensity will be [18]:

$$I = A + B\{[J_0(C) + 2\sum_{k=1}^{\infty}(-1)^k J_{2k}(C)\cos(2k\omega_0 t)]\cos\varphi(t) - [2\sum_{k=0}^{\infty}(-1)^k J_{2k+1}(C)\cos(2k+1)\omega_0 t)]\sin\varphi(t)\} \quad (5)$$

In a similar mode, with expanding the phase angle $\varphi(t)$ in relation (4), the relation (6) can be obtained as [18]:

$$\cos\varphi(t) = [J_0(D) + 2\sum_{k=1}^{\infty}(-1)^k J_{2k}(D)\cos(2k\omega t)]\cos\psi(t) - [2\sum_{k=0}^{\infty}(-1)^k J_{2k+1}(D)\cos(2k+1)\omega t)]\sin\psi(t)$$
$$\sin\varphi(t) = [2\sum_{k=0}^{\infty}(-1)^k J_{2k+1}(D)\cos(2k+1)\omega t]\cos\psi(t) + [J_0(D) + 2\sum_{k=1}^{\infty}(-1)^k J_{2k}(D)\cos 2k\omega t)]\sin\psi(t) \quad (6)$$

$J_n(C)$ and $J_n(D)$ terms in relations (5) and (6), are the Bessel functions.

Fig.1, shows PGC demodulation method based on the

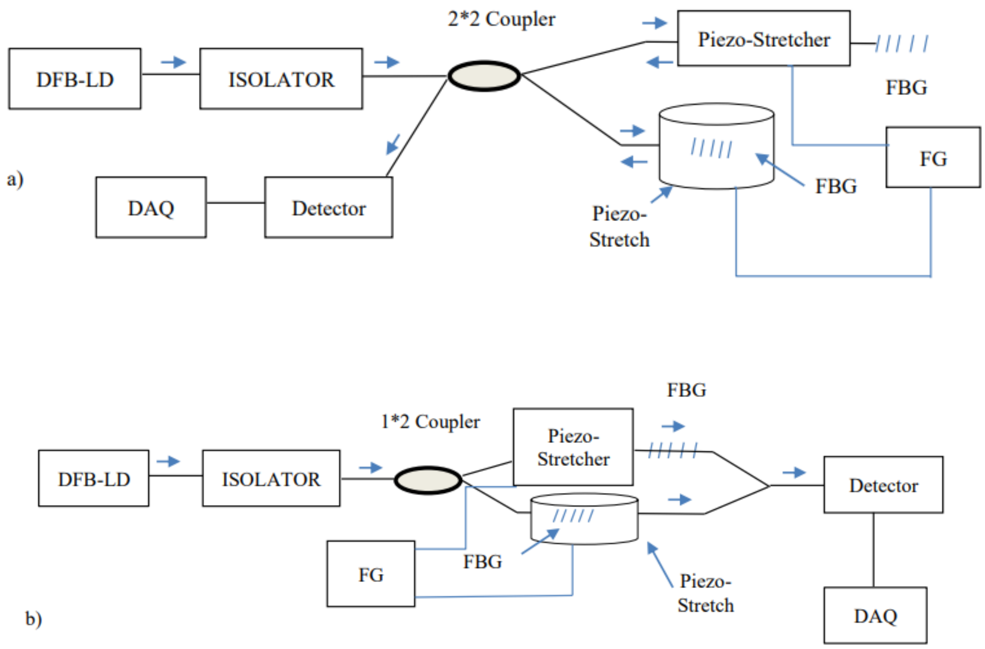


Fig. 2. Experimental Setup of optical fiber sensor based on FBG, a) Michelson interferometer and b) Mach-Zehnder interferometer

arctangent algorithm.

Final intensity of interferometer in equation (1) is multiplied with $cos(\omega_0 t)$ and $cos(2\omega_0 t)$. Low pass filter is applied to eliminate useless order harmonics terms. Residual terms are $KJ_1(C)$ $sin(\varphi(t))$and $KJ_2(C)$ $cos(\varphi(t))$. K is constant term due to intensity amplitude. If C is fixed to C=2.63 radian, [14] coefficient of $sin(\varphi(t))$ and $cos(\varphi(t))$ becomes same. Then, phase term $\varphi(t)$ that contains information about interested signal is calculated by:

$$\varphi(t) = \tan^{-1}\left(\frac{\sin(\varphi(t))}{\cos(\varphi(t))}\right) \tag{7}$$

The remaining computational details are described in [7].

3- Experiments

The experimental setup is shown in Fig. 2 (a and b). A 10 mW 1550 nm Distributed Feedback Laser Diode (DFB-LD) is utilized as a light source. Light is launched into Michelson interferometer arms via a 2*2, 3dB optical fiber coupler and into Mach-Zehnder interferometer by 2*2 optical fiber coupler. In the Michelson interferometer, upper arm acts as a reference. In this reference arm, 1m long single mode fiber (SMF) is coiled around a piezoelectric stretcher for the phase modulation (PM) of optical signal in PGC method. PM is a modulation with 33 kHz frequency is performed to the piezoelectric stretcher. In below arm of the Michelson interferometer, FBG is wounded around piezo-stretcher and acoustical signal is generated using inserting function generator (FG) signal to piezo-stretcher. Two FBGs in the Michelson interferometer have 1nm bandwidth and 50% reflection. Reflected lights from two FBGs are combined and received by a data acquisition (DAQ) unit. For Mach-Zehnder interferometer, above arm acts as reference arm. In this arm, 1m long SMF is coiled around a piezoelectric stretcher for the phase modulation (PM) of optical signal in PGC method. PM is a modulation with 33 kHz frequency is applied to piezoelectric stretcher. In below arm of Mach-Zehnder interferometer, FBG is turned around piezo-stretcher and acoustical signal is produced by applying function generator (FG) signal to piezo-stretcher. Two FBGs in Mach-Zehnder interferometer have 1nm bandwidth and 50% transmission. Transmitted lights are received using DAQ unit.

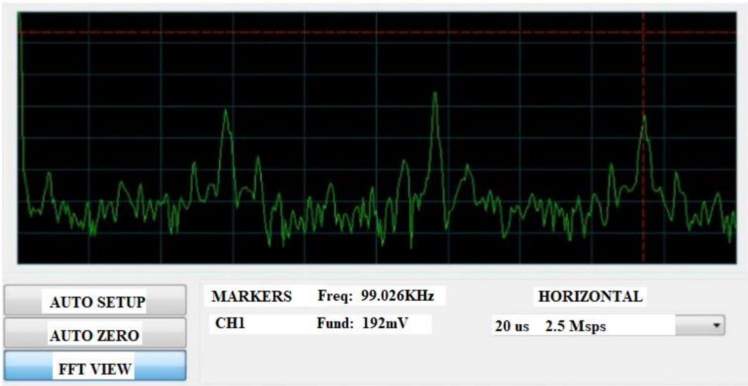
It is also packaged sensing arm of the Michelson interferometer (including FBG and 1m SMF long) by polyurethane UR5041 with cylindrical geometry. The length of UR5041 is 10cm.

It can be expressed, the signal to noise ratio (SNR) of optical fiber sensor versus applied pressure p [19]:

$$\text{SNR}=20\log\left(\frac{\varphi(t)}{p\,1rad\,/\,\mu Pa}\right) \tag{8}$$

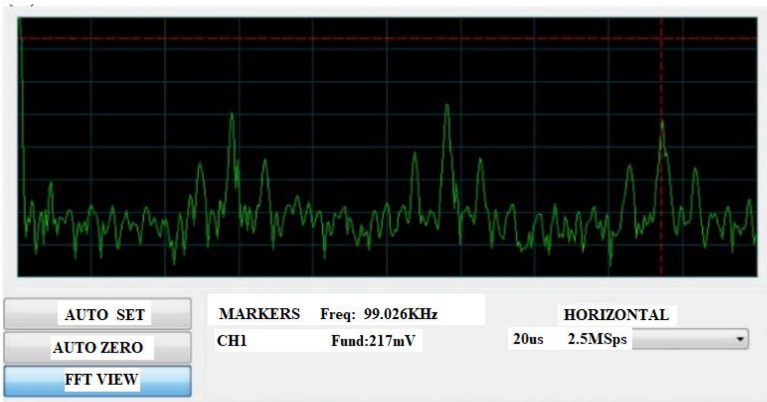
4- Experimental results

Fig. 3 shows FFT of demodulated signal for different interferometer setup and depicts the FFT of demodulated signal obtained by DAQ system where it is applied acoustic vibration. It is shown three harmonics of phase modulator



(a)

(b)



(c)

Fig. 3. Harmonics of phase modulator frequencies and acoustic signals as sidebands for 5KHz frequency for a) Mach-Zehnder interferometer, b) Michelson interferometer and c) Michelson interferometer with polyurethane coating

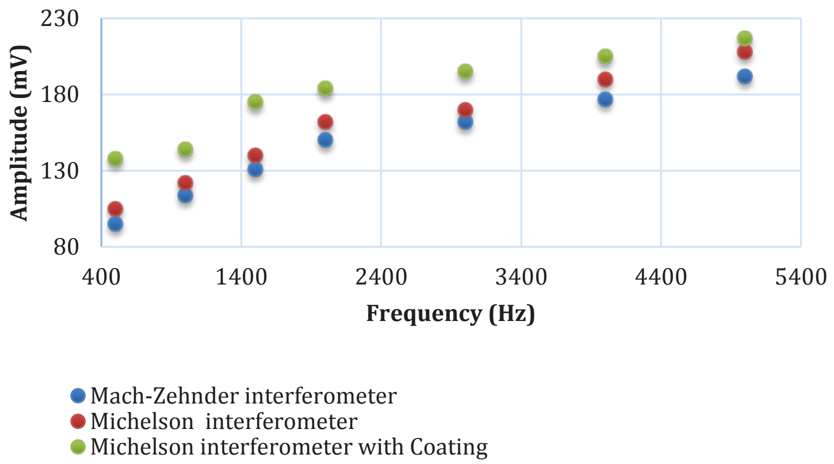


Fig. 4. Frequency response for different setup.

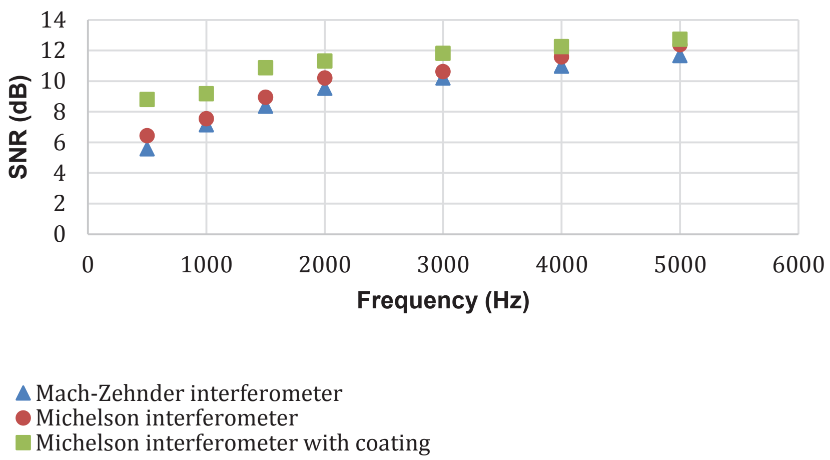


Fig. 5. Frequency response for different setup versus dB.

frequencies at 33 kHz, 66 kHz, and 99 kHz with sidebands as 5 kHz frequency. The maximum value of sideband voltage is considered as criteria of sensitivity of optical fiber sensor based on FBG. It is shown the maximum voltage belongs to the Michelson interferometer coated by polyurethane material (217 mV) as it is shown in Fig.3-c. In reality, as a response to the acoustic vibration, FBG is stretched and contracted, and the period of the grating and refractive index change. These changes cause the optical path length and consequently optical phase change.

Fig. 4 shows the measured frequency response characteristic of the optical fiber sensor for Mach-Zehnder interferometer, Michelson interferometer and Michelson interferometer with polyurethane coating. The measured voltage of the sideband in oscilloscope is from 96mV to 217mV over frequencies from 500 Hz to 5000 Hz. The results show that maximum signal to noise ratio is achieved for all acoustical frequencies by using Michelson interferometer and polyurethane coating. For all above sensors, the applied RMS voltage to function generator signal is 2V.

Fig. 5 indicates the frequency response of the optical fiber sensor versus dB for the Mach-Zehnder interferometer, Michelson interferometer, and Michelson interferometer with polyurethane coating.

The field test setup is shown in Fig. 6 based on the Michelson interferometer and polyurethane coting. With applying acoustic signal using an acoustical transmitter, optical fiber sensor and standard hydrophone receives

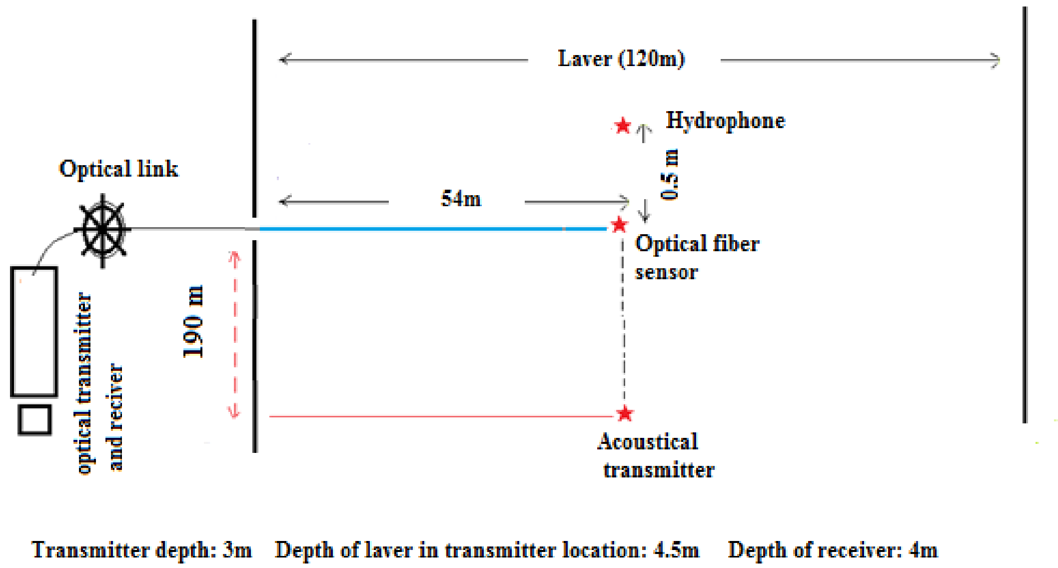


Fig. 6. Scheme of field setup

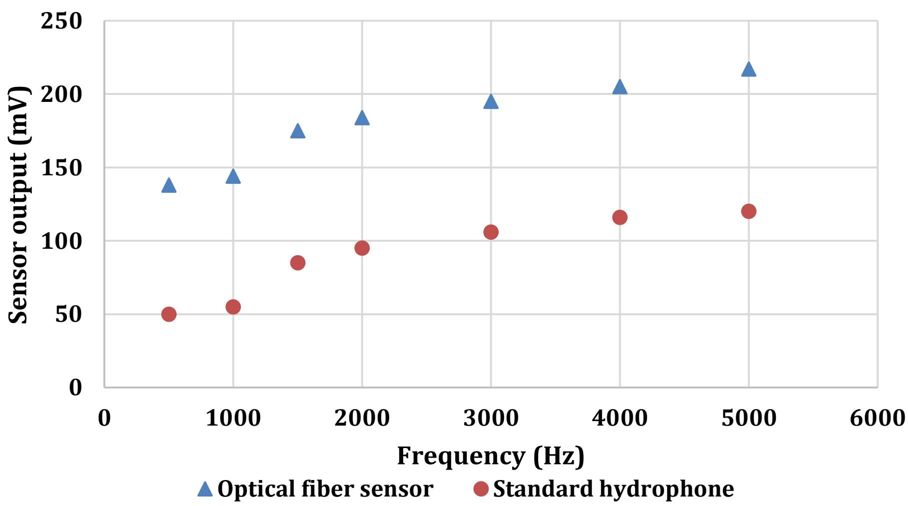


Fig. 7. Output of sensors versus acoustic frequency.

acoustical signal. For optical fiber sensors, acoustic signal application causes deformation in optical fiber length and this length change using detection and electronics system is calculated and finally, the acoustic signal is extracted from ambient noise.

It is shown in Fig. 7 that frequency response of optical fiber sensor is similar to that of a standard hydrophone. The proposed optical fiber sensor output was measured at frequencies of 0.5 kHz, 1 kHz, 1.5 kHz, 2 kHz, 3 kHz, 4 kHz and 5 kHz equal to 138 mV, 144 mV, 175 mV, 184 mV, 195 mV, 205 mV, and 217 mV respectively. The results also show that, the frequency response trend of optical fiber sensor at 0.5- 5 kHz range is similar to that of a standard hydrophone. The presence of polymer material increases the sensitivity of optical fiber acoustic sensors. So when an acoustic event strikes or impacts on the effective length of the sensor,

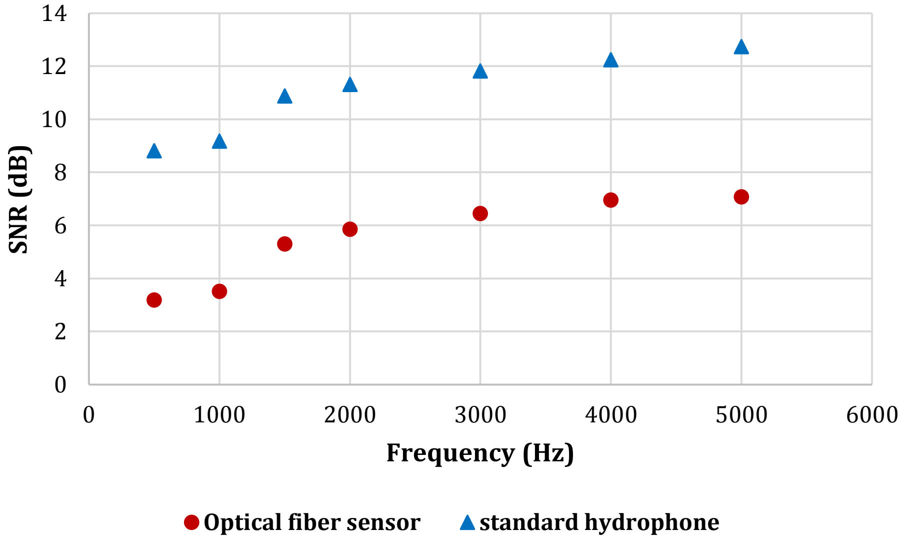


Fig. 8. Output of sensors versus acoustic frequency in dB.

the pressure exerted by the acoustic wave on the sensor is experienced by the elastic polymer layer and this makes an effective impact of stress on the optical fiber which causes some deformation on the fiber, makes a considerable loss in optical fiber.

The frequency response of optical fiber sensor and standard hydrophone in dB is shown in Fig. 8.

5- Conclusion

In this paper, the demodulated signal of an optical fiber acoustic sensor based on FBG technology is obtained. It is exhibited that an acoustic signal can be extracted from environmental noise. It is also investigated on the role of different setups as Mach-Zehnder interferometer, Michelson interferometer and Michelson interferometer with polyurethane coating. The results show in the range of 500Hz to 5000Hz, the Michelson interferometer setup with polyurethane coating has the maximum signal to noise ratio. The proposed sensor based on a Michelson interferometer with polymer coating is utilized for field tests in shallow water.

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