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Light intensity modulated fiber-optic hydrophones

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Fiber-optic sensors for underwater acoustic wave measurement have become a research focus in recent years. There are great potential for down-hole instrumentation for exploration of nature oil resources, and especially for military use of subsea acoustic measurement. This article presents a comprehensive and systematic overview of fiber-optic hydrophones based on light intensity modulation technologies. A novel fiber-optic sensor for acoustic wave measurement based on a single-mode fiber coupler is also introduced. It is anticipated that light intensity modulated fiber-optic hydrophones will be commercialized and widely applied in practice in the near future due to their compact structures and low costs.

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1. Introduction

Fiber optic hydrophone (FOHP) technology is beginning to be considered a viable alternative to conventional piezoelectric needle and membrance hydrophones, which had been widely used for all kinds of acoustic wave or sound measurement. New fiber-optic hydrophones overcome several limitations of conventional hydrophones, such as inaccurate reproduction of high negative pressures, cavitation tendency, low bandwidth, bad electromagnetic shielding and ageing problems [1]. The predominant forms of fiber optic sensing applied to acoustics can be categorized as phase or light intensity modulation sensors. In the former, optical phase interference or polarization rotation effects are often used to measure sound waves with high measurement sensitivities. Phase interferometric sensors generally require a reference fiber to compare relative phase shifting. Reference fibers, however, are also potential noise sources, being environmentally sensitive as well; temperature differences between sensor and reference can produce undesirable errors [2]. In addition, the sensor structures and signal processing methods of the phase modulation hydrophones are complex and they are also costly for practical use.

Due to the needs of simple, inexpensive and practical fiber optic hydrophones for down-hole instrumentation for exploration of nature oil resources, and especially for military use of subsea acoustic measurement, several new light intensity modulated fiber optic hydrophones have been proposed and developed in recent years, including those based on the traditional method of microbend. The aim of this article is to give a comprehensive and systematic overview of fiber-optic hydrophones based on light intensity modulation technologies. A novel fiber-optic sensor for acoustic wave measurement based on a single-mode fiber coupler is also introduced.

2. Light intensity modulated fiber optic hydrophones

Fiber-optic sensors based on all kinds of sensing principles or devices that induce the changes of transmission light intensity can be categorized as light intensity modulated sensors. Sensing principles of this kind of sensors are completely different from those phase-sensitive fiber optic interferometers. The structures of intensity-modulated fiber optic sensors are generally simple and compact. They are playing more and more important roles in both academic and engineering fields. And a great number of physical and chemical measurands have been successfully tested in different industry applications, such as measurement of displacement and surface shape [3], biofilm [4], pressure [5], water salinity and temperature [6], product quality in-line monitoring [7] and so on.

2.1 Microbend methods

Microbends are repetitive changes in the radius of curvature of an optical fiber which result in a decrease in the optical power. The increase in attenuation is due to repetitive coupling of energy between the guided modes or between the guided and the leaky modes of an optical fiber. Microbend losses have always been a curse to the cable designer, but it is this very same microbend loss effect in optical fibers that is exploited by the microbend sensor designer who has adapted the microbend effect to the measurement of many physical parameters and physical variables such as vibration and pressure. And it was said [8] that sensors based on microbend loss were first proposed and demonstrated in 1980 by Fields [9] and the early interest in microbend sensors was for hydrophone applications [10-11].

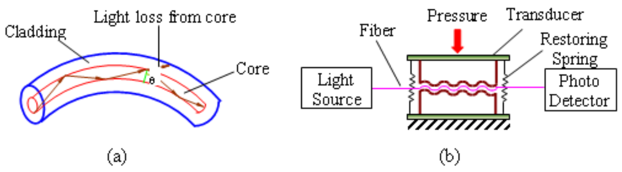

Fig. 1. (a) Microbends create a light loss from the core; (b) Principle of microbend sensor system.

Fig. 1 shows the diagrams of microbend loss and the fundamental sensor system. Microbending means that the mechanical perturbation of a multimode fiber waveguide causes a redistribution of light power among the many modes in the fiber. The more severe the mechanical perturbation or bending, the more light is coupled to radiation modes and is lost. Based on this original principle, several structures which are more suitable for underwater sound measurement have been proposed. The dynamic range of microbend sensors is remarkable. The primary disadvantage, which has many manifestations, is sensitivity to optical power level.

2.1.1 Microbend FOHP based on cylindrical element

The use of cylindrical sensing elements was first suggested by Lagakos [11]. Some of the advantages of this configuration are mechanical simplicity, acceleration insensitivity and shape flexibility. The limitation of it is that it could detect only the sound wave amplitude. The direction of the acoustic waves, however, could not be decided. In order to improve this limitation, revised versions were proposed by Vengsarkar, et al. [12], as shown in Fig.2. Fig.2(a) is called 1F/FΛ rotational hydrophone, which means a fiber is wound around a cylinder along the external threads machined throughout the length of the cylinder with fixed mechanical wavelength of periodic perturbation, Λ. Axial slots are cut deeper than the external threads and cover only 90° of the circumference of the cylinder. An incident acoustic wave induces microbends by way of deflections of the fiber within the slots; these microbends result in a reduction in the intensity of the output light. When the pressure wave is incident in the direction just towards the slots, maximum deflections will occur on the fiber, resulting in maximum reduction in light power. Direction sensing can thus be attempted by rotating the cylindrical element.

Fig. 2(b) is defined as 3F/FΛ stationary hydrophone, which means there are three fibers respectively wound on the cylinder; the cylinder is divided into three sections along its length, and the axial slots in each section are disoriented from one another by 90°. Thus, the output of each of the fiber segments can be respectively monitored, and both of the acoustic wave amplitude and the direction can be obtained.

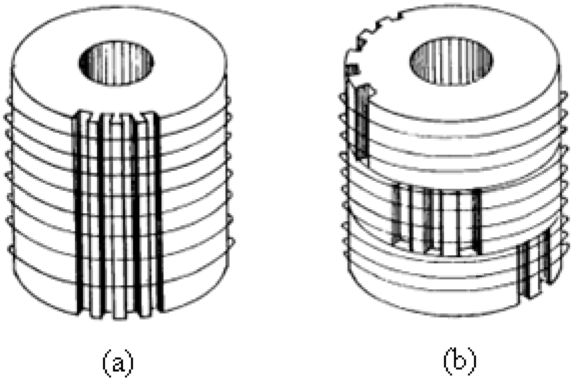

Fig. 2. Revised versions of cylindrical sensing element based fiber optic hydrophones.

One of the drawbacks of the 1F/FΛ hydrophone is the dependence on rotation rate. A certain amount of time had to be elapse after each rotation step so as to allow the water to attain a steady state. The 3F/FΛ design avoided this problem, it added, however, to the optical complexity of the system by placing the requirement of three detectors for simultaneous monitoring, and by necessitating the use of a 1×3 coupler at the input.

2.1.2 Microbend FOHP based on spiral deformer.

The principle of this kind microbend sensor is that the fiber is wound and deformed by a spiral deformer such as a stiff spring, where the period of the spiral matches the optimum fiber bend period (where the microbend loss is sharply peaked). It was first described by Oscroft [13] for weight- and pressure-sensitive safety application, and now it has been used in a number of commercial applications including tactile sensing in the bumpers of automatic guided vehicles to provide automatic shut-off. The diagram of the sensor is shown in Fig.3.

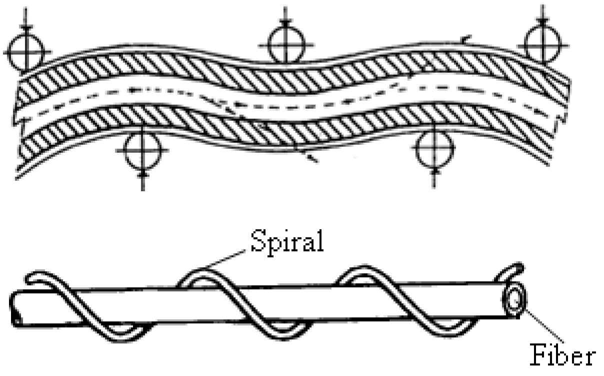

Fig. 3. Diagram of the spiral deformer based microbend sensor.

In 1990, a novel spiral sensor was fabricated by Schoenwald and Bivins [14]. As the sensor consists of a wire spiral wrapped around the fiber, and the fiber is spiralled between an inverted cone and an outer tapered sleeve, the design is called the “double spiral” sensor, as shown in Fig.4. Thin wire with a diameter of 0.127 mm is firmly wrapped around the fiber with a 2 mm pitch. It was said that sensitivity of this sensors will be improved if compression is applied between the cone and the tapered sleeve, in effect biasing the degree of microbending.

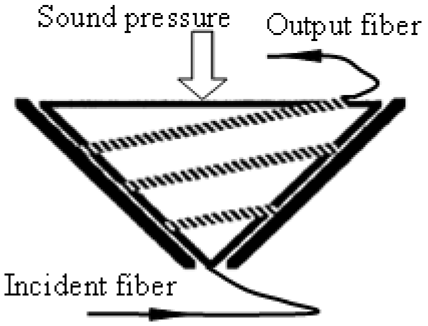

Fig. 4 Diagram of double spiral microbend fiber optic hydrophone.

2.1.3 Microbend FOHP based on pressure sensitive diaphragm.

In this kind of sensor, a web of similar fiber woven in a star configuration across the open end of a hollow tube, with a diagram attached to the center of the webbing is used as the sensing element, as shown in Fig.5 [2]. The hollow cylinder has vertical posts around which an optical fiber is wound across the cylinder endface in a “daisy” pattern. The diaphragm is bonded to the fiber at the center, where the fiber crosses back on itself. Sound incident on the diaphragm will oscillate the diaphragm, modulating the tension in the fiber. This will, in turn, modulate the degree of microbending around the posts. A similar sensor was developed by Zhou et al. in 1995 [14]. And an optimum detectable sound frequency is 155 Hz.

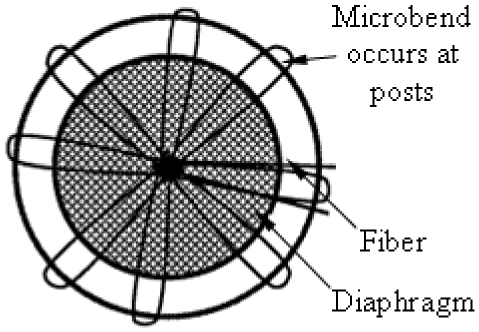

Fig. 5. “daisy” sensor strucute.

2.2 Fiber Bragg grating technology

Fiber-optic hydrophones based on the fiber Bragg grating technology have been proposed in the recent years [15-16] and have been approve to be able to detect an acoustic wave in water with good performances. The basic principle of operation commonly used in an FBG-based sensor system is to monitor the shift in wavelength of the returned “Bragg” signal with the changes in the measurand. The Bragg reflection wavelength is given by [17]

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

where Λ is the grating pitch and n is the effective index of the core.

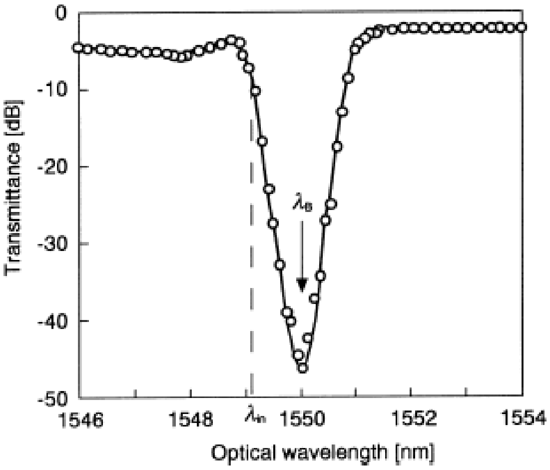

Fig.6 Measured transmitted spectrum of FBG: λ_{in} is the wavelength of the incident light, i.e. the operating wavelength

When there is a pressure applied on 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. Whereas, the rate of the wavelength shift per unit pressure is often too small to detect the sound pressure. Since the transmission spectrum curve of the FBG moves without changing its shape as the pressure is applied [18], a laser light is launched into the FBG and its wavelength tuned to the slope of the transmission spectrum curve of the FBG instead of a broadband light source, as shown in Fig.6. Then, the change of transmitted intensity is almost proportional to the sound pressure around the FBG.

The experimental setup is described in Fig.7 [16]. A PZT acoustic transducer is placed on the bottom of the vessel and driven by an oscillator. The vessel is filled with distilled water. The output wavelength of a laser is tuned to the slope of the transmission spectrum curve of the FBG. The transmitted light is detected with a photodiode (PD). With this experimental setup, the highest sound pressure of 200 dB re 1μPa and the lower limit around 120 dB re 1μPa can be measured linearly. It is very sensitive to the measured pressure, but it is also more expensive than other kind of intensity-modulated fiber-optic hydrophones.

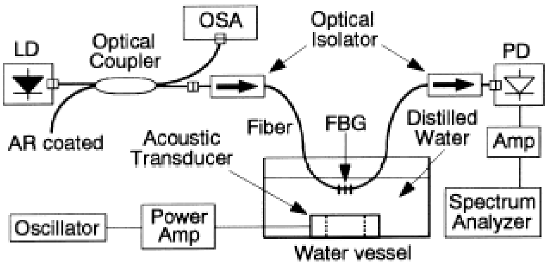

Fig. 7. Experimental setup for FBG hydrophone.

2.3 Reflection coefficient modulation method

The detection mechanism of this kind of hydrophone is based on the change of the optical reflection coefficient at the end surface of a fiber in water by pressure signals. A rise of the acoustic pressure will lead to a compression of the surrounding liquid resulting in an increase of the refraction index. The change of the refraction index of quartz glass of the fiber can be neglected because of its low compressibility. With these assumptions the coefficient of reflection R is calculated from the refractive indices of the liquid n and the fiber core n_c using the Fresnel equations. A good approximation can be achieved if light incidence perpendicular to the fiber endface is considered:

$$R = (n_c - n)^2 / (n_c + n)^2 \tag{2}$$

A sketch of the experimental setup is shown in Fig.8. A fiber-pigtailed 100 mW laser diode with wavelength of 812 nm is used as light source. The laser pigtail consists of 100/140 μm step multimode glass fiber which is guided through a commercial 3dB X-fiber coupler. The free end of the fiber is introduced into the water tank. The fiber is guided through a cannula and fixed to an external tripod in order to avoid distortion of the whole setup under the influence of sound pressure. Half of the reflected light intensity id decoupled and guided to the photodetector.

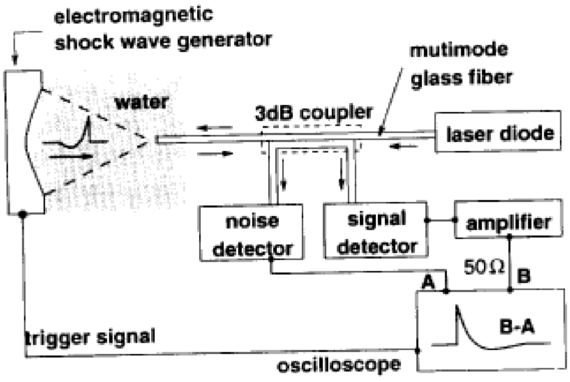

Fig. 8. Experimental setup of the fiber-optic hydrophone based on reflection coefficient modulation.

The reflection coefficient modulation based fiber-optic hydrophone is a well-suited tool for sound measurement in liquid especially in an environment where high positive or negative pressures are expected. The principle and structure are simple.

2.4 Induced displacement modulation method

The induced displacement modulation fiber-optic hydrophone employs two fibers mounted such that their end surfaces are parallel, coaxial, and separated by about several microns. The sound pressures to be measured in the medium induce relative displacement between a fixed fiber and a moveable fiber, as shown in Fig.9(a) [19]. Relative fiber motion varies the light coupled between the two fiber ends, and thus modulates the transmitted light. It was reported that the detection threshold of approximately 80 dB re 1μPa was obtained. Fig.9(b) shows another kind of the induced displacement modulation based fiber-optic hydrophone. It employs the diaphragm and grating elements which move under sound pressure. Relative displacement between the gratings in the direction perpendicular to the line pattern of the grating will modulate the transmitted light. It had been demonstrated that the detection threshold on the order of 50 dB re 1μPa was available [20].

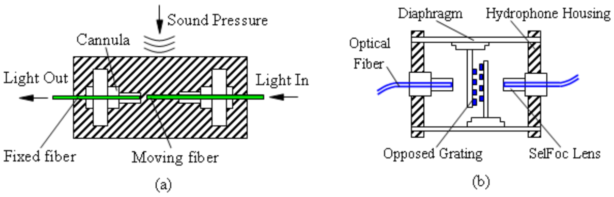

Fig. 9. Fiber-optic hydrophones based on induced displacement modulation.

The major disadvantage of the induced displacement modulated fiber-optic hydrophone is that it utilizes a pair of parallel, coaxial fibers, requires stringent mechanical tolerances, and the light is not confined to the fibers. The latter disadvantage may have a significant impact on long-term reliability.

2.5 Fiber coupler acoustic-optic modulation technology

Fig.10 shows the experimental setup of a fiber-optic hydrophone based on a fused-taper single-mode optical fiber coupler. It was first proposed by R.S.Chen and Y.B.Liao [21]. When a sound wave impinges on the mode-coupling region of a coupler, the coupling coefficient is modulated via the photo-elastic effect. Therefore, the transfer function of the coupler is modulated by the sound wave. The reported sound pressure measurement sensitivity was approximately 5.2 mV/Pa, and the bandwidth of the sensor was up to several hundred kHz. The fiber-optic hydrophone is designed with a 3 dB single-mode fiber coupler and working wavelength is 650 nm. A PZT acoustic actuator is used as the source, another PZT sound sensor and the fiber coupler hydrophone is arranged side by side and perpendicular to the sound wave front. This kind of fiber-optic hydrophone is also with a simple structure, and can be embedded in composite materials with no effect on the sensor response. But the sensitivity was observed to fluctuate with fiber bending and vibration. It is mainly attributed to the fluctuation due to the change of polarization state and can be overcome by using polarization-maintaining fiber components.

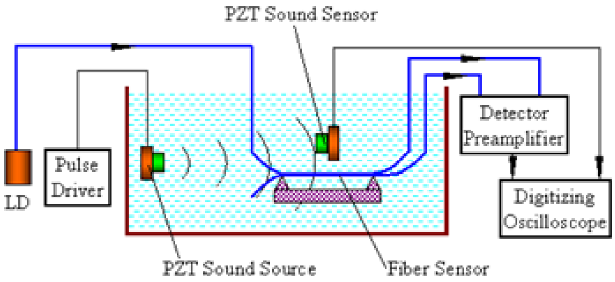

Fig.10. Experimental setup of fiber-optic hydrophone based on a single-mode fiber coupler.

3. Conclusions

Fiber-optic hydrophones especially those based on phase-modulated technologies have been proven to be a popular research interest and have been commercially used in practice. In recent years, more and more attention has paid to the intensity-modulated hydrophones because they are cheap and very simple represented not only by the sensing structure but also by the signal processing.

In this article, a systematic overview of intensity-modulated fiber-optic hydrophones based on various kinds of technologies has been given. There is no doubt that more cost effective instruments will be commercialized in the near future. More researchers and engineers have become involved in this area and research on intensity-modulated fiber-optic hydrophones will remain very active. Its inherent capability of immunity to environmental influence makes it possible to replace the traditional piezoelectric hydrophones in fields such as military antisubmarine defense, shock wave and ultrasonic measurement in water, and oil exploration.

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