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Optical Fibre Bragg Gratings for Acoustic Sensors

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ABSTRACT

In this paper, we give a short review of Fibre Bragg Grating (FBG) sensors for the detection of acoustic signals, in particular ultrasound. The primary advantage of FBGs as sensing elements is their spectral encoding of the measurand, which can be either strain or temperature. However, spectral decoding methods cannot be utilized to detect high frequency signals due to their inherent low speed. We review the interrogation method required for the high speed detection of high frequency signals, in addition to discussing the theory behind FBGs as sensors. A number of applications of FBGs will be outlined for these FBG acoustic sensors, including in-vivo biomedical sensing, acoustic hydrophones, non-destructive evaluation and structural health monitoring. In addition to this introduction to the field of FBG acoustic sensing, we also present recent results on the implementation of a novel cost effective detection system. The FBG detection system developed to convert the strain induced spectral shift of the FBG into an intensity modulation is called a Transmit Reflect Detection System (TRDS). The TRDS is an extension to the standard power detection method for FBGs. In conventional power detection schemes, the reflected portion of the incident spectrum is monitored to determine the change in the measurand. In the TRDS, both the transmitted and reflected portions of the input spectrum, from a narrow band light source, are utilised. The optical power of the transmitted and reflected signals are measured via two separate photoreceivers. As the spectral response of the FBG shifts due to the measurand, the transmitted power will increase, and the reflected power will decrease, or vice versa. By differentially amplifying the transmitted and reflected components, the overall signal is increased. This results in improved sensitivity and efficiency of the photonic sensor. We show results for the sensitivity and dynamic resolution of the detection system.

INTRODUCTION

The optical Fibre Bragg Grating (FBG) was first demonstrated by Hill et al. in 1978 [1]. However, it was not until the transverse holographic fabrication method was developed by Meltz et al. [2] that FBGs came into their own. Since then, FBGs have become widespread in optical fibre systems, for both communications and sensing. In addition to the typical advantages of Optical Fibre Sensors (OFS) over conventional sensors, including [3], improved sensitivity, reduced size, reduced weight, immunity to EMI, and electrically neutral,
FBGs also offer additional advantages, versatility, short gauge length, and ease of multiplexing.
These advantages make FBGs ideal for sensing acoustic/ultrasonic signals in specific application areas, such as structural health monitoring. The most significant of these advantages is the ability of the FBG to be sensitive to a number of measurands, while being multiplexed. One FBG in the SHM system can be a strain isolated temperature sensor, while a second can be a temperature insensitive strain sensor, and yet a third can be a SoGel covered corrosion sensor, where the absorption of corrosion by-products induces a strain in the FBG. This means that with a single sensing system almost the required measurands can be monitored.

What follows is a short review of FBG acoustic sensing. The review covers the transduction theory for FBG strain sensing. Then the various passive interrogation methods, which are used to convert the spectral shift of the FBG into an electrical signal. We go on to discuss the major applications of FBG acoustic sensors. These include hydrophones, mechanical vibration sensing (such as acoustic emissions and acousto-ultrasonic sensing), microphones, and biomedical applications.

Following the brief review, we present recent work on the Transmit Reflect Detection Systems (TRDS). We present results for the sensitivity and dynamic resolution of the detection system, along with the transfer function, frequency response, and transient response of the FBG sensor.

THEORY

Fundamental

A FBG [4]-[5] is a spectrally reflective element written into the core of an optical fibre. The FBG is made up of alternating regions of different refractive indices. The difference in refractive indices results in Fresnel reflection at each interface. The regular period of the grating, Λ, results in constructive interference in the reflection at a specific wavelength, called the Bragg wavelength, λ_B. The Bragg wavelength is given as,

$$\lambda_B = 2n\Lambda \quad , \tag{1}$$

where n is the average refractive index of the grating.

Equation 1 indicates that any measurand that causes either a change in the refractive index or grating period can be detected with the FBG. For measuring acoustic and ultrasonic signals, the measurand is applied strain. A change in grating period is a direct result of the applied strain, while the change in refractive is a result of the strain-optic effect.

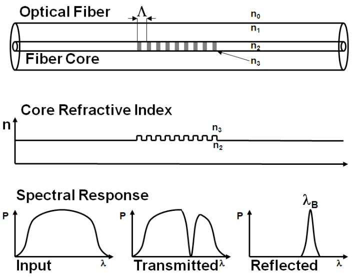

Figure 1. Fundamental principle of operation for a fibre Bragg grating

From the strain-optic effect, the change in the optical indicatrix ($1/n^2$) due to an applied strain [6] is given by,

$$\Delta\left(\frac{1}{n^2}\right)_i = \sum_{j=1}^{6} p_{ij} S_j \ . \tag{2}$$

Here, p_{ij} is the strain-optic tensor. Since the fibre is isotropic and homogeneous, the strain-optic tensor is given as,

$$p_{ij} = \begin{bmatrix} p_{11} & p_{12} & p_{12} & 0 & 0 & 0 \\ p_{12} & p_{11} & p_{12} & 0 & 0 & 0 \\ p_{12} & p_{12} & p_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & p_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & p_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & p_{44} \end{bmatrix} . \tag{3}$$

The strain vector, S_j, for an applied longitudinal strain, ε, is given as,

$$S_j = \begin{bmatrix} \varepsilon \\ -\nu\varepsilon \\ -\nu\varepsilon \\ 0 \\ 0 \\ 0 \end{bmatrix} . \tag{4}$$

Here, the strain in the two transverse directions (the diameter of the fibre), is related to the longitudinal strain by Poisson's ratio, ν. Assuming there is no shear strain, solving (2) using (3) and (4) gives,

$$\Delta\left(\frac{1}{n^2}\right)_{2,3} = \varepsilon(1-\nu)p_{12} - \nu\varepsilon p_{11} \ . \tag{5}$$

The change in the indicatrix can be related to a change in the refractive index, Δn, by [6],

$$\Delta\left(\frac{1}{n^2}\right)_{2,3} = -2\frac{\Delta n}{n^3} \ . \tag{6}$$

The change in refractive index due to an applied longitudinal strain can then be expressed as,

$$\Delta n = -\frac{1}{2} n^3 \Delta\left(\frac{1}{n^2}\right)_{2,3} \ . \tag{7}$$

$$\Delta n = -\frac{1}{2} n^3 \left[\varepsilon(1-\nu)p_{12} - \nu\varepsilon p_{11}\right] \ . \tag{8}$$

From (1) a change in the Bragg wavelength ($\Delta\lambda_B$) can be achieved by either a change in the grating period, $\Delta\Lambda$, or a change in the effective refractive index, Δn. That is,

$$\Delta\lambda_B = 2n\Delta\Lambda + 2\Lambda\Delta n \ . \tag{9}$$

The change in refractive index due to an applied longitudinal strain is given in (8). The change in grating period due to an applied longitudinal strain is given by,

$$\Delta\Lambda = \varepsilon\Lambda \ . \tag{10}$$

The change in the Bragg wavelength can then be written as,

$$\Delta\lambda_B = 2\varepsilon\Lambda n - \frac{2\varepsilon\Lambda n^3}{2}\left[(1-\nu)p_{12} - \nu p_{11}\right] \ . \tag{11}$$

Using (1), this can then be expressed as,

$$\begin{aligned} \Delta\lambda_B &= \varepsilon\lambda_B - \frac{\varepsilon\lambda_B n^2}{2}\left[p_{12} - \nu(p_{12} + p_{11})\right] \\ &= \varepsilon\lambda_B\left(1 - \frac{n^2}{2}\left[p_{12} - \nu(p_{12} + p_{11})\right]\right). \end{aligned} \tag{12}$$

Equation (12) then enables the strain applied to grating, be it from an incident pressure wave (in the case of hydrophones) or in the form of a strain wave (for mechanical vibrations), to be converted into the shift in the wavelength which can be easily determined via an interrogator.

INTERROGATION METHODS

There are essentially two broad interrogation methods available for the detection of high frequency acoustic signal with FBGs. These are edge filter detection methods, and power detection methods [7]. A small number of active detection methods are available, such as pseudo-heterodyning, but these are not considered in this review, as their implementation is small in comparison to the passive methods used.

Edge Filter Detection Methods

In edge filter detection methods, the shift in the FBG spectrum is detected by use of a spectrally-dependent filter which results in a change in intensity at the detector. The FBG is illuminated by a broadband source, such as a SLD. The change in the wavelength reflected causes the transmitted intensity to vary as the filters transmittance varies as a function of wavelength. A number of different filters can be utilised, these include a matched FBG [8], a linear edge absorption filter, an interference filter [9], a Wavelength Division Multiplexing (WDM) coupler [10], an Arrayed-WaveGuide (AWG) [11], and a Dense Wavelength Division Multiplexing (DWDM) filter.

The most straight-forward of the edge filter detection methods is the linear edge absorption filter. Typically an external filter is used. The FBG is selected such that the Bragg wavelength is at the 3dB point of the absorption filters transmittance. The light not transmitted to the detector is absorbed by the filter.

A improvement on the use of a linear edge absorption filter is the WDM coupler. This is a three port device, where the input is split between two outputs depending on the wavelength. The spectral response of the WDM coupler is such that a linear edge occurs between the wavelength of the first output and the second output. In operation, the WDM coupler works exactly the same as the linear edge absorption filter, except now the light which is not transmitted to the output is not absorbed; it is directed to the second output. This can be used to give a differential output.

The simplest form of edge filter is a matched FBG. Here an identical FBG is used as the filter which converts the spectral shift of the FBG into an intensity change. If there is no change in measurand, the reflected wavelength from the sensing FBG will match the Bragg wavelength of the filter FBG, and hence no light will be transmitted to the detector. As the wavelength of the sensing FBG shifts, the intensity transmitted by the unshifted filter FBG will increase. The only drawback to this system is that the nature of the stain (tensile or compressive) cannot be determined directly due to the symmetric nature of the curves. Also, frequency doubling will occur due to this fact since the acoustic wave is both tensile and compressive. To overcome this, the matched FBG is not identical, but typically has a linear edge, and the Bragg wavelength of the sensing FBG is matched to the 3dB point of the linear edge.

The final two edge filter detection methods, AWG and DWDM filter, are identical in their implementations. Both the AWG and DWDM filter are multichannel devices. The edges of the devices are two steep to use directly, however the channels are spaced close enough together, such that the signal will cause a differential variation in neighbouring channels, if the FBG is such that it's Bragg wavelength is located between the two neighbouring channels.

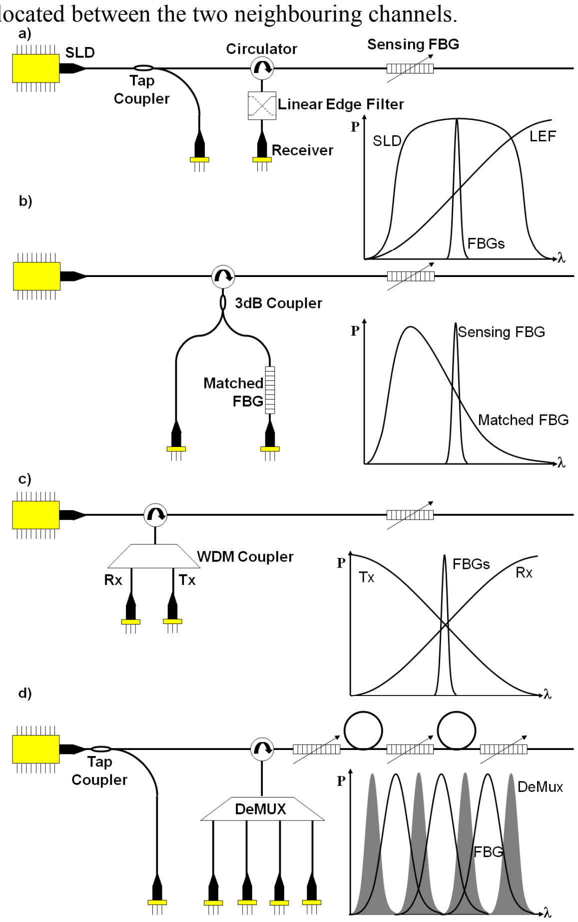

Figure 2. Optical circuits of the edge filter detection methods using a broadband (SLD) source, a) liner edge filter (LEF), b) matched FBG, c) WDM coupler, and d) AWG or DWDM DeMUX incorporating multiplexing. Insets show spectrum of the optical component

Power Detection Methods

In power detection methods, the shift in the FBG wavelength is detected by using a spectrally-dependent source, which results in a change of intensity at the detector. There are two power detection methods, linear edge source [7], and the narrow bandwidth source [12].

In the linear edge source power detection, the edge of a relatively broadband source (source bandwidth > FBG bandwidth) is used, and the FBG is chosen such that the Bragg wavelength is located at the 3dB point of the source. The wavelength shift of the FBG will then result in a direct change in the reflected intensity as it shifts up and down the edge of the source's spectrum.

The second power detection method is the opposite of the linear edge source, such that a relatively narrow bandwidth source (source bandwidth < FBG bandwidth) is set to the 3dB point of the FBG. Here, either the reflect power can be utilized [12], or the transmitted power can be utilized [13].

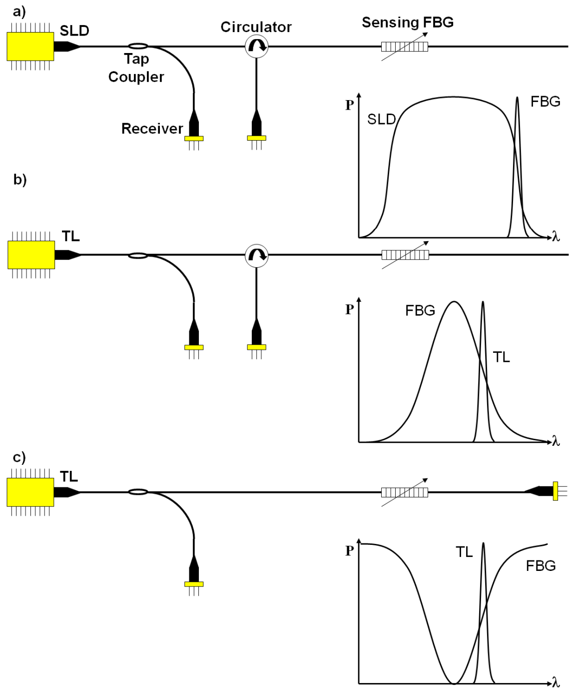

Figure 3. Optical circuits of the power detection methods, a) broadband source (SLD) power detection, and narrow bandwidth source using a) the reflected component, and b) the transmitted component. Insets show spectrum of the optical component

APPLICATIONS

FBGs have been applied to two major areas, hydrophones, and mechanical vibrations. Mechanical vibrations include non-destructive testing, smart materials and structural health monitoring. FBG acoustic sensors have also been applied to in-vivo biomedical sensing and conventional microphones.

Hydrophones

Work on FBGs for ultrasonic measurements began with the work of Webb et al. [12,14-15] in 1996. This initial work used a narrow bandwidth source power detection interrogation method. The results showed a linear transfer function between the input acoustic power and the detected signal. In addition they showed the hydrophone could detect the focal point of the 950kHz acoustic signal.

Around the same time, similar work was also being performed at the National Defense Academy in Japan by Takahashi et al. [16]. They proposed an underwater acoustic sensor using a FBG. The setup was similar to the homodyne detection method proposed by Webb et al. [12], however, the signal transmitted through the grating was detected [13]. Results, using only 20 kHz signals, show a linear relationship between the incident sound pressure and the signal intensity in dB. Results from tuning the laser show the maximum signal intensity is achieved at around the FWHM points of the FBG spectral response. Similar work was then conducted using the reflected component of the power detection signal [17]. Further work [18] included the addition of a second FBG via wavelength division multiplexing, using 2 narrow bandwidth laser diodes. It was found that the sensors worked independently of each other even though located along the same length of fibre. The two fibres were then used to determine a bearing to the source. Next, they successfully determined the spatial distribution of the acoustic field generated by the PZT transducer [19]. The FBG hydrophone results were compared to the distribution as measured by a PZT hydrophone.

Other work by Takahashi et al. has also looked at compensating for the effect of temperature [20-23]. The first method employed [20-21], used a broadband light source, which was directed to strain isolated narrow bandwidth FBGs. The reflected signal was then incident on the strain sensitive FBG located next to the narrow FBG. The result of this, is that both the narrow source FBG and the sensing FBG experience the same shift in wavelength due to the temperature. This system was shown to be compatible with the previous WDM. The second temperature compensation system demonstrated [22-23], used a feedback circuit to control a tunable laser. As the temperature changes, shifting the Bragg wavelength, the feedback tunes the wavelength to maintain the 3dB point. This systems was demonstrated with a Time Division Multiplexing (TDM) system.

Fomitchov and Krishnaswamy [24-25], also proposed the use of a FBG for the detection of ultrasonic waves in liquids and solid structures. Again the implementation is the same as that initially used by Webb et al. [12]. The system makes use of a tunable laser tuned to the operating point of the FBG, and a photodetector to measure the returned intensity. They report sensitivity over a broad frequency range, from 10 kHz to 5 MHz.

Cusano et al, presented work on polymer coated hydrophones [26]. This work investigated different geometric configurations of the polymer coating, and the effect this had on the performance. Further work investigated the effect of different polymer [27]. Combined with the geometry result, a final hydrophone configuration was presented.

An innovative hydrophone was presented by Ni et al. [28]. Here a FBG pair was used in a push-pull configuration, one inside the mandrel and the other outside. A single broadband source is used, which is incident on the first grating. The component transmitted through this grating is then incident on the second grating. The signal reflected from the second FBG is then detected. Since the FBG inside the mandrel will experience the opposite strain to the FBG outside, the received signal will increase with the applied strain.

Mechanical Vibrations

The first work on detecting high frequency dynamic strain waves was presented by Lissak et al. [29]. Again the same narrow bandwidth source power detection was used [12]. However, the system used a tap-coupler to monitor the power from the source. In addition to this, an active feedback control circuit was used to track the FBGs 3dB point.

Arround the same time, Blue Road Research was also investigating high frequency dynamic strain sensing [30-31]. This work used their in house developed matched FBG edge filter detection system. This work then led to research into detecting ultrasonic strain waves [32]. The work on acousto-ultrasonics at Blue Road Research, investigated the spatial performance of FBGs. They also presented the first FBG acoustic emissions sensor, successfully detecting the acoustic emission from a lead pencil break test [8].

In addition to the extensive work on hydrophones, the group at the National Defense Academy in Japan has also investigated mechanical vibration sensing with FBGs. This work paralleled the hydrophone development, starting in 1999 [33]. Again transmission narrow bandwidth source power detection was initially used [34], followed by the use of the reflected component [35]. Further work made use of a broadband source to illuminate multiple narrow source FBGs for WDM [37]. As with the work on hydrophones, the mechanical vibration sensing work also investigate temperature stabilisation, [38-39], and an improved method to simultaneously measure dynamic strain and temperature [40].

The most substantial work on ultrasonic Lamb waves was initially conducted by Betz, Thursby, Culshaw and Staszewski [41-44]. Starting with the usual narrow bandwidth source power detection method, Lamb waves were measured in a Perspex plate [41]. Further work then investigated the ability of this Lamb wave based acousto-ultrasonic system to detect the presence of damage [42-43]. This was followed by work utilising three FBGs in a rosette structure to locate the damage [44].

A significant body of work has also been published by the National Institute of Advanced Industrial Science and Technology (AIST) in Japan. This work, by Tsuda et al. [45] began looking at sensing dynamic strain signals with an FBG, from impacts. The interrogation system used was like that employed by the Blue Road Reserch group, a matched FBG linear edge fitler. Following this preliminary work, Tsude et al. looked at the ability to detect damage in Carbon Fibre Reinforced Plastics (CFRP) [46-47]. The same work was then repeated using a narrow bandwidth source power detection method [48]. Resulting from this work, was the development of a novel sensor head that could be easily moved around a sample, in a similar way to a convention piezoelectric transducer [49-50]. This transducer was tested on the CFRP, and again used the power detection methods. Following the work in CFRP plastic, Tsude et al. investigated the ability to use their system to monitor fatigue cracking in stainless steel [51]. The work on fatigue cracking in stanless steel was then repeated using the movable sensor head [52]. Next, Lee and Tsuda used a conventional strain isolated FBG temperature sensor as a receiver for acousto-ultrasonic signals [53]. Lee et al. then used Fabry-Perot filters for the first time in a edge filter detection system [54]. Other work by Lee et al. investigated birefringence effects in surface bonded and embedded FBG [55]; specifically, the loss associated with this, and how to overcome it.

Similar to the work by Culshaw et al., Takeda et al., presented a damage monitoring system using acousto-ultrasonics, but this time in composite laminates [56-60]. The most novel part of this new work, was the use of the AWG edge filter detection system [56]. Following the experimental work on the ability to detect Lamb waves [57], work investigated the ability of the acosuto-ultrasonic system to detect the presence of damage [58-59]. Their work also considered the ability to connect to small diameter fibre embedded within the composite laminate [60].

Cusano et al. worked in the reverse direction, to Takahashi et al., working on dynamic strain sensing prior to working on hydrophones. The work on dynamic strain sensing by this group utilised two interrogation methods, first utilising a WDM coupler for edge filter detection [9, 61]. More recent work has utilised transmissive linear edge filters [10].

Mircophones

Very little work has appeared in the literature on the use of FBG acoustic sensors as microphones. Their implementation is not very practical, with the required optoelectronic components. However, with the development of photonic technology, with the goal being the photonic processor, an optical equivalent of a conventional microphone may prove necessary. There is however, one current area of research for FBG microphones, microphone arrays.

Iida et al. presented a FBG microphone array [62]. Microphone arrays are used for sound field visualisation, and for sound source location. However, conventional electronics suffers from electromagnetic noise due to the heavy bundling of coaxial cables. The interrogation method used was narrow bandwidth source power detection, and the FBG was bonded across a diaphragm.

Another FBG microphone with applications to arrays was presented by Mohanty et al. [63]. Here the interrogation method used was a linear edge filter; however, the fibre containing the FBG was bonded longitudinally to the diaphragm, as opposed to the previous microphone, where the fibre was bonded laterally.

Biomedical Applications

The initial work on FBGs for acoustic sensing by Webb et al. was initially proposed with application to medical ultrasound [12]. The fact that FBGs are embedded within very thin optical fibres means they are ideal for endoscopic applications. The primary purpose proposed was to assess the safety of ultrasound for medical applications. The use of an endoscopic ultrasonic probe would enable the effect of the high power ultrasonic signals to be assessed in-vivo.

TRANSMIT REFLECT DETECTION

Interrogation

As previously mentioned, in narrow bandwidth source, either the reflect component or the transmitted component from the FBG can be used. However, both the transmitted and reflected components occur simultaneously. As the strain from the acoustic field varies the Bragg wavelength, the FBGs 3dB point is also shifted. As a result, the amount of optical power reflected from the FBG will change, either positive or negative, depending on which edge of the FBG was used, and the direction of the measurand. The same variation also occurs to the optical power transmitted through the grating, although in the opposite direction. Since the components vary in opposite directions, they can be differentially amplified to increase the overall signal. Figure 4 shows the optical circuit for the TRDS.The principle of operation for the TRDS is illustrated on in Figure 5.

Method

For the TRDS a tunable laser (Ando AQ 8201-13B) was used as the laser source. Light from the laser was then directed to the FBG (Broptics GF-1C-1554.13-RX2) via a circulator (FDK YC-1100-155). The light transmitted through the FBG was then directed to one of the two photoreceivers (Fujitsu FRM3Z231KT), while the light reflected was directed to the second receiver via the circulator. The preamp supply and PIN bias for the two receivers was provided by a +/- 5V DC power supply. The output of the two receivers was differentially amplified using a high speed differential amplifier (AD830ANZ). For this work, a gain of 1 was used on the amplifier. Figure 6 shows the optoelectronic circuit of the TRDS, including the power supply, receivers, and amplifier.

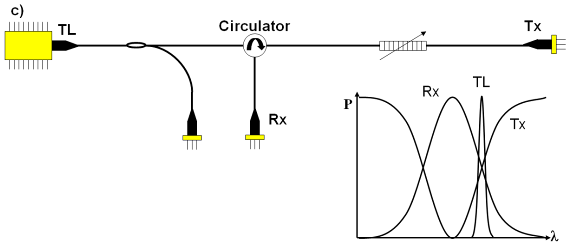

Figure 4. Optical circuit of the TRDS, with the tunable laser (TL), and the transmit (Tx) and reflect (Rx) receivers. The inset shows the spectrum of the optical components

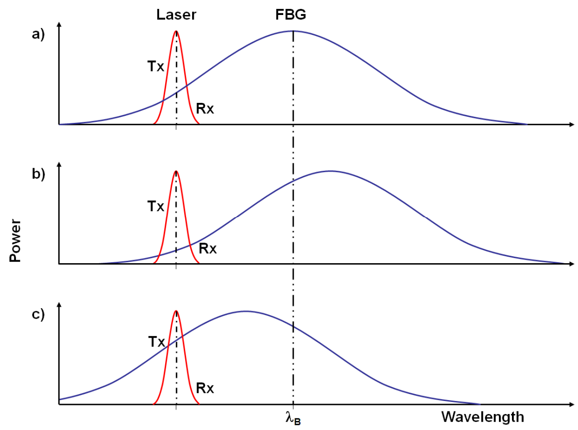

Figure 5. Operating principle of the TRDS, a) shows the FBG with no change in measurand, b) a positive change, and c) a negative change

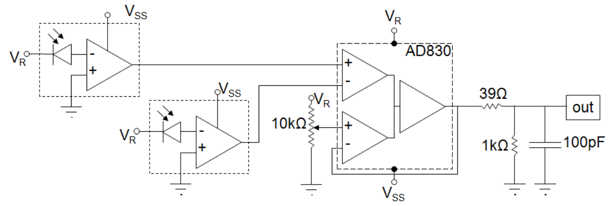

Figure 6. Circuit Diagram of the TRDS, showing the 2 receivers and the differential amplifier

First, the static strain sensitivity of the FBG sensor using the TRDS was measured. The FBG was bonded to a stainless steel sample which was used in a tensile stress strain apparatus. The connected PC was used to record the applied stress, the resultant strain, and the voltage signals from the TRDS. The laser was tuned to a wavelength just off the FBG (no reflected signal). Stress was then applied to the sample until the maximum signal was received.

The FBG was coupled to an aluminum panel (1.5mm x 200mm x150mm) using acoustic coupling gel. The FBG was located directly opposite a PZT transducer (Steiner and Martins SMQA) which had a thickness of 2.1mm and a diameter of 10mm. These dimensions correspond to resonant frequencies of approximately 1 MHz and 100 kHz, respectively. The output of the differential amplifier was connected to an RF spectrum analyser. The configuration of the dynamic strain experiment is shown in figure 7. The FBG gave the largest signal at a frequency of 108 kHz.

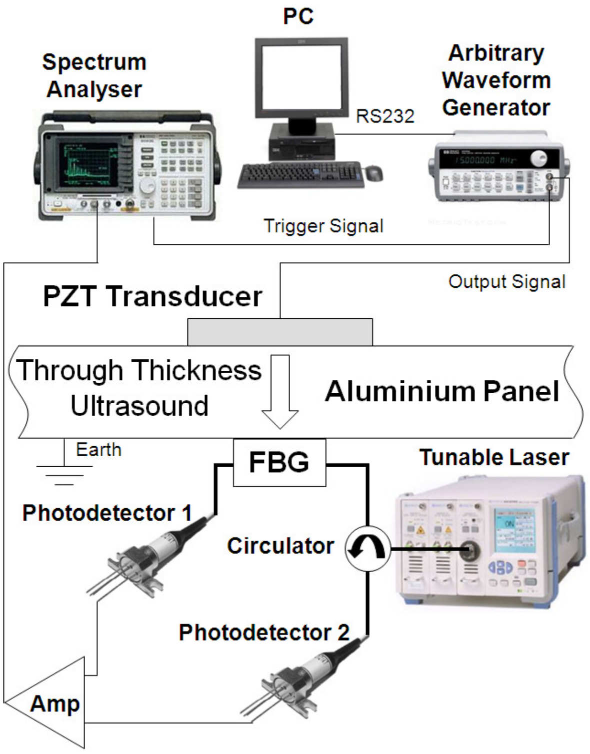

Figure 7. Experimental setup for the dynamic strain measurements

A lead pencil break test was performed to demonstrate the sensitivity of the TRDS with an FBG acoustic sensor. The result of the lead pencil break test is the generation of an AE signal. The test was performed 100mm away from the FBG, in the direction along the optical axis of the FBG. This located the pencil next to one of the panel support beams, to minimize plate flexure, which would also result in a dynamic strain signal.

Results

Figure 8 shows the results of the static strain measurement. This gives a sensitivity of 1.404V/με. The result of the dynamic strain measurement, gives a SNR of 60.22 dB, and a bandwidth of 3 Hz. Combined with the sensitivity, this gives a dynamic resolution of 460 pε/√Hz at the maximum signal strength, $2V_{Pk\text{-}Pk}$. This value is just over 3 times the value given by Lissak et al., which utilised a feedback circuit to track the 3dB point of the FBG.

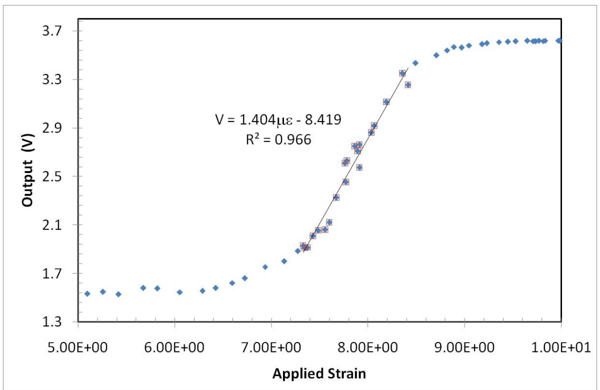

Figure 8. Static strain result, the transfer function shows a sensitivity of 1.404 volts per microstrain

CONCLUSION

In conclusion, we have presented a broad overview of fibre Bragg grating acoustic sensing, covering the theory of operation, passive interrogation methods, and applications. We have also shown the Transmit Reflect Detection System (TRDS) for FBG sensors. As an intensity based detection system, the TRDS is intended to be used for high frequency measurands, such as ultrasound. The TRDS was shown to have an increased sensitivity over conventional narrow bandwidth source power detection. The TRDS also shows a good dynamic resolution, of 460 pε/√Hz.

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