Fiber Laser Sensor Hydrophone Performance

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Abstract- **Distributed feedback fiber lasers (DFB-FL) offer potential as a new generation of sensing devices that are inherently small diameter, very sensitive and which can be interrogated over long distances over extremely thin lead in cables. They also have the advantage of requiring minimal or no electronics and thus have the potential to be very robust and reliable.**

Thales Australia, in collaboration with Defence Science and Technology Organization - Maritime Operations Division, has undertaken the development of a sea bed hydrophone array using DFB-FL hydrophones as the sensing elements.

This paper briefly discusses the theory of operation of the DFB laser and the options for using the DFB-FL as the sensing element in hydrophones. The advantages and disadvantages of various topologies, problems in assembly and measurement solutions are discussed with an overview of the optical processing system.

I. Introduction

Distributed feedback fiber lasers (DFB FL) are extremely promising devices for use in sensor applications due to their sensitivity to extremely small strains in the sub pico-strain range. This makes them applicable for use as acoustic sensors. Their ability to produce single frequency outputs which are suitable for wavelength division multiplexing [1, 2], may be exploited to build sensor arrays. They also have low relative intensity noise (RIN) and phase noise (PN) [3]. They have been proposed for microphones [4] and hydrophones [2]. However, because of their extreme sensitivity to all perturbations [5], producing a high-fidelity, wide-bandwidth acoustic response, free from parasitic contamination, presents a formidable technical challenge.

II. Background

DFB FLs are formed by doping a fiber with Erbium which will fluoresce when stimulated by laser light of either 980 nm or 1480 nm. Laser action ensues if the erbium section resides in a resonant structure with a multiple of π phase change area near the center. The resonant structure is written onto the fiber using the interference pattern of crossed UV lasers that cause a photo-induced periodic modulation of the refractive index of an optical waveguide's core at the laser characteristic wavelength. The structure gives a characteristic transmission spectra as shown in Fig 1 where the well formed laser can be seen in the very deep and very narrow (100pm) well created by the Bragg gratings.

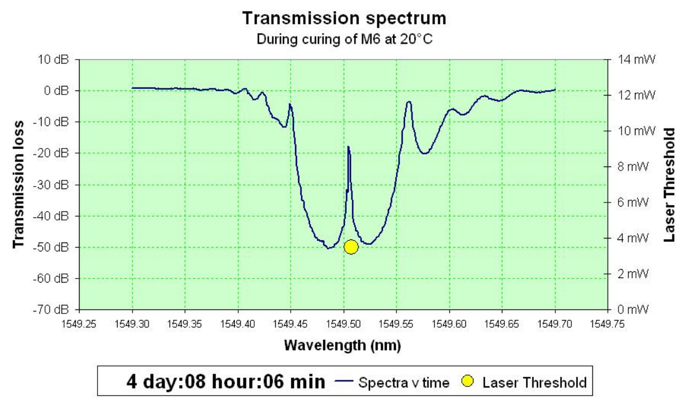

Figure 1. Transmission specta of DFB-FL showing a Bragg grating well >50dB deep and a single mode laser at 1549.51 nm wavelength. The yellow dot indictes the laser threshold and wavelength

The inherent wavelength strain sensitivity of the DFB FL is 1.24 pm/microstrain, which corresponds to a frequency sensitivity of 155 MHz/microstrain.

The laser noise is reported as 10 Hz/√Hz at 10 kHz rising to 180 Hz/√Hz at 10 Hz [6, 7]. In order for the system noise to be below Sea State 0 over the 10 Hz to 3 kHz operating range the induced strain on BFB FL needs to be greater than 1.5 nε/Pa, where nε is 10^{-9} strain. This leads to an overall sensor sensitivity of about 110 dB re 1Hz/Pa (or in familiar underwater acoustic units -10 dB re 1Hz/μPa).

Thus the sensitivity limit for detection at 1000 Hz is about 160 μPa/√Hz or strains of 0.3 pε/√Hz, which on a 50 mm laser

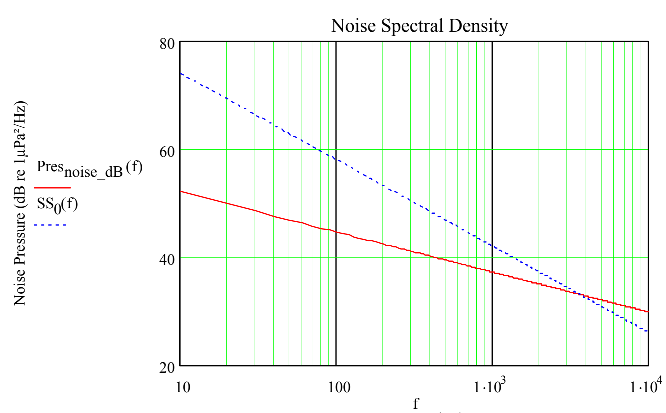

Figure 2. Equivalent noise pressure spectral density of DFB-FL compared to Sea State 0

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corresponds to a wavelength shift of 0.3 fm or a frequency shift of 46 Hz (in the light carrier frequency of 196 THz).

III. Program

Initial studies were on several variants of mechanical hydrophones employing a 4 point bending beam to supply the strain to the fiber. Controlling residual strains due to part alignment and bonding agent shrinkage proved extremely difficult and there were many failures, some seemingly at random. DSTO have managed to perfect this approach using micro-machined silicon components.

A very sensitive test set up was established to measure the transmission spectra during hydrophone assembly as well as monitor up to 3 lasers simultaneously at regular time intervals. In this way the long term behaviour of the curing shrinkage of various epoxies and the finite strains obtained with "zero" shrink UV cured bonding systems could be monitored as shown in Fig 4 and Fig 5.

A temperature controlled acoustic test box was designed to allow the sensitivity of the hydrophones to be monitored versus frequency, from 10's of hertz to a few kilohertz, usually 500Hz, and at temperatures from 10°C to 30°C, covering the usual hydrophone operating conditions.

In addition to the flexible bean design an electro-optic hydrophone design was developed. This design offers the future advantage of being able to group hydrophones in a towed array configuration for the cancellation of flow noise and longitudinal bulge waves. This means that the optical channel count can be reduced by a factor of 16 or more, resulting in a very much simplified dry end receiver hardware.

The electro-optical hydrophone consists of a high sensitivity hydrophone coupled to a piezoelectric fiber stretching strain cell. The effects of static water pressure can be easily negated by incorporating a high value resistor to act as a high pass filter. By paying particular attention to materials selection and fabrication techniques the strain cells can be engineered to give excellent isolation from pressure and low sensitivity to extraneous vibration and noise.

The equivalent circuit of the electro-optic hydrophone is shown below.

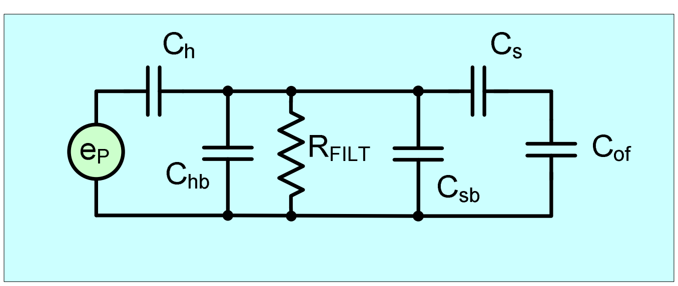

Figure 3. Equivalent circuit of the hydrophone and straincell at low f4requency, ignoring losses, but including filter resistor

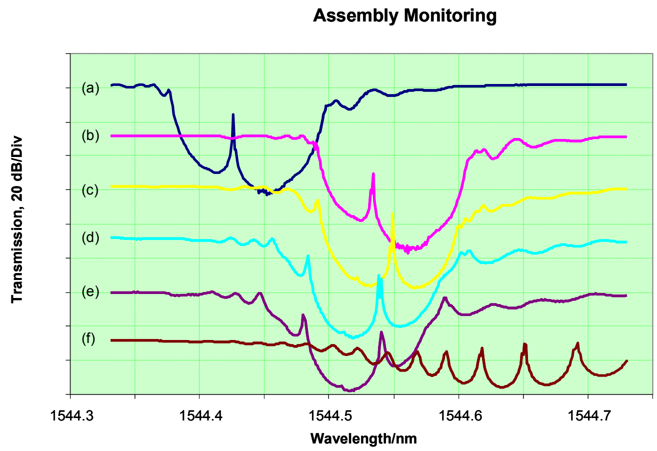

Figure 4. DFB-FL transmission spectra of (a) bare laser on bench, (b) 10 gram preload plus uncured epoxy, (c) after 12hrs cure at room temperature, (d) preload removed after 36 hrs, (e) after 72 hrs cure and (f) after second bonding operation on strain cell

Where e_p is the pressure induced voltage, C_h is the equivalent capacitance of the hydrophone compliance, C_{hB} is the hydrophone blocked capacitance, C_{sB} is the strain cell blocked capacitance, C_s is the equivalent capacitance of the strain cell compliance, C_{of} is the equivalent capacitance of the optical fiber compliance and R_{FILT} is a very high value resistor to give a low frequency cut off of a few hertz.

Maximum strain occurs in the optical fiber when $C_{of} = C_s$ and $C_{hB} = C_{sB}$. This balance cannot be met easily because of the extreme compliance of the fiber compared with monolithic PZT and the ability to fabricate and assemble items in the sub-millimeter scale.

Piezoelectric single crystals have a clear advantage in this design. They have very high piezoelectric coupling coefficients, exceeding 0.9, and are inherently very compliant, being

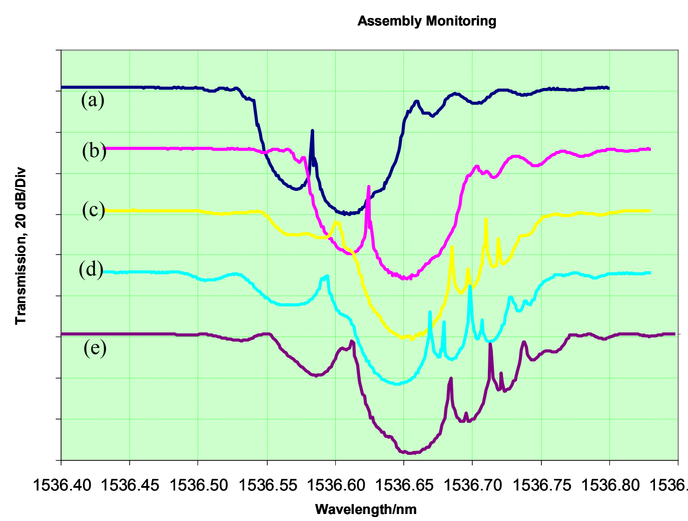

Figure 5. DFB-FL transmission spectra of (a) bare laser, (b) 10 gram preload plus liquid uncured adhesive, (c) UV cured adhesive, (d) 1 day after cure and (e) 5 days after cure

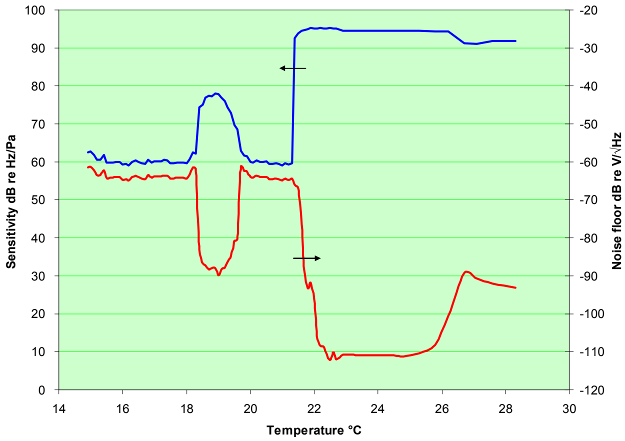

Figure 6. Early Straincell Sensitivity and Noise Floor versus temperature

4 to 6 times the compliance of PZT, so that it is easier to match the compliance to the fiber.

IV. Results Summary

Fig 4 shows the effect of epoxy curing shrinkage on a DFB-FL where after 12 hrs curing the Bragg well and laser structure appear stable although there is the sign of a second mode appearing at 1544.49 nm. This becomes more pronounced after the removal of the preload. By 72 hours there is definite bi-modal behaviour with 2 modes in the well. When the top half of the strain cell was bonded and cured the structure completely washed out giving the comb structure in (f).

Fig 5 shows that even “zero” shrinkage UV cured systems place considerable strains on the fiber during curing. In this case the curing of the epoxy induced considerable variable strain on the grating as evidenced by the splitting of the laser mode into 4 separate and unstable modes, with the 2 minor modes probably due to polarization effects.

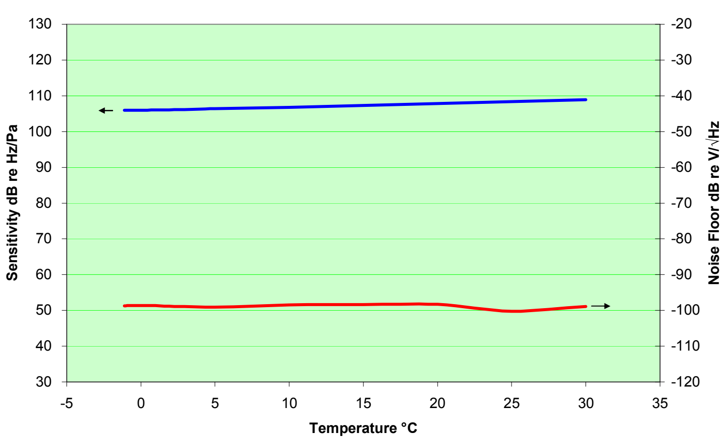

Figure 7. Later build single crystal straincell showing stable behaviour with temperature. Note different scale compared to Fig6

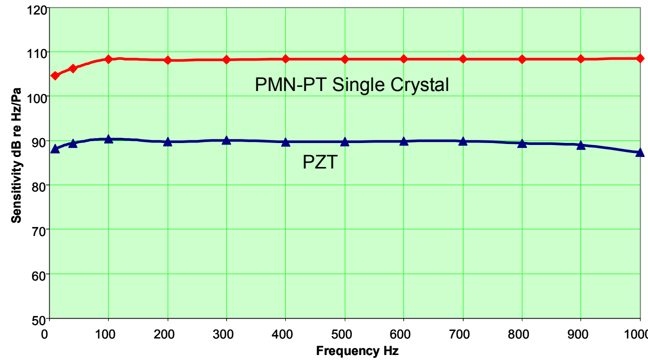

Figure 8. Performance difference between PMN-PT Single Crystal Hydrophone and standard PZT Hydrophone showing 18 dB improvement

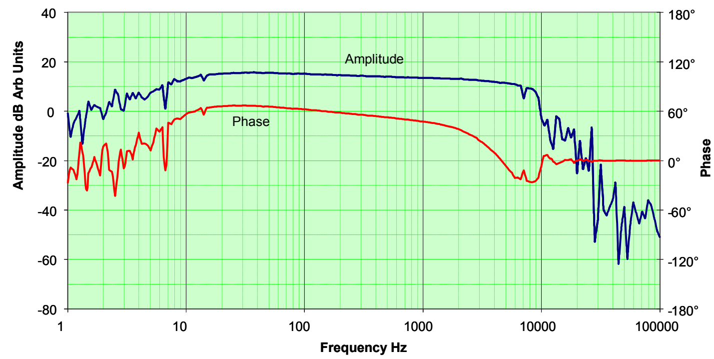

Figure 9. Frequecny response of PMN-PT single Crystal Hydrophone Strain cell

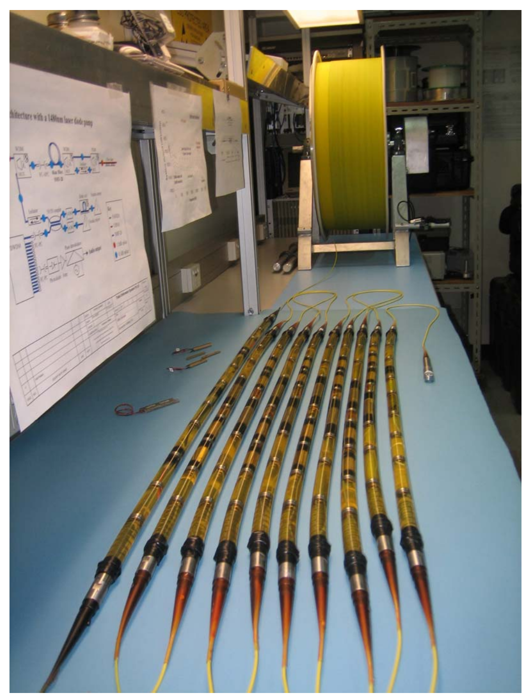

Figure 10. Eight channel hydrophone array, plus 2 optical management modules on the bench with 2 km lead in fiber on drum in background

Strains induced by differential thermal expansion were measured in the final hydrophone strain cell combinations. Using the temperature controlled acoustic box, sensitivity and noise floor were measured at 500 Hz. Figure 6 shows the operating temperature band of a typical hydrophone going from 21°C to 26°C, a temperature range too narrow for a sea deployed product. This shows that the structure is stable around the adhesive curing temperature of 22°C to 23°C. Of interest is the behavior around 19°C where another less sensitive and noisier laser becomes stable for about one degree. By a judicious selection of materials and construction techniques a hydrophone that is stable from -2°C to 30°C was achieved. Its performance is shown in Figure 7.

An array of eight hydrophones shown in Fig 10 was manufactured and trialed in Jervis Bay at HMAS Creswell. A commercial off the shelf data acquisition and sonar display was used to beam form the array. A rigid hull inflatable boat (RHIB) was used as a noise source for the validation trials. The phase demodulator in the receiver section has a low pass 3 kHz filter and even though most of the RHIB radiated noise is above this frequency, adequate detection was achieved.

After the trial an experimental hydrophone strain cell combination was assembled using PZN-PT[1] single crystals in both. As expected the single crystals gave an increase in performance of 18 dB. The system response was obtained by injecting a small signal into the line connecting the hydrophone to the strain cell. It showed that a very flat hydrophone response could be obtained up to 10 kHz. There is a small structural hydrophone resonance at 8 kHz which can easily be damped out.

V. CONCLUSIONS

The use of DFB-FL in a practical sonar system has been demonstrated for the first time. Technological issues dealing with stable performance of the devices with manufacturing environment, adhesive used, temperature and pressure dependence have been resolved. The use of single crystals to gain a marked improvement in performance has been demonstrated.

ACKNOWLEDGMENTS

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