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RECENT DEVELOPMENTS IN FIBRE OPTIC HYDROPHONE TECHNOLOGY

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Abstract

A brief overview of fibre optic acoustic sensor technology is presented, focussing on the application to ocean deployed sonar arrays. The potential advantages and limitations of different approaches are discussed. Current work by the authors on fibre laser based sensors is reported including the recent laboratory demonstration of a pressure compensated, all optical, low noise, fibre laser hydrophone.

1. INTRODUCTION

The fibre optic acoustic hydrophone was first proposed in 1977 [1], [2]. Following substantial research and development during the 1980s and 90s the technology has progressed to the extent that the first operational, military fibre optic sonar systems are now appearing. The new US Navy Virginia class submarines began acceptance trials of a large aperture fibre optic planar hull array, in 2004 [3]. The US navy is also (at the time of writing) in the process of acquiring a fibre optic towed array. To the authors' knowledge, the US Virginia hull array represents the first service deployment of a fibre optic, acoustic array.

Over the years, a wide range of potential advantages have been anticipated for fibre optic sonar systems. These include low cost, superior sensitivity, superior dynamic range, superior versatility, immunity from electromagnetic interference, covertness, superior reliability, multiplexibility and telemetry advantage [4], [5], [6]. We shall not attempt to review all of the historical claims but point out that the core reasons for pursuing fibre optic technologies can largely be attributed to telemetry and multiplexibility. Traditional electro-acoustic systems are not well suited to operating in environments remote from the operating platforms and require complex local electronics (i.e. pre-amps) at the sensor location with associated additional power and cabling requirements in order to overcome high losses, noise and environmental interference in the telemetry cable. Fibre optic systems, in comparison, have near ideal telemetry over distances up to several kilometres – it is comparatively unimportant whether the processor is 2m or 2km from the sensor and no additional components are generally necessary to compensate for telemetry losses or noise. Also, fibre optic systems readily lend themselves to multiplexing data from multiple sensors onto a single fibre with little or no increase in complexity at the deployed end of the sensor system.

These advantages translate to a reduction in complexity and bulk of the deployed sensor and promise potential weight, volume, cost and reliability enhancements in future sonar systems.

The aim of the current paper is to provide a brief introduction to the basic principles of fibre optic hydrophone technology, highlighting issues that are pertinent to current research and to present some recent results. The layout of the paper is as follows: In Section 2 the basic operating principles of the most common and mature fibre optic hydrophone – that based on fibre optic interferometry – is outlined. Section 3 describes an alternative approach to fibre optic acoustic sensing based on newly emerging compact fibre laser sensor technology, which shows significant promise as a future sonar technology. Recent results by the authors are presented, including the first report of a pressure compensated fibre laser hydrophone. We conclude with a brief summary in Section 4.

2. THE INTERFEROMETRIC HYDROPHONE

The original concept for the fibre optic hydrophone originated from the laboratory observation of acoustic sensitivity in fibre interferometers [1]. This observation has formed the basis of virtually all subsequent serious fibre optic hydrophone development. The basic property of the interferometer that makes it virtually unrivalled as an acoustic sensor is its extreme sensitivity to mechanical deformations, including, in particular, the ability to detect dynamic strains as small as 10^{-15} [6].

2.1. Interferometric strain sensing

The basic sensor principle is illustrated in Fig 1. Coherent light from a laser source is launched into an optical fibre and is split (by a fibre optic coupler) into two arms of a fibre interferometer before being recombined and received by a photo-detector. Due to optical interference, the intensity measured by the detector is modulated by the phase difference between the light from the two arms of the interferometer, given by

$$\Delta\phi = 2\pi n \Delta L/\lambda, \tag{1}$$

where ΔL is the physical path imbalance in the interferometer, n is the refractive index of the glass fibre and λ is the laser wavelength. It is this phase difference which may be taken as the actual measurand of the system. In order to track phase changes from intensity variations it is practically advantageous to introduce a carrier modulation on the phase by modulating either the laser wavelength or interferometer path imbalance. Details of techniques for doing this are provided in the literature [6].

In an interferometric sensor system, a fibre section of path length L in one arm of the interferometer (termed the delay coil) is exposed to the environment and acts as the sensor element (box B1 in Fig 1.). The remaining arm of the interferometer (termed the reference coil) is shielded from the environment.

Suppose that an acoustic disturbance exerts a strain ε on the delay coil of length L, then by (1) the change in phase is given by[1]

$$\Delta\phi_s = 2\pi n \varepsilon L/\lambda \tag{2}$$

[1] There is an additional small contribution to the phase caused by strain induced refractive index change, but this shall be neglected here for the sake of simplicity.

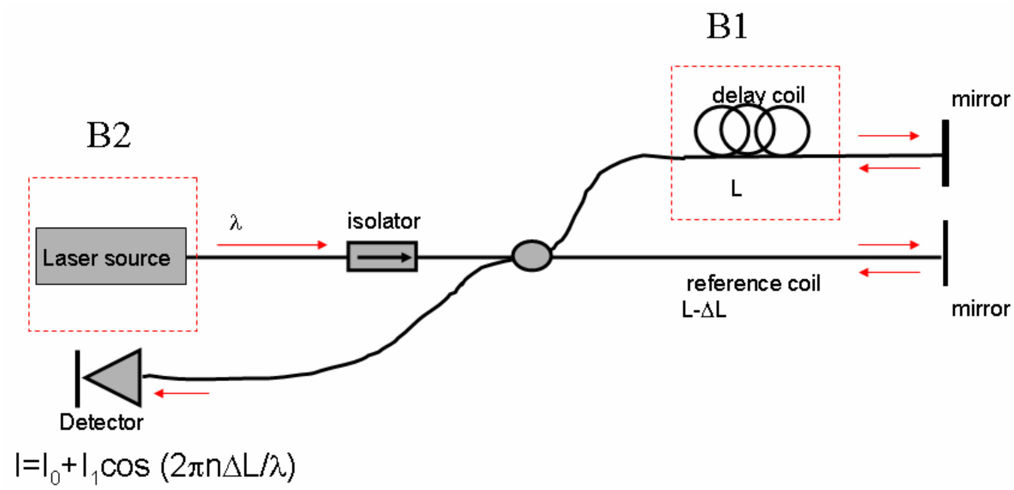


Figure 1: Michelson fibre interferometer illustrating the principle of fibre optic acoustic sensing. In calculating the path length in each arm the total transit distance of the light "beam" must be taken into account. Thus, for a reflective geometry such as shown here, the path imbalance ΔL is twice the difference in fibre lengths between the two arms. Similarly, the coil path length L is twice the actual length of fibre in the coil.

Note that the path imbalance due to a particular strain is proportional to the total length of fibre under influence. Thus the sensitivity increases as the length of the delay coil increases. The ability of the demodulation system to detect small phase changes is limited by various factors including (intensity dependent) photo-detector noise, electronic noise and phase carrier stability [6]. In practice, a high performance phase detector might reasonably be expected to achieve a minimum detectable phase shift of order $\Delta\phi_{min}$ =10μrad/√Hz.[2] Assuming a refractive index of 1.5, as appropriate for silica glass, and a laser wavelength of 1.5μm, corresponding to the optimal band for low loss telemetry (in silica fibre), this yields a minimum detectable strain

$$\varepsilon_{min} = 10^{-12}/L \tag{3}$$

Thus, sub-picostrain sensitivity requires a fibre coil of length greater than 1m. Typical fibre optic hydrophones utilise 10-100m of fibre in the delay coil. Managing this length of fibre generally requires that it be wound around a mandrel.

It can be seen from (1) that any instability in refractive index, reference coil length or laser wavelength will inject additional noise into the system. In practice the most important of these is laser noise. A perturbation $\Delta\lambda$ to laser wavelength results in a phase error

$$\Delta\phi_L = 2\pi n \Delta L(\Delta\lambda/\lambda^2) \tag{4}$$

The development of improved low-noise sources at wavelengths suitable for low loss telemetry has been important to the maturity of the technology. Note that the effect of laser frequency noise can be eliminated in principle by *path matching* the interferometer (setting ΔL=0) although this requires very specific demodulation techniques [7] and is not often used in practice [6].

[2] The units μrad/√Hz arise from the fact that the minimum detectable phase shift has been derived from (the square root of) a phase noise spectral density $<\phi(f)^2>$ which has units $\mu rad^2\ Hz^{-1}$. Note that the smallest phase shift that can be detected in practice will depend on the spectral content of the signal and may be smaller or greater than this figure.

2.2. The Acoustic Transducer

Up to this point we have characterised the interferometric sensor as a strain sensor and have not made any specific reference to acoustic pressure sensitivity. Early work focussed on the intrinsic hydrostatic sensitivity of bare optical fibre and on enhancing this by applying special compliant coatings [4]. Motivated by a desire to increase sensitivity, the modern air backed mandrel structure was introduced in the mid 80s [8]. In these designs the diameter of a compliant (air filled) cylindrical structure is perturbed by acoustic pressure variations, thereby exerting uniform strain on a fibre coil wound around the structure. Transducer sensitivities in the range -310 to -300dB re strain per μPa have been quoted in the literature [6]. To put this figure in context we need to know the phase noise floor of the detection system and the length of fibre in the delay coil. From (2) one obtains, from a state-of-the-art transducer sensitivity of -300dB, a noise equivalent pressure level (dB re 1μPa/√Hz) of

$$N= 300 + 20\log_{10}(\phi_{min}) - 20\log_{10}(L) - 20\log_{10}(2\pi n/\lambda) \tag{5}$$

At 1550nm wavelength, with a typical phase noise floor of 10μrad/√Hz and a typical fibre length of 30m, (5) yields a noise level of 35dB re 1μPa/√Hz which is well below ambient ocean noise and supports the interferometric hydrophones claim to unsurpassed sensitivity.

In addition to enhancing sensitivity, the air backed mandrel tranducer marked an important shift in the fibre optic sensing paradigm by decoupling the mechanical problem of pressure actuation from the material properties of the optical fibre. Optical fibre is relatively ill-suited to hydrostatic pressure sensing due to its long thin geometry and rigid material composition [9]. Because the sensitivity of the air backed mandrel hydrophone is determined by the compliance and geometry of the supporting mandrel, a high degree of flexibility exists in tailoring sensitivity and other important transducer characteristics to specific applications. Of particular importance is the dynamic range of the sensor, which is determined by the crush pressure of the structure. This in turn is related to the structural compliance and hence to sensitivity. Thus, important design tradeoffs must be made between transducer sensitivity and maximum operating pressure (i.e. max depth)[5], [6].

2.3. Multiplexing

Multiplexing of interferometric sensors has been achieved via a number of methods including frequency domain multiplexing (FDM)[10], time domain multiplexing (TDM) [7], [11] and wavelength domain multiplexing (WDM) [11], [6]. We shall focus on TDM which is widely used in practice and is pedagogically relatively straightforward.

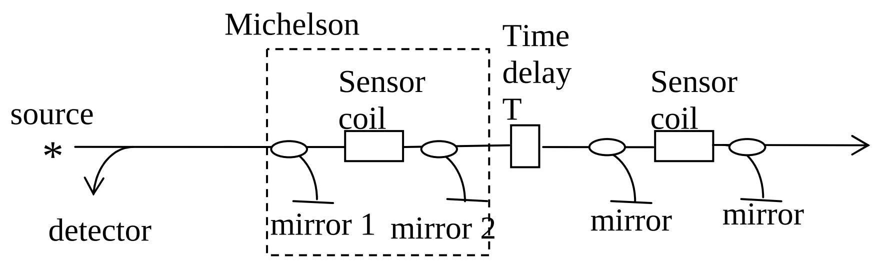


Figure 2: Outline of a serial Michelson geometry suitable for time domain multiplexing.

In a TDM system, light from a source is time gated into discrete pulses. The signal received from different sensors is distinguished by the different round trip delay time required for a pulse to travel to and from the sensor. Figure 2 illustrates a simple serial Michelson architecture, which is suitable for TDM. The pair of mirrors either side of the sensor coil constitute a Michelson interferometer. The path imbalance in the sensor coil is such that the interferometric delay time $n\Delta L/c$, where c is the speed of light, is small compared to the pulse duration, ensuring that the pulse energy reflected from mirrors 1 and 2 interferes. The time delay T between successive sensors, however, is larger than the pulse duration enabling the return from each successive sensor to be read off in succession. The duty cycle of the incident pulse train is chosen so that the time between successive pulses is larger than the longest round trip delay time in the system, ensuring that no overlap of successive pulses occurs.

Our description has been highly simplified in order to get across the basic concept. Practical implementations of TDM, and indeed all interferometric multiplexing schemes, can be very complex and challenging. Optical losses in TDM systems are high -- generally greater than $1/N^2$ for an N element array – and amount to about 50dB for a 64 element array [6]. Reduced optical throughput and the demand for optical amplification stages result in substantially degraded phase demodulation performance compared to single sensor systems [11]. Despite these challenges high performance TDM arrays of at least 64 sensors have been reported in the literature [11].

The channel count of TDM arrays is ultimately limited by time-bandwidth constraints to a figure somewhere less than 100 sensors. It has been proposed that additional multiplexing gain can be achieved utilizing WDM in conjunction with TDM [11], [6]. The complexity of multiplexing, and the fact that hydrophone performance is determined by system level parameters such as multiplexing architecture and sensor count, rather than the inherent properties of the sensor, make fibre optic arrays challenging to implement in practice and somewhat “ugly” from an engineering standpoint. Having said that, the fact that in-service systems are emerging [3], is strong evidence that the technology not only works, but that it can provide tangible benefits over traditional technologies. In the next section we discuss a more recent approach to fibre optic hydrophone technology which shows promise in delivering both high performance and an extremely simple and elegant system architecture.

3. FIBRE LASER HYDROPHONES

3.1. The Fibre Laser Sensor

It has already been noted (Eqn. (4)) that any change in laser wavelength of an interferometric sensor results in a phase shift at the detector. This suggests an alternative sensor approach whereby the laser source (Box B2 in Fig. 1) is exposed to the environment and the entire interferometer is shielded. The concept of an acoustic laser sensor dates to the early days of fibre optic hydrophone research [12], however, it is the recent emergence of extremely compact, optically powered, in-fibre lasers based on fibre Bragg grating technology, in particular distributed feedback fibre lasers DFB FL [13], that has stimulated current interest in fibre laser sensing. The modern approach of the Bragg grating laser based sensor with interferometric interrogation appears to have been first proposed by Koo and Kersey in the mid 90s [14].

A typical DFB FL is illustrated in Fig 3. The total length of the device is around 5cm. Energy is supplied by *optically pumping* with a 980nm or 1480nm laser diode as shown in Figure 3. Note that only a small fraction of pump energy is absorbed by the laser, the remainder continuing along the optical fibre. The absorbed pump energy is converted by a non-linear optical amplification process into virtually single-wavelength laser output in a range between 1500 and 1600nm. The laser wavelength is determined by a resonance condition of the Bragg grating structure within the device and corresponds to the so called

Bragg wavelength λ_b which is equal to twice the grating pitch. The wavelength of the laser can be selected at the time of fabrication by adjusting the pitch of the grating.

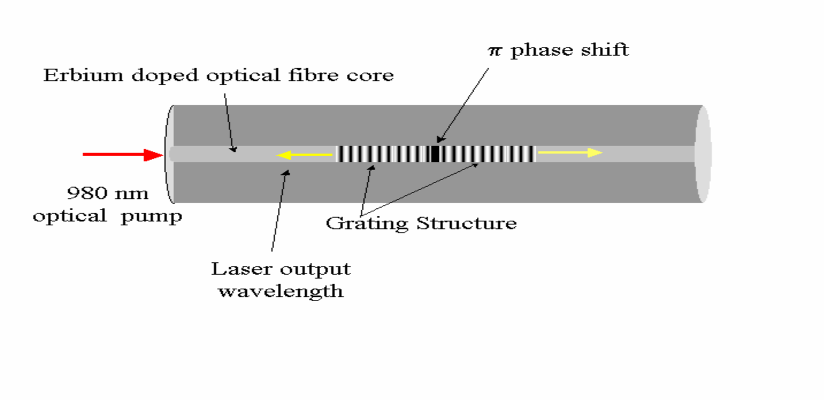


Figure 3: A Distributed feedback fibre laser.

The fibre laser sensor is based on the principle of measuring changes to laser wavelength caused by strain. When the fibre is strained the pitch of the Bragg grating changes and the laser wavelength (or equivalently the laser frequency) changes according to the approximate formula

$$\Delta\lambda/\lambda \cong \Delta\omega/\omega \cong \varepsilon \tag{6}$$

The change in wavelength may be interrogated using optical interferometric methods [14] (c.f. (4)). Because the laser output is virtually monochromatic, very small wavelength shifts, and hence very small strains, may be detected. An attractive feature of fibre laser sensors is that, unlike interferometric sensor systems, sensitivity is typically limited by the intrinsic wavelength noise (usually expressed in terms of frequency noise) of the laser sensor, rather than the noise floor of the detection system. This is essentially because the interrogating interferometer path imbalance ΔL can generally be increased to ensure that the phase shift (4) caused by laser noise exceeds the noise floor of the detection system. The typical noise floor of a DFB fibre laser is of order 1.5×10^{-11}nm/$\sqrt{\text{Hz}}$ [15] corresponding to a strain noise

$$\varepsilon_{min} \cong 10^{-13}/\sqrt{\text{Hz}}. \tag{7}$$

Thus the minimum detectable strain of a 5cm fibre laser sensor is roughly equivalent to that of a 10m long interferometric sensor coil. In terms of sensitivity per unit length of sensor the fibre laser sensor far exceeds the traditional interferometric coil, however, unlike interferometric sensors, sensitivity can not be scaled by increasing the length of sensing fibre.

3.2. Multiplexing

Perhaps the most attractive feature of fibre laser sensing is the simplicity of multiplexing [16]. A typical wavelength division multiplexed (WDM) fibre laser sensor architecture is shown in Fig 4. Laser sensors of different wavelengths are arranged serially along an optical fibre and pumped remotely by a single pump source. The multiple laser outputs, carrying the sensor information, return along the same fibre as delivered the pump. Since light waves of differing wavelengths do not interfere, a single interferometer is sufficient to enable demodulation of each of the signals from the multiple sensors. The light is split into its constituent wavelength components (corresponding to the sensor channels) by a dispersive optical component, before the intensity on each channel is recorded by an array of photodetectors. Note that the only part of this system deployed to the environment is the array of laser sensors itself, and the

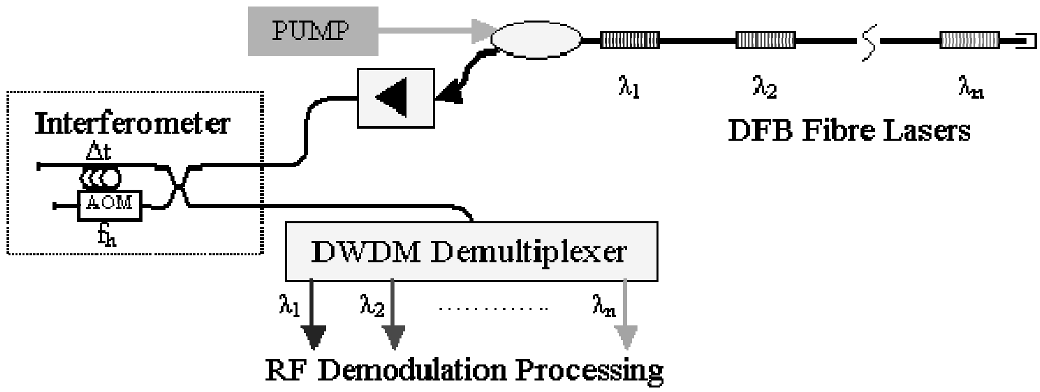


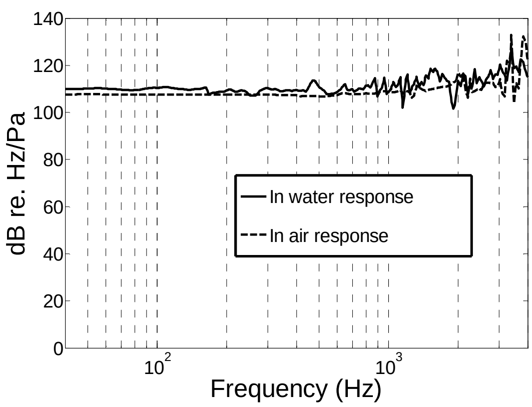
Figure 4: Multiplexed fibre laser array system.

connecting optical fibre.

Until recently, it was believed that high pump losses at the lasers severely limited the number of sensors that could be practically multiplexed in series, however, recent advances in DFB FL technology reported in [17] show that losses well below 0.5dB per device are achievable and this suggests that bandwidth limited sensor counts in the 50-100 element range are practically realizable with quite modest power requirements. These sensor counts are comparable to interferometric TDM schemes. A 16 element DFB FL sensor array with no significant degradation in noise performance compared to a single channel system has recently been reported [17].

3.3. Acoustic Transducer

The very short length of fibre required for DFB FL sensors makes possible a wide range of packaging and transduction mechanisms not available for more traditional fibre optic sensors. Initial development of DFB FL hydrophones took inspiration from the early days of fibre optic hydrophone research and focused on the hydrostatic pressure response of coated optical fibre [18]. This approach was presumably motivated by the desire for a very low complexity, ultra-thin, transducer geometry that took full advantage of the compact size of the DFB FL sensor. More recently, a range of more elaborate transducer mechanisms have been proposed, including a “guitar string” piston arrangement [19] and an air filled flexural beam “bender” transducer [20].



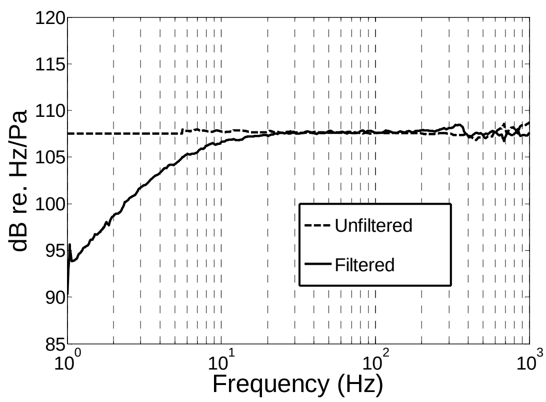


Figure 5: a) Acoustic response of fibre laser hydrophone; b) low frequency response of pressure compensated hydrophone showing roll-off below 20Hz.

Fig 5a. shows the acoustic response of an air filled fibre laser “bender” hydrophone similar to that described in [20]. Note that it exhibits a flat frequency response of around

108dB re Hz Pa^{-1} (equating to a wavelength response around -110dB re nm Pa^{-1}) from 10Hz to the first structural resonance at around 2kHz. Based on (7) this translates to a noise equivalent pressure level of around 40dB re 1μPa/√Hz, which is below lowest ambient ocean noise.

One potential drawback of fibre laser hydrophones is that the simultaneous requirement for high sensitivity and high dynamic range (to allow for the huge increase in hydrostatic pressure with depth) is not readily achievable. In our hydrophone, this problem has been circumvented by using an external pressure compensating bladder (i.e. an acoustic filter) to make the device insensitive to DC pressure changes (Fig. 6). The frequency response of the pressure compensated hydrophone compared to a non-compensated hydrophone is shown in Fig. 5b clearly indicating a smooth roll-off below the cutoff frequency of 20Hz. The pressure compensated hydrophone has been tested to a depth of 6m corresponding to a hydrostatic pressure change of 6×10^4Pa (0.6Atm) and exhibited no measurable DC wavelength shift. Furthermore, the acoustic sensitivity (above the cut frequency) was unchanged from that at atmospheric pressure.

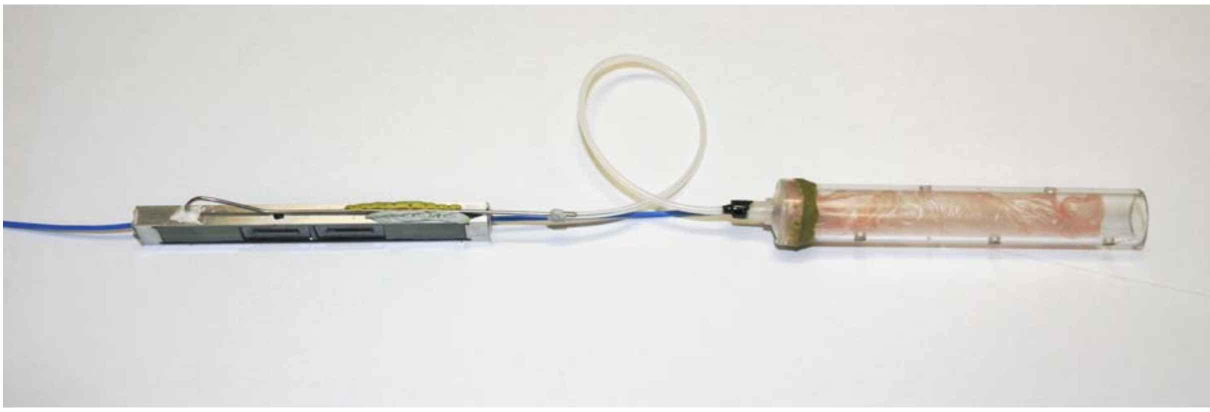


Figure 6: Pressure compensated fibre laser hydrophone showing acoustic transducer (containing fibre laser) (left) and external bladder (right).

Although crude, the arrangement shown in Fig. 6 was sufficient to provide the first demonstration of a pressure compensated fibre laser acoustic transducer. It is expected that future designs will integrate the reservoir cavity and capillary into the main transducer package, yielding a compact and robust hydrophone.

4. SUMMARY

A brief review of fire optic hydrophone technology has been presented, emphasizing the basic concepts, key historical developments and recent advances based on the fibre laser sensor approach. The first demonstration of a pressure compensated fibre laser acoustic transducer has been reported.

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