Microbend loss fiber optic direction and amplitude sensors for underwater applications

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Dual purpose fiber optic microbend loss sensors have been developed for measurement of underwater acoustic wave amplitudes and for detection of the direction of wave propagation. Three different construction schemes for cylindrical sensing elements are considered. The dual purpose hydrophones have been characterized for frequencies ranging from 15 to 75 kHz. They exhibit sensitivities in the range of -175 to -200 dB *re*:1 V/μPa and directionality sensitivity limited by geometrical construction.

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INTRODUCTION

Microbends are repetitive changes in the radius of curvature of an optical fiber that result in a decrease in the transmitted optical power. This 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. Such a loss induced by microbends has been put to advantage in fiber optic sensors[1,2] for the detection of underwater acoustic waves with sensitivities in the range of -200 dB *re*:1 V/μPa.[3,4] Most of the sensors have been used for amplitude detection and the problem of detecting the direction has been left unaddressed. A need is therefore felt to explore new fiber optic sensing schemes for the detection of both the amplitude and the direction of an underwater acoustic wave.

In most practical cases, microbend losses are induced in fibers with the help of grooved deformer plates. Applications of sensors using this mechanism, however, are limited to environments in which grooved plates can be easily installed. In such sensors, the alignment of the grooved plates is critical, the sensor bandwidth is limited and acceleration effects can deteriorate sensor performance. Hence, other geometries need to be considered for underwater applications.

The use of cylindrical sensing elements for fiber optic hydrophones was first suggested by Lagakos *et al.*[4] Some of the advantages of their configuration are mechanical simplicity, acceleration insensitivity, and shape flexibility. The designs that we report here are variations of that configuration, which could detect only acoustic wave amplitudes. Our improvizations are aimed toward detecting the direction of acoustic waves as well.

I. DESIGN

The designs of the sensing elements are shown in Fig. 1. Figure 1(a) shows a single-fiber, fixed Λ, rotational hydrophone (1F/FΛ-R). Fiber is wound around a cylinder along external threads machined throughout the length of the cylinder. Axial slots are cut deeper than these external threads and cover only 90° of the circumference of the cylinder. The fiber is exposed to the sound field only in the axial slots since the fiber within the threaded regions and outside the slots does not come in contact with the induced pressure. 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.

A schematic of a three-fiber stationary hydrophone (3F/FΛ-S) sensing elment is shown in Fig. 1(b). This design is very similar to the single-fiber hydrophone discussed in the previous section. The cylinder is divided into three sections along its length, and the axial slots in each section are disoriented from one another by 90°. Three different fibers are wound on the sections and the output of each of the fiber segments is monitored.

The design of the one-fiber varying Λ, rotational hydrophone (1F/VΛ-R), shown in Fig. 1(c), is based on the theory of mode coupling due to periodic microbends in a step-index multimode fiber. Periodic microbends, with wavelength of perturbation Λ, efficiently couple optical power between modes with longitudinal propagation constants k and k' that satisfy[5]

$$k - k' = \pm 2\pi/\Lambda . \tag{1}$$

It can also be shown[4] that for a step-index fiber, the wave number separation of neighboring modes is given by

$$k_{m+1} - k_m = (2\sqrt{\Delta}/a)(m/M) , \tag{2}$$

where m is the modal group label, M is the total number of guided modal groups, a is the core radius, and Δ is the nor-

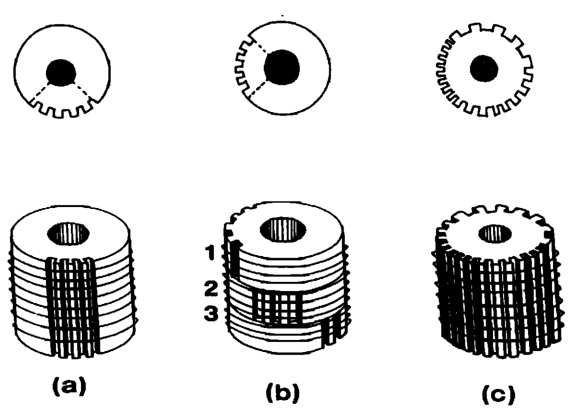

FIG. 1. Cylindrical sensing elements: (a) 1F/FΛ-R hydrophone, (b) 3F/FΛ-S hydrophone, (c) 1F/VΛ-R hydrophone.

malized refractive index difference given by $[n^2(0) - n^2(a)]/2n^2(0)$. Equating (1) and (2), we get

$$\Lambda = (\pi a/\sqrt{\Delta})(M/m)\,. \qquad (3)$$

This implies that by varying the spatial groove period Λ we should be able to couple a different modal group m to its adjacent mode. Since lower-order guided modes propagate closer to the fiber axis, it is possible to spatially filter out the different orders of modes at the output. Simple methods for implementing filtering schemes include a pinhole that samples only the lower-order modes or an annular ring, which allows only the higher-order modes to impinge on the photodetector.

Consider now a cylindrical sensing element with a varying Λ around the circumference. Acoustic waves incident on the sensor will induce microbend losses at specific Λ's dependent on the direction of the acoustic source with respect to the sensing element. The direction of the acoustic source will thus determine which modal groups will couple power most efficiently and this information can be extracted from the output waveforms.

In each of the sensor designs, the hydrophones show directivity because the cylindrical structure itself "blocks" the acoustic wave from propagating to particular sections of the sensing element.

II. EXPERIMENTS

A schematic diagram of the experimental setup is shown in Fig. 2. It consists of a He–Ne laser operating at 633 nm that injects light into a multimode fiber wound around the sensing element. The output of the fiber is spatially filtered with a pinhole aperture before monitoring the power variations with a detector. As mentioned before, spatial filtering is needed because we wish to obtain information about mode-coupling phenomena between modes of specific orders. A pulsed model 8104 Bruel & Kjaer hydrophone is used as the source in the gated mode. The input from the source, is therefore, a sequence of rectangular pulses, each pulse containing a sinusoidally modulated signal that ranges from 15 to 75 kHz. Since the positions of the source and the sensor with respect to the walls of the tank (dimensions $60 \times 60 \times 60$ cm) are known, the oscilloscope output clearly showed the first pulse from the source as well as the undesirable pulses due to the reflections at the walls. All measurements described in this paper are performed by expanding the first pulse incident on the sensor and observing the peak-to-peak voltage of the sinusoidal signal within the rectangular pulse.

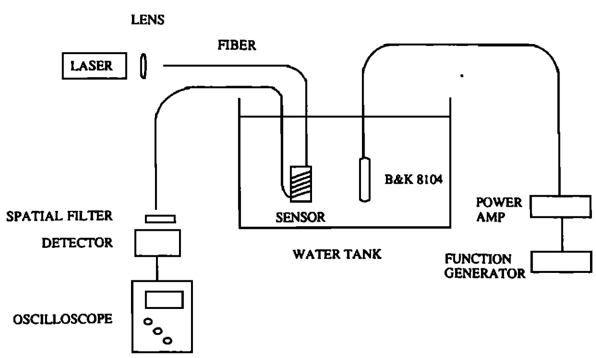

FIG. 2. Schematic of experimental setup.

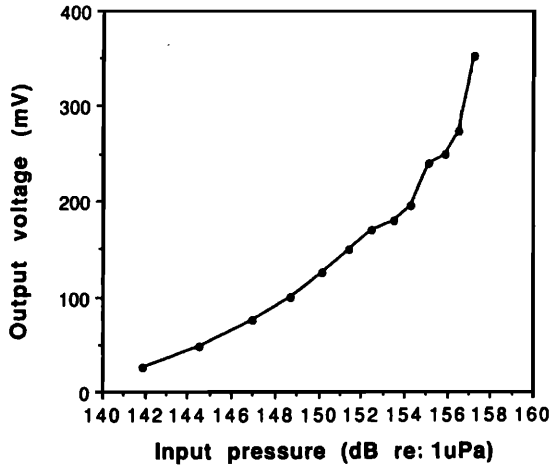

FIG. 3. Input versus output curve for amplitude sensing in the 1F/FΛ-R sensors at 45 kHz.

The 1F/FΛ-R hydrophone (external diameter 51 mm, spatial period $\Lambda = 4.3$ mm) was used as the sensing element and experimental results were obtained. The fiber used was plastic clad, step-index profile, 200/250, with a numerical aperture 0.6, manufactured by Ensign–Bickford Optics. A characteristic input versus output curve, at 45 kHz, is shown in Fig. 3. The graph in Fig. 3, which shows that the output voltage increases monotonically with increasing pressure, can be used as a calibration curve for the experiments that follow and should not be considered an indication of the linearity of the system response. The frequency response of the sensor, from 15 to 75 kHz, is shown in Fig. 4. Sensitivities in the range of -175 to -200 dB *re*:1 V/μPa were obtained and pressures as low as 100 dB *re*:1 μPa were detected. The variation of ouput power due to rotation of the sen-

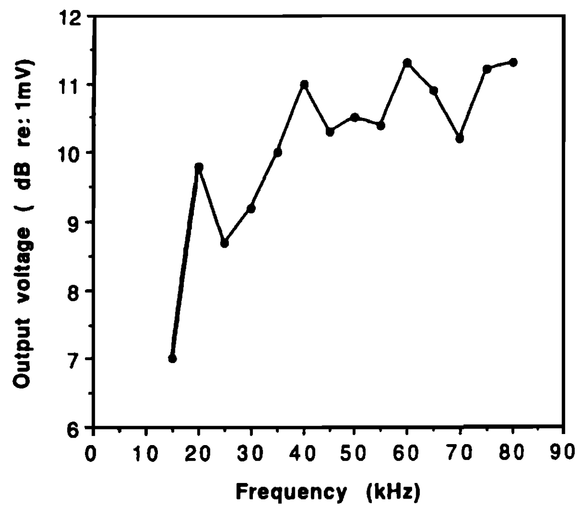

FIG. 4. Typical frequency response of 1F/FΛ-R hydrophone.

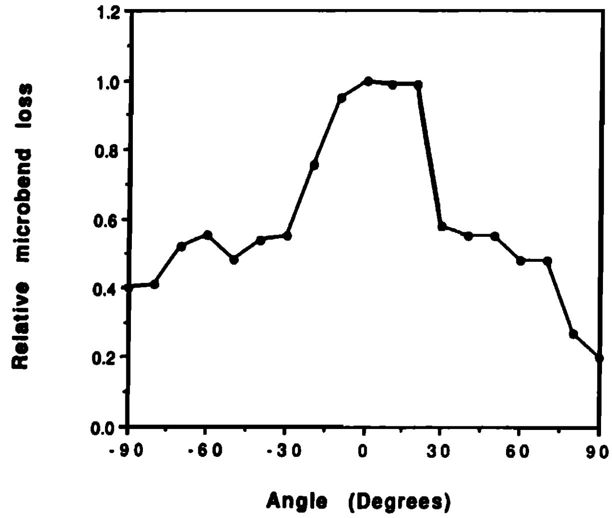

FIG. 5. Direction sensing performance of the 1F/FΛ-R sensor at 45 kHz.

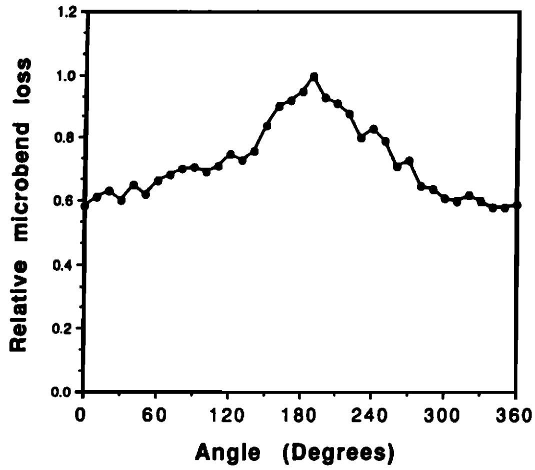

FIG. 7. Variation of microbend loss with θ in the 1F/VΛ-R sensor. The correspondence between θ and Λ is as follows: $\Lambda = 8.0$ mm between 0° and 55°, $\Lambda = 6.0$ mm between 55° and 115°, $\Lambda = 5.2$ mm between 115° and 155°, $\Lambda = 4.0$ mm between 155° and 205°, $\Lambda = 5.2$ mm between 205° and 245°, $\Lambda = 6.0$ mm between 245° and 300°, and $\Lambda = 8.0$ mm between 300° and 0°.

sor by an angle θ was calculated as follows. At a given input voltage, frequency, and distance, the maximum microbend loss was measured when the source was directly in front of the grooves. The sensing element was then rotated and the output at every θ was measured. The loss was then expressed as a fraction of the maximum loss and plotted against θ as shown in Fig. 5.

The 3F/FΛ-S hydrophone (external diameter 51 mm, spatial period $\Lambda = 4.3$ mm) was wound with a parabolic-index profile, 100/140 fiber with a numerical aperture of 0.2, manufactured by SPECTRAN. A winding procedure similar to that used for 1F/FΛ-R hydrophone was followed. Figure 6 shows the comparative outputs of the three fibers when the source is placed at different angles θ. The fiber for the

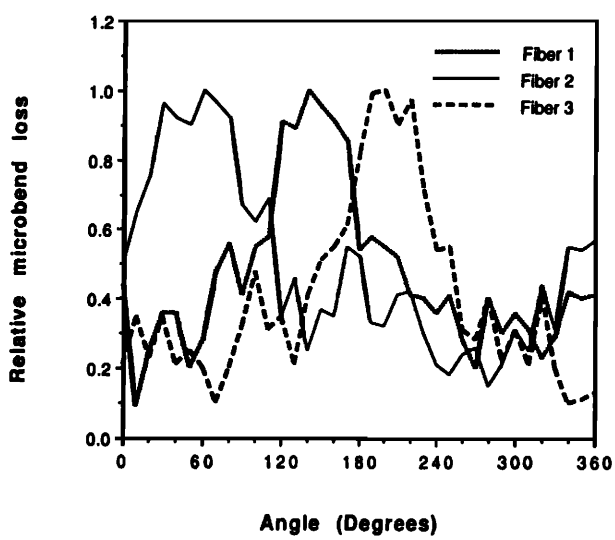

FIG. 6. Comparative outputs of three fibers in the 3F/FΛ-S sensor at 45 kHz.

1F/VΛ-R hydrophone (external diameter 50 mm, spatial periods Λ's = 4.0, 5.2, 6.0, and 8.0 mm) was step-index, 50/125, numerical aperture 0.18, and manufactured by ITT Electro-Optical Products Division. The variation of microbend loss with the rotation angle θ is given in Fig. 7.

Figures 5, 6, and 7 show that direction sensing can thus be attempted by either rotation of the 1F/FΛ-R and 1F/VΛ-R sensors or by simultaneously monitoring the three fibers in the 3F/FΛ-S sensor. Problems encountered during the experiments include the dependence of the readings on the rotation rate of the rotational sensors. That is, after every rotation of the cylindrical element, a certan time period (of the order of seconds) has to elapse prior to obtaining a steady, measurable reading at the output end. Although the 3F/FΛ-S sensor circumvents this problem, it adds to the complexity of the system by creating the requirement of three detectors for simultaneous monitoring, and by necessitating the use of three sources or a 1×3 coupler at the input. Extensions to higher frequencies seem possible; at lower frequencies, however, the cylindrical sensing elements will experience a quasihydrostatic pressure and the sensors will be inoperable.

III. CONCLUSION

The mechanism of microbend loss in multimode fibers has been used to design novel fiber sensors for detecting both the amplitude and the direction of propagation of underwater acoustic waves. Although microbend loss-based sensors are less sensitive in comparison with their interferometric counterparts, the development of these simple designs could lead to the replacement of the phased array sensors in applications where high accuracies are not needed. Three design schemes were implemented and a comparative analysis performed. Based on an experimental study, we have found some inherent disadvantages with the designs. Future work is concentrated on comparisons of experimental results with theory and on the development of a single-fiber, stationary hydrophone.

ACKNOWLEDGMENTS

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