Feasibility of fiber optical hydrophone

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Abstract

Pressure induced changes in optical pathlength are being utilized to realize a hydrophone consisting of glass fibers in a Mach-Zehnder interferometric arrangement. In our experimental setup we use single-mode fiber optical power dividers and a simple control system that maintains the polarization of both light signals so that interference with constant contrast is obtained after superposition. We use a modified phase-tracking detection system to maintain maximum interferometer sensitivity and show a design for a sensor-body with high acoustical sensitivity.

Introduction

Optical fiber sensors[1] are being worked on in research and development since the past few years now because they offer a number of advantages over existing techniques. The main features are an increased sensitivity, light weight, more freedom in geometric shape design, insensitivity against electromagnetic field disturbances including a perfect electric insulation of the point of measurement and applications in high temperature or aggressive environments. Besides there is the possibility to use optical signal and data processing methods.

Like many other optical-fiber sensors, optical hydrophones can be classified as amplitude or phase sensors. Amplitude sensors are characterized by a direct change in optical intensity proportinal to an acoustical signal. Here large-core multi-mode fibers may be utilized to advantage, but there is always the need for a more or less complicated mechanical transducer e.g. a pressure plate producing fiber-microbendings or a moving grating attached to a diaphragm. The disadvantage of a complicated mechanical design is accompanied by the loss of geometric versatility. The acoustic sensitivities reached with this configurations are more than one order of magnitude smaller than reported for phase-sensors. Therefor we prefer an interferometric arrangement based on a Mach-Zehnder interferometer which offers the advantages mentioned above.

Optical fiber interferometers

The principal interferometric arrangement consists of an ordinary Mach-Zehnder interferometer whose conventional interferometer arms are replaced by two monomode fibers. One fiber is working as sensing fiber, the other serves as reference fiber. A change in the relative phase $\Delta\phi$ of the light from the two fibers results in a change of light intensity (I) at the output of the interferometer:

$$I = I_o \, (1 - \cos \Delta\phi) \tag{1}$$

The detection of acoustic signals then takes place by pressure induced changes of index of refraction of the glass material and of fiber length. There are several important problems that need attention before practically useful devices can be fabricated:

The pressure induced phase shift in an optical fiber is a small effect; there is the possibility to use a very long sensing fiber to get adequate sensitivity; but other methods to achieve enhanced sensitivity have to be considered as well.

When linearly polarized laser light is fed into a circular-core single-mode fiber, the output light at the far end has a different state of polarization (SOP). Moreover the SOP fluctuates in a random manner with typical time constants of seconds. The fluctuations are due to internal and induced birefringeance, mechanical disturbances and temperatur drift. Changes of the SOP are a severe problem in fiber-optic interferometers since the interference of coherent light requires interacting beams with identical polarization. A complete fading results if the polarizations of the two beams are 90^o apart.

There is a distinction of homodyne and heterodyne detection systems for the interferometer output-signal. We use the first method because it promises a higher sensitivity as a literature survey indicates. But there are temperature drifts and mechanical stress which induce random phase shifts into the interferometer arms and the relative drift can easily be on the order of 2π or greater in a few seconds. For maximum sensitivity of the interferometer it is necessary to maintain a long-term $\pi/2$ relative phase difference between both fibers (the acoustically induced phase changes are small and rapid); this is known as the quadrature condition.

Interferometric sensors cannot become a real alternative to existing technologies until the bulk-optical beam splitters can be replaced by integrated optical devices for mono-mode fibers with small size and stable mechanical construction. Until now there are no such components commercially available. Laboratory prototypes are described in the literature, but their design leaves several reasonable requirements unanswered.

The experimental setup

Our experimental setup is shown in Figure 1 and offers features according to the problems listed above:

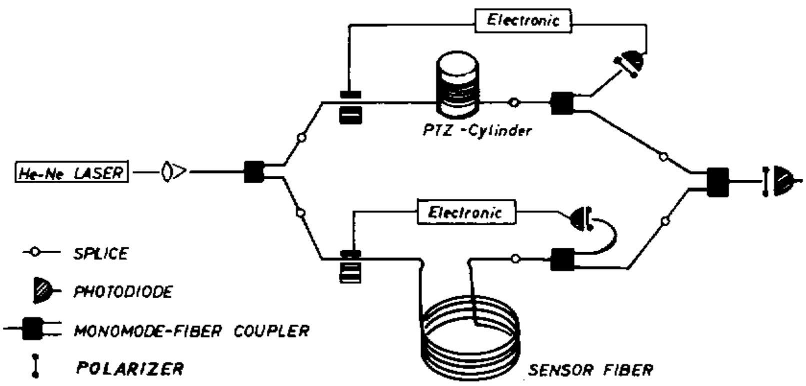

Figure 1. Experimental setup

1. We have developed mono-mode optical fiber couplers which are fabricated by a fusion process. Our experimental Y-junction couplers show a total loss of about 3 dB but this value can likely be improved by a more careful and clean processing. During the fabrication process the power splitting ratio can easily be adjusted to the desired value, e.g. 3 dB. The couplers are protected by a layer of epoxy-resin with outer dimensions of about 5x1ox15 mm^3, the fiber has a core diameter of 4 μm. Our integrated beam splitter offers two significant advantages: small size and insensitivity against mechanical disturbances. In addition we can produce true 4-port couplers using the same procedure

2. The SOP of both fiber outputs is stabilized before recombination by a single control loop each as shown in Figure 1. In this way a constant interferometric contrast is obtained. The photodiode measures the intensity of a prescribed state of linear polarization. If there is a deviation from a reference value, the amplified voltage difference is stored in an integrator. Its output current drives a fiber-squeezer introducing as much linear birefringeance into the fiber as needed for reaching the desired intensity of the SOP. This single-loop polarization stabilization is described in detail in Ref.2.

3. The PZT-cylinder shown in Figure 1 stands for our stabilization-system that keeps the interferometer in quadrature condition. It differs in detail from other phase tracking homodyne detection systems: The piezoelectric cylinder is driven by a 50 kHz a.c. voltage. This induces a small synchronous phase-signal into one interferometer arm by stretching the fiber wrapped around the cylinder. This signal is detected by the photodiode, filtered and rectified. A maximum voltage then indicates the desired quadrature-condition. Deviations from this value are compensated by applying an additional appropriate d.c.-voltage to the cylinder which controls its circumference.

4. The pressure induced phase shift in an optical fiber can be enhanced by using appropriate fiber-coatings. In Figure 2 a sensor-body is shown which we propose for omnidirectional sensing. The sensing fiber wound around the outer cylinder wall while the reference fiber is wound around the inner cylinder. In this case the fibers function like strain gauges sensing the dimensional changes of the cylindrical shell. It is important to point to the fact that here both interferometer arms are used as sensing fibers. This is possible because the inner and the outer cylinder wall react contrarily upon pressure fluctuations concerning their circumference.

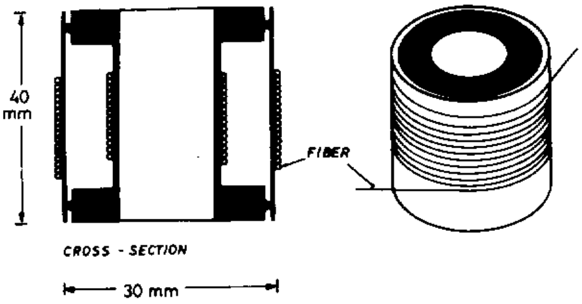

Figure 2. Sensor-body

Measurements

Fiber optical hydrophones are in competition with conventional piezoelectric hydrophones. The most important parameter in this context is the sensitivity. For that reason in Figure 3 we have drawn in the sea state zero noise-level and the minimum detectable acoustic pressure of a high quality piezoceramic hydrophone which was used for calibration purposes. The sensitivity enhancement due to the described sensor-body made out of plexiglass (lucite) with about 1 mm thick cylinder walls is significant.

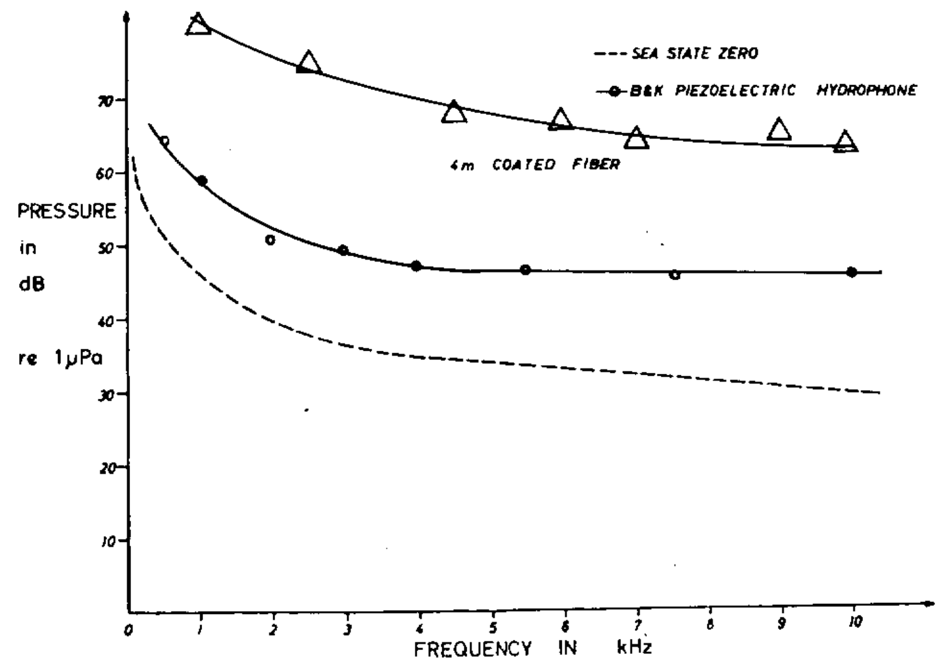

Figure 3a. Measurements

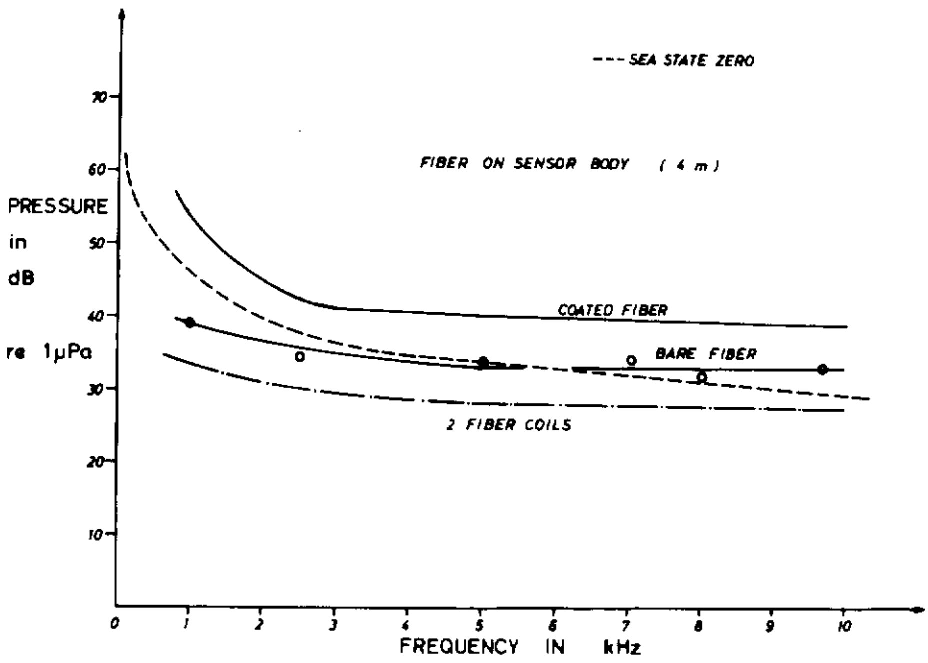

Figure 3b. Measurements

Conclusions

We have proposed solutions for the most severe problems concerning fiber optic interferometric sensors of underwater sound. Our sensitivity measurements show the feasibility of our concept which can still be improved by the use of longer sensing fibers and reduction of the noise induced in the interferometer by the control circuitry. In the future we hope for further simplification of the arrangement, since polarization maintaining fibers are offered commercially now. This should make the polarization control system superfluous. The fiber optical hydrophone should be competitive with conventional sensors if its design can be made sufficiently simple, rugged an self-contained.

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