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Long Period Grating-based optical fibre sensor for the underwater detection of acoustic waves

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ABSTRACT

In this work, a Long Period Grating (LPG)-based acoustic sensor was designed and evaluated for underwater acoustic pressure measurement. The paper presents the sensing principle and characterization of the device, prior to discussing the results of a series of experiments carried out. The optical sensor was based on a LPG clamped, placed underwater and exposed to acoustic waves generated by an underwater loudspeaker. Its characteristics were measured by varying either the amplitude, the frequency of the acoustic waves, or the distance between the sensor and the acoustic source and the depth of the sensor in the water. The LPG-based sensor was subsequently fully characterized and the results obtained are cross-compared with data obtained from acoustic sensing measurements in air.

1. Introduction

The propagation of sound in water induces alternating pressure waves in the medium and these pressure variations are usually measured by a hydrophone. The first widely used hydrophone was developed by Fessenden in 1912 [1], operating over the frequency range from 500 Hz to 3 kHz and there has been significant interest in the field, especially given the military applications of such devices.

Extensive research has been done since then and this has led to the development of different types of hydrophones, among them the fibre optic hydrophone. This concept was first proposed in 1977 by Bucaro et al. [2] who developed the first optical hydrophone which was based on a coiled multimode optical fibre and an interferrometric read-out system. The wide use of fibre optic hydrophones has been driven mainly by the benefits they offer such as light weight, low cost, limited power budget and high reliability but also their immunity to electromagnetic interference which is very important in this application and is intrinsic to optical fibre sensors. In addition to this, fibre optic based hydrophones are easy to multiplex making it possible to have a large number of sensors on a single fibre, this is ideal for seismic applications for example.

More recent techniques for acoustic sensing using Fibre Bragg Gratings (FBG) written into the optical fibre were proposed first by Webb et al. in 1996 [3]. The system they discussed was used to detect ultrasonic waves of frequency 950 kHz, where the power produced by the ultrasound transducer was up to 30 W. In 1997, Takahashi et al. [4] proposed a FBG-based hydrophone that could detect frequencies of 20 kHz at acoustic pressures over the range from 81 to 140 dB (ref: 1 μPa). The signal detected using the FBGs is typically relatively weak and thus, in order to improve the strain sensitivity to acoustic waves of the sensing element, there was a need to apply a coating to the fibre [5]. Recent work proposed by Moccia et al. in 2011 [6,7] has led to the development of a high sensitivity fibre-coated FBG-based hydrophone, operating at sound pressure levels ranging from 126 to 163 dB (ref: 1 μPa); these sound pressure levels are relatively high.

The technology of optical fibre hydrophones has now progressed to a position where it is used in operational sonar systems [8]. However most of the research carried out thus far has been focused on ultrasound detection. The system proposed in this paper makes use of the bending sensitivity of Long Period Gratings to propose a different technique and due to their high sensitivity, LPGs can be configured to detect sound waves without making use of a coating on the fibre [9]. In addition, the work carried out showed that the minimum detectable sound pressure was found to be 63 dB (ref: 1 μPa) and a linear response was obtained over the range between 82.8 dB and (at least) 112.3 dB (ref: 1 μPa). The experimental set-up thus configured was able to detect low-frequency sound waves of up to 2 kHz and thus operate well within the acoustic range.

2. Underpinning theory of sensor operation

The approach chosen was based around the use of a Long Period Grating (LPG), as such gratings show higher sensitivity in many applications than do the more widely used FBGs [10–13]. The

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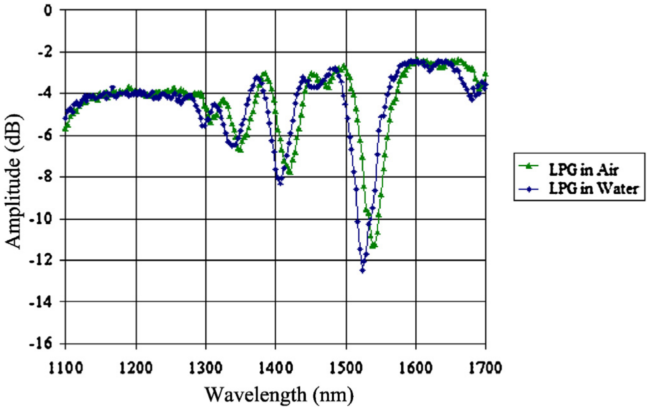

Fig. 1. Optical transmission spectrum of a LPG in air and in water when illuminated by light from a broadband light source. (For interpretation of the references to color in the text, the reader is referred to the web version of the article.)

fabrication of LPGs was first reported by Vengsarkar et al. in 1996 [14], having been achieved by periodically modulating the refractive index of the core of a B-Ge doped optical fibre by exposing it to a beam of intense ultraviolet radiation shone through an amplitude mask. As a result of this irradiation of the fibre, a series of attenuation bands could be observed in the transmission spectrum of the LPG when it was illuminated longitudinally using light from a broadband light source (Ocean Optics LS-1), as shown in Fig. 1. The wavelength of the attenuation bands is dependent upon the mode coupling between the forward-propagating core mode and the co-propagating cladding modes. This can be changed by the influence of different physical parameters such as temperature, strain, bend and refractive index surrounding the fibre. Thus when the LPG is placed in air, there is an effect from the surrounding refractive index being different to that experienced when it is submerged in water. This was used, for example, by Yan et al. in 2011 [15] to measure the water level in a glass tube. The relationship between the attenuation wavelength, λ_i, the grating periodicity, Λ, and the effective refractive index of the core and the cladding is given below:

$$\lambda_i = (n_{eff\ core} - n^{i}_{eff\ cladding})\Lambda \quad (i = 1, 2, \ldots) \tag{2}$$

where $n_{eff\ core}$ and $n^{i}_{eff\ cladding}$ are respectively the effective indices of the core mode and the ith cladding modes.

The refractive index of the medium surrounding the fibre has a direct effect on the propagation properties of the cladding modes in the fibre. Bhatia et al. have formulated the relationship between the wavelength shifts of the attenuation bands as a function of the refractive indices of the core, cladding and surface and this relationship is shown in the following equation:

$$\frac{d\lambda}{dn_{sur}} = \frac{d\lambda}{dn_{m,\,clad}}\,\frac{dn_{m,\,clad}}{dn_{sur}} \tag{3}$$

where n_{sur} is the refractive index surrounding the fibre and $n_{m,clad}$ the refractive index of the mth cladding mode.

As shown in Fig. 1, the change in the refractive index of the surrounding medium (from 1 (air) to 1.33 (water)) causes a distinctive wavelength shift towards the blue region of the attenuation bands of the same LPG, as a result of the changing phase matching conditions between the fibre core and the cladding modes and the degree of shift seen is in good agreement with reported data [16].

3. LPGs in sensor operation

LPGs have been widely used for a range of sensor applications, such as for temperature [17], strain [18], refractive index [16,19] and bending measurements [20]. It is important to consider the effect of bending on LPGs not just for geometrical measurements but because this is the effect used in this work to allow the detection of acoustic waves.

When a LPG is bent, the shift in wavelength of the attenuation bands causes an *increase* in the bandwidth of each attenuation band and a corresponding *decrease* in the band intensity. An explanation to this phenomenon was proposed by Vengsarkar et al. [21] and two phenomena are involved. The first is the bending of the LPG creating a change in the effective refractive index of the cladding, which consequently directly changes the wavelength of the attenuation bands. The second arises from the amount of light that leaks out of the fibre through the cladding-air (or other surrounding material) interface and it is this which is causing a decrease in the level of signal that is transmitted [22].

Another effect that should in some cases be taken into consideration is the split of the attenuation bands when the curvature is increased and this has been investigated by Liu et al. [20,23]. This is caused by the fact that the bending of a fibre causes a loss of symmetry in the spatially degenerate cladding modes and thus these modes in the fibre become non-degenerate causing polarization mode splitting. Subsequently this causes there to be two effective refractive index values satisfying the core/cladding coupling conditions, leading therefore to a resonance band splitting in the LPG spectrum [24]. This effect, however, arises for high levels of curvature. In this work we made sure that the curvature is low so that this effect does not arise.

Utilizing the bending phenomenon described above, a LPG-based sensor system has been created for the detection of acoustic waves in air [9]. The acoustic pressure that is caused by the sound wave induces the bending effect of the LPG and the resonant frequencies captured can be described by a modified elastic string theory.

This work herein has aimed to expand the above research by enhancing the sensor design in order to detect the acoustic pressure under water. In this work, the LPG was placed in a clamp made from Perspex, as shown schematically in Fig. 2, where the choice of the material was made in light of the environment used: the sensor was to be used underwater and thus a material such as Perspex that was unaffected by the water and, for example, did not rust was desirable. The LPG used was of length 6 mm and was placed in the middle of the clamp where the distance between the two clamped fibre ends is 120 mm.

The fact that the LPG is placed underwater causes an additional pressure on the sensor thus it makes it more difficult to calculate a precise quantitative value of the frequencies at which the sensor will detect a sound wave. Thus an empirical study was undertaken in order to understand more fully the effect of the pressure level on the sensor and its influence on the frequency response of the sensor as a function of the water level. It is very difficult to measure precisely the curvature of the LPG in water and thus to model the effect of water on the properties of the LPG and thus the empirical study was carried out.

4. Experimental set-up

The Long Period Grating-based sensor designed in this work for underwater acoustic wave detection is illustrated in Fig. 3, in which the sound emission system used comprises a power amplifier and an underwater loudspeaker controlled by using LabVIEW-based software. The acoustic signal was generated using a Digital Acquisition (DAQ) card in a PC.

The sound detection system was created by using a C-band Amplified Spontaneous Emission (ASE) source (type OLS15C) with an output power of 14.3 dBm, using an LPG chosen to have a period $\Lambda = 400\,\mu$m and length of 6 mm and a standard photodiode for