Method for intrinsic crosstalk reduction on a serial array of interferometric optical fiber hydrophones based on fiber Bragg gratings

Kenji Saijyou1,* Tomonao Okuyama2, Yasuyuki Nakajima3 and Ryotaku Sato3

1Department of Naval Systems Development, Technical R&D Institute, Ministry of Defense, 5–1 Ichigaya-Hommuracho, Shinjuku-ku, Tokyo, 162–8830 Japan
2Naval Systems Research Center, Technical R&D Institute, Ministry of Defense, 2–2–1 Nakameguro, Meguro-ku, Tokyo, 153–8630 Japan
3Defense Systems Div., Oki Electric Industry Co., Ltd., 688 Ozuwa, Numazu, 410–0873 Japan

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1. Introduction

Recently, interferometric optical fiber hydrophones have attracted some researchers’ interest. In the 1990s, a large variety of interferometric optical-fiber sensors using pairs of fiber Bragg gratings (FBGs) as reflectors were proposed [1]. An FBG has wavelength selectivity, and does not need any accessories other than the optical fiber core. By using FBGs as the wavelength-selective reflectors, an interferometric optical fiber hydrophone (hereafter referred to as a “FBG-based hydrophone”) is constructed without couplers, joints, or other interconnects that are necessary for other types of optical fiber hydrophones. Therefore, an in-line type of hydrophone array consisting of such FBG-based hydrophones can be made less complicated and more reliable than hydrophone arrays using other types of optical fiber hydrophones [2,3].

When some optical fiber hydrophones are multiplexed in an array, crosstalk among the hydrophones becomes a critical issue in the performance of the array; it is therefore necessary to minimize the crosstalk [3]. Up to now, many studies on multiplexing schemes that use combinations of several detectors have been conducted, and the arising crosstalk phenomena have been examined [3–5]. However, such studies have been conducted only for the in-line, Fabry–Perot hydrophone array.

In this study, we investigate crosstalk that occurs in an in-line array of FBG-based hydrophones. As mentioned above, such an array can be made simple and reliable, but it cannot be free of crosstalk because all hydrophones are connected in series. In the conventional configuration for an in-line type of array, crosstalk is induced when laser pulses, returning from FBG-based hydrophones, pass again through preceding hydrophones. Therefore, to minimize the influence of crosstalk, we propose a configuration in which the returning laser pulses do not pass through the preceding hydrophones. Subsequently, we also conducted experiments in a water pool to verify the effectiveness of the proposed configuration.

2. Configuration of FBG-based hydrophone

Figure 1 shows the basic configuration for an FBG-based hydrophone array with two hydrophones. In the configuration, the received signal is demodulated by a path-matched differential interferometry scheme with a $3 \times 3$ coupler (hereafter referred to as a “PMDI–3 × 3 coupler scheme”) [6,7]. Here, the fiber length between FBG1 and FBG2 in Hyd1, and the fiber length between FBG3 and FBG4 in Hyd2 are defined as the optical path differences (OPDs) $L_1(t)$ and $L_2(t)$, respectively. Similarly, the difference between the lengths of the two fibers in the compensating interferometer, in which one fiber is connected with the coil and the other is not, is defined as $L_0$. $L_0$ is constant, whereas $L_1(t)$ and $L_2(t)$ are functions of time $t$. These three OPDs are adjusted so that $L_1(t) = L_2(t) = L_0$ when there is no sound pressure.

Figure 2 shows the internal structure of the FBG-based hydrophone. Helmholtz resonator 1 consists of an inner cylinder and orifice 1, and Helmholtz resonator 2 consists of an outer cylinder and orifice 2. Hydrostatic pressure is compensated by the two resonators, whereas a sound wave induces a dynamic pressure difference between the two resonators. The inner cylinder changes radius dynamically as a result of the pressure difference, and hence the OPD of the optical fiber coil, which is wound around the inner cylinder, also changes. Such a hydrophone has a simple structure and can be streamlined easily.

In the configuration shown in Fig. 1, the returned pulses from FBG1 and FBG2 (and/or FBG3 and FBG4, and so on) are coupled via the compensating interferometer, and the interference (optical) signals are converted to electrical signals by the detector. The two electrical output signals from ports p1 and p2 are given by

$$S_1 = A_1 (1 + V_1 \cos(\phi_{\text{acoust}}(t) + \pi/3)), \quad \quad S_2 = A_2 (1 + V_2 \cos(\phi_{\text{acoust}}(t) - \pi/3)), \quad (1)$$

where $A_1$ and $A_2$ are the average intensities of interference signals, $V_1$ and $V_2$ are the fringe visibilities, and $\phi_{\text{acoust}}(t)$ is the phase that indicates the variation in the OPD owing to acoustic pressure. The amplitude of the light wave oscillates at a much higher frequency (>193 THz) than that of the...
optical-electro conversion bandwidth of the detector (<1 GHz). Thus, the power of the oscillating light wave is averaged to intensity \( I_1 \) (and/or \( I_2 \)) through the detector. The orthogonal components of the acoustic signal are derived from the interference signals \( S_1 \) and \( S_2 \) as

\[
\cos \phi_{\text{acoust}}(t) = \frac{S_1 - A_1}{A_1 V_1} + \frac{S_2 - A_2}{A_2 V_2},
\]

\[
\sin \phi_{\text{acoust}}(t) = \frac{1}{\sqrt{3}} \left[ \frac{S_2 - A_2}{A_2 V_2} - \frac{S_1 - A_1}{A_1 V_1} \right].
\]

and the phase \( \phi_{\text{acoust}}(t) \) is obtained by comparing the two values of \( \cos \phi_{\text{acoust}}(t) \) and \( \sin \phi_{\text{acoust}}(t) \). The value of \( \phi_{\text{acoust}}(t) \) varies between \(-\pi\) and \(+\pi\), and jumps discontinuously when it increases above \(+\pi\) or decreases below \(-\pi\). This discontinuity of \( \phi_{\text{acoust}}(t) \) can be modified by adding (or subtracting) multiples of \( 2\pi \). To apply the demodulation process, the average intensities of the interference signals \( A_1 \) and \( A_2 \), and the fringe visibilities \( V_1 \) and \( V_2 \) must be determined. These variables can be obtained from the intensities of the output pulses \( P_{1\text{f}} \), \( P_{1\text{r}} \), \( P_{2\text{f}} \), \( P_{2\text{r}} \), \( P_{3\text{f}} \), and \( P_{3\text{r}} \), which are shown in Fig. 1. The detailed process for deriving \( A_1 \), \( A_2 \), \( V_1 \), and \( V_2 \) is shown in [7].
As shown in Fig. 3(b), the preceding pulse 3 and the following pulse 4 from Hyd\(_2\) pass through Hyd\(_1\). Then, the phase of the preceding pulse shifts by \(s_1 P_1(t)/2\), and the phase of the following pulse shifts by \(s_1 P_1(t + \Delta t)/2\). The coefficient 1/2 indicates that propagation is in only one direction. Therefore, the phase difference between the preceding pulse 3 and the following pulse 4 is described as

\[
\frac{s_2 P_2(t) + \frac{s_1 P_1(t + \Delta t)}{2} + \phi_0}{s_2 P_2(t)} = \frac{s_1 P_1(t)}{2} \quad \text{(3)}
\]

where the first term on the right side of Eq. (3) refers to the received sound pressure \(P_2(t)\) and the third term describes the induced phase change during the one-way propagation through Hyd\(_1\). The third term accounts for the cause of crosstalk. The crosstalk is defined in terms of the ratio of the third term on the right side of Eq. (3) to the true phase difference resulting from the received sound pressure, \(s_2 P_2(t)\), and is expressed mathematically as

\[
\text{Crosstalk} = 20 \log \left( \frac{s_1 \frac{dP_1(t)}{dt} \Delta t}{s_2 P_2(t)} \right). \quad \text{(4)}
\]

Assuming that all of the multiplexed hydrophones have the same receiving sensitivity and that they receive the same sound pressure (i.e., \(s_1 P_1(t) = s_2 P_2(t)\)), Eq. (4) can be rewritten as

\[
\text{Crosstalk} = 20 \log \left( \frac{\frac{dP_1(t)}{dt} \Delta t}{|P_1(t)|} \right). \quad \text{(5)}
\]

When the array receives a narrow-band acoustic signal with frequency \(f\), Eq. (5) is written as

\[
\text{Crosstalk} = 20 \log(\pi f \Delta t). \quad \text{(6)}
\]

This is the generation mechanism for crosstalk in an in-line array of FBG-based hydrophones.

4. Method for reducing crosstalk in an in-line array of FBG-based hydrophones

As described in the previous section, when the returning pulses from the downstream hydrophones pass back through the upstream hydrophones, the sound pressure received by the upstream hydrophones changes the phases of the returning pulses undesirably and crosstalk occurs. Therefore, to reduce the crosstalk, the transmission line must be built so that the returning pulses do not pass through the upstream hydrophones.

An example of such a configuration is shown in Fig. 4. In the example, pulses from the laser source propagate through all hydrophones to the tail of the hydrophone array. These propagating pulses are partially reflected by each hydrophone, and the returning pulses from Hyd\(_1\) (i.e., pulse 1 and pulse 2) pass only through coupler\(_1\) (cf. Fig. 4(a)). On the other hand, returning pulses from Hyd\(_2\) (i.e., pulse 3 and pulse 4) pass through the delay coil, coupler\(_2\), and coupler\(_1\) (cf. Fig. 4(b)).

In this way, none of the returning pulses containing acoustic signals pass through any upstream hydrophone. Consequently, the crosstalk in the demodulated acoustic signals is reduced.

5. Experiments

To verify the effectiveness of the proposed method, an experimental system is constructed and crosstalk levels are measured. The experimental system consists of two FBG-based hydrophones and a compensating interferometer. The transmission path configurations are shown in Figs. 3 and 4. The major specifications of the FBGs and laser are given in Table 1. The two FBG-based hydrophones are designed in accordance with the same specifications. Because the bandwidth (about 1 nm) of the FBGs is much broader than the wavelength shift (about \(\pm 0.2\) nm) caused by the changes in pressure and/or temperature, the launched light pulses are always subject to the influence of the environmental conditions. The “output power” of the laser means the pulse output power of the Er-doped fiber amplifier (EDFA) in Fig. 1. The OPD between FBG\(_1\) and FBG\(_2\) is about 50 m, as is that the OPD between FBG\(_3\) and FBG\(_4\). The path line length between the two hydrophones is about 15 m. This experiment was conducted using the water tank at the Naval Systems Research Center. The tank is 15 m in length, 9 m in width, and 8 m in depth. Hyd\(_1\) was immersed into the water tank and received a narrow-band acoustic signal from a transducer.
Here, let us consider the relationship between the suppression of crosstalk and frequency. The crosstalk level of the common transmission-path configuration increases with increasing frequency, as shown by Eq. (6). On the other hand, the crosstalk level of the separate transmission-path configuration seems to be frequency-independent, because the crosstalk is due to the noise of the measurement system. As a result, the crosstalk suppression effect of the proposed configuration increases with increasing frequency.

6. Summary
In this report, we investigated crosstalk that occurs in the in-line type of FBG-based hydrophone array, and proposed a configuration that would enable us to reduce the crosstalk. Crosstalk is induced when laser pulses, returning from FBG-based hydrophones, pass again through preceding hydrophones in a conventional transmission-path configuration. To reduce crosstalk, the transmission paths of the reflected pulses must be separated from the upstream hydrophones.

The effectiveness of the proposed method was examined during experiments conducted in a water tank. The results of these experiments indicated the following.

1. The measured crosstalk levels for the common transmission-path configuration agreed well with the theoretical crosstalk levels.
2. From the comparison with the crosstalk levels of the conventional transmission-path configuration, it may be seen that the measured crosstalk levels of the proposed separate transmission-path configuration were sufficiently suppressed.

These results confirmed the effectiveness of the proposed method. Hence, we recommend the method in the construction of sonar systems.

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