Development of a High Sensitivity DFB Fibre Laser Hydrophone – Work in Progress at National University of Singapore

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Abstract—Over the last three decades, extensive research has been carried out towards the development of fibre optic hydrophones. The initial designs focused on strain sensitivity enhancements through coatings and coiling long fibres on compliant mandrels. With the advent of fibre Bragg gratings and fibre lasers with ultra high sensitivity to strain, the interest has shifted towards employing these technologies in underwater acoustic sensing. In this work, we present the results from on-going development of Distributed Feedback Fibre Laser (DFB-FL) hydrophones at the Acoustic Research Laboratory (ARL), National University of Singapore in collaboration with Institute of Infocomm Research (I2R) under A*STAR (Science and Technology Agency for Research), Singapore. We also compare the sensitivities of Fibre Optic Hydrophones (FOH) encapsulated in three different configurations and present the results from Finite Element Analysis (FEA) and modelling. It is seen that an air-backed Teflon encapsulation provides a sensitivity enhancement as high as 15 dB from resin moulded one

***Index Terms*— Fibre Optic Hydrophone, DFB Fibre Laser, Phase Demodulation**

1. Introduction

DFB-FL based hydrophone designs have been gaining momentum recently owing to their high sensitivity, narrowband operation and also due ease of multiplexing several sensors on a single fibre resulting in a hydrophone array [1-4]. Though there are many claims on the performance of these hydrophones both in the lab and field tests, there are no off the shelf product yet that can be readily purchased and used. Also a one to one comparison with conventional piezo-ceramic based hydrophones in the field is also not available to benchmark the performance against conventional acoustic sensing technologies. Papers published have limited test results made available. There are also claims that a coating on the fibre can improve the performance, but at times these coatings could damage the grating structure rendering them useless [3]. In DFB-FL hydrophone, a Fabry-Perot laser cavity is formed by a $\pi/2$ shift in the Bragg grating written on an erbium-Ytterbium doped optical fibre. As the resonance cavity is maintained at $\lambda/4$, DFB lasers can achieve single mode operation that generates a very narrowband laser at a frequency centred at the stop band of the Bragg grating. The wavelength λ of the fiber laser depends on Bragg grating pitch and refractive index of the fiber. Any modification of these properties by strain, stress or temperature will result in corresponding variation in the emission wavelength. In the current design of Fibre optic hydrophone (FOH), the wavelength changes caused by acoustic waves are converted to corresponding phase changes in a Mach-Zehnder interferometer of 150 meter optical path difference (OPD). A PGC demodulation scheme is employed to retrieve the phase changes introduced due to the dynamic pressure fluctuation in an acoustic signal. In this paper we discuss some of the results obtained and problems that we faced while evaluating the DFB-FL hydrophone performance. We also noticed that choosing the right modulation frequency for the phase modulator in the demodulation chain is very important when characterising the FOH. Three different encapsulations and their effects on sensitivity of the hydrophone have been discussed. A preliminary FEA has been carried out on the structure with a view to predict the sensitivity and the results have been compared with the experimental data.

2. DFB-FL Hydrophone Construction and its Optical Characteristics

A few prototypes of DFB-FL hydrophones were constructed by I2R in their fabrication facility. Gratings of 3.5 cm active length were written into an Erbium -Ytterbium doped fibre using UV laser and employing the phase mask approach. A phase shift of π was created by introducing a $\lambda/4$ cavity between two gratings near the centre. To optimize the power output to one end of the fibre, this phase shift was offset by about 2cm towards the right from the left most grating. The bare fibre laser was then coated with a UV curable resin to protect the gratings from mechanical fracture. It was then baked in an oven for an hour at 100°C to stabilize the centre wavelength of operation (which in this case was 1552 nm). The overall diameter of the DFB-FL was only 250 µm. One end of the fibre was then spliced on to a single mode general-purpose telecommunication fibre. The properties such as bandwidth, intensity and phase noise were measured and were found to be as good as any other DFB fibre laser systems. The relaxation oscillation frequency of the fibre laser was found to be 684 kHz.

3. Acoustic Performance Evaluation

Once the optical hydrophone was fabricated, the next step was to evaluate its performance in the lab followed by some measurements in the sea. Measurements were carried out on both coated and uncoated DFB-FL hydrophone. Three different configurations of the DFB-FL hydrophones were evaluated in the present study viz. resin coated, DFB FL in a fluid filled tube and a DFB-FL packaged in an air-backed Teflon shell with provision for adjusting the pretension (see Figure 1). The experimental setup employed and the results of measurements are given in the following sections.

3.1 Experimental Set-up

The experimental set up used to evaluate the acoustic characteristic of the DFB-FL hydrophone is shown in Figure 2. The Phase demodulator employed a Phase Generated Carrier (PGC) demodulation technique and the phase changes resulting from the acoustic pressure variations were computed using arc tangent operation [5]. The modulating frequency for the phase modulator inside Mach-Zhender Interferometer (MZI) was adjusted prior to each measurement so as to ensure the linear operating region, which otherwise generated harmonics and spurious responses. Correct choice of modulating frequency was important to ensure the performance of FOH and a frequency of 50 kHz was found to be optimum in our setup. The performance of the FOH was compared against a standard hydrophone B&K 8104. The transmitter employed was B&K 8105 transducer.

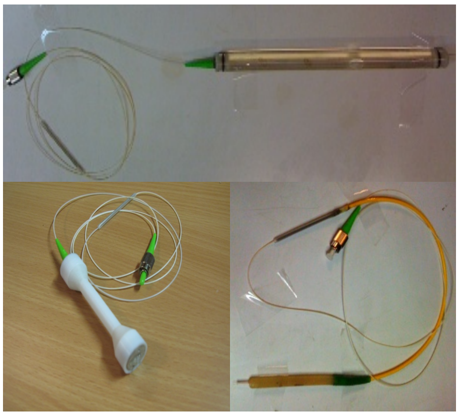

Figure 1 DFB-FL hydrophones with 3 different encapsulations: fluid filled (top), air backed Teflon (bottom left) and resin moulded (bottom right)

3.2 Results from Measurements

The DFB-FL hydrophones were encapsulated before putting them to test. The encapsulations serve two purposes. Firstly, it physically isolates the sensor from seawater and secondly it enhances the sensitivity of hydrophone [3]. Three different encapsulations were tried out. In the first case the fibre was tensioned and housed inside a fluid filled Perspex tube. In the second case the whole active area was moulded with a room temperature curing resin (Poly 74-30 RTV series polymer distributed by Polymer Technologies Pte Ltd, Singapore) and in the third case a special air-backed Teflon housing was used to increase the sensitivity. The photographs of the three different hydrophones are shown in Figure 1.

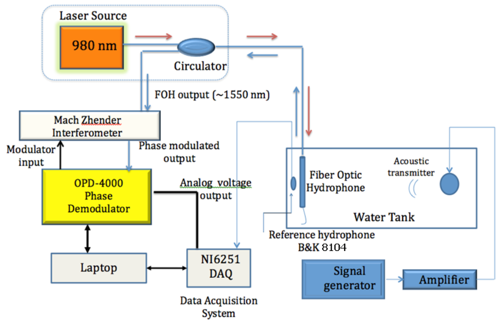

Figure 2 Experimental setup for measuring the sensitivity of DFB-FL hydrophone

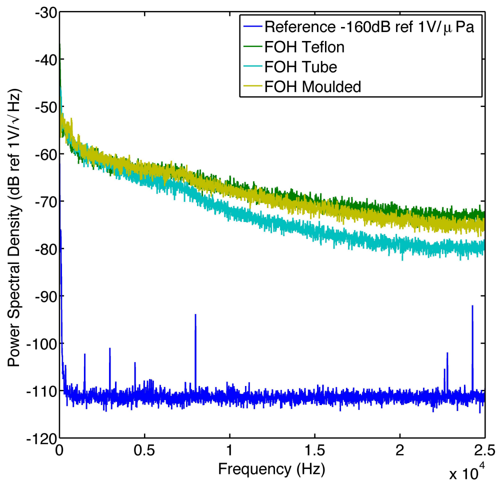

Figure 3 comparison of background noise level as measured by the DFB-FL hydrophone and a conventional hydrophone in the ARL water tank.

Figure 3 shows a comparison of the background noise levels between the optical hydrophones with different encapsulations and the reference hydrophone as measured in the acoustic tank. It is clear that the background noise level measured by the DFB-FL hydrophone is way too high compared to that of the conventional piezo-ceramic hydrophones. The exact reason for this high noise level has not been identified, but is believed to be from the intrinsic noise of the fibre laser itself amplified by the OPD in the interferometer. It was also observed that the proper selection of high enough PGC modulation frequency is necessary for achieving spurious free (Aliasing of phase changes from FDB-FL) output from the FOH. This modulation frequency is given in equation (1) where, η is the acoustic sensitivity, Φ_e is slow varying phase change caused due to environmental factors Φ_{FL} is the phase noise from the DFB-FL and P is the acoustic signal.

$$f_m > \frac{1}{\pi}\left(\eta\,\frac{dP}{dt} + \frac{d\phi_e}{dt} + \frac{d\phi_{FL}}{dt}\right) \; where\; \eta = \frac{d\Phi}{dP} \qquad (1)$$

Figure 4 shows the comparison between the sensitivities of the DFB-FL hydrophones with different encapsulations. The sensitivity value will depend on factors like the OPD in the interferometer, sensitivity of phase demodulator's electronic gain etc. The sensitivity values reported in this paper correspond to an OPD of 150 m, and demodulator sensitivity of 2V/radians. It can be seen that the air-backed Teflon housing has provided a sensitivity enhancement of 15 to 20 dB compared to the other two forms of encapsulations. Since the fibre is only supported at the two ends compared to a full moulding, there is less risk of damaging the gratings and hence the sensor. The fibre can be kept under a required pre-tension by slightly turning the terminating screw at one end. The impact of pre-tensioning on the fibre sensitivity is being explored.

A typical plot from field measurements at 9 kHz for the three samples is given in Figure 5. Note that here all three sensors have been scaled to give a sensitivity of -160 dB ref 1V/µPa. The performance improvement of the DFB-FL with air-backed Teflon housing is evident.

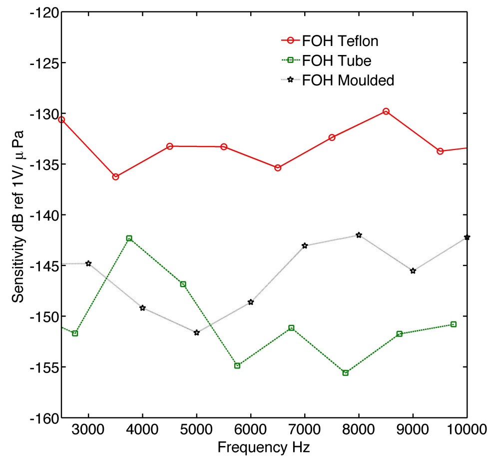

Figure 4 Comparison of sensitivities of the DFB-FL hydrophone with different encapsulations

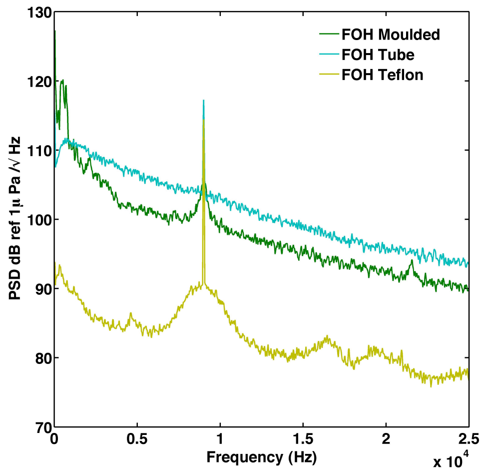

Figure 5 Field measurement results for sensitivities of three FOH hydrophones. The sensitivities have been scaled for a value of -160 dB ref 1V/µPa

4. Finite Element Analysis

Finite Element Analysis (FEA) was carried out to optimize the acoustic sensitivity of the DFB-FL hydrophone. The sensitivity values obtained from the FEA were used to simulate the FOH output and to estimate the expected sensitivity of fibre optic hydrophone (FOH) configurations.

The sensors were tested in an acoustic tank over frequency range of 2-10 kHz and a fairly flat frequency response is observed. Figure 6 compares the experimental results with the simulated results obtained using sensitivity values estimated from FEA. The Teflon shell packaging of the sensor showed a 15 dB improvement in sensitivity compared to the DFB FL packaged in a fluid filled tube. Although the FEA showed a higher sensitivity at lower frequency range due to a natural mode, it was not evident in the experimental results.

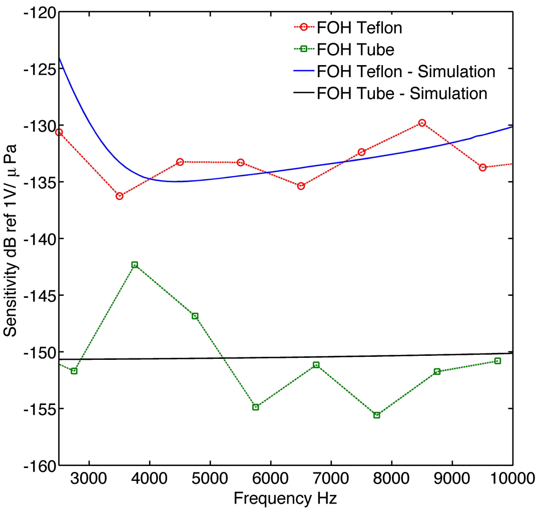

Figure 6 Comparison of sensitivity – experimental and FEA results

5. Conclusions

We have compared the sensitivities of DFB-FL hyrophone encapsulated in 3 different configurations and found that an air-backed teflon packaging can improve the sensitivity by 15 to 20 dB over a band of frequncies from 2 to 10 kHz. The FEA analysis carried out showed reasonable agreement with the experimentally observed sensitivity. It has been observed that the noise floor of the current design is pretty high. We are currently investigating the reasons for high noise floor and will be followed by techniques to reduce it.

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