Distributed Optical Fibre Smart Sensors for Structural Health Monitoring: A Smart Transducer Interface Module

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***Abstract*—In this paper, we present a Smart Transducer Interface Module (STIM) for distributed optical fibre smart sensors. The STIM is a general purpose interface that has been designed to be used with intensiometric optical fibre sensors. The interface is made up of 2 optical fibre PIN receivers, a differential amplifier and a digital signal processor. The two received signals are differentially amplified to increase sensitivity and the signal-to-noise ratio. A DSP evaluation board is used as the intelligence of the STIM, which has onboard ADC. The STIM was successfully used as an embedded system monitoring both temperature and strain, and to simply switch on the onboard LED when these measurands exceeded a predetermined threshold value. The sensing system, without the DSP, was also used to successfully detect dynamic strain signals. We also present the future directions for work on distributed optical fibre smart sensors.**

I. Introduction

The focus of Fibre Bragg Grating (FBG) sensing work is usually based on the ability to multiplex FBGs. As Optical Fibre Sensors (OFSs), FBGs have several other properties that make them of interest to sensing areas, especially Structural Health Monitoring (SHM) [1]. The most significant of these advantages include reduced size and weight, immunity to electromagnetic interference, and most significantly, the versatility of FBGs to detect different measurands. For SHM, an FBG system can be used to detect Acoustic Emissions (AEs), actively generated Acousto-Ultrasonic (AU) signals, dynamic strain (eg vibration), static strain (eg load monitoring), and corrosion, as well as with a variety of other measurands.

As with other OFSs, FBGs have found a niche in applications utilizing multiplexing, such as distributed sensing for large scale structure, including bridges and other civil structures. A number of multiplexing architectures can be applied to FBG sensing, include Wavelength Division Multiplexing (WDM) and Time Division Multiplexing (TDM) [2]. However, multiplexed OFSs, with a single fibre, a single source, a single detector and a single processor, have an inherent flaw, a lack of redundancy. If damage occurs to the structure, resulting in damage to any of the four elements of the system, then potentially the system can become inoperative. Optical Fibre Smart Sensors (OFSSs) represent a robust technology with inbuilt redundancies for both sensors and intelligence. This property goes towards achieving NASA's goal of robust or ageless aerospace vehicles, as outlined in the Airframe Structural Integrity and Airframe Airworthiness Programs [3], Ageless Systems.

As with other smart sensors, OFSSs utilise local processing power to add intelligence. The use of a local processor then requires an interface to the OFSs monitored by the processor. In this work, we present a Smart Transducer Interface Module (STIM) for FBG sensors to realise OFSS. Typically, FBGs are used as spectral transduction elements due to the absolute nature of spectral encoding and the immunity to optical power fluctuations. However, spectral decoding methods, which are typically slow, cannot be used for high frequency signals, such as ultrasound. FBGs can also be used as intensiometric sensors, were the sensor signal is recovered via either power detection, or edge filter detection [4]. For the STIM to monitor high frequencies, it has been designed to use a Transmit Reflect Detection System (TRDS) [5]. The TRDS utilises both the transmitted and reflected components from the FBG sensor, which are differentially amplified to increase sensitivity and signal to noise ratio.

II. Fibre Bragg Grating Sensor

A. Fibre Bragg Grating

A FBG [6] is a spectrally reflective component that uses the principle of Fresnel reflection. The grating is made up of alternating regions of high and low refractive indices. The periodic grating acts as a filter, reflecting a narrow wavelength range, centred about a peak wavelength. This wavelength, known as the Bragg wavelength (λ_B), is given by,

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

where n is the average refractive index of the grating, and Λ is the grating period.

Any measurand that has the ability to affect either the refractive index or the grating period can be measured using an FBG as a sensor. The change in the measurand will corresponds to a change in the peak reflected wavelength.

B. FBG Intensiometric Detection Methods

Power detection was the first methods implemented for FBG sensors to detect high frequency acoustic signals [7]. Figure 1, shows the reflectivity as a function of wavelength for a typical FBG. Centered about λ_0, there is a linear region, $\Delta\lambda$, between reflectivities of approximately 20 and 80 percent. This linear "edge" of the FBG is used as an optical filter. A narrowband laser source centered about λ_0 is then intensity modulated by the strain induced shift in the wavelength. That is, the reflected optical power is varied as the linear edge of the FBG is shifted in the spectrum. The detection of the signal is then achieved using a simple photoreceiver.

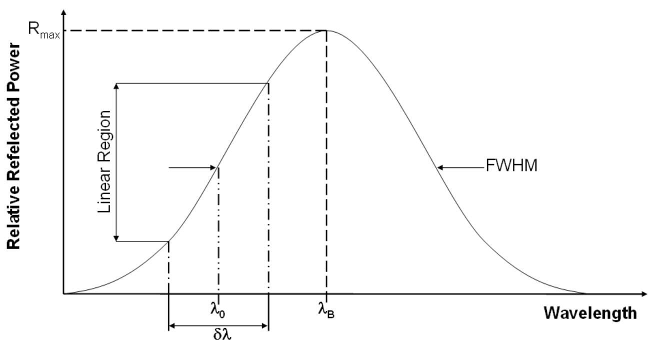

Fig. 1. The relevant parameters for power detection with a FBG shown on a typical reflectivity plot.

In edge filter detection for high frequency acoustic signals [8], a broadband light source is used to illuminate the FBG. The narrowband signal reflected from the FBG is then passed through an edge filter. The filter used typically has a linear edge. As the Bragg wavelength of the sensing FBG shifts up and down in the spectrum of the linear edge filter, the amount of light transmitted through the filter varies accordingly. The simplest edge filter detection system uses an identical FBG as the filter. However, a matched FBG, which has one of its 3dB points matched to the Bragg wavelength of the sensing FBG, is a better option. Alternatively, an absorption or interference filter can be used. The advantage of this is that a single filter could be used for multiple FBGs if the gradient of the linear edge is suitable. Figure 2 shows the spectral properties of the components used in edge filter detection.

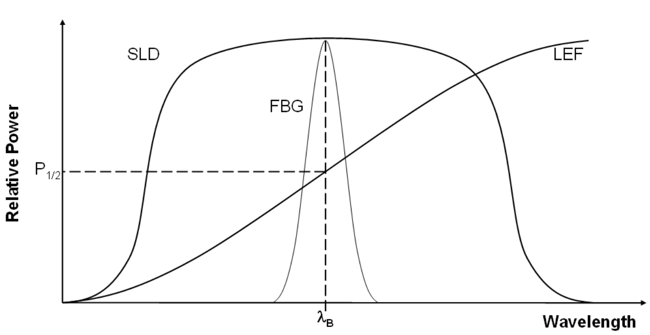

Fig. 2. Spectrum of components used in edge filter detection; a superluminescent diode source (SLD), a linear edge filter (LEF), and FBG.

C. Transmit Reflect Detection

In power detection, the reflected optical power is modulated by the measurand. This modulation also occurs to the transmitted signal. Previous FBG sensing has used the transmitted signal as opposed to the reflected [9]. When the change in the reflected optical power is positive, the change in transmitted optical power is negative, and vice versa. Since one change in measured signal is positive, and the other is negative, the two signals can be differentially amplified, giving an increased signal. This is the operational principle of the TRDS. Figure 3 illustrates this idea, showing how the transmitted (Tx) and reflected (Rx) components of the narrow width laser are varied as the FBG spectrum is shifted by the measurand.

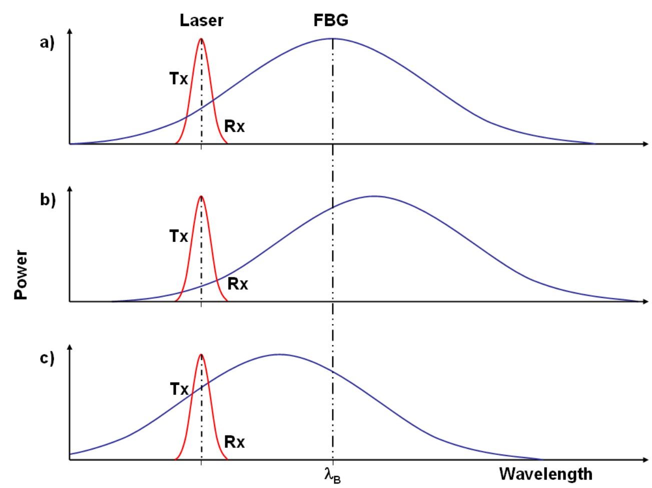

Fig. 3. Operating principle of the TRDS, a) shows the FBG with no change in measurand, b) a positive change, and c) a negative change.

Figure 4 shows the optical circuits associated with the different intensiometric detection methods used for FBG sensors. These include matched grating edge filter detection, figure 4 a), power detection using the reflected signal, figure 4 b), power detection using the transmitted signal, figure 4 c), and transmit reflect detection, figure 4 d).

III. Smart Transducer Interface Module

A. Microcontroller

The STIM for the FBG sensors is based on a Texas Instruments (TI) TMS320LF2407A Digital Signal Processor (DSP). The DSP is mounted on an eZdsp general purpose evaluation board. This TI DSP was chosen due to its onboard high speed ADC. The variety of general purpose I/O and expansion options also enables further development for future work. The evaluation board has a 16 channel onboard ADC, and 50 general purposed digital I/O. The DSP is programmable via the parallel port, using the C programming language.

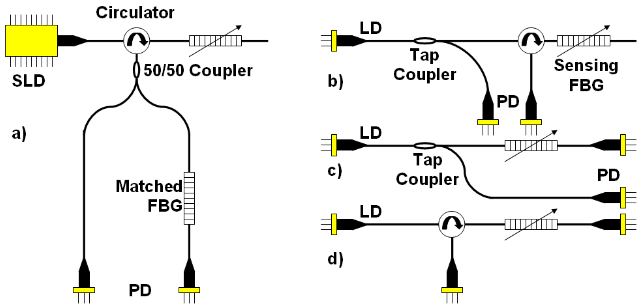

Fig. 4. Optical circuits of FBG intensiometric detection methods, a) edge filter detection, b) power detection (reflection), c) power detection (transmission), and d) transmit reflect detection. Components are a superluminescent diode (SLD), laser diodes (LD) and photodetectors (PD).

B. Sensor to DSP interface

To detect the optical signals, the STIM utilises 2 PIN receivers (Fujitsu FRM3Z231KT). The preamp supply and PIN bias for the two receivers is provided by an onboard +/- 5V DC power supply (which can also power the DSP). The output of the two receivers is differentially amplified using a high speed differential amplifier (AD830ANZ). A 2.5V DC offset is supplied to the second summing input of the difference amplifier via a voltage divider from the +5V. Due to the sensitivity of the TRDS, a gain of 1 was used on the amplifier. Ideally this should be approximately 2.5 to utilise the full 5V range of the ADC. Figure 5 shows the circuit diagram of the STIM, including the power supply, receivers, amplifier, DSP and laser.

In the preliminary test of the STIM, the laser source controlled was a distributed feedback Laser Diode (LD), controlled by the I/O of the DSP via a BC547 NPN bipolar transistor, with appropriated current limiting resistors. The proposed source to be added in future work is a two channel [10] Thermoelectric Cooler (TEC) tunable LD. The LD would be tuned by the STIM in a closed loop feedback system to maintain the 3dB point of the FBG.

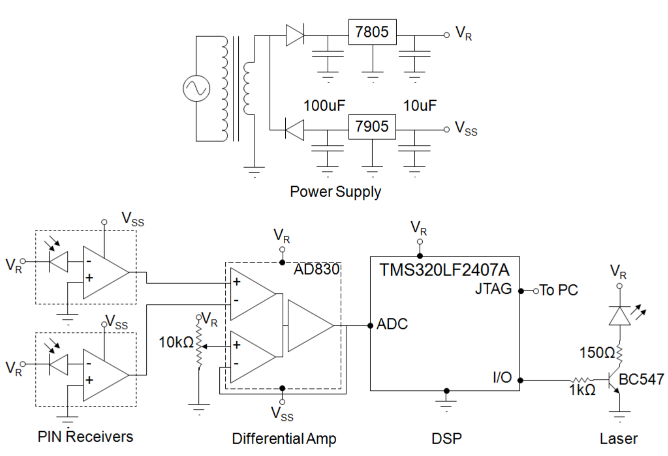

Fig. 5. Circuit diagram for the major components of the STIM, including the DC power supply, PIN receivers, differential amplifier, DSP and laser source which has been biased to operate at approximately 2mW.

IV. EXPERIMENTS

A. Sensor

At this stage, a bench-top laser module was used in place of the LD. The module used was a tunable laser (Ando AQ 8201-13B). This was then connected to the FBG (Broptics GF-1C-1554.13-RX2) via an optical circulator (FDK YC-1100-155). The reflected signal was directed down to the first photoreceiver via the optical circulator, and the transmitted signal from the FBG was directed to the second receiver. The optical circuit used was identical to that shown in figure 4 d).

B. Static Measurements

Current experimental work with the STIM has focused on embedded detection of quasi-static measurands. The TRDS has previously been used to detect quasi-static quantities [11]. The STIM was used to monitor both static strain and temperature, in a switching system. The DC signal from the TRDS was used to determine if the onboard LED should be switch on or off. Initially the laser source was tuned to the Bragg wavelength using an optical spectrum analyser. This gave a maximum reflected signal and a minimum transmitted signal. The two receivers were then chosen to give a minimal DC value, approximately 1.5 V. The corresponding maximum value was approximately 3.5 V.

For temperature, the sensing system was used to monitor the temperature of water. The FBG, immersed in a beaker of water, was slowly heated using a hotplate. A value of 3 V was used as the turn on value for the onboard LED, and 2 V was used as the turn off Value. For the strain, the sensing system was used to monitor the longitudinal strain applied to a steel sample. The FBG was bonded to the sample using cyanoacrylate. A stress strain apparatus was used to apply a tensile force to the test sample. Again the same turn on and off values were chosen.

C. Dynamic Measurements

Tests were performed to ensure that the TRDS and the amplifier could be successfully used to detect dynamic signals. Dynamic strain signals were generated by actively vibrating the aluminium panel the FBG was coupled to. Also, a piezoelectric transducer was used to actively generate ultrasonic signals. The output signal from the amplifier was monitored on a DSO. So the amplifier could be used to drive the capacitive load of the DSO, the output of the circuit was modified. This required the addition of a series resistor, as well as a parallel capacitor and a parallel resistor, as shown in figure 6.

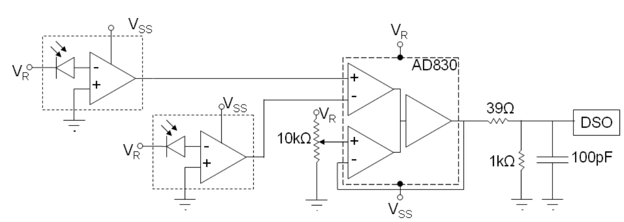

Fig. 6. Modified circuit diagram to use the TRDS with a DSO.

V. Future Work

Although in this work we present a single STIM, the goal of the Distributed Optical Fibre Smart Sensors (DOFSSs) work, is to network multiple STIMs together in a smart sensor network. This will enable a robust SHM system to be realised utilising OFS. This will culminate in the development of a test-bed structure, made up of a three by four array of STIMs.

Future research on the test-bed will look at fundamental aspects of the system, and sensing with the STIMs. At the system level, future work will look at developing two aspects of the network. These fundamental parts are communications and power. At the sensing level, the primary work will be developing the ability of the DOFSS system to detect as many different measurands as possible.

In current ongoing work, optical circuits will be investigated to be able to not only detect, but locate AE. This will require 3 sensors to be multiplexed together to be able to triangulate the source of the acoustic signal. If the three FBG sensors are configured in an equilateral triangle configuration, not only could they be used to detect and locate AE or actively generated AU signals, they could also be used as a strain gauge rosette, to determine the coefficients of the in-plane strain.

Since three sensors are required for triangulation, and for the strain gauge rosette, small scale multiplexing will be required. Both WDM and TDM could be utilised with the STIM.

The simplest method would be to utilise a broadband, superluminescent diode (SLD) as the source, and a linear edge filter. Linear edge filters have previously been report for the detection of dynamic strain signals [12]. Both detectors from the STIM would be utilised to eliminate the effect of input optical power fluctuations, by using a tap coupler, with the appropriate splitting ratio. The TDM would be achieved by pulsing the signal from the SLD. The fibre loops length would be chosen such that the delay between the FBGs is such that the three signals could be resolved by the ADC onboard the DSP. Figure 7 a) shows the optical circuit of the TDM. Figure 7 b) shows a superior, but more complicated configuration. An identical reference fibre would be utilised. This reference length would have identical FBGs and delays. This has the advantage of being directly compatible with the dual detector system of the STIM. If possible, the reference fibre length could be collocated with the sensing fibre length. If the reference FBGs were then strain isolated [13], to reduce, or eliminate the sensitivity to static and dynamic strain signals, then this configuration could be utilised to remove the FBGs cross sensitivity to temperature, as both the sensing and reference FBGs would experience the same temperature.

Pure WDM would require the use of more than two detectors. This would not be a problem for the STIM, as the current evaluation board has 16 ADCs. The advantage of pure WDM is the continuous monitoring of all three sensors simultaneously. The use of pure WDM requires the addition of a wavelength demultiplexer (DeMUX) to the optical circuit. There are two options for the WDM, using multiplexed lasers, or a single SLD.

For the multiplexed lasers, each laser would be set to a 3dB point of an FBG, which are located in the pass bands of the DeMUX. The optical circuit of this system is shown in figure 8 a) while figure 8 b) shows the spectrum of the DeMUX pass bands (filled in), the lasers (delta functions), and the FBG (unfilled Gaussians).

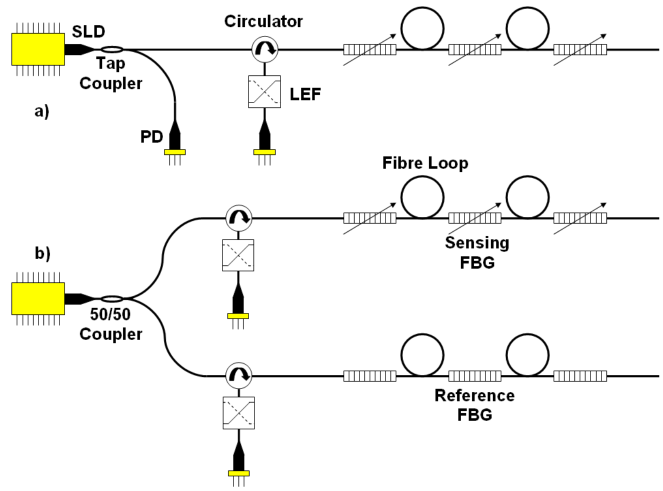

Fig. 7. TDM of three FBGs using a broadband superluminescent diode (SLD) and linear edge filters (LEF), using either a) a tap coupler, or b) a reference fibre length to compensate for input optical power fluctuations.

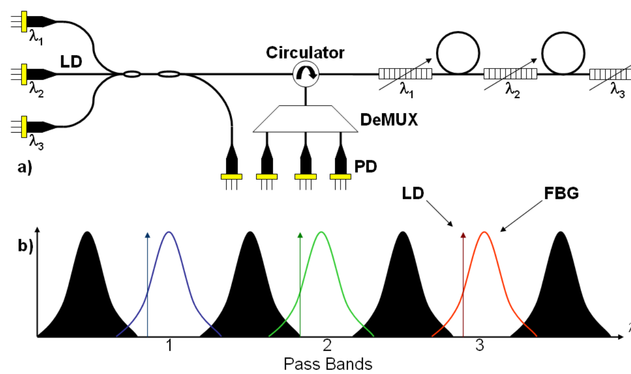

Fig. 8. a) WDM of three FBGs using three laser diodes (LD) using a demultiplexer (DeMUX), and b) the spectral response of the optical component, where the DeMUX channels are in black, the FBGs are the Gaussian functions, and the lasers are the delta functions.

For pure WDM using a single SLD, the pass band edges of the DeMUX would be used as the linear edge filter. A similar method has previously been reported using an arrayed waveguide [14]. Two configurations are possible with this WDM. The FBGs could be narrow and set to the 3dB point of the DeMUX pass band edge, which is edge filter detection. Alternatively, a broader FBG could be used, that has its Bragg wavelength exactly in the centre of the DeMUX pass band, and the 3dB point of the FBG cross the 3dB point of the pass band edges, on both sides. The second configuration would be more tolerant to cross sensitivity issues. Ideally, adjacent channels of the DeMUX would not be used, so crosstalk between the channels could be minimised. Figure 9 a) shows the optical circuit of this option, with both FBG configurations depicted in figure 9 b) and c)

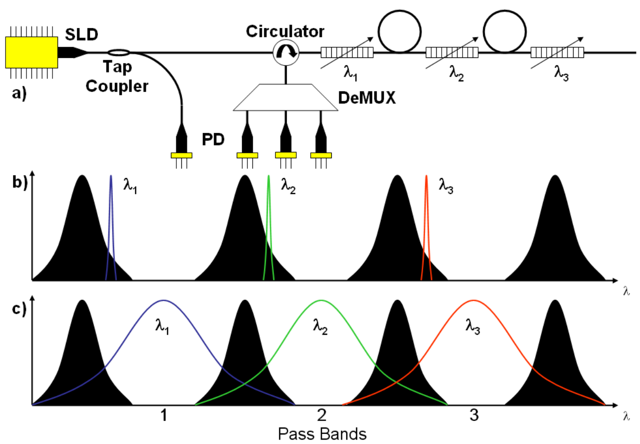

Fig. 9. a) WDM of three FBGs using a single broadband source, either using b) narrowband FBGs located on the edge of the DeMUX, or c) broadband FBGs located in the middle of the pass bands, crossing at the 3dB points.

To remove the need for additional receivers, WDM could be combined with TDM. For the multiplexed lasers, this would result in a dramatic simplification of the optical system, as shown in figure 10 a). For the single SLD, an optical switch would need to be added to select the appropriate FBG. This is shown in figure 10 b).

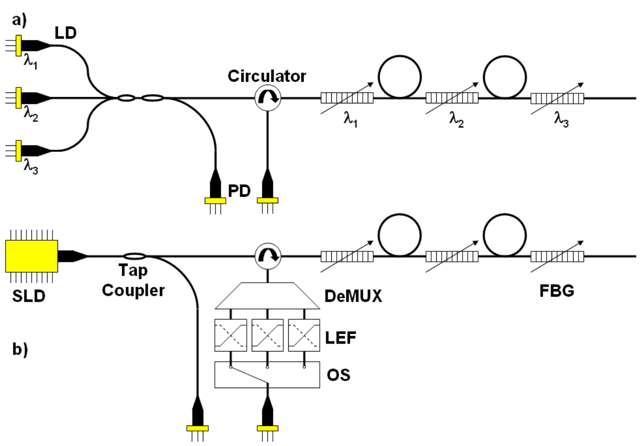

Fig. 10. Combined WDM and TDM for a) three multiplexed laser diodes, and b) a single broadband source, which requires the addition of the optical switch (OS).

Clearly the use of optical fibres suggest that, although against current trends in smart sensing technology [15], the system should be "wired" with the use of optical fibre. In this way, the optical fibres would not just be used for sensing, but to link the STIMs together for communications. Ideally, the system would utilise the same fibre for both sensing and communications, simultaneously. This would require the addition of a communications specific laser, possible at 1310nm, if the sensing is done at 1550nm. This would then enable a 1550nm/1310nm combiner to be utilised to multiplex the wavelengths together, without the loss associated with an additional conventional coupler. Several different network topologies will be investigated to determine the merits and flaws of each. The simplest of these topologies would be a four way nearest neighbour single link. A step up from this would be a dual link, which would help increase the robustness of the system. These two connection topologies are shown in figure 11.

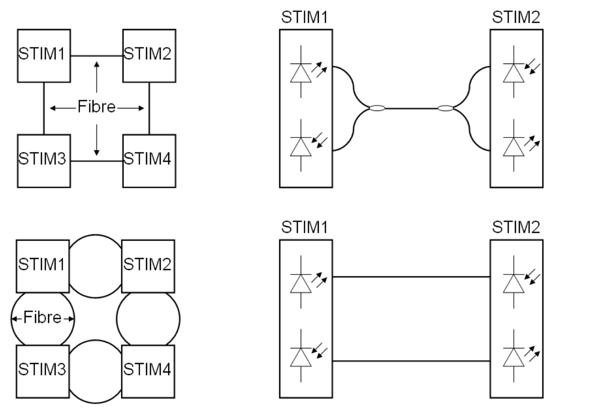

Fig. 11. Four way nearest neighbour topography of the DOFSS network, with either a single or dual fibre link.

However, the use of three FBGs suggests a hexagonal topology could be utilised to form sensor rings between the STIM nodes of the sensor network. The sensor ring would enable all three sensors to be accessed by all three nodes that connect to the sensor ring. This access would include both the transmitted and reflected components. Figure 12 a) shows the sensor ring structure, with the three STIMs connected, while figure 12 b) shows how the ring is formed with 3dB couplers on both sides of the FBGs. In figure 12 b), one fibre from the STIM would be for the signal out and the component reflected, while the second fibre connection would be for the component transmitted around the ring.

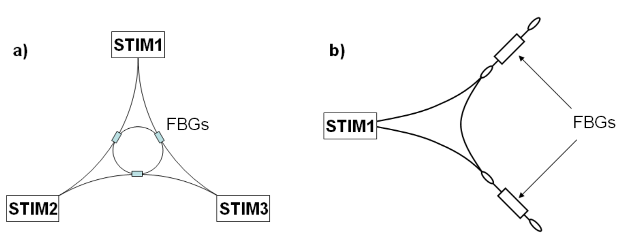

Fig. 12. Three way, hexagonal topology for the DOFSS network using the sensor ring structure.

The primary advantage of wired sensor networks is the easy distribution of power through the network. This also represents the primary drawback of wireless sensor networks:

the requirement for a local power supply, or the need to harvest power in some way. Since the "wired" part of the DOFSS network is the optical fibres, it may be possible to distribute power optically through the network. Although photovoltaics is seen as a low efficient way of generating power, this is only because the low efficiency of silicon as an optoelectronic material. With the choice of a suitable material and wavelength, the efficiency of optical generation and reception may be improved to a suitable level for the DOFSS network. As with the optical fibre communications, the optical power would ideally utilise the same fibre as that used for sensing. Again the optical power signal would be at a different wavelength.

VI. Conclusion

In conclusion, we have presented a Smart Transducer Interface Module (STIM) for Fibre Bragg grating (FBG) sensors. The STIM has been designed to realise Distributed Optical Fibre Smart Sensors (DOFSSs) which can be used in a robust sensor network for Structural Health Monitoring (SHM). The STIM was successfully used to monitor both temperature and static strain. The sensing system was also used to detect dynamic strain signals. We also showed how a DOFSS system could be configure to detect and locate acoustic emissions, while simultaneously monitor static strain. Different network topologies were also discussed.

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