Def Sci J, Vol 34, No 1, January 1984, pp 85-96

Fibre Optics in Undersea Applications

A. K. TALWAR & D. K. SRIVASTAVA
Instruments Research and Development Establishment, Dehra Dun-248008

Received 16 January 1984

Abstract. Role of optical fibres for underwater communication cables and hydrophones is discussed. The fibre optics cables provide an excellent solution to the historical bandwidth-diameter problems of conventional coaxial cables. Fibre optic hydrophones are found to have many more advantages apart from high sensitivity and large dynamic range, over the classical sound sensors used in underwater work.

1. Introduction

The optical glass fibres in underwater applications has gained much support. The present applications envisaged are in communication cables and hydrophones. Underwater optical fibre cables provide an excellent solution to the historial bandwidth-diameter problem of conventional coaxial cables. On the other hand hydrophones based on optical fibres are bound to be much more sensitive over a large dynamic range than the conventional ceramic transducers used in sonars and other applications. The paper reviews the research and development activities in these two areas of fibre optics.

2. Undersea Fibre Optic Cable

2.2. *Coaxial Cables*

The last decade has seen a rapid increase in the degree of sophistication required of cable-controlled system which are used for search, recovery and general work operations on or near the deep sea floor. This sophistication has precipitated a serious conflict between the simultaneous needs for higher information bandwidth and reduced cable diameter. Much higher bandwidth is required to support such tools as search and mapping sonars, chemical/magnetic/nuclear sensors and high resolution real-time television. The cable much smaller in diameter is needed to reduce drag and to improve system depth performance in a towing mode or in the face of ocean currents.

While cable bandwidth and diameter are the chief factors, other cable parameters i.e., strength, flexibility in air/water weight, payload capacity power transfer and operational safety factor also play important roles.

Now, consider a typical tether cable commonly used to tow instrumentation packages at depths to 6 km.

Breaking strength	15,400 kg
Weight (in air)	1,050 kg/km
Over-the-side weight for operation at 6 km	5,100 kg
Safety factor with no payload	3
Bandwidth (8 km length)	1.6 MHz

Addition of any payload will further reduce this safety factor. This kind of cables are often used to support deep sea operations at a safety factor of 2 and hence the incidence of cable failures is high. The bandwidth of 1.6 MHz is insufficient to transmit real-time television without severely degrading the resolution and will certainly not allow a real-time stereo television. This cable has only marginal capability for supporting todays high search rate sonars. If two or more such sensors are to be operated, the cable is totally inadequate. In fact, a bandwidth of 30-50 MHz is required to simultaneously transmit useful data from all the sensors that should be deployed for an effective deep sea search and mapping application.

In fact, this problem is not limited to the deep sea search/work system. It is encountered whenever high frequency information must be transmitted through a cable which has a constrained diameter. Other examples are—the data-link between a deep sonobuoy and its surface transmitter, a video data tether between a diver and a remote monitoring station and the monitor/control link for a wire guided torpedo.

2.2. Coaxial Cable, Bandwidth *Solution*

The historical approach to increase the bandwidth of a coaxial cable has been to increase the diameter of dielectric spacer, while maintaining constant coverage by the shield conductor. However, this increases the overall diameter, storage volume, drag cross-section and the weight of the cable. A much larger cable will be required to compensate for the ocean drag, so that a part of additional bandwidth achieved is lost and system's safety factor is also reduced due to increased dead weight of added copper. Finally a larger handling system and ship will be required to carry and deploy the system. In summary, a conventional approach which narrowly focused on the need for greater cable bandwidth has forced the entire system to grow to monstrous size and cost.

2.3. Optical Fibre Cables

Some of the above disadvantages can be alleviated through the use of special cable materials, However, this approach does nothing to alleviate the basic dependence of bandwidth on cable diameter. This is the primary role of fibreoptic data-link cables which provide very high bandwidth with only a few micron diameter fibre. The main advantages of a fibre optic cables are as follows :

(i) Improved bandwidth, (ii) Reduced cable diameter, (iii) More information per unit weight and volume of cable, (iv) Light weight, cheap and easy to install, (v) Non-inductive, hence detection free if power carrier metal wires are not required (Military advantage), (vi) Do not produce impedance changes while reeling or unreeling, (vii) No short circuit problem, and (viii) Can be used as buoyant or bottom sunk cable.

Optical glass fibres have offered a unique solution to bandwidth diameter problem of conventional coaxial undersea cables. It should never be expected to carry an appreciable load, as it cannot; e.g., a 125 μm diameter fibre could survive a load not greater than 8.6 kg. This is negligible compared to strength required in most undersea cables. Hence other load-bearing elements are included to support the necessary load as well as provide necessary strength to absorb the cable weight also with a reasonable safety factor.

The undersea fibre optic cable design is partially based on technology developed for analog coaxial undersea cables. The cable is designed to provide necessary strength and weight for ocean installation and recovery operations. It must be built to withstand the hydrostatic pressures encountered as well as should give the fibre protection against water, tensile/radial stress and microbends.

The technological problem in undersea fibre optics cable design are severe but surmountable making feasible the development of reliable undersea fibre optic cables.

2.4. *Experimental Fibre Optic Cables*

Although several cables have been designed and tested for undersea applications, a few representative examples are furnished here.

2.4.1. ***Single*** **Fibre Cable**—This cable, can be used as an optical data link for use with an undersea, self-powered instrument package. The optical fibre is coincident with the cable axis. The load-bearing S-glass filaments are paraxial, and occupy a 64 per cent volume fraction within their annulus. The main cable parameters arc as follows :

Fibre diameter	127 μm
Cable diameter	1.27 mm
Cable weight	2.09 kg/km
Average breaking strength	255 kg/km
Safety factor for operation at 6 km depth	51
Payload capacity in water (safety factor 5)	46 kg

The 8 km of cable necessary to support operation at 6 km can easily be carried by one person only.

2.4.2. Two Fibre Cable (For *Sonobuoy* **and** *Towing* Applications)——In this design (Fig. 1 a) stranded steel wires are employed as loadbearing members to increase the cable's tensile modulus. Its main features are as follows:

Fibre diameter	127 μm
Cable diameter	1.73 mm (major axis) 1.53 mm (minor. axis)
Cable weight	7.58 kg/km
Breaking strength	122 kg
Safety factor (cable only) for tethered operation at 6 km	4.0

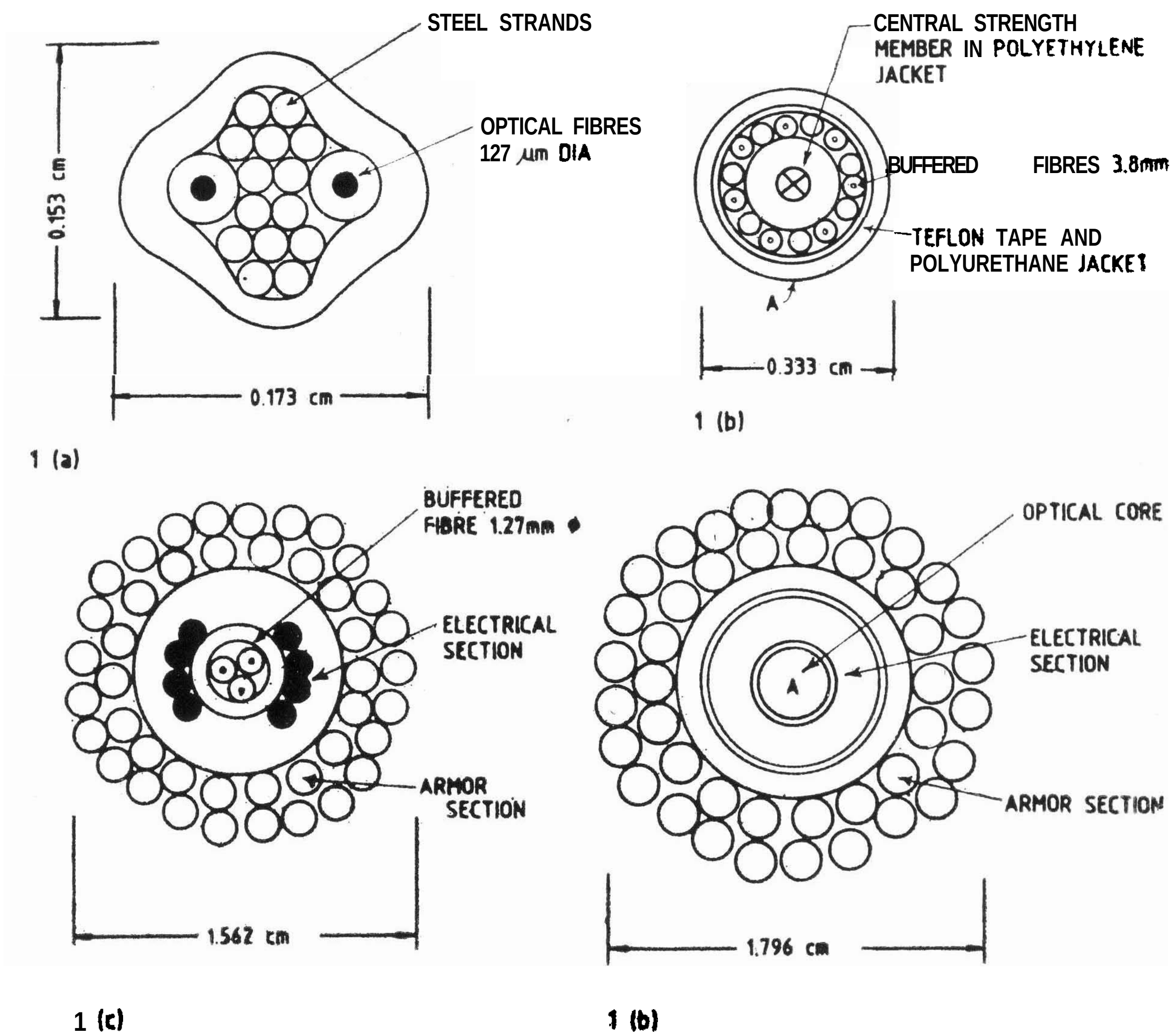


Figure 1. **(a)** Twin fibre **cable,** (b) **Six fibre** cable, (c) Three fibre cable.

3.2. *Basic Design*

Fibre optic hydrophone essentially includes a light source (LED or laser diode), a detector, single mode or multimode fibre in a suitable configuration, necessary electronic circuitry processing electronics and a suitable housing. The fibre optic sensor is an electrically passive device that is connected to a light source and detector. When the signal is impressed on the sensor, the amount of light reaching the detector changes in accordance with the input signal.

Multimode as well as single mode fibres are used in fibre optic hydrophones. Many of the less demanding applications can be served by multimode fibre optic hydrophones. However, in some military applications in which extreme sensitivity is of paramount importance, it is likely that more complicated single mode fibre optic sensors would be used. Multimode fibre optic hydrophones use multimode fibres in a configuration such that when input signal is there the light reaching the detector or the collecting fibre is changed. Single mode fibre hydrophones, by contrast, use single mode fibres in such arrangement that with input signal the phase of light passing the sensing fibre varies as against the reference fibre. The first type is called as non-interferometric while the later as interferometric fibre optic hydrophones.

3.3. *Non-Interferometric* Hydrophones

3.3.1. Hydromicrophone—Fibre optic microphone structure[2] (Fig. 2) provides a simple example of this type of hydrophone. In this case one end of the fibre is fixed

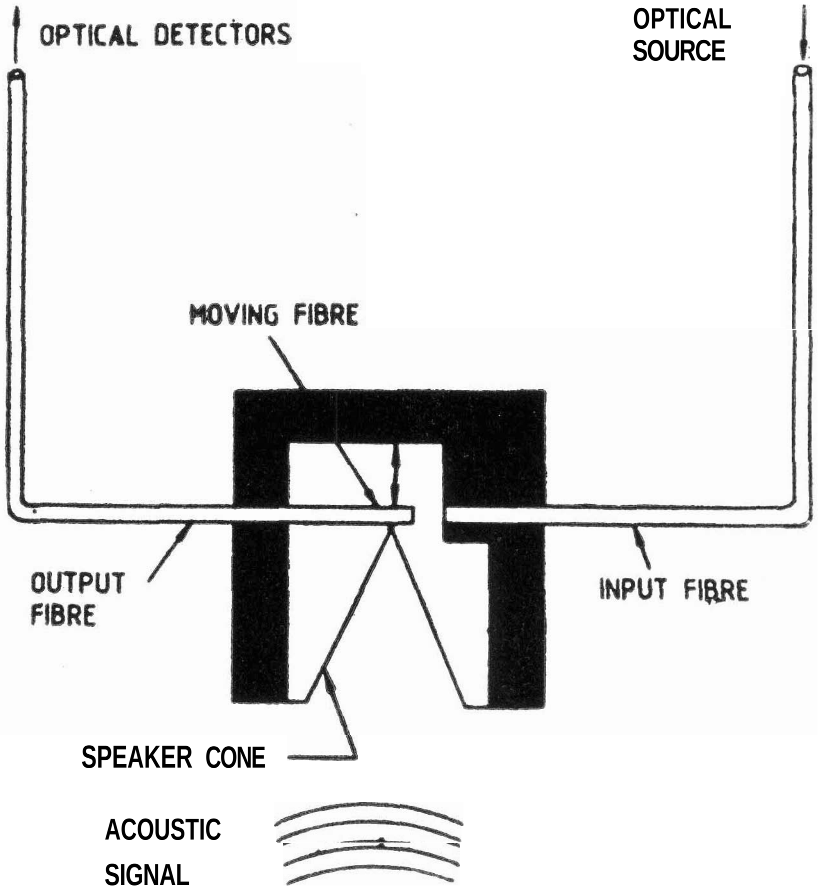
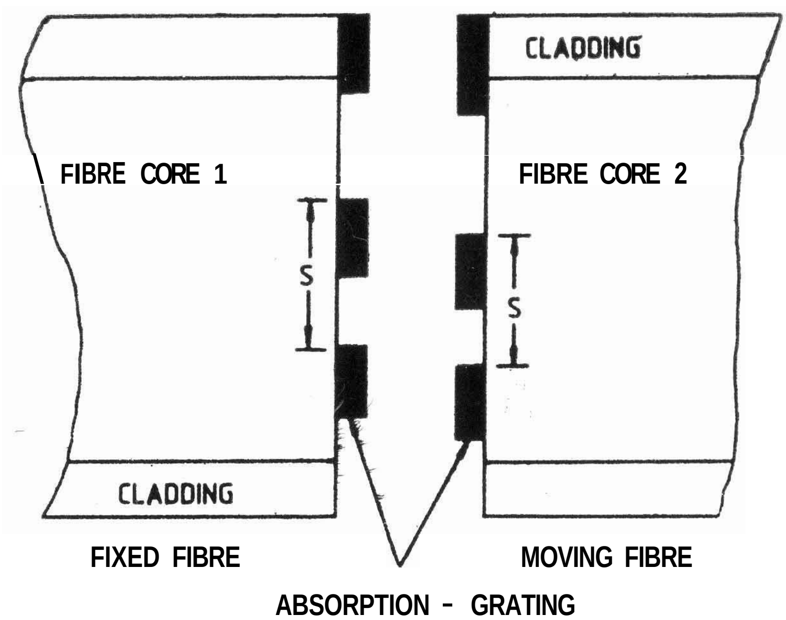


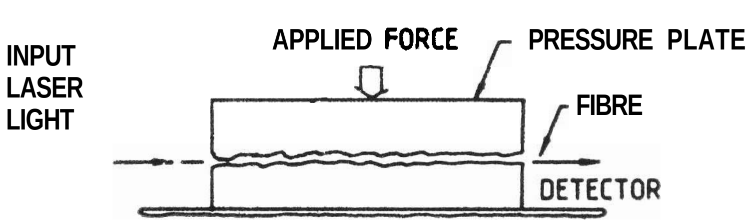
Figure 2. Multimode acoustic hydrophone.

and the other end is connected to a diaphragm. The motion of diaphragm displaces the fibre with respect to a beam of light from an input fibre, causing the output light to vary. For a typical multimode fibre of core diameter 100 μm, a fairly linear response occurs over a movement distance of 0.005 cm, and 100 per cent modulation occurs if one fibre is transversely displaced 10^{-2} cm with respect to the other. However, this requires much more sensitive processing system due to small vibratory motion of microphone diaphragm for underwater application.

3.3.2. Absorption Grating ***Hydrophone*—A** more sensitive approach[2] is suggested in Fig. 3(a). Fine absorption grating stripes are made on the opposite ends of two large core multimode fibres. A transverse displacement equal to the stripe width causes 100 per cent modulation. A typical hydrophone constructed with this approach uses a graded index lenses to collimate light from the fibre and to refocus the collimated light into an output fibre. An aligned dual-grating structure is assembled separately and inserted into the collimated-beam portion of the hydrophone for easier fabrication. Opposed grating members are connected to diaphragm on opposite sides of the hydrophone case. Acoustic pressure vibrates the diaphragm and thus by displacement of gratings produces proportional signal. With grating stripes 5 μm



(a)



(b)

Figure 3. (a) **Absorption grating,** (b) Microbend **hydrophone.**

wide, the hydrophone is sensitive to sound pressure of less than 60 dB (relative to one micropascal) for frequencies between 100-3 KHz.

3.3.4. Microbend Hydrophone—The microbend sensor[3] (hydrophone) holds a fibre between two corrugated plates (Fig. 3 b). Sound pressure vibrates one of the plates against the other so that the fibre is alternatively bent into the grooves and released from them. When fibre bends, some of the light rays propagating through it, escape the core and this produces an intensity drop in the output light. The transmitted beam is, therefore, modulated by sound pressure. The microbend effect is considerably enhanced if the corrugation has the correct periodicity, which can be calculated from the structure of the fibre itself. Sensitivity of 60 dB (relative to one micropascal) has been achieved with this type of hydrophone.

3.3.5. FTIR Hydrophone—This hydrophone (Fig. 4) based on frustrated total internal reflection effect[4] is most sensitive and promising among the non-interferometric hydrophones. A typical frustrated total internal reflection hydrophone has been constructed that exhibits a sensitivity comparable to deep-sea noise level ambient. The sensor consists of two fibres placed very close to each other. The ends of fibres are polished at an angle such that the light is totally internally reflected at the face. One of the fibres is fixed, and the other is connected to the hydrophone diaphragm. When one fibre moves relative to other, the gap between the fibres changes and a large fraction of light is coupled to the other fibre.

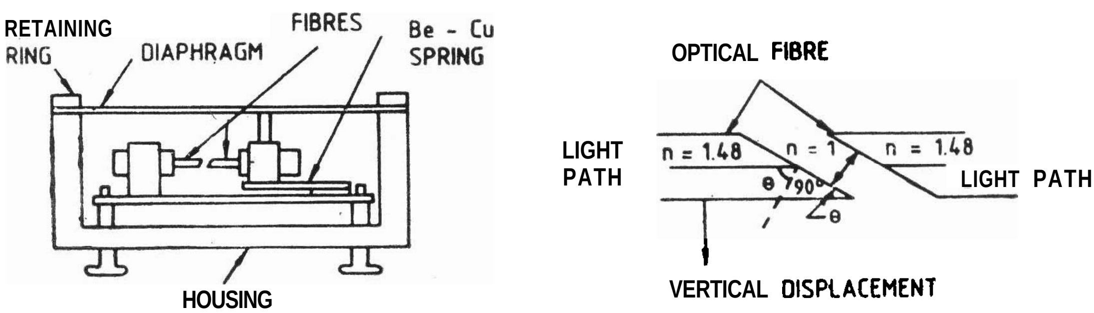


Figure 4. FTIR hydrophone.

If refractive index of fibre core is n, the air gap has a thickness X_g of unity index, the wavelength of light is λ and θ is the angle of incidence then the light coupled to the other fibre T is given by following expression

$$T = 1 - \left| (Z^2 + \delta^2)^2 \left[(Z^2 - \delta^2)^2 + 4\, Z^2 \delta^2 \coth^2 \left(\frac{\beta}{2} \right) \right]^{-1} \right|$$

where

$$\beta = \left(\frac{4\pi X_g}{\lambda} \right) (n^2 \sin^2 \theta - 1)^{1/2}$$

$$Z = \frac{1}{(n \cos \theta)}$$

$$\delta = -(n^2 \sin^2 \theta - 1)^{-1/2}$$

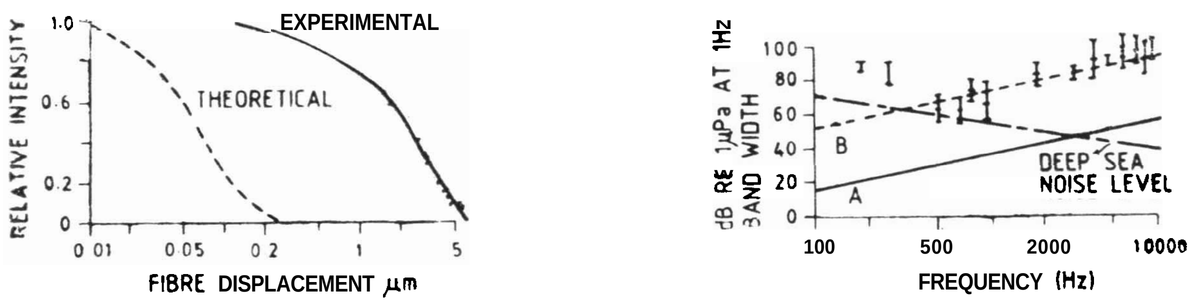


Figure 5. FTIR hydrophone minimum detectable pressure vs frequency theoretical (A) and experimental (B) sensitivity.

for light propagating with its polarization perpendicular to the plane of incidence. For light polarized in the plane of incidence.

$$Z = \frac{\cos \theta}{n}$$

$$\delta = (n^2 \sin^2 \theta - 1)^{1/2}$$

Experimental measurements have been made for change of intensity as a function of static vertical displacement and to determine minimum detectable pressure (SNR = 1) as a function of frequency from 100 Hz to 10 KHz. A set of experimental data is shown in Fig. 5. Typical values for static vertical displacement and minimum detectable pressure are found as 4.8×10^{-3} Å and 62 dB (relative to 1 μPa at 500 Hz) respectively.

4. Interferometric Hydrophone

A typical fibre optic hydrophone which utilises an acoustically induced optical phase retardation transduction is shown in Fig. 6. Light from a laser source is split into two equal-intensity parts which are launched into a reference fibre coil and a sensing fibre coil. The lengths of two coils are nearly equal, *so* that the beams recombine to produce an interference pattern. Acoustic waves modulate the interference pattern by producing uncompensated phase changes in the sensing coil. These phase changes are partly due to change in refractive index and partly by a change in the length of sensing coil. The phase of the optical beam traversing the sensing fibre is given by the following expressions :

$$\Delta \phi = K \quad dn \quad n \; dl \quad PI = KSPI$$

where n is the refractive index of the fibre core, P is the acoustic pressure, I is the fibre length, K is the optical wave number and *S* is the sum of terms within brackets and-is of the order of 0.6×10^{-12} for silica fibre.

In the case of plastic coated fibres value of S is one order higher in magnitude than for the uncoated fibre. This effect is due to the reason that plastic coating has

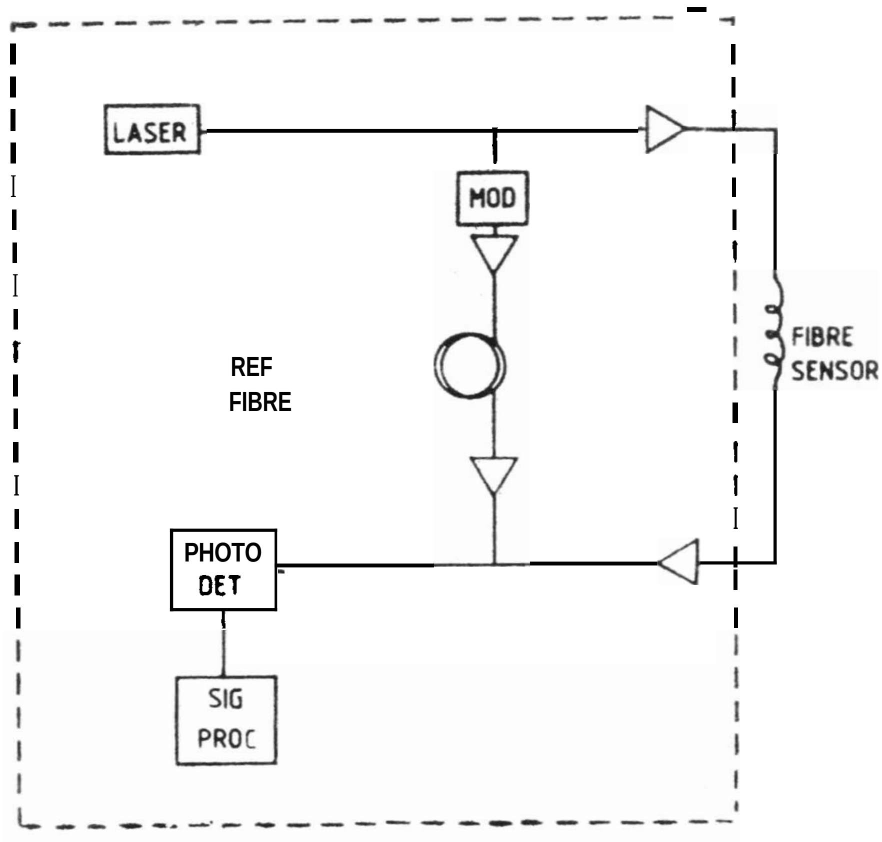


Figure 6. Fibre optic hydrophone.

much higher Poisson ratio and compressibility and hence elongate much more than bare glass fibre, thus pulling the glass fibre within it.

For this type of hydrophone with fused silica fibre 10 m long, theoretical shot-noize-limited sensitivity is 24 dB (relative to 1 μPa), a value that is well below the noise level at great depths in the ocean. In fact, experimental models of interferometric hydrophones are sensitive enough to detect the acoustic noise level at great depth in quiet ocean.

For maximum sensitivity the difference in the lengths of the coils must be maintained to $\lambda/4$ and should be accurate to within $\lambda/8$. A temperature change of 10^{-3}°C in the sensor coil with respect to the reference coil will change the length enough to disrupt the operation unless the compensation is made for this. Various feed back loops and signal processing techniques are used to maintain this maximum sensitivity condition. An additional problem with the single mode fibres used is modal noise due to random polarisation fluctuations. To avoid this either an elliptical core fibre is used or stress and deformation over the entire length of fibre are carefully restricted.

Hetrodyne detection methods remove some of these restrictions. In this case standard frequency modulation techniques can be utilized and hydrophone output is given by :

$$i_f \propto A\, \phi_{max} \sin w_s t$$

where i_f = signal current

w_s = acoustic frequency

5. Minimum Detectable Pressure

The minimum detectable pressure levels are determined by the intrinsic noise levels of the hydrophone components e.g., laser, fibre, detector and interferometer module.

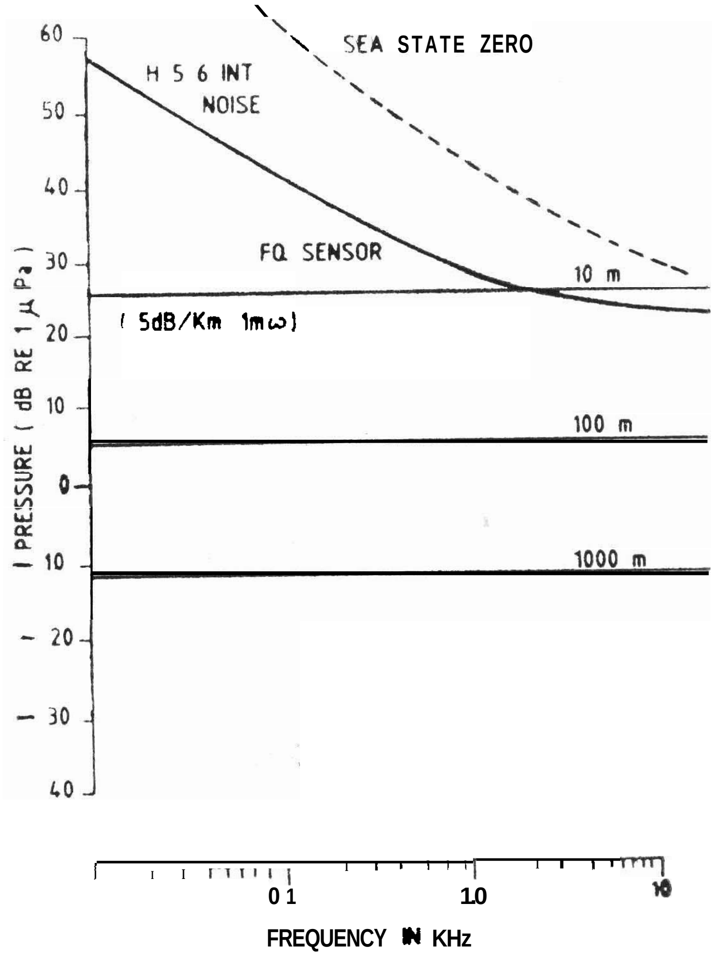


Figure 7. Quantum limited minimum delectable pressures.

The minimum pressure to quantum limit is given. by

$$P_{min} = \frac{1}{I_s}\left(\frac{BhC}{2\pi Kq P_{i_s} 10^{-\alpha l}}\right)$$

where C is the speed of light, q is the quantum efficiency of detector, B is the bandwidth of detector, a is the attenuation constant of the fibre and h is Planck's constant.

These shot-noise-limited minimum detectable pressures, in a 1 Hz band, are shown in Fig. 7 for 10,100 and 1,000 metre of fibre length (α = 5 dB/km) with 1 mW input optical power. For comparison, the pressure associated with a quiet ocean (sea state zero) and the equivalent pressure corresponding to internal noise of H56 low-noise, hydrophone are also shown.

6. Dynamic Range

The dynamic range of the optical fibre hydrophone is not limited by the acousto-optic effect. The coupling coefficient '*S*' for the silica fibre is linearly related with pressure changes upto several kilobars. At the low pressure end, the dynamic range is limited by the internal noise and at the high pressure, the limit is determined by the form of processing circuitry used. If one takes for the minimum pressure the ultimate determined by the shot-noise-limit, it appears that dynamic ranges well in excess of 100 dB are possible.

7. Conclusion

Underwater optical fibre specially designed cable can help a lot in improving the performance of many present day underwater systems like search and mapping instrumentation, sonobuoy, towed arrays, guided torpedo etc. which use metal wire cables. Fibre optics hydrophones showing sensitivity in the range of -186 dB re to $1\text{v}/\mu Pa$ for 10 metre and -157 dB re to $1\text{v}/\mu Pa$ for 1 km long fibre can provide much more sensitive and compact sensors than present day ceramic sensors research and development activity in the field of fibre optics, therefore, seems to be quite important from the point of view of enhancing the capability of many present day naval system.

References

1. Wilkins, G. A. & Estley, R. A., AGARO Conference Proceedings. No 219, Oct 1977.
2. McMohan, D. H. et al. Spectrum, Dec 1981, p 24.
3. Tebo, A. R., EOSD, Feb 1982, p 39.
4. Spilman, W. B. Jr, & McMohan, D. H. *App. Opt.*, **19** (1980), 113.