

Serial No. 450,214

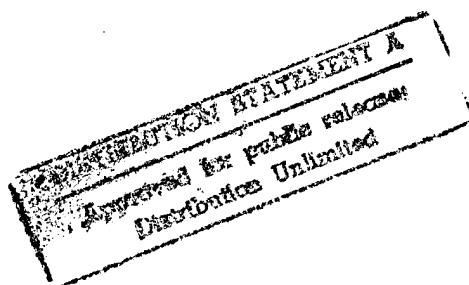
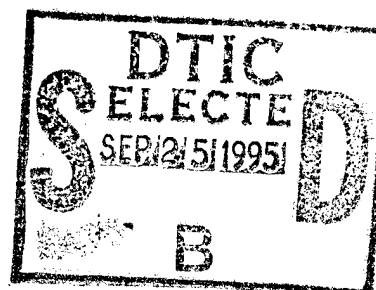
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## DEPLOYABLE HYDROPHONE

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### BACKGROUND OF THE INVENTION

#### 10 Field of the Invention

The present invention relates generally to an acoustic sensor, and more particularly to a fiber-optic hydrophone.

#### Description of the Related Art

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A fiber optic hydrophone system 10, as shown in Figure 1, is generally comprised of a light source 12 or laser for producing an optical light beam which is applied to an acoustic-optic sensor 14, or hydrophone, to detect changes in acoustic pressure, and a means  
20 for displaying the detected changes in acoustic pressure 16.

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The design of acoustic-optic sensors is based upon the phase shift in light passing through a fiber when subjected to acoustic waves. Generally, an optical fiber is attached to an interferometer sensor which is comprised of an acoustically sensitive fiber arm and an environmentally-shielded reference fiber arm. A laser beam transmitted along the optical fiber is split by an optical coupler and transmitted through both the reference and sensor arms. The difference in phase shift between the sensor and

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reference arms is related to the strength of the sensed acoustic field.

SUMMARY OF THE INVENTION

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The object of this invention is to provide a hydrophone for integration into an array of a larger number of hydrophones interrogated over longer distances than hydrophone designs utilizing metal sensing mandrels.

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Another object is to provide a hydrophone that is very responsive under high hydrostatic pressures.

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Another object is to provide an improved fiber optic acoustic hydrophone of rugged construction and increased pressure sensitivity to meet the installation and operational requirements of an all-optical deployable hydrophone system.

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Another object of this invention is to allow a hydrophone array to be constructed having a large number of hydrophones integrated over longer distances than allowable by the prior art.

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The objects of this invention are achieved by wrapping an optical fiber forming a sensing fiber arm, under tension, around a compliant mandrel in such a manner that the optical fiber increases

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the structural integrity of the plastic mandrel. The additional structural integrity of the compliant mandrel allows the hydrophone to withstand higher hydrostatic pressures before failure than conventional mandrels. A reference optical fiber arm, of  
5 approximately equal length to the sensing fiber arm, is wrapped around a rigid metal mandrel and isolated from the acoustic field by an air gap which forms part of the compliant sensing mechanism. The center of the hydrophone is potted with a hard epoxy and then the entire hydrophone is dipped in polyurethane to prevent the  
10 sensing fiber arm from being damaged during handling and deployment.

BRIEF DESCRIPTION OF THE DRAWINGS

15 **Figure 1** shows a typical fiber optic hydrophone system.

**Figure 2** shows a cross-section of a deployable hydrophone of the Michelson-type.

20 **Figure 3** shows the maximum normalized acoustic sensitivity as a function of operational depth for several values of the maximum strain in the optical fiber.

**Figure 4** shows the amount of optical sensing fiber required as  
25 a function of hydrophone responsivity for a Michelson-type

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interferometer with the maximum normalized acoustic sensitivity as a parameter.

5 **Figure 5** shows the change in responsivity in the ideal case as more layers of optical fiber are added to form the sensing fiber arm.

**Figure 6** shows the maximum dimension of a hydrophone with respect to the maximum frequency of omnidirectional response.

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DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

In the preferred embodiment for the optic detector, or hydrophone **20**, **Figure 2**, a Michelson-type interferometer is used. In the Michelson-type interferometer, an input optical fiber **22** passes a light beam through a directional coupler **24** which separates the light beam into two portions. A first portion is propagated through a reference fiber arm **26** and a second portion through a sensing fiber arm **28**. The reference arm **26** and the sensing arm **28** are of substantially the same length. Mirrors **26a** and **28a** are deposited at the free or cleaved ends of the reference fiber arm **26** and sensing fiber arm **28**, respectively, reflecting the optical light beam back through the respective fiber. The technique of double passage of the optical light beam through the fibers utilized in the Michelson-type interferometer increases the

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sensitivity of the sensor 20 by a factor of two. The reflected light beams from the reference and sensing fiber arms 26 and 28 are recoupled into an optical signal by the directional coupler 24 which is applied to the output fiber optic cable 32. The  
5 difference in phase shift of the optical signal between the reference and sensing fiber arms 26 and 28, respectively, is proportional to the acoustic pressure of the medium that is applied to the sensing fiber arm 28.

10 Mirrors 26a and 28a terminating the reference and sensing fiber arms 26 and 28, respectively, may be replaced with a Faraday rotator mirror (FRM) (not shown). Utilizing such a termination combination of mirrors and FRM, there is a 45° rotation of the phase angle as the optical light beam transits in each direction in  
15 the reference and sensing fiber arms 26 and 28, respectively, thereby correcting the optical light beam for polarization and fade. The optical fiber forming the reference fiber arm 26 and sensing fiber arm 28 may be any currently utilized in the art.

20 Reference fiber arm 26 is wrapped on a rigid metal mandrel 34 and is further isolated from the acoustic field by the presence of an air gap 36 of 0.007 - .0.014 inches, preferably 0.01 inches, forming part of the compliant sensing mechanism.

25 The sensing fiber arm 28 is wrapped on a compliant sensing

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mandrel 38, or sensing mandrel, which forms the outside of the hydrophone 20 so that it can be insonified by the acoustic field. The sensing mandrel 38 is a hollow cylindrical polycarbonate tube approximately 1.9 - 2.54 cm in outside diameter (preferably 1.9 cm and having a wall thickness of approximately 1.5 - 3.5 mm, preferably 1.5 mm. The preferable material forming the sensing mandrel 38 is a polycarbonate, such as that manufactured by Thermoplastic Processes of Sterling, NJ. The polycarbonate material is superior to the metal sensing mandrels found in the prior art because it is capable of withstanding higher hydrostatic pressures before crushing.

The maximum static strain in an optical fiber occurs as a result of the hydrostatic pressure at the operational depth. This maximum strain gives a maximum normalized acoustic sensitivity  $d\phi/\phi dP$  for a hydrophone of

$$\frac{d\phi}{\phi dP} = \zeta \left( \frac{dr}{r} \right) \left( \frac{1}{dP} \right) \quad (1)$$

(Figure 3 shows the maximum normalized acoustic sensitivity as a function of operational depth for several values of the maximum strain in the optical fiber.)

The total phase  $\phi$  present in a hydrophone 20 is linearly

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related to the amount of optical fiber L in the sensing arm 28 of the device as

$$\phi = \frac{2\pi Ln}{\lambda} \quad (2)$$

Where  $\lambda$  is the frequency and n is the index of radiation of the optical fiber. The hydrophone 20 responsivity  $d\phi/dP$  is related to the normalized acoustic sensitivity  $d\phi/\phi dP$  by the total phase  $\phi$ . Figure 4 shows the amount of optical sensing fiber required as a function of hydrophone 20 responsivity for a Michelson-type interferometer with the maximum normalized acoustic sensitivity as a parameter. The maximum normalized acoustic sensitivities were derived from Figure 3 for the cases of maximum strain in the fiber at a depth of 1000 meters (1.0% (-303 dB re  $1/\mu\text{Pa}$ ), 0.5% (-309 dB re  $1/\mu\text{Pa}$ ) and 0.2% (-317 dB re  $1/\mu\text{Pa}$ )).

In this embodiment, the sensing fiber arm 28 is composed of a layered wrapping of optical fiber approximately 100 meters in length. If the sensing mandrel 38 is wrapped in more than three layers forming the sensing fiber arm 28, there is no resultant increase in hydrophone sensitivity. The change in responsivity in the ideal case as more layers of optical fiber are added is shown in Figure 5. As can be seen in Figure 5, even in the ideal case the incremental gain achieved by having more than three or four layers of optical fiber on the sensing mandrel 38 is small. In experimental devices of this embodiment the situation was even less

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favorable than the ideal condition because the optical fiber loads the mandrel material and the sensing mandrel 38 compliance becomes a function of the composite structure rather than the plastic mandrel material alone. However, the amount of optical fiber that will comprise three layers may vary with the diameter and length of the mandrels 38 involved. The hydrophone center is potted with a hard epoxy 42, preferably Chock-fast Orange®, manufactured by ITW Philadelphia Resins of Montgomeryville, PA.

10 The structural integrity of the hydrophone 20 is further increased by the mounting of an end-plate 44 at one end of the hydrophone 20 attached to the metal mandrel 34 upon which the reference fiber arm 26 is wound. The end-plate 44 is constructed of naval bronze, a material well known to those skilled in the art, and may be of any desired thickness and is secured to the metal mandrel 34 by a plurality, preferably four, of set screws 46 and has an opening through which the cable 48 containing the cable output and input optical fibers 22 and 32, respectively, passes. The set screws 46 are preferably 4-40 brass screws having a length of approximately 3/16 inches, however any appropriately sized set screw may be utilized. A combination of the fit of the cable 48 in the opening of the end-plate 44 and the hard epoxy material 42 potting the interior of the hydrophone 20 forms a watertight seal.

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The air gap between the metal mandrel 34 and compliant sensing mandrel 38 is formed by a collar 54 at each end of the metal mandrel. These collars are may be made of a naval brass of the same type as used in the end plate 44.

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After assembly, the exterior of the hydrophone 20 is dip-coated in polyurethane 56, such as Uralite 3140, manufactured by Hexcel Corp. of Chatsworth, CA, to prevent damage to the sensing fiber arm 28 during handling and operation. The polyurethane 56 also forms a watertight seal at the opposing end of the hydrophone 20 from the end-plate 44.

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The hydrophone 20 frequency response in a resonance free mandrel structure is determined by the physical size of the device. A plot of the hydrophone 20 maximum dimension with respect to the maximum frequency of omnidirectional response is shown in Figure 6. As the wavelength of the sound wave in water approaches the dimension of the hydrophone 20, a null occurs in the hydrophone response. For the case where the required omnidirectional frequency response is to 10 kHz, the maximum dimension of the hydrophone 20 must then be  $\leq 7.5$  cm for an approximately flat frequency response.

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For structural integrity when multiple hydrophones 20 are used in an array, the cable 48 containing the output and input optical

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fibers 22 and 32, respectfully, and strength member (not shown) may pass through the inner part of the hydrophone 20. In this configuration an end-plate 44 may be placed at both ends of the hydrophone 20. When the cable 48 and the strength member (not shown) pass through the hydrophone 20, a hydrophone array may be constructed having a large number of hydrophones along the cable 48 which may be interrogated over longer distances than hydrophone designs utilizing hydrophones having only metal sensing mandrels. Further, this hydrophone is very responsive at great depths, ~ -122 dB re rad/ $\mu$ Pa with a 1500 psi hydrostatic pressure capability.

The precise materials used to construct the hydrophone 20 and the wall thickness of the various components of the reference and sensing fiber arms 26 and 28, respectively, may be varied to suit manufacturing needs. The length and diameter of the finished hydrophone 20 may be changed if the frequency response requirement changes. Therefore, numerous modifications and adaptations of the present invention will be apparent to those skilled in the art. Thus, it is intended by the following claims to cover all such modifications and adaptations which fall within the spirit and scope of the invention.

This embodiment provides an improved fiber optic acoustic hydrophone of rugged construction and increased pressure sensitivity to meet the installation and operational requirements

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of an all-optical deployable hydrophone system. This invention allows a hydrophone array to be constructed having a large number of hydrophones integrated over longer distances than allowable by the prior art.

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Numerous modifications and adaptations of the present invention will be apparent to those skilled in the art. The precise materials used to construct the hydrophone and the thicknesses and sizes of the various components composing the sensing and reference mandrels may be varied to suit the manufacturing needs of the user. Further, the length and diameter of the finished hydrophone may be changed if the frequency response required of the device is different than that described in the preferred embodiment. Thus, it is intended to cover all such modifications and adaptations which fall within the spirit and scope of the invention.

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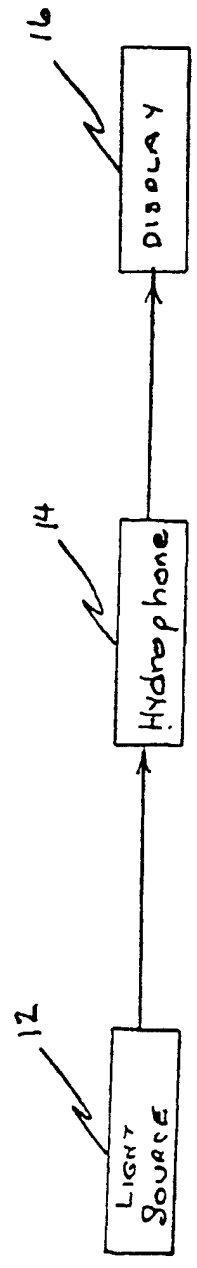
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ABSTRACT

A hydrophone having an optical fiber wrapped compliant mandrel forming a sensing fiber arm and an optical fiber wrapped metallic mandrel placed within the compliant mandrel having an air space between the two mandrels. The sensing and reference fiber arms are so configured as to form a Michelson interferometer for detecting pressure variations in a surrounding medium. The fiber wrapping of the compliant is such that the structural strength of the compliant mandrel is increased so as to withstand pressures generated at extreme depths to prevent crushing of the compliant mandrel into an air space. Within the center of the metallic mandrel is located a means for coupling the input and output optical fibers of an optical cable to the sensing and reference fiber arms. The area surrounding the coupler within the metallic mandrel is filled with an epoxy material and the entire hydrophone is encapsulated in polyurethane to render the hydrophone watertight but still transparent to the pressure variations in the surrounding medium.

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PRIOR ART

FIG. 1

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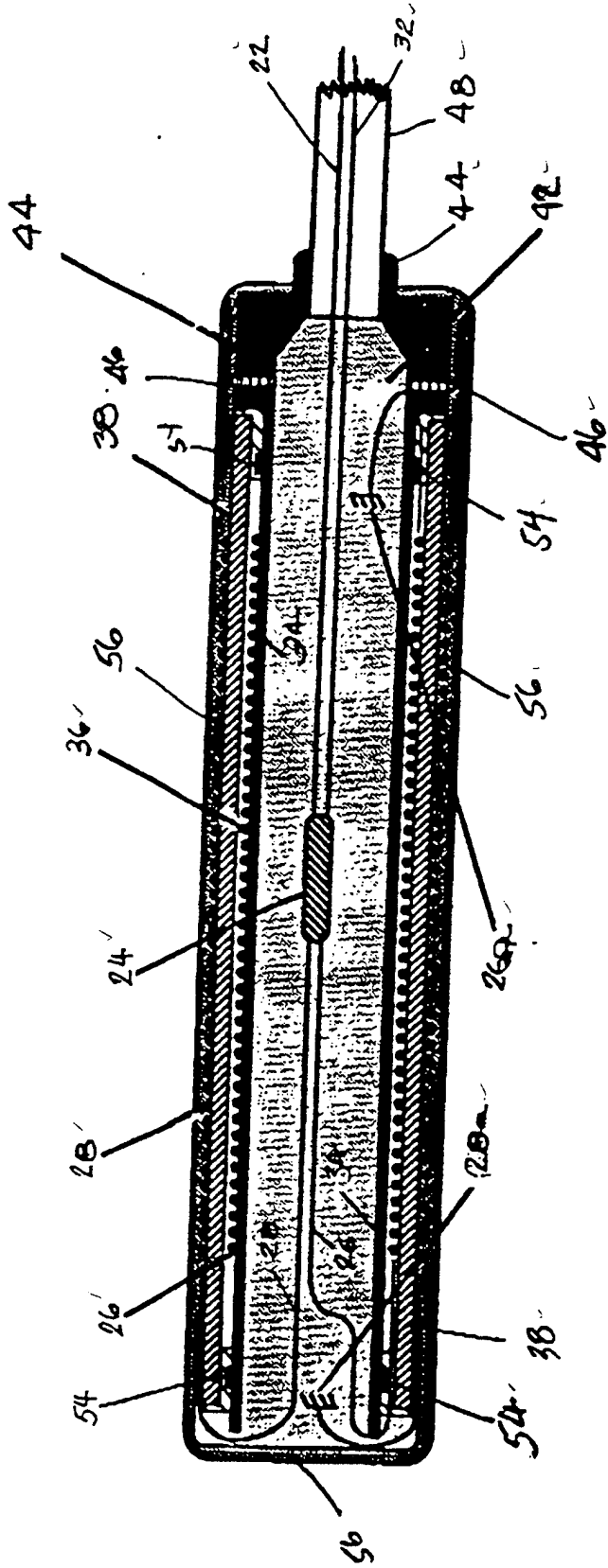


FIG. 2

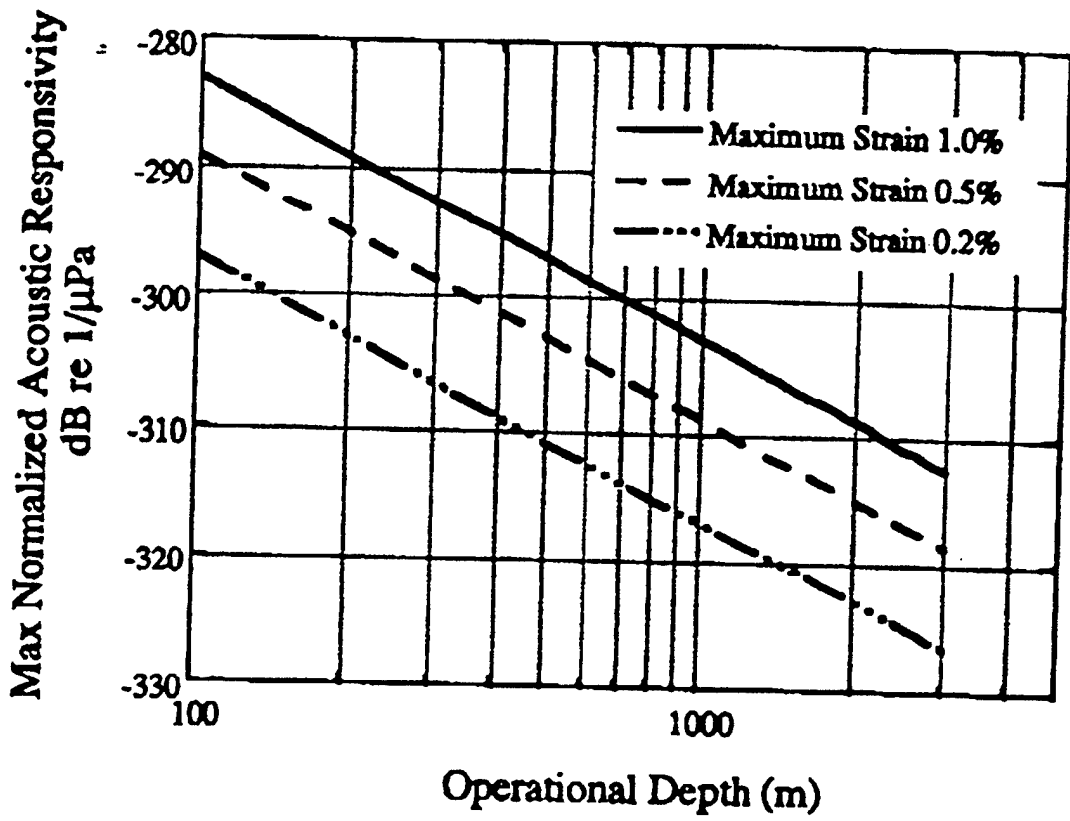


Fig. 3

### Michelson Interferometer

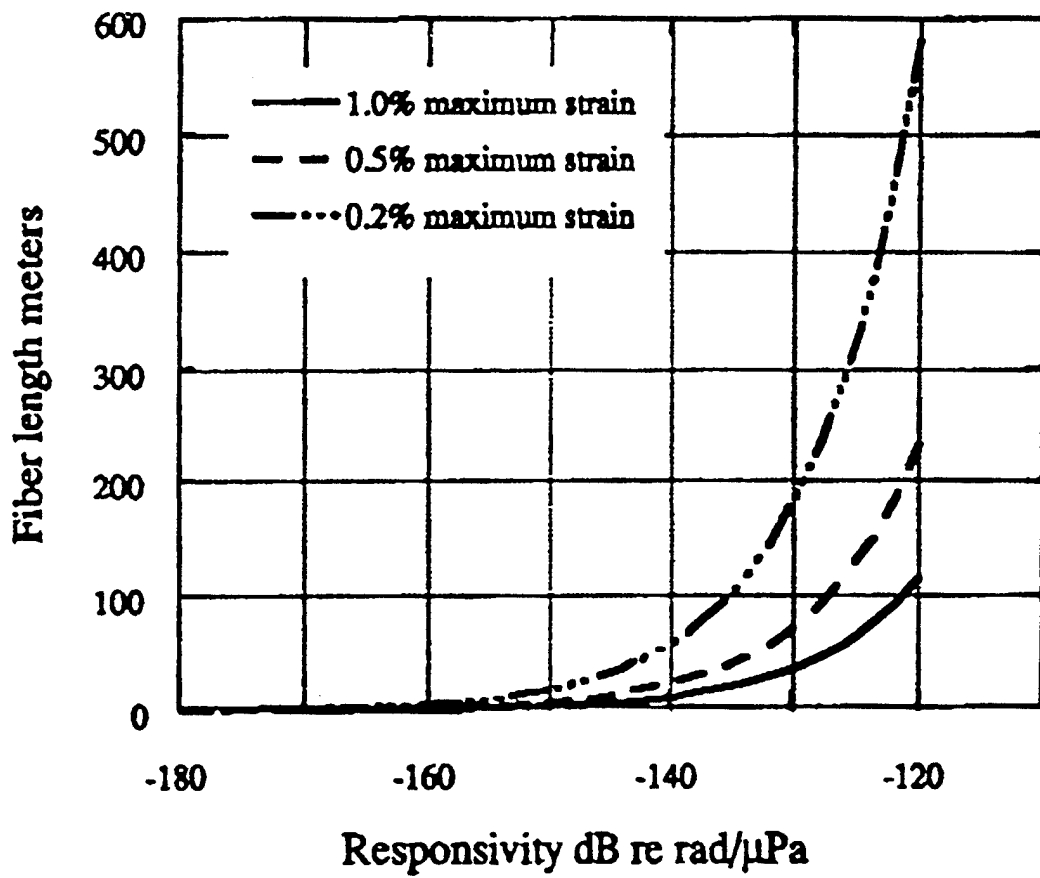


Fig 4

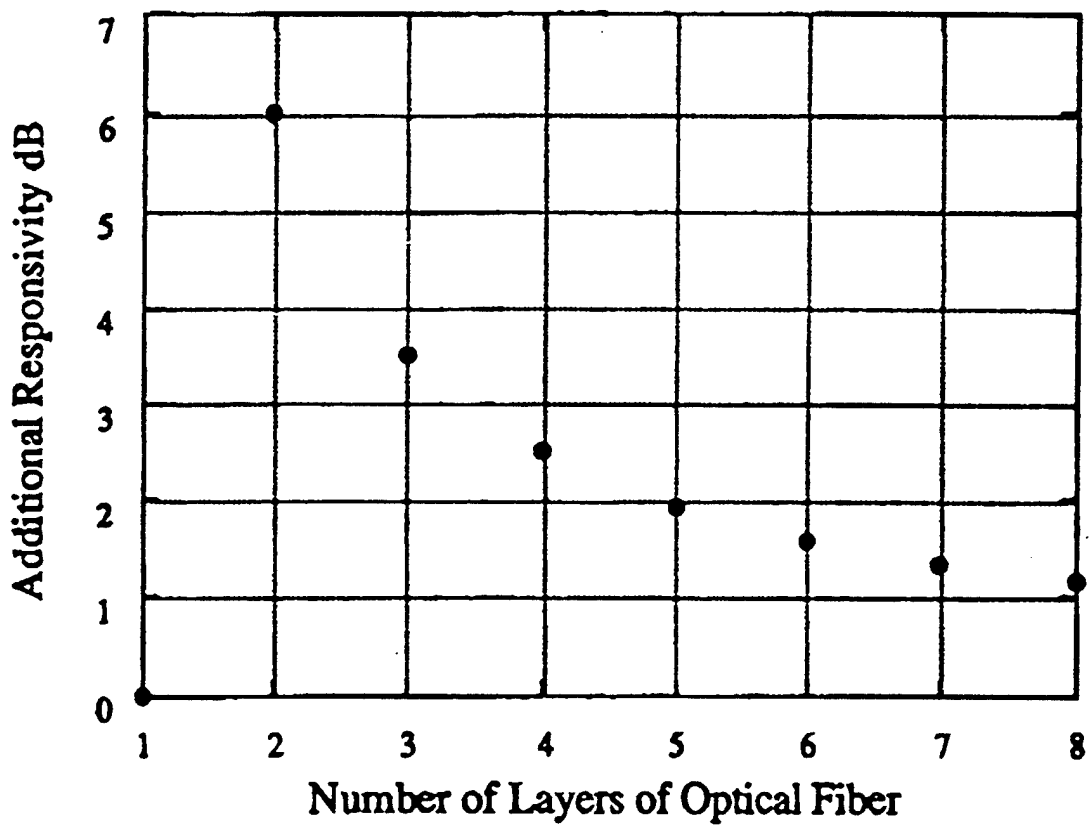


Fig 5

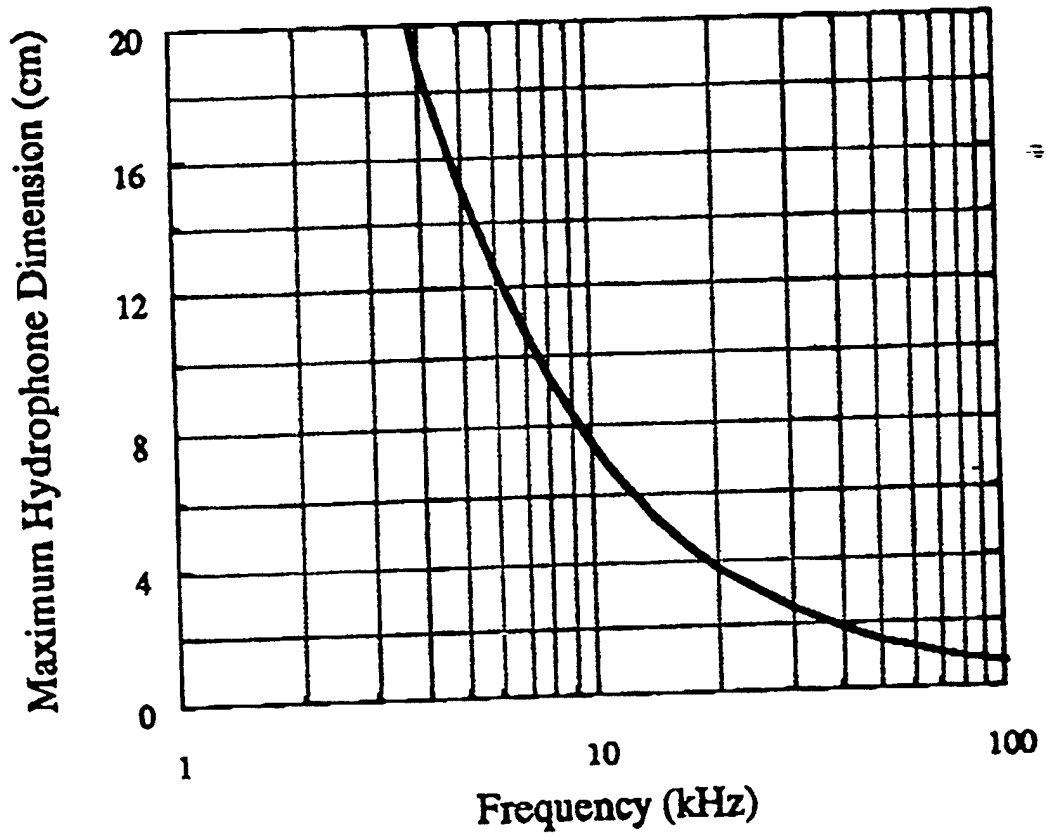


FIG. 6