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Hydrophone design utilising Spectral-Shifts from Strain-Optic Interactions

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SUMMARY

Alternative technologies for the production of hydrophones using optical sensing are reviewed with respect to performance and manufacturability. Sensor designs utilising spectral shifts as a result of strain-optic interactions are uncommon, and we believe they merit further investigation as geophysical sensors due to good sensitivity and relative ease of manufacture Specifically, a Long Period Fibre Grating placed onto a mandrel appears to be as promising candidate as a future compact hydrophone sensor.

A mathematical model has been created for a compliant mandrel coupled with a Long Period Fibre Grating inscribed into plastic fibre. The modelling results indicate that such a sensor should provide a sensor of minimal size, with desirable sensitivity characteristics. Compared to the Rayleigh based optical fibre sensors being evaluated in geophysical applications currently the modelled sensor is predicted to have significantly greater sensitivity, with the mandrel acting as a mechanical amplifier. The main limitation of the spectral shift method is the number of sensors that can be multiplexed on a single fibre. However, a combination of time-domain and wavelength domain multiplexing could significantly increase the number of sensors per fibre to usable numbers for geophysical applications.

Key words: hydrophone, instrumentation, design, Long Period Fibre Grating.

INTRODUCTION

Fibre-Optic Hydrophones come in a variety of designs and arrays, utilising different multiplexing schemes that to achieve sufficiently high sensitivity, interferometric techniques measuring phase change must be used (Yu and Yin, 2002, p. 425). We present an alternative pressure sensing method; in particular a method where strain applied on a fibre causes spectral shifts via a Long Period Fibre Grating (LPFG). A significant problem with present fibre-based sensors is that they have limited signal-to-noise compared with existing geophones and hydrophones. One means to assist with this issue is to use mechanical amplification of the strains produced by the elastic stress field by winding the fibre onto a mandrel. The mandrel amplifies the effective strain on the fibre and can also change the fibre from a uniaxial sensor to a hydrophone. Thus, significant gains in sensitivity may be obtained at the expense of a fully distributed sensing system.

Comparison of Fibre-Optic Seismic sensing solutions

Sensing phase shifts in the optical path is the means most sensors operate, where a change in the length on one of two arms of an interferometer creates a detectable change of phase corresponding to acceleration of a mass or change in pressure. Such a choice allows Time-Domain-Multiplexing (TDM), plus it is fairly easy to implement Wave-Division, or Frequency-Domain Multiplexing (WDM or FDM), to create large arrays needed for 3D/4D surveys and marine seismic. Despite almost 40 years of research in this field, starting with Shajenko *et al.* (1978), these optical phase sensing solutions have only recently begun to compete with piezoelectric hydrophones (Yu and Yin, 2002, p. 449). Common phase sensing designs include Mach–Zehnder and Michelson interferometers, which require lengthy sensing and reference arms; Fabry-Perot interferometers, which are in contrast very compact, but suffer from small dynamic range; and Sagnac loop interferometers, which offer various noise reducing advantages, at the cost of being difficult to multiplex. WDM is usually implemented using Fibre Bragg Gratings (FBGs) in the sensing arms to create narrow notches in the optical spectrum defining individual sensors, before the light is mixed with the reference arm to create amplitude fluctuations in this mixed signal, that correspond to the change in phase. More recent ideas involve Rayleigh backscattering Optical Time Domain Reflectometry (OTDR) as a distributed sensing mechanism relaying changes in phase at any points in the cable over time (Lu *et al.*, 2010). However, even with specialised wavelet de-noising methods by Qin *et al.* (2012), this technology is still developing due to poor noise characteristics.

Another, less common, means to measure strain on a fibre is by measuring spectral shifts in the interrogating optical signal. An example of strain-optical shift is the FBG, which creates a back reflection at a designed wavelength, and this wavelength actually shifts very slightly depending on the strain that is on that fibre. FBGs inscriptions are chosen to define WDM, because this shift is very small, but there are other ways to see strain-optic shifts in a fibre. These include Brillouin, Raman and Rayleigh backscattering Optical Frequency Domain

Reflectometry (OFDR), as well as Long Period Fibre Gratings (LPFGs), which are similar to FBGs with much longer distances between refractive-index contrast inscriptions, i.e. a longer period.

A major drawback for OFDR sensors is that implementing multiplexing for these sensors is difficult since the instrument of measurement is a changing wavelength/frequency so WDM and FDM schemes are not practical. TDM is possible to implement, but it is more challenging get the number of channels (1000's) needed for some 3D/4D surveys. In theory it should be possible to implement Phase-Division Multiplexing (Leonard and Cimini, 1989) since the detection of spectral shifts is often done through a heterodyne, where phase information is preserved by using a balanced heterodyne arrangement (Protopopov, 2009, pg. 45) that measures the relative change in intensity of the two outputs representing signals of π phase difference.

Because of difficulties in implementation, OFDR sensors are not as widely used. Nonetheless, we have chosen to look into the challenges and benefits of building an OFDR sensor because we feel these can be more sensitive and easier to manufacture into the fibre. The most important aspect of such a sensor would be high sensitivity, in terms of wavelength shift per Pascal of pressure. Table 1 illustrates the strain sensitivities of some OFDR sensors examined in literature.

Sensing Mechanism	**Sensitivity (nm/mε)**	**Ref.**
Brillouin backscattering	6.35×10^{-4}	Mizuno *et al.* (2012)
FBG shift as WDM in Fabry-Perot cavity	1.1	Chen *et al.* (2009)
Rayleigh backscattering	~2.0	Froggatt and Moore (1998)
Rayleigh backscattering, tapered	17.17	Wang *et al.* (2012)
LPFG	2.2	James and Tatam (2003)
LPFG, asymmetric grating	7.6	Xiao *et al.* (2006)
LPFG, near turning point (high γ)	30.31	Shu *et al.* (2002)

Table 1. Comparison of strain sensitivities in various OFDR sensors; Large strain sensitivities are desirable as they will determine the magnitude of a wavelength shift due to pressure, hence improve sensitivity characteristics and suppress certain noise sources by giving a spectral measurement more certainty.

All distributed Rayleigh OFDR backscattering devices, tapered or otherwise, use a tuneable laser source (TLS), which can take a significant time to perform a sweep across sufficient wavelengths and process the data (Ding *et al.*, 2013) to be able to examine the vibration state at any point in the cable. Thus, seismic sensor sample rates are difficult to achieve. Research into these sensors is very recent and evolving rapidly. However, since the most sensitive Rayleigh OFDR requires tapered fibre sections, we have concerns about the structural integrity of the fibre and manufacturability of hundreds of sensors. LPFGs appear to be a better option for a hydrophone sensor, since they are robust and require short lengths of fibre, which enables the use of mandrels to further increase sensitivity. In addition, the interference arises not from internal reflections within the fibre-waveguide (e.g. FBG devices), but through changes in the cladding and waveguide coupling. Hence it is easier to manufacture the grating of the sensor into the fibre as the only the cladding/fibre boundary is changed, e.g. by CO2 laser, rather than the entire waveguide section, which is difficult to alter without cutting and resplicing.

The theory for LPFGs is well established by Erdogan (1997a, 1997b); a theoretical model for the construction of a sensor employing these gratings is something that can currently be accomplished, with details on maximising their sensitivity covered by Shu *et al.* (2002), and elaborated in the next section. A novelty of the LPFG is that the active sensing length needs not be very long; thus by utilising a plastic fibre, a very small, and tightly wound, mandrel can be constructed to act as sensor. The use of plastic optic fibre is novel and untried to our knowledge, but it should result in a better match in mandrel and fibre properties for maximising fibre strain versus external stress.

METHOD AND RESULTS

Long Period Fibre Grating Theory

The goal of the theoretical modelling is to provide solutions for the sensitivity characteristics of an arbitrary fibre, wrapped around an arbitrary mandrel. From Shu *et al.* (2002), the key to achieving high LPFG sensitivity, is maximising γ in the following equation:

$$\gamma = \frac{1}{1 - \Lambda \frac{d\Delta \mathrm{n_{eff}}}{d\lambda}}$$

This occurs when the following is satisfied:

$$\frac{1}{\Lambda} = \frac{d\Delta \mathrm{n_{eff}}}{d\lambda}$$

Where Λ is the period of the inscribed grating, λ is the laser frequency, and Δn_{eff} is the difference between the effective refractive indices of the core mode, and any one of the cladding modes described by Erdogan (1997a). Solving this expression requires numerically evaluating Δn_{eff} across a range of equally spaced λ values of interest, and finding what period grating, Λ, is required to solve the equality for each individual cladding mode. For this to be useful, only period gratings, Λ, which result in absorption lines at the laser central frequency, λ, are useful, i.e. λ must equal the following equation (Erdogan , 1997b):

$$\lambda_D = \Delta \mathrm{n_{eff}} \Lambda$$

Where λ_D is the absorption wavelength defined by the LPFG design. The solution $\lambda = \lambda_D$, can be found by interpolating the λ dependence of each mode, and finding a wavelength where γ is maximised. There is a solution for every cladding mode, but only the solutions within the range of wavelengths where the optic fibre has the best propagation characteristics are useful.

With a laser operating at and around a wavelength of interest, the desired period grating, Λ, is found for the cladding mode in question. This allows for the solution of the corresponding coupling strength of the co-propagating core and cladding modes, giving a solution to the required length of the grating thanks to Erdogan (1997b), depending on a choice of grating refractive index contrast. This allows for a complete picture of the absorption spectrum, including the spectral width and strength of the absorption (depth of notch).

To illustrate, Figure 1 is an example of a modelled absorption spectrum, showing the contribution of cladding mode interferences of all modes that affect the given spectrum.

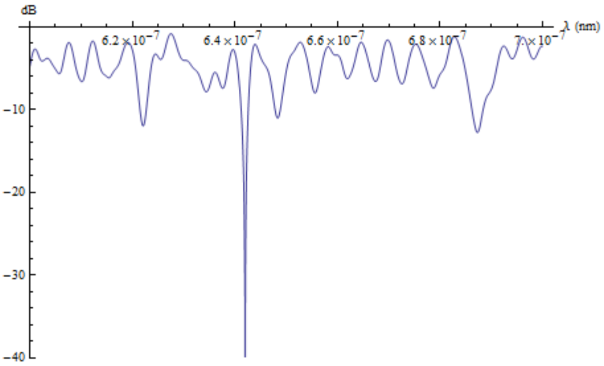

Figure 1. Modelled absorption spectrum for a LPFG, covering spectrum from 600 nm to 700 nm, illustrating a strong absorption at 642 nm, which is approximately 1 nm wide at half maximum.

This particular example of an absorption spectrum models a polymethyl methacrylate (PMMA) step index fibre, ideally coupling mode number 26, with a period grating of 240.5 µm, with a total length of roughly 4.9 cm, yielding a strain-optic sensitivity of about 2200 nm/mε. Careful design allows for the small spectral width and a strong absorption notch in the spectrum, which will grant LPFGs excellent noise characteristics.

Mandrel Design

There are several ways to implement LPFGs as pressure sensors/hydrophones, however, a compliant mandrel offers the most compact configuration. If we aim to construct the most compact sensor possible then the use of tightly bending optical fibre, and highly compliant mandrel material lends itself ideally for this purpose. With PMMA optical fibre the radius of curvature cannot be less than 5 mm. While other, graded-index, optical fibres can bend more tightly, the graded-index structure, carrying multiple core modes, introduces many complexities into the LPFG theory (Su *et al.*, 2006), which requires further analysis and experimental work; although single mode graded-index fibres have been known to have excellent sensitivity characteristics (Ctyroky *et al.*, 2006).

Work by Waagaard (2001) shows that the pressure to acceleration responsiveness of a mandrel is maximised when the length of the mandrel is a certain ratio to the radius, creating ideal mechanical gain. This leads a problem when solving for a helically wound LPFG you are limited to one turn, if your fibre is 4.9 cm long. To overcome this winding of the LPFG will have to involve inactive fibre, to preserve equal contribution of the fibre wrapping to the mandrel stiffness. This is important because when using a small mandrel, it needs to be highly compliant, and as such the wrapping fibre would create a non-negligible contribution to the stiffness of the compliant mandrel.

The current model of the mandrel assumes that the mandrel is made of a polyurethane elastomer as this is often used with conventional hydrophones as a jacket material. Expanding on the work done by Pechstedt and. Jackson (1995), it can be calculated that the frequency shift of the absorption peak is approximately 3 MHz/Pa (or 1 pm/Pa, corresponding to the strain sensitivity of 2200 nm/mε), across a broad range of frequencies relevant to seismic acquisition, with a resonance frequency at about 10 kHz. These numbers are likely be different when this mandrel is prototyped and tested, due to the fact that the resonant frequency calculation relies on the existence of a seismic mass, whereas this treatment assumed no seismic mass, which breaks an assumption in the resonant frequency equation. However, the small size ensures that any resonances will be above several kilohertz, and the well damped nature of a polyurethane mandrel ensures that resonances will not be problematic. A lack of information regarding this aspect in the literature requires the numbers to be resolved experimentally in the future.

Lastly, the spectral model used to generate Figure 1 is incomplete. Bending effects on a wound fibre can create strong birefringence within the fibre, and the resonance peak of interest will split into two separate "modes", described by the polarizations states of light experiencing different refractive indices within the fibre (Block *et al.*, 2006). A further complication is that only silica fibre has been discussed in most literature; and the radii of curvature of less than about 25mm have not been experimentally examined (Allsop *et al.*, 2004). Experiments are needed to understand these effects for bends of tight radius in plastic fibres. Regardless, with careful polarization control, the bending effects could be negated if the polarization of light is at 45 degrees to the bending direction (Wang Y. *et al*, 2007). On the other hand bending effects could also be harnessed to improve sensitivity and as such should be investigated for this possibility. For example, Chiavaioli *et al.* (2013) illustrated external refractive index change sensitivity improvements in specially designed LPFGs, and according to Shu *et al.* (2003) improvements in external refractive index sensitivity are not independent from strain sensitivity as they both vary as a function of γ.

CONCLUSIONS

Strain-optic sensors are a largely unexplored alternative, due to multiplexing research focused on phase-shift sensing instruments. One of the main goals of this extended abstract was to illustrate that strain-optic sensors, in particular Long Period Fibre Gratings, have advantages in size and sensitivity that should not be overlooked

From theory and mathematical modelling, a good understanding of the performance of a Long Period Fibre Grating implemented as a Hydrophone has been constructed. However, there are several important considerations that need to be resolved experimentally concerning implementation with a mandrel, before a prototype can be constructed, due to lack of literature covering certain border-line conditions the model intends to utilise.

In theory the Long Period Fibre Grating can lead to the production of a highly compact hydrophone, which can be utilised in seismic acquisition, including VSP, or marine acquisition. The DET CRC research in downhole sensors envisions that implementation of this sensor is for a future logging while drilling instrument is worth pursuing, thanks to the compact nature of the sensor and its ability to be integrated into coiled tubing drill rigs.

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