Fiber optic interferometric hydrophone using fiber Bragg grating with wavelength division multiplexing

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1. Introduction

Interferometric fiber optic sensors have been studied by many researchers because of a number of advantages over conventional electrical sensing technologies that make them attractive for use in a wide range of application areas. One area of particular interest is underwater acoustic sensor (i.e., hydrophone).

In 1990, a Fabry-Perot interferometer using pairs of fiber Bragg gratings (FBGs) as reflectors was proposed [1]. The use of FBGs as reflectors in fiber optic interferometric hydrophones (abbreviated as “fiber optic hydrophone,” hereafter) greatly simplifies the construction of the distributed chain of the hydrophones by eliminating the required large number of couplers, joints, and other interconnects in other types of fiber optic hydrophones. We have demonstrated the usefulness of this type of hydrophone by implementing a prototype [2]. To develop techniques that allow multiple-hydrophone arrays, we have proposed a method of designing the reflectance distribution of FBGs with a time division multiplexing (TDM) scheme and demonstrated it experimentally [3]. Another scheme for multiplexing is wavelength division multiplexing (WDM) [4–6]. WDM allows many TDM signals at different wavelengths to be combined on a single fiber. Therefore, when we apply the WDM scheme to construct an array system of fiber optic hydrophones, a trade-off between the number of hydrophones and sampling frequency [7,8] does not exist. In other words, WDM enables us to construct a multiplexing scheme with high sampling frequency in contrast with TDM whose sampling rate is inversely proportional to the total number of hydrophones [3,7,8].

In this study, we propose the application of the WDM scheme to construct an array system of fiber optic hydrophones, and the effectiveness of the proposed WDM scheme is demonstrated by experiments.

2. Principle of operation

The measurement setup used in this study is shown in Fig. 1. A pair of FBGs with identical reflecting wavelengths is separated along with the length of the fiber that detects an acoustic signal. A repetitive pulse signal is sent out from a laser at a wavelength of the selected pair of FBGs (i.e., $\lambda_{\text{BRAGG}} = \lambda_A$ or λ_B). The return signals from the pair of FBGs

are coupled to a compensating interferometer that recombines the pulses from the two FBGs to bring about their interference and measure the phase change due to the acoustic signal on the fiber section between the pair of FBGs on the basis of the path-matched differential interferometry phase-generated carrier (PMDIPGC) technique [9]. Another pair of FBGs can be selected with a laser at its wavelength. Therefore, two signals with different wavelengths are running simultaneously in the WDM scheme. This implies that the delay coils used for the TDM scheme [3] are unnecessary for the WDM scheme. An attenuator is incorporated between hydrophones to satisfy the requirements of the dynamic range of the detection system.

The reflectance spectra of two pairs of FBGs of two hydrophones used in this study are shown in Fig. 2. As seen in Fig. 2, each hydrophone has two FBGs. The wavelengths of the lasers are adjusted to 1554.1 nm for hydrophone A and 1547.9 nm for hydrophone B to construct the WDM scheme. A partially overlapped wavelength (from 1550 nm to 1551.5 nm) allows us to construct the TDM scheme on the basis of the reflectance distribution design method [3].

3. Experiments

Figure 3(a) shows the pulse train received at the optical-electrical converter (O/E). This is the pulse train without an optical filter. Reflected pulses from the hydrophones are running simultaneously, and they overlap. To separate these pulses at two wavelengths of the lasers, the passbands of the tunable filters are centered at the wavelengths of 1,554.1 nm and 1,547.9 nm. Figure 3(b) shows pulse trains from hydrophones that are clearly separated.

The sensitivities of the hydrophones as a function of frequency are shown in Fig. 4. The mean sensitivities of hydrophone A with the WDM scheme and a single-hydrophone scheme that corresponds to an unmultiplexed hydrophone are -140.5 dB and -139.4 dB, respectively, in the frequency range below 4 kHz, which is the operating frequency. The cutoff of the operating frequency (e.g., 4 kHz) is lower than the mechanical resonance frequency to avoid amplitude and phase distortion in the detected signal. Those of hydrophone B are -136.1 dB and -136.5 dB, respectively. This result shows that the differences in sensitivity between WDM and a single-hydrophone scheme at hydrophones A and B are 1.6 dB and 1.2 dB, respectively, at a frequency below 4 kHz. Hydrophone B is designed with its

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Fig. 1 Measurement setup of a serial array of fiber optic hydrophones using FBGs with WDM.

Fig. 2 Reflectance spectra of FBGs used in hydrophones and the wavelengths of the lasers used in this study.

Fig. 3 Pulse train received at O/E (a) without optical filter and (b) with optical filter.

Fig. 4 Hydrophone sensitivity versus frequency with WDM and a single-hydrophone scheme: (a) hydrophone A and (b) hydrophone B.

rubber boot filled with silicon oil instead of castor oil to achieve higher sensitivity.

The frequency noise properties of hydrophone A are shown in Fig. 5, where the solid line and dotted line represent measured results of ambient noise with WDM and a single-hydrophone scheme, respectively, in the frequency range of 10 Hz to 4 kHz. The results show that the WDM scheme does not affect the frequency noise property.

These results demonstrate the effectiveness of the fiber optic hydrophone using FBG with WDM.

4. Summary

In this work, we construct the WDM scheme of fiber optic hydrophones using FBGs, and experiments were carried out.

Fig. 5 Frequency noise properties of hydrophone A with WDM and a single-hydrophone scheme.

The experimental results show that 1) the sensitivities of hydrophones with WDM and a single scheme are similar and 2) WDM scheme does not affect the frequency noise property of the fiber optic hydrophone. As a result, the effectiveness of the proposed WDM scheme is exhibited.

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