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Contents

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Enhanced Acoustic Sensitivity in Polymeric Coated Fiber Bragg Grating

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Abstract: In this work, a new fiber optic hydrophone based on the intensity modulation of the laser light in FBG (Fiber Bragg Grating) under the influence of the sound pressure is experimental proved. In order to increase the sensitivity, FBGs have been coated with proper materials characterized by elastic modulus much lower than the fiber one. The minimum detectable acoustic pressure has been found to be of the order of ~10Pa in the investigated frequency range, with excellent performances in terms of linear response and wide dynamic range. The experimental analysis also reveals that, by a proper design of the coating features, sensor bandwidth and sensitivity can be tailored for specific applications. *Copyright © 2007 IFSA.*

Keywords: Fiber optics sensors, Fiber Bragg Gratings, Hydrophones

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1. Introduction

In the last years, fiber optic hydrophones have been attracting considerable interest due to their potential advantages, such as immunity to electromagnetic interference, remote sensing, stability in harsh environments, wide dynamic range. Several fiber optic sensing schemes have been reported, including interferometric techniques [1-3], polarimetric techniques [4-6] and fiber grating techniques [7-10].

While a conventional fiber optic hydrophone is composed of an ordinary optical fiber and relies on the phase shift of the laser light propagating through the sensing fiber under the influence of the sound pressure, the operating principle of a FBG-based hydrophone is typically based on the intensity modulation of the laser light due to the shift of transmission power spectrum curve of the sensing element under the influence of the acoustic field. The important feature of the intensity-modulated FBG-based hydrophone is its simplicity. Since the detection is carried out by the measurement of light intensity, which is generally easier than that of a shift in wavelength or phase, the structure of an FBG-based hydrophone is expected to be more compact and simpler compared to a conventional optical fiber hydrophone. Unfortunately, the low sensitivity to acoustic pressure of this class of sensors will limit their use in underwater applications, where piezoelectric transducers are widely used despite their dimensions, complex signal processing and electronic front-end and difficult multiplexing.

In this work, for the first time to the best of our knowledge, the experimental demonstration of novel fiber optic hydrophones involving fiber Bragg gratings embedded in polymers of low elastic modulus is presented. For a given acoustic pressure, the basic effect of the FBG coating, if thick enough, is to enhance the dynamic strain experienced by the sensor of a factor given by the ratio between the fiber and the coating elastic modulus. This effect can be efficiently adopted to enhance the acoustic sensitivity if materials with low acoustic damping and acoustic impedance approaching that of the water are used.

2. Theory

In order to outline the strain amplification in coated FBGs, the interaction between a uniform Bragg grating of length L, written into the core of a standard single-mode fiber, and an incident acoustic wave is theoretically analyzed. For a spatial uniform sound pressure $P(t)=p\cdot\sin(\omega_S t)$ around the FBG (where p and ω_S are the amplitude and angular frequency of the sound pressure, respectively), the corresponding normalized Bragg wavelength shift $\Delta\lambda_B/\lambda_B$ is given by ref. [9]:

$$\frac{\Delta\lambda_B}{\lambda_B}(t)=\left[-\frac{(1-2\nu)}{E}+\frac{n^2}{2}\frac{(1-2\nu)}{E}(2p_{12}+p_{11})\right]P(t) \tag{1}$$

where $n=1.465$, $E=70\text{GPa}$, $\nu=0.17$ and $p_{11}=0.121$ and $p_{12}=0.270$ are the effective refractive index of the guided mode, the Young's modulus, Poisson ratio and the elasto-optic coefficients of the optical fiber, respectively. Thus, the spectral response of the FBG moves, without changing its shape, at the same frequency of the applied acoustic pressure. For a Ge-doped FBG at 1550 nm, $\Delta\lambda_B/\Delta P$ was measured as -3×10^{-3} nm/MPa over a pressure range of 70MPa [10]. This means that with interrogation units able to perform wavelength shift measurements with a resolution of 10^{-4}pm in the investigated acoustic frequency range, an acoustic pressure limit of detection of hundreds of Pa can be obtained.

When optical fiber is coated with plastic material, they exhibit several order of magnitude increase in its pressure sensitivity [11-12].

Indeed, according to the Hocker analysis [15], if the FBG is coated with a thick layer of polymer, the normalized wavelength pressure sensitivity is given by:

$$\frac{\Delta\lambda_B}{\lambda_B}(t)=\left[-1+\frac{n^2}{2}\left[p_{12}-\nu\left(p_{11}+p_{12}\right)\right]\right]\frac{\left(1-2\nu_{coa}\right)}{E_{coa}}P(t), \qquad (2)$$

where E_{coa} and ν_{coa} are the Young's modulus and the Poisson ratio of the coating, respectively.

Therefore, it can be seen from eq. (2) that for coatings with small Young's modulus compared with the fiber one, the wavelength pressure sensitivity of the FBG can be increased significantly.

In Fig.1 it is shown the theoretical gain in pressure sensitivity as function of transverse section for cylindrical geometry for different values of Young's module in the range 1MPa-1GPa and for fixed Poisson ratio ν_{coa}=0.30 of the applied coating.

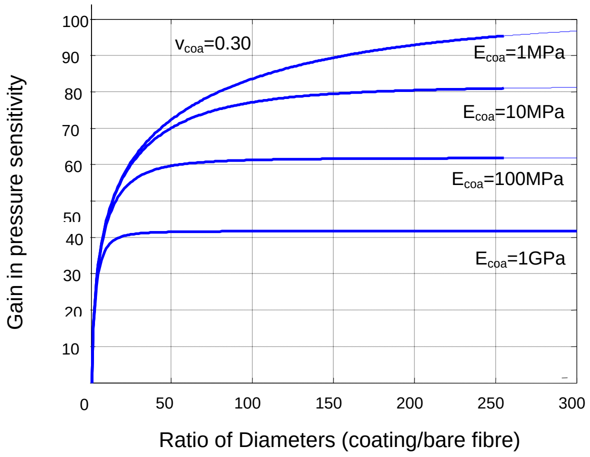

Fig. 1. Theoretical gain in pressure sensitivity vs. transverse section for cylindrical geometry for different values of Young's modulus.

This means that by a proper choice of the coating elastic properties and thickness, excellent pressure sensitivity gain is possible. The experimental demonstration of the pressure gain sensitivity was proved in the static case [16], but the concept can be extended to the case of an acoustic field if the coating dimensions are small compared with the acoustic wavelength.

In addition, the results extension is valid if the acoustic damping within the overlay is low in order to not affect the dynamic strain amplitude within the coating itself. Also, the acoustic impedance, related to the coating thickness and elastic modulus, should be very close to that of the water in order to minimize the acoustic reflection at the water-coating interface.

3. Experiment

As mentioned before, the wavelength shift of the FBG spectrum curve is directly related to the incident sound pressure. To demodulate the dynamic wavelength shift, a low cost intensity based demodulation technique that relies on the use of a narrowband source and a broadband FBG is used [8]. In the transmission mode and by working on the edge of the grating spectrum, the transmitted optical power Pt is directly related to the sound pressure according to the following expression:

$$P_t(t)=P_i\left[T_0+\frac{\partial T}{\partial\lambda_0}\frac{\partial\lambda_0}{\partial p}P(t)\right], \tag{3}$$

where P_i is the incident optical power, T_0 is the transmission value at FWHM, $\partial T/\partial\lambda_0$ and $\partial\lambda_0/\partial p$ represent the edge slope of the grating spectral response and the wavelength sensitivity to the pressure, respectively. Yet, in order to achieve the maximum sensitivity and dynamic range, the laser wavelength should be set in correspondence of the full width at half maximum (FWHM), on either the longer or shorter wavelength side of the spectrum curve. It is seen from eq. (3) that the ac component of the transmitted light power is proportional to the sound pressure experienced by the FBG. Thus, the detection of the light with a photodiode provides an electrical output directly proportional to the acoustic field in the water. From the resulting temporal waveform, the amplitude, the frequency and the phase of the field can easily be measured after a proper calibration procedure.

The experimental set-up is shown in Fig. 2. The acoustic field is generated by a PZT acoustic transducer, immersed in a very large water tank (11m long, 5m large and 7m deep) together with the reference PZT hydrophone and the hydrophone under test, at a distance of 1m and 2.2m from the PZT transducer, respectively. A computer-controlled scanning stage that allows independent translations in X, Y, and Z directions and rotations about the vertical axis is used to place the optical fiber hydrophone.

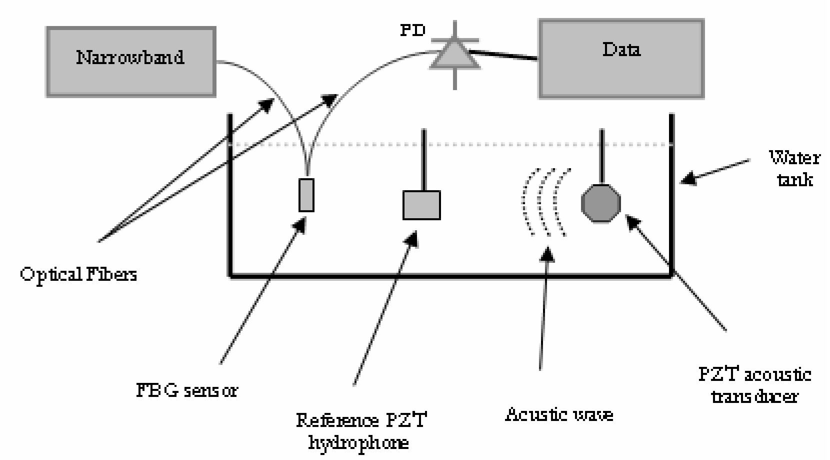

Fig. 2. Lateral view of the experimental set-up.

The utilized fiber Bragg gratings (one characterized by a central wavelength of 1554.20nm and a FWHM of 0.5nm and the other by a central wavelength of 1547.6nm and a FWHM of 0.45nm) were embedded in a polymer of cylindrical geometry with diameter of 4mm and length of 25mm exhibiting an elastic modulus of ~100MPa and in a polymeric material of spherical geometry with diameter of 4.4cm (exhibiting elastic modulus lower than 100Mpa, acoustic impedance that matches the water one and a low damping), respectively. The tested hydrophones are shown in Fig. 3.

The optical source was a stable narrowband wavelength tunable laser and its output wavelength is tuned to the center of the slope of the transmission spectrum curve of the FBG under investigation. The power of light was set to a value of 6mW. The laser light intensity modulated by the FBG subjected to the sound pressure is detected by a fast photodiode.

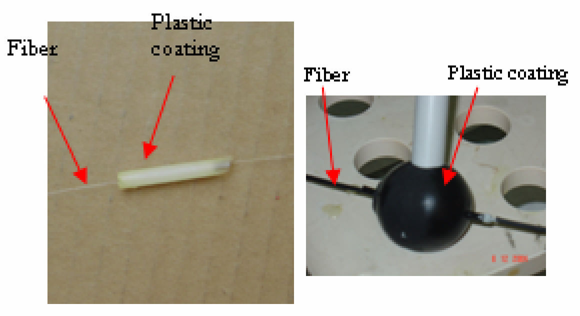

Fig. 3: Photographs of the tested hydrophones.

Two optical isolators, one at the output of the laser, and another at the input of the photoreceiver, are inserted in order to stabilize the sensor output signal. The resolution of the system was estimated to be slightly less than 1pm in the frequency range of interest. The outputs of the optical and piezoelectric (PZT) hydrophones were collected in a PC by an A/D acquisition system.

4. Results

In this section, we report the measurements carried out to evaluate the sensitivity, the linearity and the resolution of the new optical fiber hydrophone and to compare the obtained performances with a reference PZT hydrophone.

The first experiment was carried out by using a fiber optic hydrophone based on a bare Bragg grating but no significative signal could be detected. Successively, a very weak signal extracted by using a complex filtering processing was detected in the case of FBG coated by 250μm acrylate coating. In this case, the pressure sensitivity gain is limited by the coating thickness although its low elastic modulus. Finally, the fiber optic hydrophones based on a coated Bragg grating were tested showing a significant enhancement of the pressure sensitivity, as illustrated in the following.

Fig. 4 shows a comparison between the typical temporal response of the cylindrical-coated FBG hydrophone under test and the reference PZT hydrophone to a sound pressure pulse of 2kPa at the frequency of 10 kHz. It can be seen from the figure that the FBG hydrophone operates as good as the piezoelectric technology. The phase difference between the two responses is due to the different distance from the acoustic source whereas the fluctuations at the end of the traces are due to the eco signals from the wall of the tank. In particular, since the FBG is more far from the acoustic source and nearest to the end of the tank, it exhibits a noisier response with respect to the PZT ones due to both a weaker direct signal and higher eco signals. Using the measured signal-to-noise ratio from the FFT of sensor response in Fig. 4, the minimum detectable pressure level was estimated to be about 10Pa.

In Fig. 5, the calculated sensitivity curves of the FBG hydrophones are presented. Each sensitivity curve (directly related to the Frequency Response) was obtained in two different ways: the first consists in the sensor interrogation with a train of sine-wave pulses of increasing frequency, the second consists in the sensor interrogation with a wideband pulse. In both cases, sensor sensitivities were estimated by using the piezoelectric data as reference. It can be seen from Fig. 5 that the FBG hydrophones present a decreasing response from low frequencies up to about 27 kHz and 16 kHz for the cylindrical and spherical coating, respectively. For upper frequencies the signal to noise ratio approaches the unity around the value of -235dB reV/μPa. Furthermore, it can be seen from Fig. 5 that, with respect to the cylindrical coating, the spherical-coated hydrophone exhibits a higher sensitivity (up to 30dB re V/microPa) due to a better acoustic impedance matching with the water, to a slightly smaller acoustic modulus and to a lower damping. On the other hand, the spherical-coated hydrophone exhibits a smaller bandwidth compared to the cylindrical-coated hydrophones, due to a damping factor that increase with the frequency, whereas the cylindrical coating damping is almost constant, and due to the dimensions that became comparable with the acoustic wavelength.

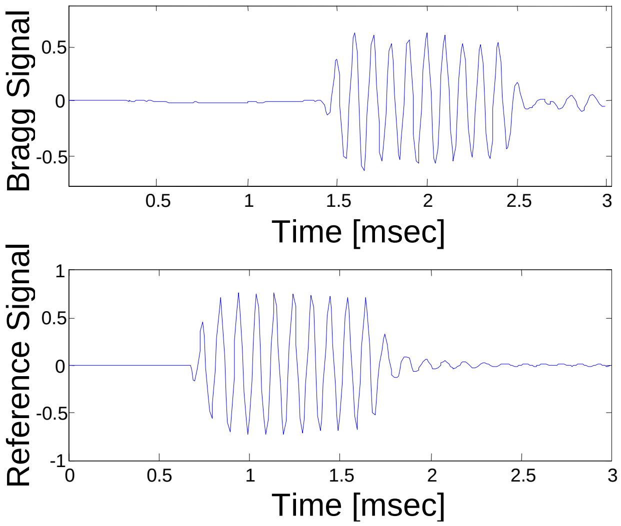

Fig. 4. Typical temporal response of the cylindrical-coated hydrophone under test (upper) and the reference hydrophone PZT (lower) to a sound pressure pulse of 2kPa at the frequency of 10 kHz.

Indeed, the dimensions play a fundamental role in determining the overall bandwidth of the spherical hydrophone: the coating should be thick enough to ensure an adequate strain amplification (see Fig. 1), but less than the acoustic wavelength of interest to avoid the acoustic diffusion at the coating interface.

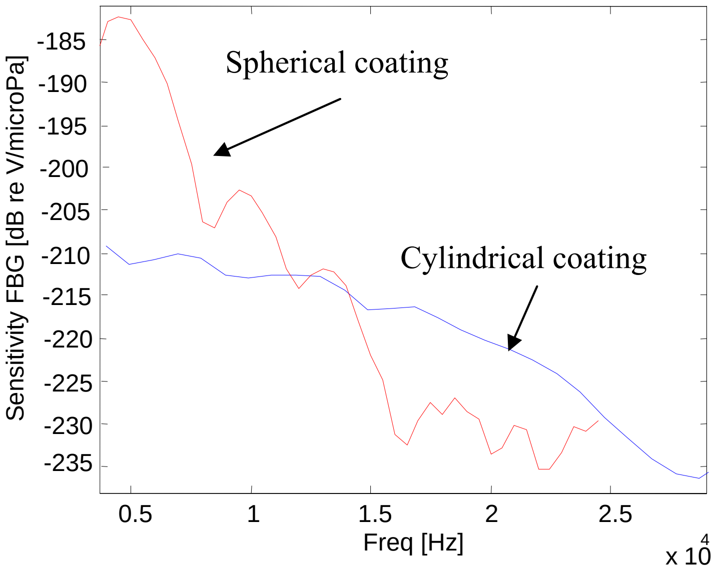

Fig. 5: The calculated sensitivity curves of the FBG hydrophones.

Also, directivity measurements have demonstrated an isotropic behavior of the fiber optic hydrophone response with the cylindrical coating, as shown in Fig. 6. A weak directivity was observed in the case of the spherical coating especially if the acoustic wave travels normal or parallel to the fiber axis.

5. Conclusions

In conclusion, in this work, the feasibility analysis on the use of polymeric coated FBGs as novel hydrophones with tunable characteristics in terms of sensitivity and bandwidth is reported. By acting on the geometrical and acousto-mechanical properties of the polymeric coating it is possible to achieve different sensitivity characteristics, leading to significant improvements in the acoustic detection by FBGs based sensors.

By using a low cost detection scheme, a maximum resolution of ~10Pa was obtained. Preliminary results, thus, demonstrate performances that could be really competitive with conventional and widely used piezoelectric based hydrophones for underwater applications. Finally, it is clear that much work should be carried out in order to outline and well understand the complex dependence of the sensitivity characteristic on all the coating features for the definition of optimization criteria.

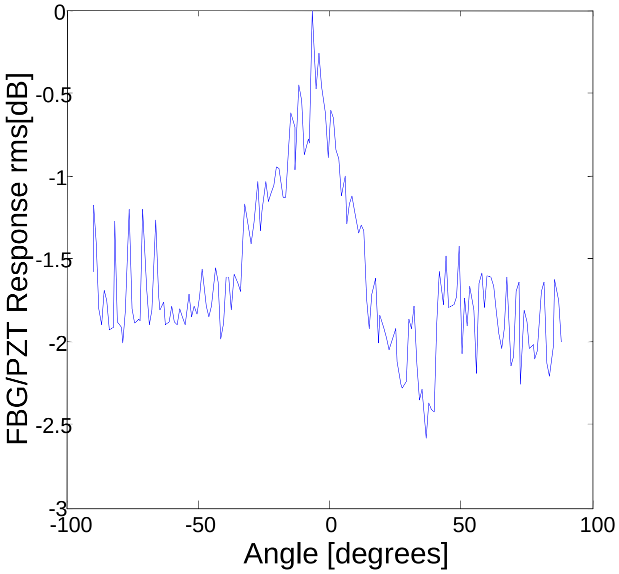

Fig. 6. The measured directivity of the cylindrical FBG hydrophone

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