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Underwater Acoustic Sensing with Optical Fibres

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Abstract. The use of optical fibres for the detection of acoustic pressure underwater has been discussed with particular reference to the recent literature on the development of fibre optic hydrophones.

1. Introduction

The use of optical fibres for Naval applications has been suggested for quite sometime. These include (i) connection for towed sensors, and (ii) interconnection for subsystems on board. The applications arise due to the advantages associated with optical fibres in terms of size and weight, large bandwidth capability and freedom from electromagnetic interference. Recently however, a new application in the area of Naval Research has been demonstrated by which very high sensitivity acoustic detection underwater can be achieved by using an optical fibre in such a way that light propagating in the fibre is phase modulated by small changes in the length or refractive index of the fibre due to pressure variations of an acoustic wave incident on the fibre[1,2]. Both single mode and multimode fibres have been used[3,4], and effect of plastic covering on the fibre has been investigated[5]. Static[6] as well as dynamic pressure[7] sensitivity has been calculated and variations of the principle like the FTIR hydrophone[8], have been proposed as sensitive acoustic sensors. As against phase modulation, the bending loss modulation caused by flexural vibrations has also been reported[9].

It is the purpose of this paper to review the developments that have taken place in the area of acoustic sensing by the use of optical fibres and to describe the optical fibre hydrophones that have been developed for detection of acoustic vibrations below the level of human audibility[5] and measurement of deep sea noise level in the 100 Hz to 10 KHz range[8].

2. Optical Fibres as an Acoustic Sensor

If an optical fibre through which light is passing is subjected to mechanical strain, axial and radial, there are four principal effects that cause change in the phase of the optical carrier : (a) Change of refractive index (photoelastic effect), (b) Change of lenth (longitudinal strain effect), (c) Change in propagation constant with core radius (wave guide effect) and (d) Change in diameter (Poisson effect).

The photoelastic effect is present when either the axial or the radial strain is present and is given by

$$\delta_p = \frac{2\pi Ln}{\lambda}\left(\frac{n^2}{2} p\Sigma\right) \tag{1}$$

where

δ_p = phase change

L = Length of the fibre exposed to acoustic interaction

n = Average refractive index of core and cladding

λ = Wavelength of acoustic wave

p = Photoelastic constant ($p_{12} \simeq 0.2$ for longitudinal strain and $p_{11} + p_{12} \simeq 0.3$ for radial strain)

Σ = Relevant strain

The longitudinal strain effect which causes change in length is given by

$$\delta_{LS} = \frac{2\pi Ln}{\lambda} \Sigma_L \tag{2}$$

It is important when longitudinal strain is the governing factor. The wave guide effect arises when axially symmetric radial strain in applied and propagation coefficient β changes with the core diameter a. This is given by

$$\delta_{WG} = \frac{2\pi Ln}{\lambda} \frac{\lambda a}{2\pi n} \frac{d\beta}{da} \Sigma_r \tag{3}$$

$$= La \frac{d\beta}{da} \Sigma_r$$

with a typical value[9] of $\frac{d\beta}{da} \simeq 0.172$ rad/μm^2 for $a = 0.8$ μm.

The Poisson effect generally is negligibly small. For longitudinal strain, it is $\simeq 0.2$ per cent of that due to change of length whereas for radial strain this drops out when wavelength λ of compressional acoustic wave is much less than interaction length L.

At higher frequencies (> 1MHz), it becomes difficult to obtain adequate interaction length L as both λ and transducer become small. Therefore, the available phase change decreases. For such cases, it is convenient to make modulators using radial compression of the fibre. Modulations based on radial compression have the advantage of being made into a clip on type construction.

For single mode fibres of sufficiently long length the important parameters of significance are the $\frac{dn}{dP}$ and $\frac{dL}{dP}$ corresponding to the photoelastic and longitudinal strain effects. The phase change due to these effects for the acoustic pressure $P \sin \omega_s t$ can be expressed as[5]

$$\phi(t) = \left(\frac{dn}{dP} + \frac{n}{L}\frac{dL}{dP}\right) kLP \sin \omega_s t \tag{4}$$

where n = Effective refractive index of the single mode fibre,

$k = 2\pi/\lambda$ and L is the length of fibre exposed to sound field.

The index change includes the change due to axial strain as well as the radial strain. For a linearly polarised HE_{11} mode,

$$\left(\frac{dn}{dP} + \frac{n}{L}\frac{dL}{dP}\right) = \frac{\phi}{kLP} = \frac{n^3}{2}(p_{11} + p_{12})\frac{(1-\sigma)}{E} - n^3 p_{12}\frac{\sigma}{E} + 2n\sigma \tag{5}$$

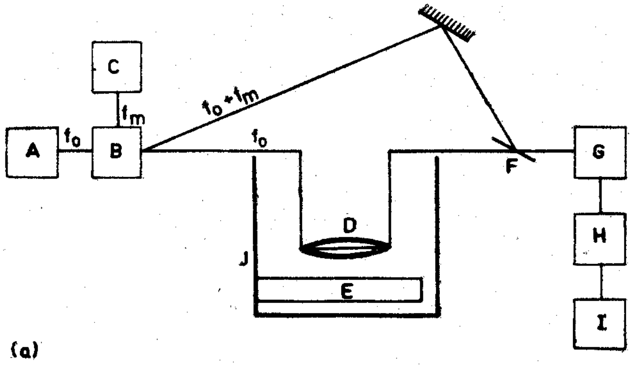
where p_{ij} are pockels coefficient, E is the Young moduls and σ is the Poissons ratio such that radial strain $= P(1-\sigma)/E$ and axial strain $= 2\sigma P/E$.

The 1st and 2nd terms on the RHS of Eqn. 5 denote the index change due to radial strain and axial strain respectively while the third term gives the contribution due to change of length.

High sensitivity detection of optical phase shifts can be achieved by adopting the laser heterodyne arrangement[1,5]. In one such arrangement (Fig. 1a) the laser frequency f_0 is changed to $f_0 + f_m$ by modulation with f_m in a Bragg Cell and forms the reference phase arm. In the other, the radiation of frequency f_0 is passed through the fibre coil which is subjected to the accoustic field and this suffers pressure induced phase change. The two radiation are then collimated and mixed in a photodetector followed by an FM discriminator.

The sensitivity of the arrangement increases as the product qL, where

$$q = \left(\frac{dn}{dP} + \frac{n}{L}\frac{dL}{dP}\right).$$



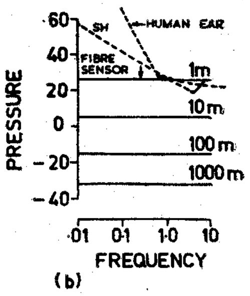


Figure 1a. Laser heterodyne arrangement : A—Laser source, B—Bragg Cell, C—OSC (modulating freq.), D—Fibres coil, E—Acoustic transducer, F—Beam combiner, G—Photodetector, H—FM discriminator, I—Display, and J—Fluid tank.

Figure 1b. Minimum detectable pressure *vs* frequency.

Alternatively as q increases, less fibre length is needed for same sensitivity. It has been stated[10] that optical phase shifts of $\sim 10^{-5}$ rad should be detectable with laser heterodyne arrangement. Accordingly it is suggested[4,7] that with single mode fibre 1 Km in length, a pressure level of 0.002 dynes/cm^2 should be detectable, thus equalling the sensitivity of best available acoustic hydrophones.

Assuming that the acoustic detector is quantum limited, the minimum detectable pressure $P_{\min}$ is given by[5]

$$P_{\min} = [hcB/2\pi kQP_f 10^{-\alpha L})^{1/2}]/qL \qquad (6)$$

Where h is planck's constant, c is velocity of light, B is detection bandwidth, Q is photodetector quantum efficiency, P_f is the optical power input to the fiber and α is the optical absorption coefficient of the fibre. Fig. 1 (b) shows the plot of equation 6 for a power of 1 mw into a plastic coated 5db/Km fibre in a 1-Hz band for various lengths of the fibre with $q = 7 \times 10^{-12}$ cm^2/dyne. Also shown are the $P_{\min}$ for a sensitive hydrophone (SH), and for the average human ear. It is seen that high sensitivities (below the human audibility) are possible even with moderate lengths of fibre (5 – 10 m). Much higher sensitivities are however possible with longer lengths. According to Culshaw *et al.*[7], the detection threshold P_t for an uncoated fibre is given by

$$P_t = \frac{1}{L}\,(B/5 \times 10^9\, P_f)^{1/2} \qquad (7)$$

For a fibre length of 1 Km, optical power of 1 mw and unit bandwidth, a pressure of the order of 10^{-6} Newton/m^2 will produce a detectable signal. This is 26 db below the threshold of hearing.

The ultimate lower limit is set by the noise in the optical source. The increase in optical power also increases the sensitivity. For single mode fibres however, 1 watt of optical power is about the maximum.

The main source of non-linearity in pressure induced phase change is the non-linearity in photoelastic constant (Eqns, 4, 5). Assuming that measurement is linear upto about 1 per cent change in refractive index, the effective linearity for phase change is upto 10^5 rad/m which means a dynamic range of 180 db for $L = 1$m. The overall linearity, therefore, is set by the phase discriminator rather than by the fibre.

3. Use of Single Mode and Multimode Fibres

The single mode fibre is generally used in a two path interferometer in which one path is formed by an acoustically irradiated fibre submerged in fluid (a fibre coil is used to increase the interaction length). The second path is formed either by an identical length of fibre in which case a relatively low coherence optical source can be used or a short air path is used with a high coherence source. After traversing two paths the beams are collimated and combined to form an interference pattern that is probed with a photomultiplier. Using this, it is possible to detect a beat signal in the photo current, when the submerged fibre coil is irradiated with sound. The best signal in the photocurrent can be fed directly to an oscilloscope using a high pass filter to eliminate low frequency noise. In this arrangement using a fibre 4m long, with core diameter 2.5 μm attenuation 0.5db/m at $\lambda = 514.5$ nm, measurement have been made in the 40 to 400 KHz range[4].

For relatively low amplitude sound irradiation, the beat signal approximates closely a sinusoid at the acoustic frequency. However, as the sound intensity is increased (or as the interacting fibre length is increased by coiling) the beat signal becomes more complicated[3], developing frequency components at the harmonic of the acoustic frequency as is expected for a phase modulation phenomenon. The amplitude of *n*th harmonic is $CJ_n(\phi)$ where J_n is an integer order Bessel function of the first kind, ϕ is acoustically induced optical phase shift and C is a constant determined by the optical beam intensity and photomultiplier sensitivity.

In the multimode fibre, only a single path length is required since it is possible to produce beat signal interaction between the various propagating modes. In this case, it is the relative phase shift between separate optical modes that is detected. The multimode fibre, in a way, provides its own multipath discriminator. Each individual mode is differently modulated and travels through different path to the detector. The modes combine on the detector to convert phase modulation to amplitude modulation and produce a signal that is related to the phase modulation. For a given amplitude sound wave, the optical phase shift per unit length is substantially smaller than that observed with two path interferometer arrangement. (The decrease is upto two orders of magnitude).

It has been found experimentally[7] using high frequencies ($>$ 1MHz) and short lengths ($<$ 5cm) that differential phase modulation of the various modes will give an amplitude modulated component at the detector. This is linear for small differential phase modulation ($<$ 0.1 rad) and is subject to deep fades which arise from fluctuations in the path differences involved in the multipath discrimination action. For optical power 1mw, the multimode SNR is typically 20db worse than the single mode system.

An arrangement has also been described[3] in which the simplicity of single fibre length interference (as in multimode fibre) and inherently high sensitivity of the two beam interferometer (as in single mode fibre) are combined. In this system the internally reflected optical beams from the ends of a single mode fibre interfere to produce the beat signal. Considering the optical beam at the exit end of the fibre, the acoustically induced phase shift between the two beams of amplitude TE_0 and TE_0R^2 would be twice that of a beam that makes a single pass through the fibre, where T is the transmission coefficietn, R is the reflective coefficient and E_0 is the optical amplitude in the fibre. The amplitude of the *n*th harmonic in the beat signal would be R^2CJ_n (2ϕ), where J_n is the integer order Bessel function of first kind. This has been experimentally demonstrated.

4. Measurement of Static Pressure

Most of the work reported above related to the dynamic pressure changes. Recently however[6,11], papers have appeared which relate specifically to the measurement of static pressure using optical fibres. In all cases, the measurement of pressure is attributed to variation in the relative phase between light propagating in the two interferometer arms. Variations in the relative optical phase are attributed to pressure induced changes in the optical propagation characteristics (change of refractive index and change of length in the propagation direction) in the arm exposed to thc applied pressure. Variation in relative phase are observed as modulation in light intensity at a selected position in the interference pattern. An experimental configuration of the fibre optic interferometer for static pressure is shown in Fig. 2. The test arm containing a single mode fibre coil is exposed to the static pressure. Plastic box is used to reduced temperature induced phase changes. Imaged interference pattern is a series of concentric dark and bright rings with the centre of the pattern positioned on the light sensitive area of photo detector. The magnitude of the pressure induced phase change is determined from the number of minima or maxima written on the XY recorder chart.

5. Effect of Plastic Coating on Fibre

An amplification of pressure induced phase changes was observed[5], when single mode fibres were coated with a plastic. This was attributed to an enhanced axial strain due to the plastic jacket. The coupling coefficient $q = \left(\frac{dn}{dP} + \frac{n}{L}\frac{dL}{dP}\right)$ for plastic coated fibre was found to be an order of magnitude larger than in the uncoated fibre. This was explained as due to the fact that the plastic coating, having much higher Poisson ratio and compressibility elongates much more than a bare glass fibre, thus pulling the glass fibre with it. The fact that such coatings increase the coupling coefficient is important for acoustic detection applications. It may also be possible to coat with materials which decrease the sensitivity to acoustic wave for specific regions of the fibre, if it is so desired.

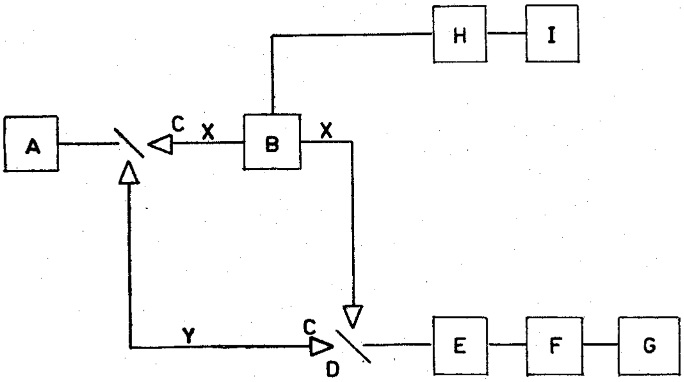
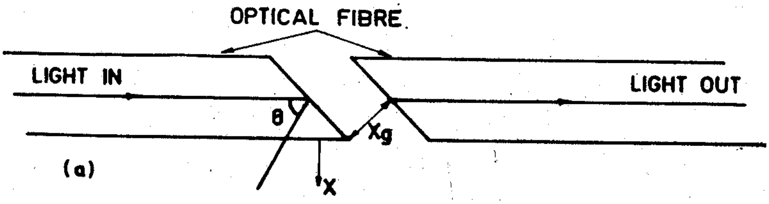


Figure 2. Fibre optic interferometer for static pressure measurement: A—Laser, B—Pressure Cell, C—Fibre coupling (X10 microscope objective), D—Beam combiner, E—Photodetector, F—Oscilloscope, G—XY recorder, H—Pressure guage, I—Pump, X—Test arm of interferometer (fibre), Y—Ref. arm of interferometer (fibre).



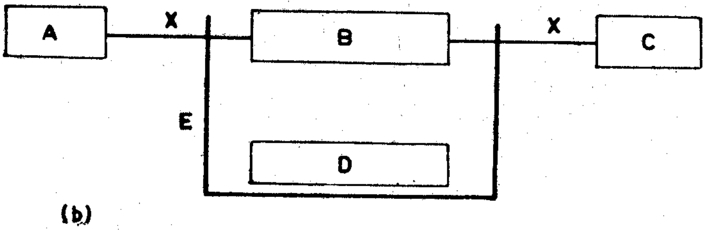


Figure 3a. Principle of FTIR Hydrophone.
Figure 3b. FTIR Hydrophone arrangement: A—Laser, B—Optical Hydrophone, C—Detector, D—Acoustic source, E—Fluid tank, X—Optical fibre.

6. FTIR Hydrophone

The principle of frustrated total internal reflection ((FTIR) has also been used in constructing a multimode fibre optic hydrophone. In this system the light is coupled between two multimode optical fibres via FTIR. By bringing the two fibre ends sufficiently near to one another, a large fraction of light power can be coupled between the two fibres. Modulating the gap thickness X_g (Figs. 3a & b) by means of a relative vertical displacement X between the two fibres causes the amount of light power coupled between the fibres to be modulated.

This concept has been shown to be a sensitive multimode method of detecting acoustic waves[8]. The minimum detectable pressure was 62db relative to 1 μPa at 500Hz and static displacements as small as $4.8 \times 10^{-3} A^0$ can be detected. The sensor is compatible with presently available multimode fibres, optical sources, and detectors etc. and can be used to detect the deep sea noise level from 100 Hz to 10 KHz. The sensitivity to static pressure can be reduced or eliminated by pressure relief holes and bellow chambers.

7. Conclusion

Optical fibres, single mode and multimode, have been successfully used for the sensitive detection of acoustic waves underwater. A wide dynamic range is possible and presently available components can be effectively employed in the fabrication of a fibre optic hydrophone.

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