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Research of a novel fiber Bragg grating underwater acoustic sensor

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Abstract

A new type of optical fiber underwater acoustic sensor (hydrophone) constructed with two fiber Bragg gratings (FBG) and a self-demodulation method is presented in this paper. Unlike other FBG sensors which have separate sensing and demodulating elements, this FBG hydrophone has only a single structure for both sensing and demodulating using a pair of matched FBGs. The cylindrical structure of the hydrophone solves the problems of low sensitivity and cross-sensitivity of the bare fiber Bragg grating acoustic sensors. Theoretical analysis of measurement sensitivity is described. Simulation and preliminary experimental results indicate that the measurement sensitivity can reach 0.78 nm/MPa for underwater acoustic pressure in range of 100–200 dB re 1 μPa.

Keywords: Fiber Bragg grating; Acoustic sensor; Optical hydrophone; Self-demodulation

1. Introduction

Fiber optic hydrophone is a new type of hydrophone came with the development of the optic fiber optoelectronics. J.A. Bucaro (1997) [1] first reported their research on applying optic fiber technology to the underwater acoustic sensor system. Fiber Bragg grating sensors not only have the advantages of conventional fiber optic sensors, but also have some other unique features: FBG sensors are immune to the disturbance to front-end optical fibers; An FBG sensor uses reflection of narrow wavelength bandwidth and therefore can be readily wavelength/time/spatial division multiplexed for multipoint sensing or simultaneous measurement of various quantities [2].

FBG was first applied to measure the underwater acoustic by Nobuaki Takahashi (2000) et al. [3]. A FBG reflects selectively incident light when its wavelength is equal to the Bragg reflection wavelength. When there is a pressure applied to an FBG, the Bragg reflection wavelength shifts because of not only the physical lengthening/shortening effect due to the elasticity of the fiber but also the change in the index of refraction of the fiber core due to the photoelasticity. They made use of this characteristic to detect the signal of underwater sound field and got wonderful results including high linearity, wide dynamic range, small probe size and so on. However, the Bragg wavelength shift induced by acoustic pressure is very small, which is about 6 pm/MPa [4] and this caused a lot difficulty in signal detection and demodulation.

In this paper, we developed a novel underwater acoustic sensor based on fiber Bragg gratings driven by elastic materials, which significantly improves the underwater acoustic sensitivity of the FBG sensor. Moreover, the sensor equips two FBGs for measuring and has differential output, which leads to further improvement of sensor's sensitivity and immunity to the environment temperature change. Besides, a self-demodulation method is used in the sensor unit, which makes the structure more simplified.

2. Principles and sensor construction

Figs. 1 and 2 show the structure of the fiber Bragg grating underwater acoustic sensor probe. The rigid structure which has an 'I' shape cross section in Fig. 1 is made of inelastic material. There are two elastic elements attached to the inner and outer side of the rigid structure. FBG1 is attached on the surface of the outer elastic elements and FBG2 is attached on the surface of the inner one.

Fig. 3 shows the system configuration of the fiber Bragg grating underwater acoustic sensor. The light from an optical broad-band source (BBS) transmits selectively through FBG1.

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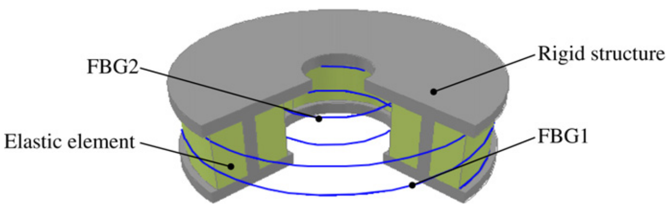

Fig. 1. Hydrophone head 3D view.

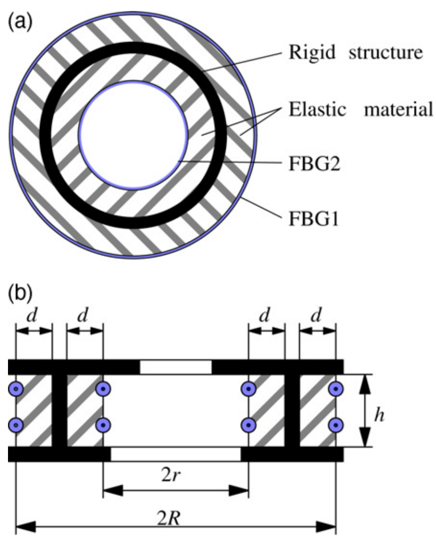

Fig. 2. Hydrophone section view. (a) Cross-section; (b) longitudinal section.

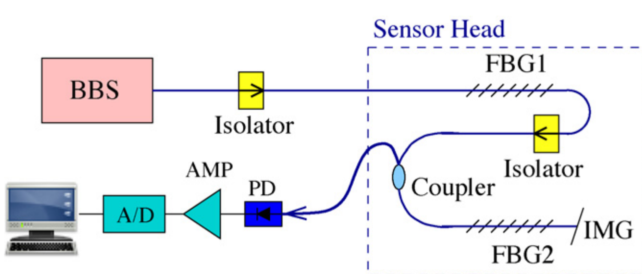

Fig. 3. System configuration.

The transmitted light goes through the optical coupler and then reflected selectively by FBG2 at its Bragg wavelength. Optical isolators are inserted before and after FBG1 to stabilize the sensor signal. The reflected light is detected by a photodiode (PD) and converted into digital signal after amplification. A high-pass filter is used to get rid of the fluctuation caused by the light source and the surrounding environment since the acoustic frequency we interested in ranges from 1 kHz to several MHz, yet the fluctuation frequency is relatively low. FBG1 and FBG2 in Fig. 3 are both used for acoustic measurement. Fig. 4 shows that when there is an external acoustic pressure p, the fiber Bragg grating which attached to the surface of outer elastic element (FBG1)

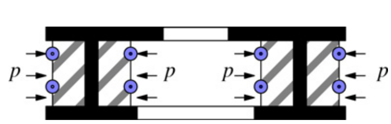

Fig. 4. Hydrophone unit in the underwater acoustic field.

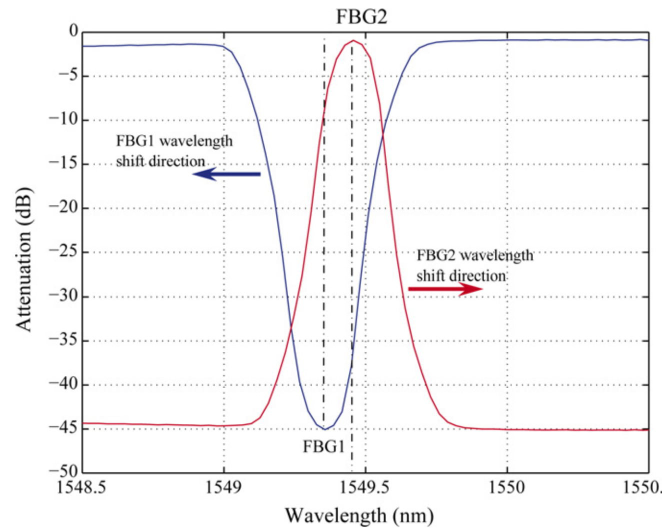

Fig. 5. Self-demodulation demonstration.

will be compressed while the fiber Bragg grating which attached to the surface of inner elastic element (FBG2) will be stretched due to the distortion of the elastic element. The sensitivity of the sensor is doubled because the Bragg wavelength of FBG1 and FBG2 shifts in opposite direction.

Fig. 5 shows that FBG1 and FBG2 demodulates each other's optical signal mutually during the measurement. When the trough position of FBG1's transmissive spectrum and the peak position of FBG2's reflective spectrum matches (it is the initial measurement state), the light reflected from FBG2 has the lowest intensity. As the two spectrums separate, the intensity of the reflected light grows gradually. Therefore, the light intensity detected by the photodiode indicate the distance between the trough position and the peak position, from which acoustic signal can be retrieved.

Another advantage of the sensor system is that the environment temperature variation effect on the measurement results can be reduced. When the external temperature varies, the effect on FBG1 and FBG2 are approximately the same since they are close to each other. Thus, wavelength shift caused by temperature is in the same direction and the relative movement between the spectrums of the two FBGs is negligible. The environment temperature variation has little influence on the output of the sensor.

Denoting the intensity of the incident light by $I_s(\lambda)$, where λ is optical wavelength, the intensity of detected light is given by

$$I_d(\lambda) = \alpha(\lambda) \cdot I_s(\lambda) \cdot [1 - R_1(\lambda)] \cdot R_2(\lambda) \tag{1}$$

where $R_1(\lambda)$ and $R_2(\lambda)$ are the reflectivity of the FBG1 and FBG2, respectively. $\alpha(\lambda)$ is the light power attenuation factor of light route. When the sound pressure around the sensor is $p = p_A \cos \omega t$, where p_A and ω are the amplitude and angular frequency of the sound pressure, respectively, the detected light intensity is given by

$$I_d(\lambda) = \alpha(\lambda) \cdot I_s(\lambda) \cdot [1 - R_1(\lambda - \Delta\lambda_1(p))] \cdot R_2(\lambda + \Delta\lambda_2(p)) \tag{2}$$

Since the wavelength shift induced by the external sound pressure is relatively small, it is then assumed that the higher order terms can be neglected, we get

$$I_d(\lambda) = \alpha(\lambda) \cdot I_s(\lambda) \cdot \left[1 - R_1(\lambda)|_{p=0} + \frac{\partial R_1(\lambda)}{\partial p} \cdot p\right] \times \left[R_2(\lambda)|_{p=0} + \frac{\partial R_2(\lambda)}{\partial p} \cdot p\right] \tag{3}$$

then

$$I_d(\lambda) = \alpha(\lambda) \cdot I_s(\lambda) \cdot \left\{(1 - R_1(\lambda)|_{p=0}) \cdot R_2(\lambda)|_{p=0} + \left[\frac{\partial R_1(\lambda)}{\partial p} \cdot R_2(\lambda)|_{p=0} + \frac{\partial R_2(\lambda)}{\partial p} \cdot (1 - R_1(\lambda)|_{p=0})\right] \cdot p_A \cos\omega t\right\} \tag{4}$$

Thus, the total intensity received by the photodiode can be denoted by

$$W = \int_0^{+\infty} \rho(\lambda) \cdot \alpha(\lambda) \cdot I_s(\lambda) \cdot (1 - R_1(\lambda)|_{p=0}) \cdot R_2(\lambda)|_{p=0}\, d\lambda + p_A \cos\omega t \cdot \int_0^{+\infty} \rho(\lambda) \cdot \alpha(\lambda) \cdot I_s(\lambda) \cdot \left[\frac{\partial R_1(\lambda)}{\partial p} \cdot R_2(\lambda)|_{p=0} + \frac{\partial R_2(\lambda)}{\partial p} \cdot (1 - R_1(\lambda)|_{p=0})\right] d\lambda \tag{5}$$

where $\rho(\lambda)$ is the wavelength sensitivity function of the photodiode. It can be seen from Eq. (5) that the AC component of the received light intensity is proportional to the sound pressure around the sensor.

3. Sensitivity analyses

Assume that the height of the underwater acoustic sensor unit is h, the thickness of the elastic element is d and its bulk modulus is B, the inner and the outer diameter of the sensor is $2r$ and $2R$. When the sound pressure around the sensor is $p = p_A \cos \omega t$, the volume of the inner elastic element changes is

$$\Delta V = \frac{p \cdot V}{B} = p \cdot \frac{\pi \cdot [(r+d)^2 - r^2] \cdot h}{B} \tag{6}$$

where V and ΔV are the initial volume and volume alteration of the inner elastic element, respectively. Denoting the alteration of the inner diameter by $2\Delta r$, we get

$$\pi \cdot [(r+d)^2 - (r+\Delta r)^2] \cdot h = \pi \cdot [(r+d)^2 - r^2] \cdot h - \Delta V \tag{7}$$

Substitute Eq. (6) into Eq. (7), we get

$$2 \cdot r \cdot \Delta r + \Delta r^2 = \frac{p}{B} \cdot (2rd + d^2) \tag{8}$$

Since Δr induced by the external sound pressure is relatively small, we neglect the higher order terms and arrive to

$$\Delta r = \frac{p}{B} \cdot \frac{2rd + d^2}{2r} \tag{9}$$

Thus, the strain of the inner FBG in axial direction is given by

$$\varepsilon_{z_2} = \frac{\Delta L_2}{L_2} = \frac{2\pi \cdot \Delta r}{2\pi \cdot r} = \frac{p}{B} \cdot \frac{2rd + d^2}{2r^2} \tag{10}$$

where L_2 and ΔL_2 is the initial length and the length alteration of FBG2. The FBG2 wavelength shift induced by the strain in axial direction is given by

$$\frac{\Delta\lambda_{\mathrm{Bragg}_2}}{\lambda_{\mathrm{Bragg}_2}} = (1 - P_{ei}) \cdot \varepsilon_{z_2} \tag{11}$$

where $\lambda_{\mathrm{Bragg}_2}$ and $\Delta\lambda_{\mathrm{Bragg}_2}$ is initial Bragg wavelength and wavelength shift of FBG2, respectively. The elasto-optical coefficient of silica fiber denotes by $P_{ei} = 0.22$ [5], thus

$$\Delta\lambda_{\mathrm{Bragg}_2} = 0.78\lambda_{\mathrm{Bragg}_2} \cdot \frac{p}{B} \cdot \frac{2rd + d^2}{2r^2} \tag{12}$$

The same argument can be used to show that

$$\Delta\lambda_{\mathrm{Bragg}_1} = 0.78\lambda_{\mathrm{Bragg}_1} \cdot \frac{p}{B} \cdot \frac{2Rd - d^2}{2(R-d)^2} \tag{13}$$

where $\lambda_{\mathrm{Bragg}_1}$ and $\Delta\lambda_{\mathrm{Bragg}_1}$ is initial Bragg wavelength and wavelength shift of FBG1, respectively. Thus, the total sensitivity of the system can be written by

$$\mathrm{Sensitivity} = \frac{\Delta\lambda_{\mathrm{Bragg}_1} + \Delta\lambda_{\mathrm{Bragg}_2}}{p} = \frac{0.39}{B} \cdot \left(\frac{2Rd - d^2}{(R-d)^2} \cdot \lambda_{\mathrm{Bragg}_1} + \frac{2rd + d^2}{r^2} \cdot \lambda_{\mathrm{Bragg}_2}\right) \tag{14}$$

The inner semi-diameter of the sensor unit $r = 10$ mm, outer semi-diameter is $R = 22$ mm. We choose polyethylene as the material of the elastic element, the bulk modulus is $B_{PE} = 3.22 \times 10^9$ Pa and the thickness is $d = 5$ mm. We presume that the light power attenuation factor of light route $\alpha(\lambda) = 0.0468$, which is constant. The Bragg reflection wavelength of Both FBGs is 1550 nm. We get the system sensitivity is

$$\mathrm{Sensitivity} = 3.613 \times 10^{-7}\ \mathrm{nm/Pa}. \tag{15}$$

4. Experiments and discussions

Simulation and preliminary experiment of the underwater acoustic sensor was carried out to examine the validation of the theory. The specifications of the FBGs used in simulation and experiment are as follows: the Bragg reflection wavelength of FBG1 is 1549.41 nm. The reflection 3 dB band width is 0.221 nm. The Bragg reflection wavelength of FBG2 is 1549.36 nm. The reflection 3 dB band width is 0.223 nm. The reflectance at the Bragg reflection wavelength of both FBGs is

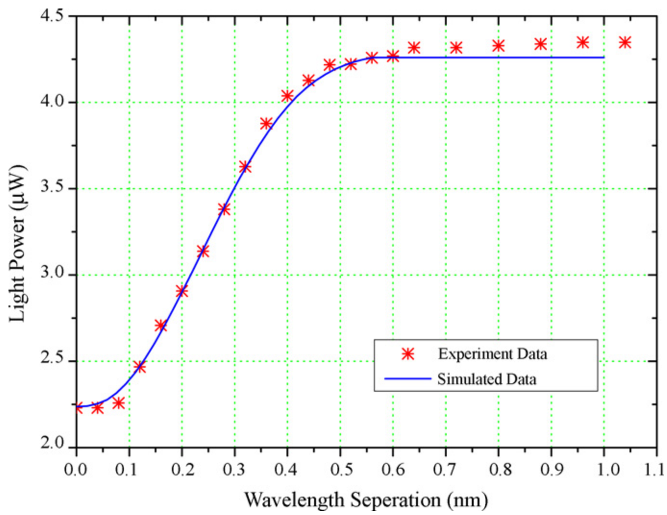

Fig. 6. The relationship between the detected light power and the total wavelength shift of two FBGs.

more than 90%. The specification of the sensor unit is the same as that in the previous section. Fig. 6 shows the relationship between the light power detected and the total wavelength shift of two FBGs. The star points are the measurement values, and the continuous line is drawn by simulation results.

The wavelength separation is within 3.614×10^{-3} nm in the sound pressure of our interest in the range from 100 to 200 dB re 1 μPa. We extended FBG1 a little before it was fixed to the elastic element, so that there is an initial separation of 0.2 nm between the trough position of FBG1 spectrum and the peak position of FBG2 spectrum when there is no external sound pressure. In this case, the sensor works at the starting point of the unbent section on the curve (at the position of 0.2 nm) in Fig. 6, so the output comes to a higher linearity. We presume that the photodiode has a constant sensitivity for the light in all wavelengths, and we take the photodiode sensitivity function as unity. Fig. 7 indicates the dependence of acoustic pressure and

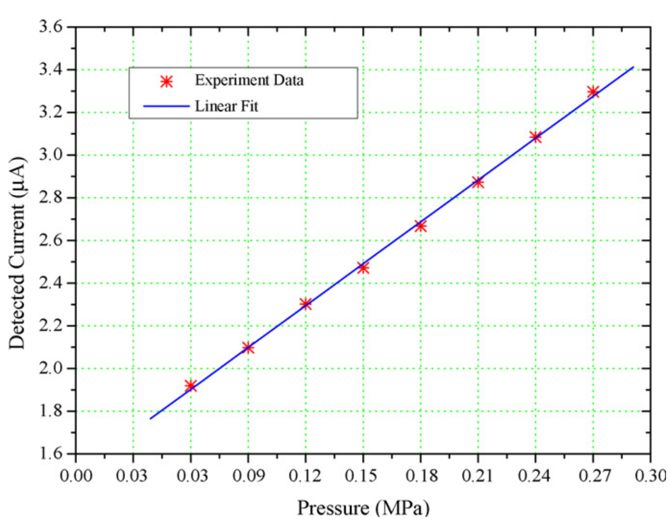

Fig. 7. Acoustic pressure dependence of FBG hydrophone unit.

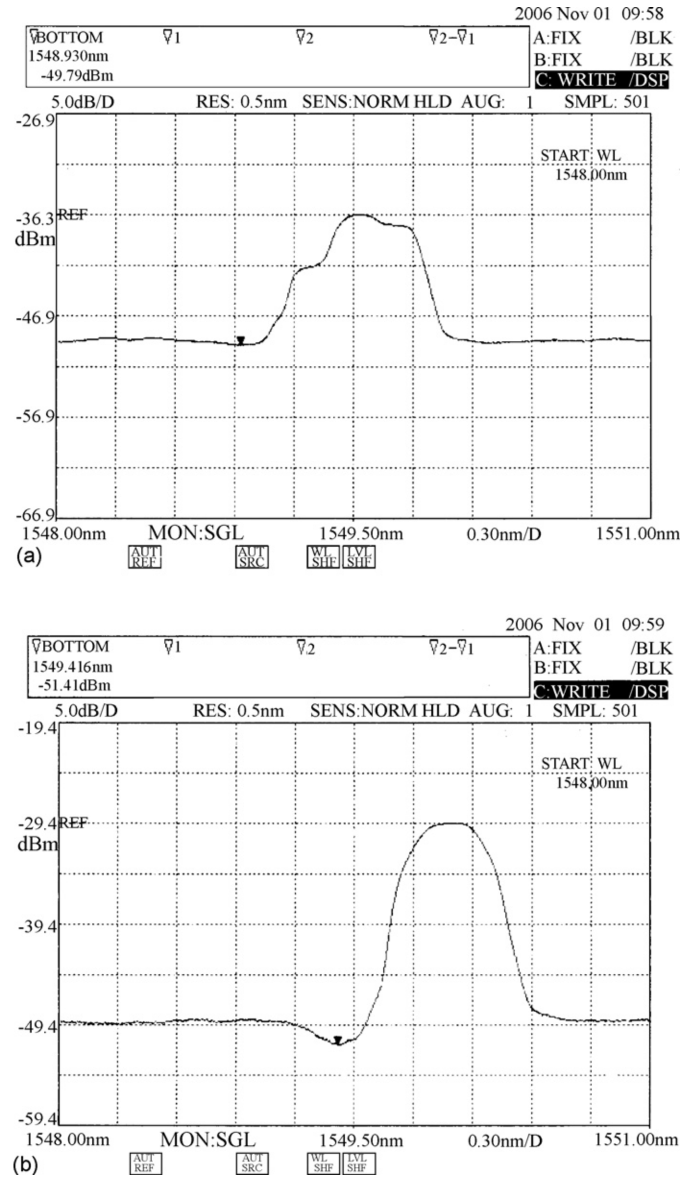

Fig. 8. The received spectrum transforms when pressure varied from low to high. (a) Received spectrum in low pressure. (b) Received spectrum in high pressure.

the output signal current of FBG underwater acoustic sensor. The star points in Fig. 7 are the measurement values, and the straight line is the linear fitting curve, with the linear fitness of 0.999. It can therefore be said that the output signal is proportional to the sound pressure applied to the FBG sensor. From the slope of the line we can see the sensitivity of photodiode output is approximately 6.5 μA/MPa. The responsivity of the photodiode in 1550 nm is about 0.85 A/W, The dependence of light power and wavelength separation which can be told from the linear section of the curve in Fig. 7 is about 6 μW/nm. Thus, the system total sensitivity in the experiment is about 7.8×10^{-7} nm/Pa, which is over 130 times more then bare FBG acoustic sensors which have a sensitivity of 6 pm/MPa [4]. The experimental results match approximately the theoretical prediction. Fig. 8 shows the received spectrum transforms when pressure varied from low to high observed in optical spectrum analyzer in the experiment. As can be seen from the figures, the trough and the peak in the spectrum have little separation when the applied external acoustic pressure is low, and the total light power is also low in this case. As the acoustic pressure grows higher, the separation between the trough and the peak in the spectrum are gradually becomes greater, and the total light power is also getting higher.

5. Conclusions

A pair of matched fiber Bragg gratings are utilized to construct a new type of optical fiber underwater acoustic sensor. The operating principle of the FBG underwater acoustic sensor is based on the intensity modulation of laser light transmitting through and reflecting back from a pair of matched FBGs under influence of sound. The output of the FBG underwater acoustic sensor is proportional to the sound pressure applied, which agrees with the theoretical prediction. The new type of FBG underwater acoustic sensor has the following advantages: (1) it has a greater sensitivity, which is up to 0.36 nm wavelength shift/MPa, compares to the bear FBG acoustic sensor. (2) It has been implemented the self-demodulation method, treating both sensing and demodulating as a whole and (3) having a simple structure and a comprehensible operation principle.

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Biographies

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