DFB – FL HYDROPHONE : A brief review

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Abstract: A brief review of the Distributed Feedback Fiber laser hydrophone has been presented. The review is primarily focused on distributed feedback as it applies to hydrophone technology. Limitations and advantages of DFB-FL hydrophones over piezoelectric hydrophones have also been discussed. The paper also incorporates various measures taken for sensitivity enhancements such as compliant coating, pressure compensation, multiplexing and use of fiber bragg gratings within the fiber laser.

Index Terms: **Distributed feedback, Fiber laser, Fiber Bragg Grating, Interferometer, Multiplexing, Hydrophone.**

1. Introduction

Invention of the LASER technology in the late 1950s independently by Maiman and Gould opened up new realms of wide applications ranging from medicine to communication. One such profound application came up in the use for sensing purposes. The Distributed Feedback Fiber laser hydrophones were introduced as an application of laser and fiber for sensing purpose.

A hydrophone is an underwater microphone designed to monitor noise inside water bodies. The first hydrophone was invented by Canadian inventor Reginal Fesseden in 1914 [1]. This device, known as the Fesseden oscillator was further improved by the French, British and American scientists during the World War II to detect German U-boats [2]. Earliest hydrophones were based on the principle of piezoelectricity i.e. piezoelectric transducers [3] which when subjected to a pressure change or strain, generate electricity. With the invention of Fiber laser in 1963 by Ellias Snitzer [4] [5], fibre optic hydrophones have been gaining momentum since the late 1970s due to their high sensitivity to extremely minute strains in the sub pico range. These hydrophones owe their functioning to the response of the Fiber laser's output to small disturbances in their environment. Measurable fluctuations in frequency happening near the fiber laser cavity due to local acoustic perturbations can be analyzed by interferometric methods. [6] [7] However, this property of the Fiber Laser makes them highly responsive to non-acoustic vibrations as well, making them undesirable for sonar applications. To compensate for this, supporting the fiber mechanically becomes necessary in order to increase its pressure sensitivity, whilst minimizing its response to non-acoustic disturbances such as mechanical acceleration [8].

A shift of $\pi/2$ in the fiber bragg grating written on an optical fiber doped with erbium-ytterbium creates a Fabry-Perot laser cavity in the DFB-FL hydrophone[9]. The resonance cavity is kept at $\lambda/4$, the fiber laser can achieve single mode operation leading it to generate a very narrowband output at a frequency centered at the center of the bragg grating. DFB – FL hydrophones are a great substitute for ceramic based piezoelectric hydrophones because of advantages such as their large bandwidth, lightweight, higher sensitivity, immunity to EMI(Electromagnetic Interference), ease of forming an array by multiplexing multiple sensors on a single fiber and low cost. A wide range of different techniques in fibre optic hydrophone systems have been developed but the most promising are the ones based on interferometry. Thus, key developments in this field will depend upon the ways in which the present hydrophone design techniques could be combined with the ongoing optical system and component developments.

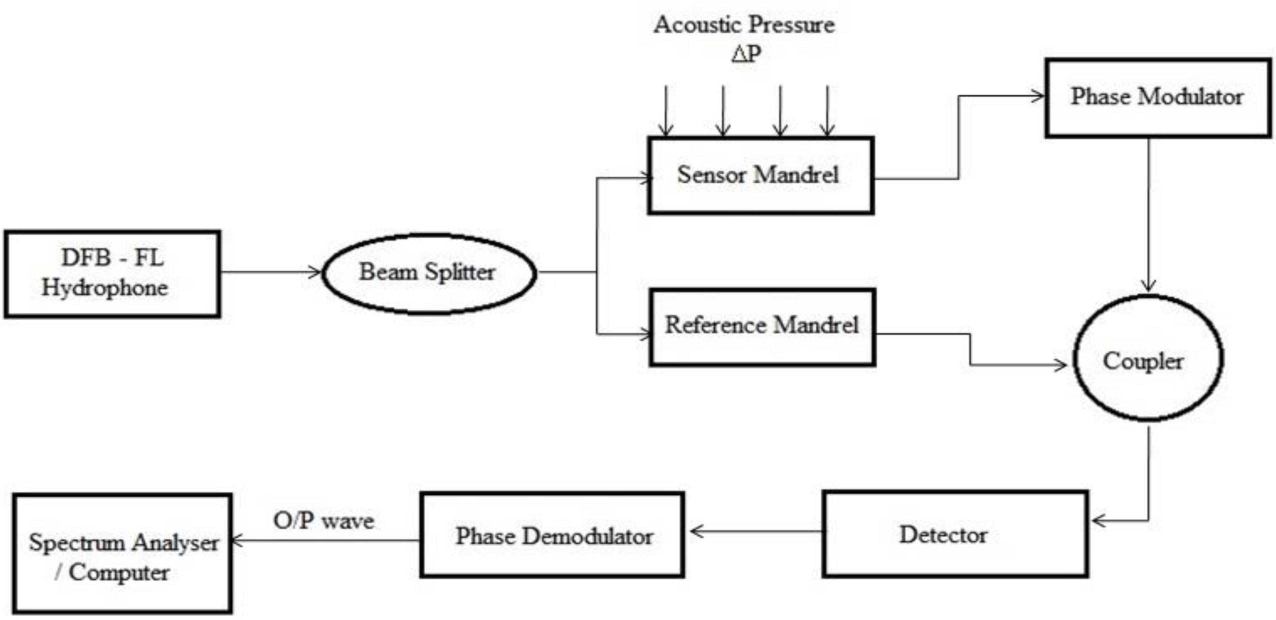

Figure: A basic block diagram of DFB - FL hydrophone.

2. **DFB – FL Hydrophone : Origin and development**

The development of the fiber optic hydrophone began in the late 1970s [10] [11], a decade later from when the fiber laser was first proposed by Elias Snitzer et al. in 1963. Consequent improvements in the fiber optic domain in the following two decades led to the development of the DFB – FL Hydrophone.

DFB – Fiber laser was first proposed by J. T. Kringlebotn et al. in 1994. They used a single bragg grating written on a 2 cm long Er^{3+} doped fiber co-doped with Yb^{3+} .Co-doping with Yb^{3+} increased the absorption at pump wavelength 980 nm by close to 2 orders of magnitude. Localized heating was used to create the necessary phase shift in the bragg grating. This paper was pivotal for all the future works deploying distributed feedback fiber laser technology for acoustic sensing purposes.

K P Koo and A D Kersey in 1993, demonstrated a method of strain sensing using a FBG based laser operating in both single-longitudinal mode and multi-longitudinal mode. They described an interferometric scheme using a Mach Zehnder time-out interferometer (MZI) for reading wavelength encoded signals from the laser sensors and then converting them into changes in phase of the interference pattern. They also demonstrated the multiplexing of multiple FBG laser sensors onto a single network using wavelength division multiplexing. The strain resolution obtained for single-longitudinal mode was $5.6 \times 10^{-14}/\sqrt{Hz}$ and for multi-longitudinal was $7 \times 10^{-15}/\sqrt{Hz}$. The strain resolutions obtained were subject to limitations inflicted by cavity length fluctuations of the laser induced thermally. Their work was essential for establishing the importance of FBGs in interferometric interrogation.

In 1999, D.J. Nash et al. [12] developed a fiber laser sensor array employing the heterodyne interrogation scheme by means of an unbalanced MZI (Mach Zehnder Interferometer) with WDM (Wavelength division multiplexing) channel selection. To ease the interrogation of the fiber laser sensor, single mode fiber lasers were used. They investigated two approaches in their work, distributed bragg reflector (DBR) and the distributed feedback (DFB), comparing examples based upon both. By altering the Bragg grating characteristics, the cavity length and the doping in the fiber, they achieved optimization of the DBR as per their requirements. They used a matched pair of 50 mm long FBGs written in an erbium doped fiber with an absorption of 5.7 dB/m at 153mm, with the cavity length set at 45mm. The fiber laser gave a 100mW output at 1547.5 nm when pumped by a LDPM (Laser diode pump module) operating at 980nm while delivering a power 80mW. DFB lasers, around 50 mm long, gave an output which was single longitudinal and single polarization mode, with no mode hopping. They reported the DFB laser having burst free operation and with a smaller linewidth than 30 kHz and a – l0dB m output when pumped at 100mW by a 1480nm pump. High amount of doping was done with erbium on the fiber. Theoretical and experimental increments in acoustic sensitivity achieved by means of an elasto-plastic coating on the fiber laser were also reported. A 'thick' coating of polyurethane, 200mm long with a diameter of 5mm was applied to the fiber laser. Though it was expected for the coatings to increase the pressure sensitivity of the hydrophone due to their low bulk modulus, the DBR – FL stopped lasing as the two gratings were differently strained due to the bending in the coating. This happened due to a mismatch of the two reflected wavelengths, destroying the fiber laser's cavity and causing it to stop emitting light. The DFB however, continued to lase even after coating, since it has a more compact structure and is immune to the effects of differential strain. Moreover, splicing three DFB fiber lasers together resulted in negligible change in both the phase noise and the intensity noise suggesting the absence of any optical crosstalk limitation in forming sensor arrays.

In 2005 Scott foster et al. [8] proposed an acceleration insensitive DFB – FL hydrophone which unlike the previous models, was highly susceptible to vibrational noise. Their work intended to achieve low sensitivity to bulk accelerations along with sea state zero pressure sensitivity. The bare DFB FL hydrophone is unsuitable for pressure sensing as it has a strong tendency to respond to vibrations in its local neighborhood (both mechanical and acoustic). Thus, the work is based upon the assertion that to construct a DFB – FL hydrophone, supporting the fiber laser mechanically is mandatory so that its pressure sensitivity could be enhanced whilst minimizing its response to mechanical acceleration and other environmental perturbations. A hydrophone assembly composed of several hydrophones designed to function from DC to 3 kHz for low frequency passive sonar was made. The hydrophone had the dimensions 56mm x 7mm x 5mm. The assembly could be thought of as a mechanical actuator, converting external pressure into longitudinal strain. The pressure and acceleration sensitivity could be manipulated to suit the application by adjusting the configuration and materials of the actuator. To quantify the performance of the hydrophone, two figures of merit were used. First, the normalized response to be the fiber laser sensor's response (in Hz/Pa) divided by the frequency noise floor of the laser (in Hz/√Hz). A normalized sensitivity greater than 70 dB is considered good enough. Second, the relative acceleration sensitivity to be the laser's response (in Hz/ms^{-2}) to acceleration of the outer housing divided by its response (in Hz/Pa) to pressure. Ideally, the figure should be kept be kept very low. Commercially available PZT based hydrophones are generally able to achieve a relative acceleration sensitivity figure around 0 dB. The implementation of the hydrophone turned out to be sub-optimal, mainly since the outer housing had higher stiffness than initially intended.

In another paper in 2006, Scott foster et al. [13] reported a 16 channel wavelength division multiplexed linear array of DFB FL sensors pumped at 980 nm designed specifically for optimal array multiplexing performance. Erbium doped silica fibers were used for lasers with large numerical aperture (NA~0.28 @ 1550nm) so as to make the power density as high as possible at pump wavelengths and hence, minimize the laser threshold. Sixteen fiber lasers were made at evenly spaced wavelength between 1535 nm and 1560 nm. They were designed to have low out of band reflection and low pump attenuation as is required for multiplexed sensor array applications. The pump attenuation was found to be well below 1dB per device, whilst the laser threshold around 1mW, making them suitable for multiplexing. A slight variation in the output power around 10 dB can be observed. This variation can be attributed to a number of factors such as the dependence of the gain medium characteristics on wavelength, statistical variability among the lasers, differences in the packaging of laser and attenuation of the pump power. The demodulation of the laser frequencies was done using a Michelson interferometer and demultiplexing with a 16 channel American Wire Gauge (AWG), demonstrating a theoretical 16 channel sensor system.

Wang Jin-Yu el al. in 2007 [14] demonstrated a new DFB – FL hydrophone incorporated by a Mach Zehnder Interferometer (MZI) experimental setup. In the unbalanced MZI, a beam of light is divided into two beams with the help of a directional coupler, they are then recombined at another directional coupler, the detector has two optical outputs. One arm of the MZI has a 50 m imbalance coil wrapped directly on a mandrel and a PZT phase modulator while the other is attached with the output and the input of the interferometer. Inside the MZI, the wavelength shift of the DFB-FL induced by acoustic pressure is changed into the phase shift of the carrier signal which was then sent to an oscillograph. A loudspeaker driven sinusoidally at 1.5 KHz was used to give the DFB-FL a standard single frequency signal, placed approximately 60 mm above DFB-FL. Its response was recorded. Then, a piezoelectric sensor without packaging was used. No signals were obtained when the loudspeaker was placed above it even after using filter and amplification. So the loudspeaker was placed directly on the PZT sensor, and the response was recorded. The frequency spectrum of the DFB-FL and the PZT detector was plotted after fast fourier transform. It was found that the bare DFB-FL was considerably more sensitive than the PZT sensor, the former could receive signals 60mm far from it, but the latter couldn't. Hence, this paper showed that the bare DFB fiber laser hydrophone is considerably more sensitive as compared to the piezoelectric hydrophone to detect and reflect weak acoustic signals.

Though the DFB –FL hydrophone seems a promising alternative to it's piezoelectric counterpart, it does have a potential problem. The more sensitive designs of the hydrophone are more fragile, making them highly prone to damages by means of high hydrostatic pressure, meaning we must trade sensitivity for higher hydrostatic pressure stability. The process of achieving this is known as pressure compensation. One pivotal study in overcoming this limitation was done by S. Goodman et al in 2008 [15]. Their work presented the first pressure compensated DFB – FL hydrophone. They used a compliant air-filled vessel attached to the hydrophone through a pipe to let the air pass between them. The pipe used to connect the bladder and the hydrophone was used as a low pass acoustic filter so that only pressure fluctuations (changing hydrostatic pressure) of low frequency could enter the hydrophone. Since the hydrophone was much less compliant than the bladder, only the bladder would undergo volume change with changing pressure, and there would be minimal deformation of the hydrophone. Experiments indicated that a 90mm long pipe with diameter 350mm was optimal for obtaining the desired low cut-off frequency, while the hydrophone volume was kept at 700mm^3. With filtering, the response of the hydrophone began rolling off at approximately 20 Hz indicating the possibility of achieving pressure compensation. The results of the measured pressure sensitivity in air between filtered and unfiltered hydrophone was observed and compared with the pressure sensitivity of the hydrophone between water (6 m deep). Both the results seemed almost identical, as was expected. Thus, the hydrophone was found to be hydrostatic pressure insensitive up to a depth of 6m in water. Additionally, they reported a pressure compensation of up to 25m depth during tests in sea.

Another attempt at sensitivity enhancement by means of coating was reported by Unnikrishnan Kuttan Chandrika et al. in 2011 [16]. They used Erbium – Ytterbium fibers on which grating of 3.5mm were written. By setting a quarter wavelength between the two gratings, they were able to create a phase shift of π. To protect the gratings from mechanical fracture, a UV curable resin was used to coat the fiber laser. Once the fabrication of the hydrophone was done, measurements were made on coated and uncoated DFB-FL hydrophone. Three different coating arrangements of the fiber laser hydrophone were investigated in the study viz. resin coated, a DFB-FL packaged in an air-backed Teflon shell and a fluid filled DFB - FL. Results showed that the coating by air backed-teflon gave a sensitivity increment of 15 to 20 dB as compared to the other two coating configurations over a frequency range from 2 to 10 kHz. A Finite Element Analysis (FEA) was also carried out and showed reasonable agreement with the experimentally obtained sensitivity.

In 2012, Y. L'eguillon et al [17] proposed a multiplexed array of 12 DFB – fiber lasers for the first time on a single fibre, separated by just 100 GHz (0.8 nm) in the C-band. A 200mW laser diode operating at 1480nm was used to pump the 12 lasers. Each fiber laser, developed specifically for serial multiplexing, was designed to exhibit low lasing threshold, usually between 1 and 2 mW, low frequency noise and very low intensity noise. The lasers, after having traversed through a long lead fibre (up to 10 km) were pumped by a wavelength division multiplexer (WDM). The acoustic pressure was then converted into a frequency modulation of the lasing frequency of the laser through strain transfer to the cavity, then into a phase shift using an interferometer. The outputs of all the hydrophones were separated by the DWDM (dense wavelength division multiplexer) and then read by very low noise demodulation system using a heterodyne method. Experimental results indicated the feasibility of reaching a total loss/device of around 0.8 dB, pointing the possibility of driving 19 DFB FLs. Reducing this number to 0.6 dB and improving the quality of splices could further lead to an array of 32 DFB – FLs.

Scott Foster et al. in another paper in 2014 [18], demonstrated an 8 element DFB FL hydrophone array, positioned on the south coast of Australia 33m deep seabed for field testing. It marked the first time that a fiber laser hydrophone was successfully used to measure the sea state zero (SS0) sensitivity. The system contained very few metallic components as well as no outboard electronics which made it extremely compact and light. The system was telemetered through a 4km long lead cable, however, the trials vessel RV Ngerin was fastened at a distance of only 400m from the location of sensor array. During the experiment, all the hydrophones were found to be fully functional throughout the trial except hydrophone 5 which failed during deployment. The results obtained demonstrated excellent agreement over the full bandwidth of the projector (500 Hz-KHz). Moreover, it was found that the system exhibited high bandwidth (5 kHz), uniform response, consistent processing gain, exceptional dynamic range and the first field demonstration of SSO (Single-Sign On) sensitivity in case of an FL hydrophone.

In 2017, Ming Li et al [19] reported another 8 element multiplexed distributed feedback fiber laser hydrophone but with improved sensitivity through sensitivity enhancement packaging. The core component of the hydrophone was a low-noise DFB fiber laser, while polyurethane was used for the sensitization package of the fibre laser. In order to demodulate the signal, two different PGC demodulation [20] schemes were deployed. For pumping the fiber laser, a 1480 nm semiconductor laser was used. A 2.4m arm length Michelson interferometer was used for converting the laser optical signal into phase signal. It was found that the sensitization packaging significantly improved the hydrophone performance, resulting in a background noise of 10^{-5} pm within the frequency range 10 Hz – 1 kHz, with the noise spectral density [21] being 2.6 X 10^{-7} pm/√Hz (32.5 dB/√Hz).

Conclusion

Fiber laser based hydrophones are a new approach which could be used as a better alternative in place of conventional piezo-electric hydrophones for thin-line towed array applications. This paper presented a brief overview of the recent key developments in fiber laser hydrophones since the demonstration of first DFB – fiber laser in 1994. Some of the most significant advancements in the fiber laser hydrophone technology have been discussed, while the areas where improvements in developing new devices has to been seen have been highlighted. Additionally, how taking various measures such as compliant coating, pressure compensation, varying the doping in the fiber and mechanical support result in enhanced sensitivity of the hydrophone have also been discussed.

Over the past 25 years, there have been many demonstrations of fibre optics sensors for military sonar applications by many navies around the world [22] [23]. More recently, there have been substantial efforts in the application of fiber optic hydrophones in commercial gas and oil research as well as homeland security applications [24]. Different optical architectures have been developed for each of these areas, constituting a good case study on what facets of a particular application affects the optical architecture.

To enhance the performance of the existing technology, the use of high performance materials in construction of the sensor can be considered. Other ingenious techniques and methods enabling strain sensitivity enhancements without impacting sensor's frequency response characteristics also present room for exploration. By employing a fibre laser with low noise in construction, the performance of the laser sensor could further be enhanced and could lead to a more compact sensor. A low noise fibre laser will also enable us to use fill materials within the sensor chambers. Preliminary simulation studies have shown that liquid filling the sensor with materials having lower acoustic impedance than water can lead to a more compact sensor but at the cost of acoustic sensitivity. In addition to meeting high performance requirements, DFB – FL hydrophone also improves efficiency and reliability, and lower system cost. As a result, DFB – FL hydrophone will continue to play a vital role in fiber optic based sensing devices.

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